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# Performance Analysis of UWB Channels for Wireless Personal Area Networks

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**Abstract:** Ultra-wide Band (UWB) communication is one of the most promising technology for high data rate networks over short-range communication. The ultra-wide bandwidth offers pulses with very short duration that provides frequency diversity and multipath resolution. UWB channels raise new effects in the receiver, the amplitude fading statistics being different compared to the conventional narrow band wireless channels. Here we focus on modeling of ultra-wide band channels, especially for simulation of personal area networks and also discuss the benefits, application potential and technical challenges in wideband communication. The concept of Orthogonal Frequency Division Multiplexing (OFDM) has recently been applied in wireless communication systems due to its high data rate transmission capability with high bandwidth efficiency and its robustness to multi-path delay. UWB OFDM communication was proposed for physical layer in the IEEE 802.15.3a standard which covers wideband communication in wireless personal area networks. Since the channel model for multicarrier UWB communication is different from that of plain ultra-wide band channel, a novel modification method in UWB channel model is proposed with specific center frequency and multipath resolution. Moreover, dynamic channel estimation is necessary before demodulation of UWB OFDM signals since the radio channel is time varying and frequency selective for wideband systems. The performance of the proposed method is statistically analyzed using LS and MMSE based channel estimation methods.

**Key words:** Channel estimation, UWB OFDM, multipath, LS, MMSE

## INTRODUCTION

In recent years, ultra-wide band communication has received great interest from both research community and industry. Several GHz of bandwidth has been authorized for license free communication by the Federal Communication Commission (FCC) in United States. FCC has mandated that the UWB radio transmission lies between 3.1 and 10.6 GHz with a minimum instantaneous bandwidth of 500 MHz or a fractional bandwidth of more than 20%[1-4]. The fractional bandwidth is the ratio of -10 dB bandwidth of the signal and the carrier frequency ($f_c$). UWB systems with $f_c$>2.5 GHz need to have a -10 dB bandwidth of at least 500 MHz, while those with $f_c$<2.5 GHz need to have a fractional bandwidth at least 0.20. Such systems rely on ultra-short waveforms that can be free of sine wave carriers and do not require IF processing. The Shannon heartly theorem states that the channel capacity grows linearly with the bandwidth and decreases logarithmically as SNR decreases. This relationship suggests that the channel capacity can be increased more rapidly by increasing the bandwidth than SNR. Accordingly, the transmission bandwidth, which is greater than 500 MHz provides high data rate communication for indoor applications. The power levels of UWB signals are kept very low (-41.3 dBm)[5] which allows the UWB technology to overlay other available services such as Global Positioning System (GPS) and the IEEE 802.11x Wireless Local Area Networks (WLAN).

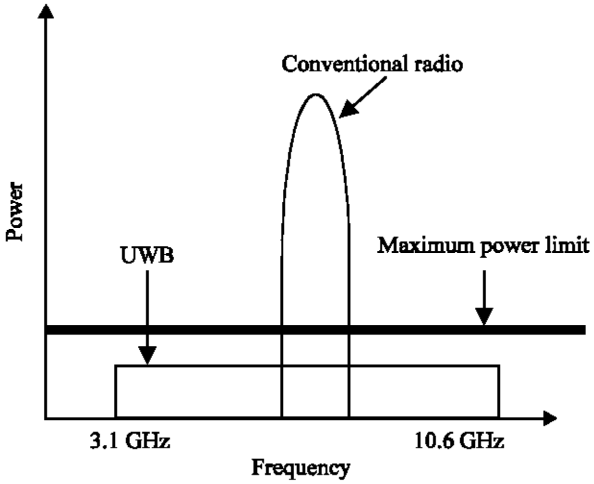

Fig. 1: UWB signal spectrum

UWB signals (Fig. 1) with short duration of pulses provide unique advantages in short-range applications which include easy penetration through obstacles,

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high precision ranging and low processing power. The different multipath components in the channels are characterized by different delays and attenuation. The exact modeling of the parameters describing the multipath component is the art of channel modeling and it is the key parameter which is considered in the physical layer. Several papers are dealt modeling of narrow band channels[6-8]. Saleh-Velenzuela (S-V)[9] model is the main indoor channel model which is considered for wide band systems with the amplitude fading statistics are based on Rayleigh distribution. However, recent study[4,9] shows different amplitude fading statistics for UWB channel under practical measurement conditions. The channel model for UWB OFDM[10-12] communication is different from plain UWB channels because of different multipath resolution and operating frequencies. So the UWB channel is modified for the typical values of the above mentioned case and it has been analyzed with existing channel estimation methods. Here we reviewed the IEEE 802.15.3a UWB channel model and it is compared with the IEEE 802.11 narrow band wireless channel.

## UWB CHANNEL

A reliable channel model which captures the important characteristics of the channel is a vital prerequisite for system design the accurate design of channel model is a significant issue in UWB systems. The most famous multipath UWB indoor channel models are tap-delay line Rayleigh fading model[13], Saleh-Valenzulea model and Δ-K model[14]. Recently Intel proposed a modified S-V model[4] for UWB communication.

The large bandwidth of UWB channels may raise new effects in the receiver compared to narrow band wireless channels. For example, only a few multipath components overlap within each resolvable delay bin, so that the central limit theorem is not applicable and amplitude fading statistics are different. Sometimes, there can be delay bins into which no Multipath Components (MPC) fall and thus are empty. The arrival time of multipath components of a wide band signal is same as the S-V model approach.

The S-V channel measurement shows that the multipath components are arriving in a cluster form. Since UWB signals can be up to 7.5 GHz wide, the MPC are separated by 133 ps and it can be individually resolved at the receiver. The different paths of such wide band signal can rise to several multipath components, all of which will be part of one cluster.

Table 1: UWB channel characteristics

| Channel characteristics | $CM_1$ | $CM_2$ | $CM_3$ | $CM_4$ |
|---|---|---|---|---|
| Distance | 0-4 m | 0-4 m | 4-10 m | >10 m |
| (Non) line of sight | LOS | NOLS | NLOS | NLOS |
| Cluster arrival rate | 0.0233 | 0.4 | 0.0667 | 0.0067 |
| Ray arrival rate | 2.5 | 0.5 | 2.1 | 2.1 |
| Cluster decay factor | 7.1 | 5.5 | 14 | 24 |
| Ray decay factor | 4.3 | 6.7 | 7.9 | 12 |

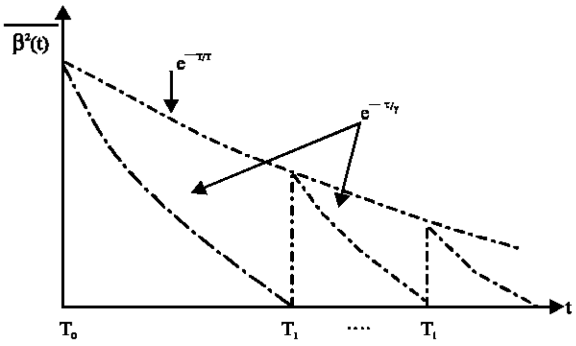


Fig. 2: Schematic representation of UWB channel model

The arrival of multipath components is modeled by using a statistically random process; it is based on Poisson distribution. The multipath arrival of UWB signals are grouped into two categories: cluster arrival and ray arrival within a cluster. This model requires four parameters to describe indoor channel environments. They are cluster decay factor (Γ), ray decay factor (γ), cluster arrival rate (Λ) and ray arrival rate (γ). The above parameters for four different UWB channel environments are listed in Table 1.

Ray arrival rate is the arrival rate of path within each cluster. The cluster arrival rate which is always smaller than the ray arrival rate. The rays within each cluster are also based on poisson process (Fig. 2).

The amplitude statistics in S-V model are based on Rayleigh distribution, the power of which is controlled by the cluster and ray decay factor. However recent measurements in UWB channel show that amplitudes do not follow rayleigh distribution rather it follows lognormal distribution. The impulse response of UWB channel can be written as:

$$h(t) = X \sum_{l=0}^{L-1} \sum_{k=0}^{K-1} \alpha_{kl}\, \delta(t-T_l-\tau_{kl}) \qquad (1)$$

Where, $\alpha_k l$ is the multipath gain coefficient of kth ray related to lth cluster. $T_l$ is the delay or arrival time of first path of lth cluster. $\tau_{kl}$ is the delay of kth path within the lth cluster relative to $T_l$. X is the lognormal shadowing term.

The ray arrival and cluster arrival distribution time are given by:

$$p\,(T_l/T_{l-1}) = \Lambda \exp\,[-\Lambda\,(T_l-T_{l-1})]\ l > 0 \qquad (2)$$

$$p\,(\tau_k/\tau_{k-1}) = \lambda \exp\,[-\lambda\,(\tau_k-\tau_{k-1})]\ l > 0 \qquad (3)$$

The channel coefficients are the product of large scale and small scale fading components which is given by:

$$\alpha_{kl} = p_{k,l}\, \beta_{kl} \qquad (4)$$

If the channel coefficients are considered as real, then $p_{k,l}$ takes real random value +1 or -1. For complex channel coefficients, base band equivalent channel model would need to be convolved with complex base band representation of transmitted waveform.

For UWB pulsed system, the meaning of pulse is a bit ambiguous since it is not carrier based. If complex base band channel is considered, the channel co-efficient phase is uniformly distributed over the interval $[0, 2\pi]$. $\beta_k l$ is the amplitude of the UWB signal and it is based on lognormal distribution. This is given as:

$$20 \log 10\,(\beta_{k,l}) \propto \text{normal}\,(\mu_{k,l}, \sigma_1^2 + \sigma_2^2) \qquad (5)$$

Where, $\sigma_1$ is the standard deviation of cluster lognormal fading term. $\sigma_2$ is the standard deviation of ray lognormal fading term. The behavior of averaged power delay profile is:

$$E\,[\,|\beta_{k,l}|^2] = \Omega_0\, e^{-Tl/T} e^{-\tau k/\gamma} \qquad (6)$$

This reflects the exponential decay of each ray as well as decay of the total cluster power with respect to delay. X is the shadowing term and it is characterized by following:

$$20 \log 10(X) \propto \text{Normal}\,(0, \sigma^2) \qquad (7)$$

$\sigma$ is the standard deviation of lognormal shadowing term.

**Modification method:** The above channel model is quite general and it is described for 167 ps multipath resolution or 7.5 GHz bandwidth. In IEEE 802.15.3a wireless personal area networks, the entire UWB spectrum is divided into $N_T$ band each with a bandwidth of B. The multipath resolution and center frequency for each band is different. So the above multipath UWB channel model is no longer applicable and it has to be resampled with respect to specific UWB pulse shape. An arbitrary realization of the channel can be represented with a finite impulse response filter as:

$$h(t) = \sum_{r=0}^{N-1} \alpha_r \delta(t - r\Delta) \qquad (8)$$

Where, $\alpha_r$ is the path gain, $\Delta = 167$ ps is the multipath resolution and $N\Delta$ is the maximum delay spread. Assume that UWB pulse within the 2GHz-8GHz band is x(t); $0<t<T_p$. Where, $T_p$ is the pulse width. The minimum multipath resolution $T_P$ is needed in the receiver to match the received signal. The tapped delay line channel model for a multipath resolution $T_P$ is given as:

$$h_m(t) = \sum_{i=0}^{M-1} \beta_i\, \delta(t - iT_p) \qquad (9)$$

Where, $\beta_i$ is the path gain and $MT_P$ is the maximum delay spread. When x(t) is passed through the multipath channel in Eq. 8, the received signal is:

$$r(t) = x(t)*h(t) = \sum_{r=0}^{N-1} \alpha_r x(t - r\Delta) \qquad (10)$$

If $T_P >> \Delta$, the overlapping lapping between multipath component will occur which leads to pulse distortion. To construct an optimum receiver a local reference signal should be constructed as in Eq. 8. But this is not possible practically and the strength of the received signal is very poor. However, the receiver performance can be improved by modifying the realistic multipath channel model into tapped delay line model. For the particular waveform x(t), the UWB channel model is modified as shown in Fig. 3.

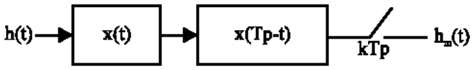


Fig. 3: Channel modification method

The realization of UWB channel model are filtered with a filter x(t) and its matched filter $x(T_p\text{-}t)$. A switch is adopted to sample the matched filter signal with a time spacing $T_p$. To compare the difference between modified channel model and the original channel, Eq. 10 can be decomposed as:

$$r(t) = \sum_{r=0}^{N-1} \alpha_r x(t - r\Delta) = \sum_{r=0}^{M-1} \beta_i x(t - iT_p) + err(t) \qquad (11)$$

Where, err (t) is the modification error. It can be easily deduced such that err(t) is orthogonal with Eq. 9.

$$\int err(t) \sum_{i=0}^{M-1} \beta_i\, x\,(t - iT_p)\, dt = 0 \qquad (12)$$

err(t) should be considered as energy loss in the link budget analysis.

## SIMULATION MODEL

The performance of four different UWB channel model is analyzed based on the parameters of IEEE 802.15.3a standard. The entire UWB operating bandwidth is considered as 7.5 GHz and it is divided into 13 bands of 528 MHz each. The multipath resolution of each band is 1.8938 ns. The 528 M Hz bandwidth is divided into 128 tones and cyclic prefix of 32 carriers are appended. Here 10 of 128 subcarrier are used as guard carrier and 12 as pilot carriers. So the subcarrier frequency spacing is 4.125 MHz and OFDM symbol duration is 312.5 ns. The UWB channel model $CM_1$, $CM_2$, $CM_3$ and $CM_4$ are considered with a multipath resolution of 1.8938 ns. It is assumed perfect synchronization between transmitter and receiver and that perfect channel knowledge is available at the transmitter unless specified. In the receiver, channel equalization is done by LS and MMSE based channel estimation method.

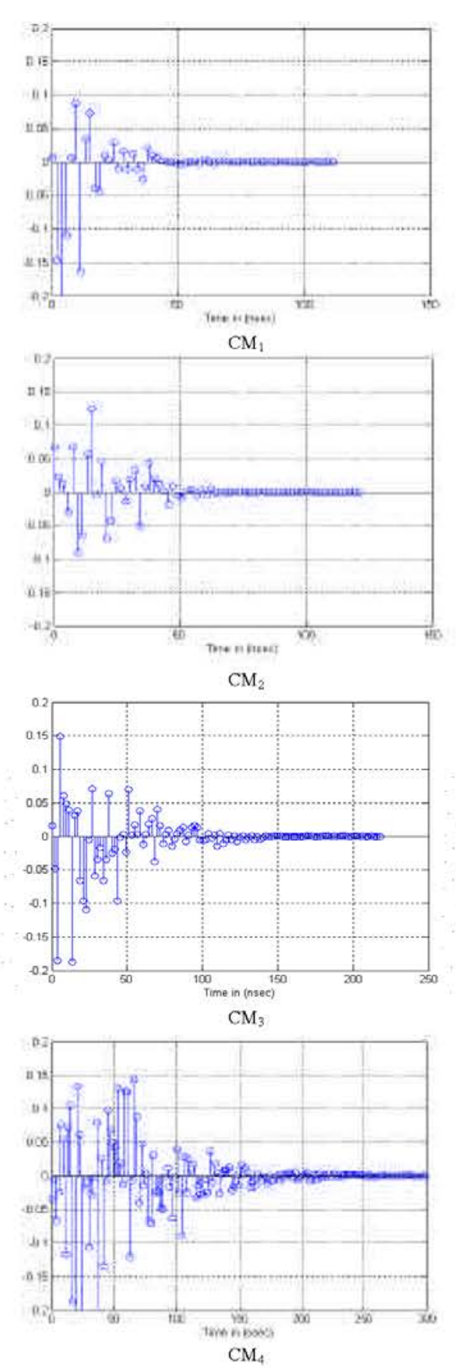
**Channel estimation in OFDM:** The channel estimation in OFDM[15-18] can be performed by either inserting pilot tones into all of the subcarrier of OFDM symbol with a specific period or inserting pilot tones into each OFDM symbol. The first one is block type pilot channel estimation and it has been developed under assumption of slow fading channel. The second one is comb-type pilot channel estimation and it has been introduced to satisfy need for equalizing when the channel changes from one OFDM block to the subsequent one. This study mainly focuses on block type channel estimation. The estimation of the channel at the pilot frequencies for block type based channel estimation can be based on Least Square (LS) and Minimum Mean Square Estimation (MMSE) methods. Least square estimation which is also called frequency domain estimation, the received symbols are simply divided by the known pilot sequences to get channel estimates. The estimate of the channel at pilot subcarriers based on LS estimation is given by:

$$H_{LS} = Y_P/X_P \tag{13}$$

Where, $Y_P$ and $X_P$ are output and input of the particular subcarrier. Since LS estimate is susceptible to noise and ICI, MMSE is proposed while compromising complexity. A major assumption in MMSE based channel estimation is the time domain channel vector h is Gaussian and it is uncorrelated with channel noise W. The frequency domain MMSE estimate of h is given by:

$$H_{MMSE} = F\, R_{hy}\, R_{yy}^{-1} Y \tag{14}$$

Where, $R_{hy}$ and $R_{yy}$ are the cross covariance matrix between h and Y and the auto-covariance matrix of Y, respectively. F is the Fourier transform matrix and its dimension is based on number of subcarriers in an OFDM symbol. We have considered the complex equivalent base band model of the system in the simulations.



$CM_1$

$CM_2$

$CM_3$

$CM_4$

Fig. 4: Realization of modified UWB channel model

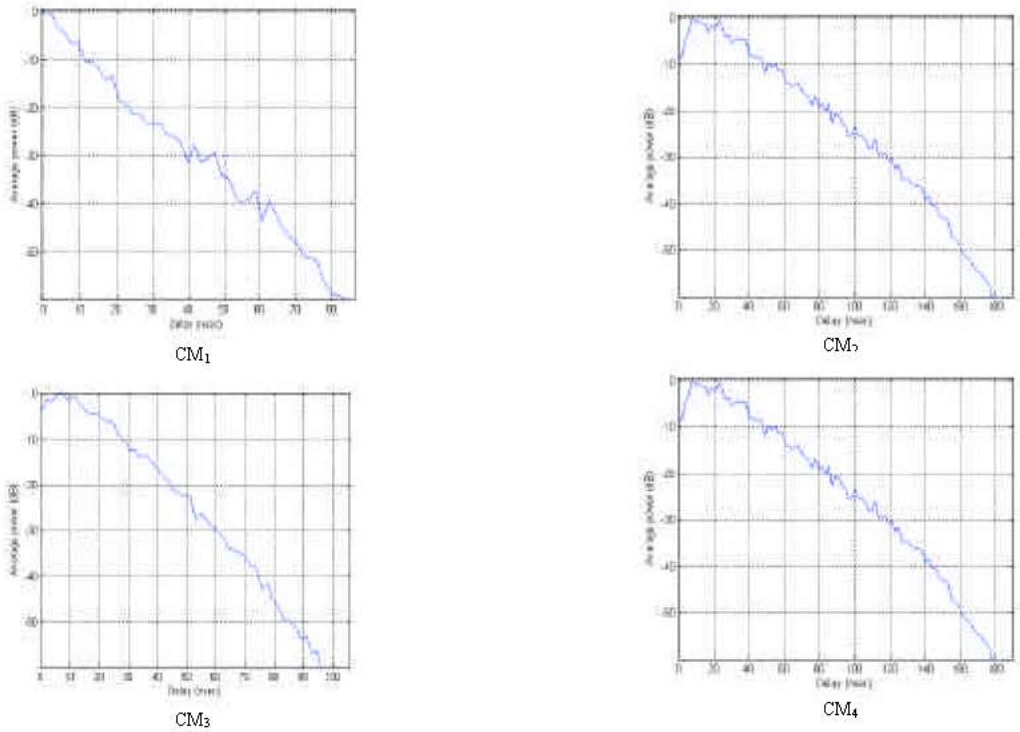
Table 2: Characteristics of UWB channel model

| | Channel model | | | |
|---|---|---|---|---|
| Statistics | $CM_1$ LOS | $CM_2$ NLOS | $CM_3$ NLOS | $CM_4$ NLOS |
| Mean excess delay (nsec) | 5.4627 | 9.7628 | 15.4725 | 27.3022 |
| RMS delay (nsec) | 5.6879 | 8.3800 | 14.2170 | 25.4445 |
| NP (85% energy) | 14.0000 | 16.5300 | 25.9000 | 63.7100 |
| NP (10 dB peak) | 22.9100 | 35.3600 | 63.7100 | 116.4900 |

LOS: Line of sight, NLOS: Non line of sight

## RESULTS AND DISCUSSION

An example of modified channel realizations is shown in Fig. 4. In order to asses the statistics of the modified channel realization, we generate and modify the 1000 realizations for each of $CM_1$, $CM_2$, $CM_3$ and $CM_4$. Table 2



$CM_1$ $CM_2$

$CM_3$ $CM_4$

**Fig. 5: Power delay profile for modified UWB channel**

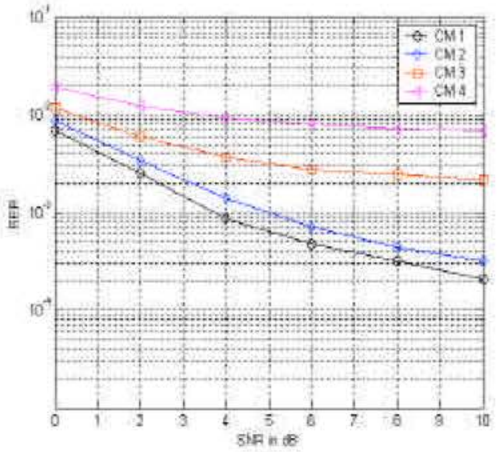


**Fig. 6: LS method**

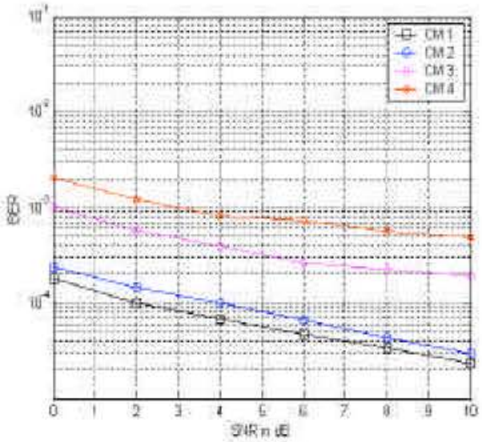


**Fig. 7: MMSE method**

Table 3: Statistics of original channel realizations and modified ones

| | Channel model | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $CM_1$ | | $CM_2$ | | $CM_3$ | | $CM_4$ | |
| Statistics | Original | Modified | Original | Modified | Original | Modified | Original | Modified |
| Mean excess delay (nsec) | 5.4627 | 5.9854 | 9.7628 | 10.4428 | 15.4725 | 16.2088 | 27.3022 | 29.1430 |
| RMS delay (nsec) | 5.6879 | 5.6847 | 8.3800 | 8.6050 | 14.2170 | 14.7270 | 25.4445 | 25.9955 |
| NP (85% energy) | 14.0000 | 4.2500 | 16.5300 | 6.7700 | 25.9000 | 9.3900 | 63.7100 | 15.7700 |
| NP (10 dB peak) | 22.9100 | 4.5000 | 35.3600 | 6.9400 | 63.7100 | 8.5900 | 116.4900 | 12.8800 |

shows the characteristics of typical UWB channel for four different environments. Table 3 shows the comparison of mean delay, RMS delay spread, number dominate paths (85% of energy) and number of significant paths (within 10 dB peak) are decreased greatly. Figure 5 shows that for all channel realizations, the PDP is decreasing exponentially. Because the pulse width $T_P$ is much greater than 0.167 ns, paths in the modified channel will consist of a lot of paths with 0.167 ns resolution. The modified channel fading statistics will differ from lognormal distribution. From the MMSE estimate (Fig. 7), it can be seen that 10-15 dB gain in Signal-to-noise Ratio (SNR) exists for the same mean square error of channel estimation over LS estimate (Fig. 6).

## CONCLUSIONS

A novel modification method is proposed which modifies the multipath UWB channel model into a tapped delay line channel model with specific center frequency and multipath resolution. The modified channel model matches the simulation capabilities of the particular UWB waveform. The modified example shows that the mean delay, RMS delay spread and the average multipath power delay profile of the modified channel are similar to the original but the number of dominant paths decreases greatly. In MMSE method, 10 dB better performance is achieved compared to the other. These results are of great importance in UWB design and its analysis.

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