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Influence of High Priority Users on the System Capacity of Mobile Networks

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Abstract— **Wireless mobile radio systems have to serve users with different Quality of Service (QoS) requirements. Scheduling algorithms like Weighted Proportional Fair (WPF) have been proposed considering channel gains to improve the system capacity in terms of sector throughput as well as user priorities to fulfil QoS requirements. These scheduling algorithms allow assigning different priority factors to users and services so that different QoS requirements can be fulfilled. This paper provides an analysis of the influence of users with different priorities on the sector and user throughput. It is shown analytically and by system level simulations that the average user throughput can be adjusted by choosing a specific priority factor. Furthermore, it is shown that the sector throughput decreases if WPF scheduling for users with different priorities and Full Buffer model are considered compared to a scenario with users having equal priority. If QoS requirements for realistic traffic models, e.g. FTP, have to be fulfilled, for each high priority user low priority users have to be removed from the system in order not to exceed an acceptable number of unsatisfied users. It is shown that the decrease in sector throughput with a realistic traffic model and QoS requirements is higher than for the Full Buffer model.**

I. INTRODUCTION

Wireless mobile radio systems have to serve different services like file download, web browsing, audio streaming and voice transmission. Each service has different Quality of Service (QoS) requirements regarding throughput and delay. Therefore, e.g., in IEEE 802.16 WiMAX [1] several scheduling service classes are defined which can be used to assign different parameters, e.g., minimum reserved data rate. Furthermore, it becomes important to operators to provide different QoS guarantees to users, e.g., if there are users which pay more money for higher QoS than other users with the same service. In the following, it is assumed that service classes and QoS requirements are represented by a single parameter called priority factor. Approaches to find the optimal priority factor are not addressed in this paper and can be found in [2-4]. Without loss of generality, it is assumed that each user has only one service and the term user priority is used throughout this paper.

Conventional scheduling algorithms for wireless packet-switched networks like Proportional Fair (PF) scheduling only consider channel gains and previously achieved user throughput, but different QoS requirements are not considered [5-7]. System capacity in terms of sector throughput can be improved if users are only scheduled in high channel gain conditions. If different QoS requirements shall be considered in addition, approaches like Weighted Fair Queueing (WFQ) [8] or Weighted Proportional Fair (WPF) scheduling [2-4] are applicable. The performance of PF scheduling algorithms regarding user performance in Wireless Systems using Orthogonal Frequency Division Multiple Access (OFDMA) is well investigated [4, 9, 10]. These approaches allow users with higher QoS requirements to transmit data even in situations when their channel gains are low. It is obvious that this strategy reduces the sector throughput compared to PF scheduling, but it differentiates services according to their QoS requirements. The influence of users with different QoS requirements on the system capacity is little investigated.

This paper investigates the impact of scenarios with different user priorities on the sector throughput and the effective SINR distribution during transmission. Priorities are assigned to users according to the QoS requirements of the service. Different QoS requirements are possible for the same service, e.g., if different amount of money is paid by different users for the same service. User priorities are considered in a WPF scheduler who is exemplarily investigated in this paper. The influence of users with different priorities on the system capacity is analysed in terms of average achieved user throughput, average achieved sector throughput and the distribution of the channel gain which is obtained if only the channel gains of scheduled users are considered. The latter is called effective channel gain of the system in the following and a comparison of the probability density function (pdf) of the effective channel gain with WPF scheduling and PF scheduling is provided in this paper. If higher effective channel gains are obtained, the capacity of the system can be improved due to achieving higher throughput or reducing interference. Furthermore, results for sector and user throughput as well as Signal-to-Noise-plus-Interference Ratio (SINR) distributions are provided from system level simulations.

This paper is organised as follows. In section II-A, the WPF scheduling algorithm is described. Sections II-B and II-C provide the analysis of WPF scheduling regarding the average achieved user throughput and the pdf of the effective channel gain. In section III-A, the assumed system model for the system level investigation is described. Section III-B and section III-C show the results of the system level simulation for a Full Buffer and FTP traffic model, respectively. Finally, conclusions are drawn in section IV.

II. Scheduling of Users with different Priorities

A. Scheduling Algorithm

In this section, the WPF scheduling algorithm is described starting from the description of the PF scheduling algorithm [6, 7]. The smallest unit that is allocated to a user during scheduling decision is called a slot. A slot has finite length in time which is called timestep. In the following, $R_k(t_i)$ denotes the actual achievable throughput of user k in timestep t_i. The average achieved throughput $\overline{R_k}(t_i)$ is calculated for a time interval T which contains several previous timesteps. The PF scheduling algorithm allocates a slot in timestep t_i to the user k with the highest ratio between $R_k(t_i)$ and $\overline{R_k}(t_i)$. The consideration of $R_k(t_i)$ and $\overline{R_k}(t_i)$ during scheduling decision enhances the sector throughput compared to a Round Robin (RR) approach and provides higher fairness compared to Max CIR scheduling when only the user with best $R_k(t_i)$ is scheduled. In order to consider different QoS requirements, in [2-4] the PF scheduling algorithm has been enhanced to the WPF scheduling algorithm by introducing a priority factor $p_k \in \mathbb{R}$ for each user. During WPF scheduling decision, slots are always allocated to user k^* with

$$k^* = \arg\max_k \left(p_k \cdot \frac{R_k(t_i)}{\overline{R_k}(t_i)} \right). \tag{1}$$

The PF scheduling decision can be obtained from (1), if $p_k = 1$ for all k.

B. Average Achieved User Throughput

In the following, the average user throughput of users with different p_k is analysed. For this reason, an analysis of PF scheduling given in [7, 11] is extended to WPF scheduling. In this analysis, it is assumed that user k is biased with an average SINR a_k which only depends on the distance to the base station and system traffic load. The actual SINR in timestep t_i results from superposition with a fading process. The relationship between $R_k(t_i)$ and the actual SINR for user k at timestep t_i is assumed to be proportional. The stationary user throughput $\overline{R_k}$ is obtained from $\overline{R_k}(t_i)$ for a time interval $T \to \infty$. It has been shown in [7, 11] that the ratio between $\overline{R_k}$ and a_k is constant for all users leading to

$$\frac{\overline{R_k}}{a_k} = \text{const for all } k. \tag{2}$$

Applying (2) to the WPF scheduling algorithm according to (1) results in

$$\frac{\overline{R_k}}{p_k \cdot a_k} = \text{const for all } k. \tag{3}$$

It can be seen that, e.g., users with $p_k = 2$ achieve double stationary throughput compared to users with $p_k = 1$ having the same a_k. By choosing the value of p_k, a specific user throughput can be adjusted for user k and different QoS requirements can be fulfilled.

C. Effective Channel Gain of the System

Due to the scheduling decision, the effective channel gain distribution when considering only the channel gains of the scheduled users is different to the Rayleigh fading density of each single user. In the following, the pdf of the effective channel gain is derived if two users with different priorities and WPF scheduling are considered. a_1 of user 1 and a_2 of user 2 are assumed to be equal. Saturated user throughputs are assumed, so that the scheduling decision only depends on the actual channel gain x of user 1 and y of user 2 normalised to a_1 and a_2, respectively [11]. The actual channel gains x and y are Rayleigh distributed with equal power and independent of each other. The pdf is given by $f_x(x)$ and $f_y(y)$ for $x, y \geq 0$, respectively. The joint pdf of the channel gains is given by

$$\begin{aligned} f_{xy}(x,y) &= f_x(x) \cdot f_y(y) \\ &= \frac{x \cdot e^{\frac{-x^2}{2s^2}}}{s^2} \cdot \frac{y \cdot e^{\frac{-y^2}{2s^2}}}{s^2} \end{aligned} \tag{4}$$

with s the power of the Rayleigh process. The parameter

$$\alpha = \frac{p_1}{p_2}. \tag{5}$$

is introduced which depends on the priority factors p_1 and p_2 of user 1 and 2, respectively.

In the following, it is assumed that user 1 is scheduled if its channel gain x weighted with $\sqrt{\alpha}$ is higher than the channel gain y of user 2. The pdf of the channel gain considering only the timesteps when user 1 is scheduled is given by

$$\begin{aligned} f_x(x|\sqrt{\alpha} \cdot x \geq y) &= \int\limits_0^{\sqrt{\alpha} \cdot x} \frac{x \cdot e^{\frac{-x^2}{2s^2}}}{s^2} \cdot \frac{y \cdot e^{\frac{-y^2}{2s^2}}}{s^2} \mathrm{d}y \\ &= \frac{x \cdot e^{\frac{-x^2}{2s^2}}}{s^2} - \frac{e^{\frac{-x^2(\alpha+1)}{2s^2}}}{s^2}. \end{aligned} \tag{6}$$

With (6), the probability $P(\alpha)$ that slots are allocated to user 1 can be calculated by

$$P(\alpha) = \int\limits_0^{\infty} \left(\frac{x \cdot e^{\frac{-x^2}{2s^2}}}{s^2} - \frac{e^{\frac{-x^2(\alpha+1)}{2s^2}}}{s^2} \right) \mathrm{d}x = \frac{\alpha}{\alpha+1}. \tag{7}$$

If $\alpha = 1$, both users get half of the slots allocated and fairness is maintained. This is equal to PF scheduling. In this case user 1 is scheduled if the channel gain is higher than the channel gain of user 2. For $\alpha = 1$ the effective channel gain of the system is given by (6) due to fact that both users having the same pdf of the channel gains obtained during scheduling and get half of the resources allocated. With increasing p_1 of user 1 while maintaining p_2 of user 2 constant, user 1 gets a higher priority than user 2 and gets more slots allocated. To achieve the pdf of the effective channel gain of the system for the case with different user priorities, the pdf of the channel gain obtained by user 1 has to be combined with the pdf of the channel gain obtained by user 2 both weighted by the amount of slots allocated to user 1 and 2, respectively.

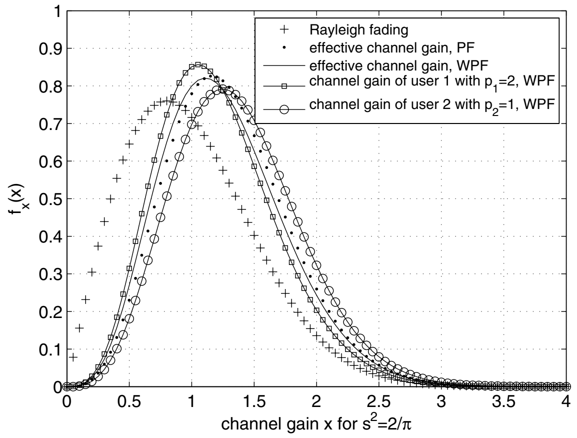

Fig. 1. pdf of Channel Gain

Fig. 1 shows the pdf of the channel gain of user 1 and 2 for WPF scheduling according to (6) for $p_1 = 2$ and $p_2 = 1$ as well as the pdf of the effective channel gain of the system of both users 1 and 2 together, and for comparison reason the pdf of the effective channel gain when using PF scheduling and the Rayleigh pdf are shown. It can be seen that the pdf of the effective channel gain for PF scheduling is shifted to the right compared to the Rayleigh pdf due to scheduling users only when having high channel gain. A high channel gain leads to higher SINR of the user so that the user throughput can be increased which also leads to an increased sector throughput.

If there is one high and one low priority user in the system and WPF scheduling is used, slots are allocated to the high priority user even if the channel gain is lower compared to that of the low priority user. The amount of slots allocated to the high priority user is higher than the amount allocated to the low priority users as indicated by (7). It can be seen from Fig. 1 that the pdf of the channel gain of the high priority user with WPF is worse than for PF scheduling but it is still better than the Rayleigh pdf. On the other hand, the pdf of the channel gain of the low priority user with WPF is better than with PF scheduling, but the low priority user only gets a small amount of slots allocated. To derive the pdf of the effective channel gain for WPF scheduling, the amounts of allocated slots to the high and to the low priority user have to be considered. It can be seen that the pdf of the effective channel gain for WPF scheduling is slightly worse than the pdf of the effective channel gain in case of PF scheduling due to the higher amount of slots allocated to the high priority user and the lower channel gains of the high priority user. If α is increased compared to the value of $\alpha = 2$ in Fig. 1, the pdf of the effective channel gain gets closer to the pdf of the Rayleigh pdf in case of one high and one low priority user. For high values of α, the high priority user gets almost all slots allocated and the pdf of the channel gain of the high priority user in (6) tends towards the Rayleigh pdf.

III. SIMULATION RESULTS

A. System Model

In the following, the influence of users with different priorities on the sector throughput and user throughput is evaluated based on system level simulations made with the implemented OFDMA based Network Performance Simulator (ONe-PS). A cellular wireless mobile radio system in the downlink with 9 cells is assumed. Each cell has 3 sectors and directional antennas are used. The whole scenario is extended by a wrap around approach to avoid border effects [12]. The pathloss is

$$L_p = -12.88 + 35.22 \log_{10}\left(\frac{d}{\text{metres}}\right) \tag{8}$$

according to Okumura-Hata [13, 14] with d the distance between base station and mobile station. Lognormally distributed slow fading with standard deviation of 6 dB is assumed. ONe-PS is snapshot based. During one snapshot, pathloss and slow fading is assumed to be constant. Frequency selective fast fading is modelled at timestep resolution according to a Vehicular A tapped delay line model [15]. New user positions are generated for each snapshot.

The wireless mobile radio system uses OFDMA as multiple access scheme which is used, e.g., in WiMAX and is also a promising candidate for 3GPP long term evolution and future networks. The assumed system is not totally compliant to any particular standard. However, the investigation and the results are in principle valid for any system of that type. The system bandwidth is 1.25 MHz. Resources are allocated to users in terms of slots. A slot may cover one, two or four timesteps in time domain and 48, 24 or 12 out of 128 available subcarriers in frequency domain, respectively. Two new slots become available for scheduling decision in each timestep. 32 subcarriers are used for control channel and guard interval and are not considered during the investigation. The assignment of subcarriers to slots is performed according to a random hopping process, which is different for different cells. This leads to interference averaging and frequency diversity effects. QPSK, 16QAM, 64QAM and 256QAM modulation combined with LDPC codes with coding rates from 1/6 to 5/9 are used. This leads to user throughputs from 137 kbit/s to 2.4 Mbit/s per slot.

Two types of users are considered in the following, high and low priority users. The priority factor of low priority users is $p_2 = 1$ throughout the following investigation. The priority factor p_1 of the high priority users is varied during the following investigation and the ratio of the priority factors is given by α according to (5).

Two different traffic models are used. With the Full Buffer model, each user has always enough data available for transmission [16]. In this scenario, no QoS requirement is considered and on average 20 users per sector are placed in the simulation environment. When using the Full Buffer Model the system is always fully loaded. Secondly, an FTP traffic model with packet calls is considered [17]. The parameter setting can be found in Table I. For FTP traffic, the satisfied user

TABLE I

FTP TRAFFIC MODEL

parameter	value	distribution
Packet Size S	1500 byte	deterministic
File Size	Mean = 2 Mbytes, Std. Dev. = 0.722 Mbytes, Maximum = 5 Mbytes	lognormally
Subscribed Data Rate D_{subscr}	Mean = 100 kbit/s	deterministic
Interarrival time	Mean $= S/D_{subscr}$	geometrically
Traffic Load	Adjusted that 5 % of users are unsatisfied	geometrically

criterion of [15] is assumed as QoS requirement. During the simulation a user gets unsatisfied if the user throughput falls below $D_{\text{thres},k} = 0.1 \cdot p_k \cdot D_{\text{subscr}}$ within an interval of 5 s. The system is in outage if more than 5 % of the users are unsatisfied and the sector throughput is measured for 5 % unsatisfied users.

B. Full Buffer Model

In this section, results of ONe-PS for two groups of users with different priorities using the Full Buffer model are provided. Fig. 2 shows the average user throughput obtained using the Full Buffer model as a function of the percentage of high priority users and of α. The number of users per sector is on average 20. It can be seen that for all cases in which there are low priority users or only users with equal priority, i.e. only low or only high priority users or $\alpha = 1$, the same average user throughput is achieved. Furthermore, it can be seen that the high priority users get a higher average user throughput than the low priority users if there are users with different priority factors. The ratio between the average user throughput of high priority users and the average user throughput of low priority users does not reach completely the ratio calculated by (3). This is because of a nonlinear relationship between achievable user throughput and SINR. The assumed link adaptation uses discrete modulation and coding schemes with SINR thresholds and looks like a step function. If the ratio between the average user throughput of high and low priority users as given in Fig. 2 is calculated it can be seen that the ratio only depends on α but is almost independent of the number of high and low priority users. With increasing α, the ratio between the average user throughput of the high and low priority users increases.

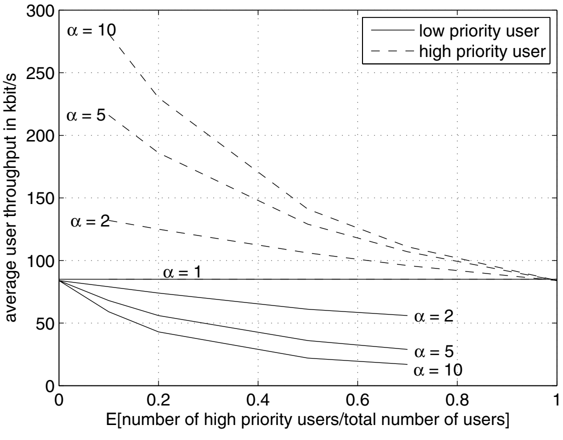

Fig. 2. Average User Throughput with Full Buffer Model

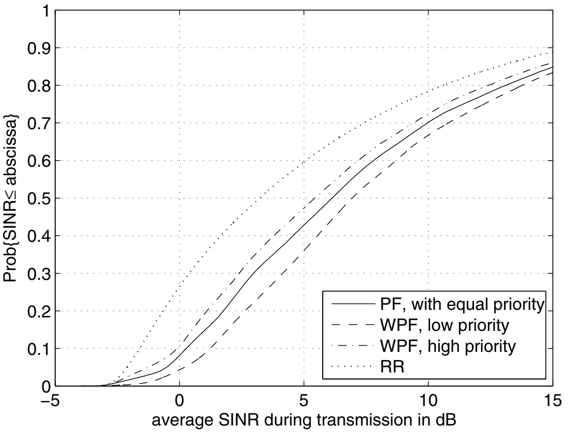

Fig. 3. Average SINR distribution experienced by the user for $\alpha = 10$ and 50 % high priority users

Fig. 3 shows the distribution of the average SINR experienced by the users for PF, WPF and Round Robin scheduling. During WPF scheduling, $\alpha = 10$ and 50 % of the total users are high priority users. The average SINR experienced by the users is calculated from SINR values obtained when the base station transmits data to the user. It can be seen that PF leads to a better SINR distribution due to scheduling users only in high channel gain conditions. The SINR distribution of the low priority users with WPF scheduling is around 1 dB higher than with PF scheduling while the SINR distribution of the high priority users with WPF scheduling is around 0.5 dB lower. The principle behaviour is expected according to the results obtained in subsection II-C.

Table II shows the ratio of slots allocated to high and low priority users obtained by system level simulations and from (7), if on average equal number of high and low priority users are assumed. The results obtained from system level simulations fit well with the results obtained from (7). It can be seen that with increasing α, more slots are allocated to high priority users.

The worse SINR distribution of high priority users as seen in Fig. 3 and the higher amount of slots allocated to the high priority users as seen in Table II lead to a decreased sector

TABLE II

RATIO OF ALLOCATED SLOTS TO HIGH AND LOW PRIORITY USERS

	High : Low Priority Users	
α	simulative	according to (7)
2	0.64 % : 0.36 %	0.67 % : 0.33 %
5	0.80 % : 0.20 %	0.83 % : 0.17 %
10	0.88 % : 0.12 %	0.91 % : 0.09 %

throughput for WPF scheduling compared to PF scheduling. Simulations with the Full Buffer model with 50 % high priority users which is the worst case scenario and WPF scheduling with $\alpha = 2$ and $\alpha = 10$ show that the sector throughput is around 1 % and around 4 % lower than for PF scheduling, respectively.

C. *FTP Traffic Model*

The same effects as described in subsection III-B for the Full Buffer model apply also when using the FTP traffic model. Furthermore, QoS requirements have to be fulfilled in case of FTP traffic, in particular each user has to achieve at least $D_{\mathrm{thres},k}$ as user throughput. Due to the FTP traffic model it is possible that a user has no data to transmit at a certain timestep. In this case, the user is not considered for scheduling decision and these intervals are excluded from the user throughput calculation.

In the following, a scenario without high priority users and applying PF scheduling, termed Scenario I, is compared to a scenario in which 10 % of the users have high priority and applying WPF scheduling, termed Scenario II. Low priority users still have a priority factor of 1 and high priority users have a priority factor of 2 leading to $\alpha = 2$.

Fig. 4 shows the distribution of the average user throughput for users in Scenario I and for low and high priority users in Scenario II. In Table III, the results for the offered traffic and the sector throughput are shown for Scenario I and II. The offered traffic is defined by the total amount of data which is provided to the base station in a given time interval equal to a snapshot and it is proportional to the number of active sessions during a snapshot. The measurements are made if on average 5 % of all users are unsatisfied. High and low priority users get unsatisfied if the average user throughput is below 20 kbit/s and 10 kbit/s, respectively.

Fig. 4 shows that in Scenario II the average user throughput of high priority users is higher than the average user throughput of the low priority users. 35 % of the high but only 15 % of the low priority users achieve user throughputs above 100 kbit/s. High priority users get more slots allocated and are scheduled more often than low priority users so that high priority users achieve a higher average user throughput than low priority users.

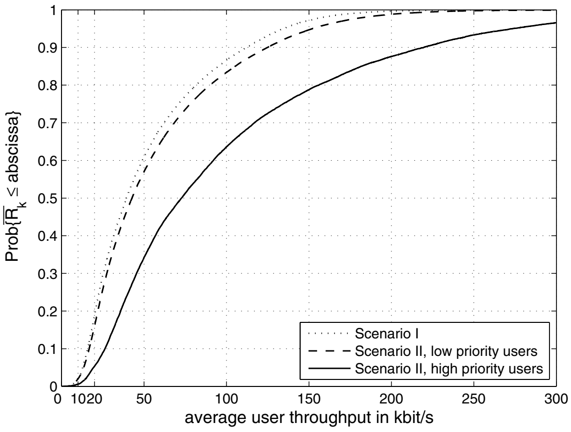

Fig. 4. User Throughput Distribution

TABLE III

PERFORMANCE ANALYSIS WITH FTP TRAFFIC

	Scenario I	Scenario II	difference in %
offered traffic in Mbit	36.7	29.2	-20.4
mean sector throughput in kbps	1725	1506	-12.7
10 %-ile sector throughput in kbps	1471	1255	-14.7

In Table III, it can be seen that the offered traffic is reduced by around 20 % from Scenario I to Scenario II. This means that for each high priority user, low priority users have to be removed from the system to achieve a maximum of 5 % unsatisfied users. Therefore, the total number of users is decreased in Scenario II compared to Scenario I. In Scenario II, high priority users get more slots allocated than low priority users, but due to the lower number of users the average number of slots allocated to low priority users is in the order of the average number of slots allocated to users in Scenario I. Therefore the average user throughput of low priority users in Scenario II is slightly better than the average user throughput in Scenario I as can be seen in Fig. 4. The lower number of users also leads to lower user diversity during scheduling decision and a higher probability of idle durations when the base station has no data to transmit. This is in contrast to the Full Buffer model where a constant number of users is assumed and each user has always data to transmit. Therefore, the decrease in sector throughput is with nearly 13 % higher than in the Full Buffer model. An even lower sector throughput is expected when the number of high priority users gets closer to the number of low priority users or when α increases.

IV. CONCLUSION

The influence of high priority users on the system performance when using WPF scheduling to cover different QoS requirements for users with different priorities is investigated. High priority users are also scheduled in low channel gain conditions to achieve the required average user throughput. Therefore, low priority users get lower amount of slots allocated and suffer from a lower throughput. Analytical investigations show an increased throughput for high priority users when using WPF scheduling compared to low priority users. Furthermore influences on the system capacity are shown by investigation of effective channel gain pdf when applying WPF scheduling which is obtained if only the channel gains of scheduled users are considered. System level simulations show that users with different priority factors achieve different average user throughputs. A higher priority factor leads to a higher average user throughput. The sector throughput is reduced in case of a user distribution with different priority factors compared to scenarios with users having equal priority. With introduction of high priority users the overall number of users has to be reduced in order to keep the satisfied user criterion, i.e. the application of different user priorities limits the number of users. Consequently, the sector throughput is decreased due to smaller user diversity during scheduling and a higher probability of idle durations.

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