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New Quasi-Synchronous Sequences for CDMA Slotted ALOHA Systems

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SUMMARY One of unique features of CDMA slotted ALOHA (CDMA S-ALOHA) is that user must synchronize his transmission to given slot. Thus orthogonal sequence as spreading sequence would achieve ideal throughput if each of packets accomplish perfect synchronization. In the presence of any ambiguity in synchronizations, however, quasi-synchronous (QS) sequences suit well with CDMA S-ALOHA system. In this paper, we introduce new QS-sequences obtained from the orthogonal Gold sequences and discuss their performance when applying to CDMA S-ALOHA systems. As a result, withstanding to access timing error, good performance is ensured with this sequence under the environment of AWGN, MAI (multiple access interference) and frequency non-selective fading, that is, micro or pico cellular systems and indoor wireless LANs.

key words: *CDMA slotted ALOHA system, QS-sequences, access timing error, orthogonal Gold sequences, flat fading channel*

1. Introduction

Recently, a packet communication system on mobile computing have drawn much attention as a new communication device.

Code Division Multiple Access (CDMA) based on spread spectrum techniques is the most likely candidate as a next generation communication system, thus so many works have been made aiming at improving the system performance [1]–[4].

Most remarkable feature of CDMA ALOHA is the capability of simultaneous packet transmission given by CDMA and minimization of multiple access interference (MAI) improves the performance. Focusing on spreading sequence, most fundamental approach to combat with MAI, orthogonal sequence achieves ideal performance if perfect synchronization is fulfilled. It suggests CDMA S-ALOHA as an appropriate candidate, however difficulty of synchronous packet transmission in reality may spoil its superiority to CDMA Unslotted ALOHA.

To ease the sensitiveness to ambiguity in synchronizations, it is preferable to design sequences that have zero cross correlations within a certain range of chips. Then one may enjoy ideal throughput within that range of access timing errors. This concept has already been studied as QS-CDMA system, however the sequences are obtained from asynchronous spreading sequences that zero cross correlations can never be achieved.

In this paper, we will evaluate CDMA S-ALOHA system employing QS-sequences (QS-CDMA S-ALOHA system) that are generated from orthogonal Gold sequences. Those have the cross correlation value of 0 near the synchronization timing, thus these are orthogonal within a small amount of access timing error. For this property, even if there exists a few chips of access timing errors in packet synchronizing, QS-CDMA S-ALOHA system will have better performance than CDMA S-ALOHA system employing orthogonal sequences or sequences for CDMA Unslotted ALOHA system. Moreover, the sequences can reduce the effect of amplitude fluctuations by fading, so that better throughput performance would be obtained than it when using conventional QS-sequences.

2. New Quasi Synchronous Sequences

In QS-CDMA S-ALOHA system, the access timing error is restricted to a few chips, because of the timing control of packet access by the base station [5]. Hence, for this system it should be that the spreading sequences have very small value of cross correlation near the access timing, ideally, the value should be zero.

In previous studies, binary QS-sequences has been made from Gold sequences and so on, so those had -1 as the smallest cross correlation values [5]–[7]. Because of this property, in the case that there are many simultaneous users, it can be guessed that the performance of the system will degrade from the multiple access interference.

In this study, we generate new QS-sequences which are selected from orthogonal Gold sequences. The reason of selecting this sequences as the base of QS-sequences is that the sequences can be 0 as the cross correlation value [8], [9].

Firstly, we will describe orthogonal Gold sequences.

2.1 Generation of Orthogonal Gold Sequences

The elements of each sequences are binary, that is 0 or

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1. A pair of preferred M-sequence of degree n of length $N-1$ is

$$\mathbf{u} = (u_0, u_1, \cdots, u_{N-2}) \tag{1}$$

$$\mathbf{v} = (v_0, v_1, \cdots, v_{N-2}). \tag{2}$$

Element 0 is added to each sequence, then,

$$\begin{aligned}\mathbf{U} &= (u_0, u_1, \cdots, u_{N-2}, 0)\\ &= (\mathbf{u}, 0)\end{aligned} \tag{3}$$

$$\begin{aligned}\mathbf{V}_i &= (v_i, v_{i+1}, \cdots, v_{N-2}, v_0 \cdots, v_{i-1}, 0)\\ &= (\boldsymbol{T}^i\mathbf{v}, 0)\end{aligned} \tag{4}$$

where $\boldsymbol{T}^i$ is i times cyclically shifter. From (3) and (4), a set of orthogonal Gold sequences $\mathrm{OG}(\mathbf{u}, \mathbf{v})$ of length $N = 2^n$ is

$$\begin{aligned}\mathrm{OG}(\mathbf{u}, \mathbf{v}) = \{&\mathbf{U}, \mathbf{U} \oplus \mathbf{V}_0, \mathbf{U} \oplus \mathbf{V}_1, \cdots,\\ &\mathbf{U} \oplus \mathbf{V}_{N-2}\}.\end{aligned} \tag{5}$$

where $\oplus$ is the modulo-2 adder.

In this sequence set, each sequence is orthogonal, so the value of crosscorrelation function with 0 cyclic shift is

$$\theta_{\mathrm{U,V}}(0) = \sum_{n=0}^{N-1} u_n \oplus v_n = \begin{cases} N & \mathbf{U} = \mathbf{V} \\ 0 & \mathbf{U} \neq \mathbf{V} \end{cases} \tag{6}$$

where, $\theta_{\mathrm{X,Y}}(l)$ means a crosscorrelation function for sequences X and Y with l-th cyclic shift.

From the next subsection, we consider the sequences as bipolar binary sequences whose element are -1 or $+1$ (0 is mapped $+1$ and 1 is -1).

2.2 QS-Sequences Based on Orthogonal Gold Sequences

QS-sequences selected from Gold sequences are described in [3]–[7]. In this study, we will derive the QS-sequences based on orthogonal Gold sequences by the similar way of [6].

Figure 1 indicates an example of cross correlation function of orthogonal Gold sequences of length $N = 64$. When the access timing error is 0, cross correlation value is 0, namely, these sequences are orthogonal each other. However, in the case of being some access timing errors, the cross correlation values are not always 0.

Figure 2 is also an example of cross correlation function of the same sequences. In this case, even if the access timing error is -1 to $+1$ chip time duration, the pair of sequences are orthogonal. Thus, it terms "QS(OG-r)" which is the set of sequences that each pair of sequences in the set has the cross correlation value 0 for r chips continuously. Due to this orthogonality, the sequences QS(OG-r) can allow the access timing error from $-\frac{r-1}{2}$ to $\frac{r-1}{2}$ chips. Where, "OG" means that the set of sequences selected from orthogonal Gold sequences. According to the same manner the conventional QS-sequences can be shown as QS(G-r), which is the set of sequences selected from Gold sequences and have the cross correlation value -1 for r chips continuously.

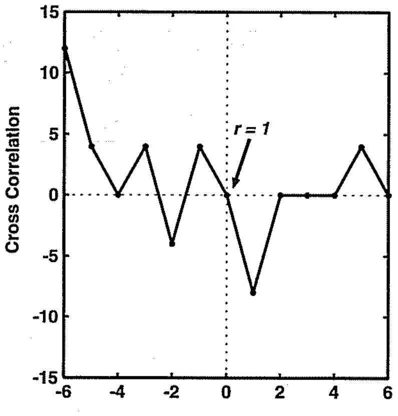

Fig. 1 An example of cross correlation function of orthogonal Gold sequences.

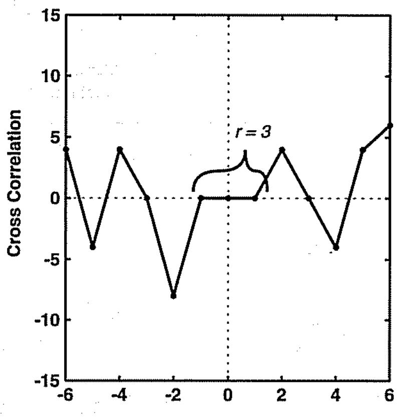

Fig. 2 An example of cross correlation function of QS(OG-3).

Then, we describe the way of deriving QS(OG-r). Firstly, a sequence from a set of orthogonal Gold sequences is selected and contained in the set of QS(OG-r). Then, a sequence is selected from the set of $N-1$ sequences. The cyclic permutation is successively applied to the sequence to examine whether or not the cross correlation with any sequences in QS(OG-r) exhibits 0 for r chips continuously. If a phase such that a continuous cross correlation value 0 for r chips, the sequence is entered in the set of QS(OG-r). This search is applied to the remaining $N-2$ sequences, and QS(OG-r) is derived.

Table 1 indicates the number of sequences contained in QS(OG-r) for various values of r and sequence length. When the number of r increases, the number of sequences decreases. Therefore, if many users will transmit simultaneously, long length sequences must be used.

Table 1 The number of QS(OG-r) for various sequence lengths.

Sequence Length N [chips]	$r = 1$	$r = 3$	$r = 5$	$r = 7$	$r = 9$	$r = 11$
32	32	8	2	2	-	-
64	64	16	4	3	2	2
128	128	32	8	2	2	2

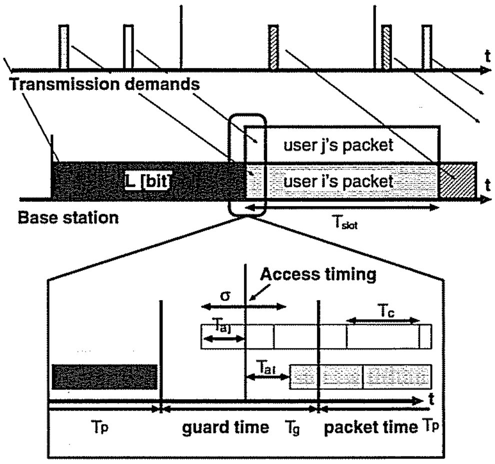

Fig. 3 Channel status of QS-CDMA S-ALOHA system.

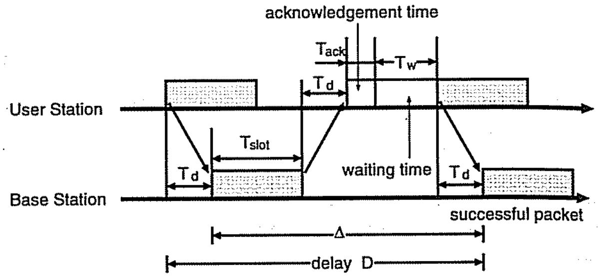

Fig. 4 The procedure model of retransmission.

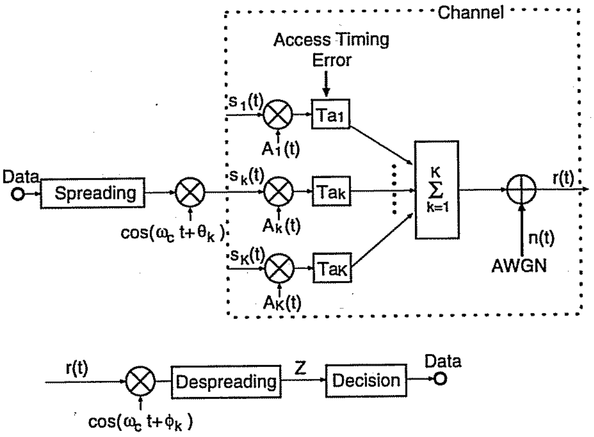

Fig. 5 The model of transmitter and receiver.

3. System Model

We consider a single-hop CDMA packet radio network with finite number of user stations K_{sys} and a base station.

Figure 3 shows the model of channel state at the base station in QS-CDMA S-ALOHA system. In this system, the time axis is divided into slots (one slot time is T_{slot}), which are composed of guard time T_g and packet time T_p. A packet contains L binary information symbols (1 symbol duration is T_b). We define the access timing as the center of guard time, and the access timing error of k-th user T_{a_k} as the time between the access timing and the time of each user's packet's head. The base station broadcasts information about packet synchronization to user stations, then each user transmits his own packet according to that information. In this study, it is assumed that the access timing error is distributed following the Gaussian distribution with $T_a = 0$ as the center and σ^2 as the variance.

Packet generation, including both transmission and retransmission, is assumed to be binomial distribution with rate λ. We define the offered load G as the average number of generating packets in a slot, so $G = \lambda \cdot T_{slot}$.

Figure 4 illustrates the case where a collision occurs and retransmission is required. Firstly a packet is transmitted and then received after a time T_d. After examining the entire message, if one or more errors are detected, a retransmission request message of duration T_{ack} will return to each user after waiting for exponentially distributed average time intervals T_w, so that, hopefully, the users who collided before will not do so again. Otherwise, a transmission success message will return.

3.1 Transmitter and Receiver Model

Figure 5 indicates the model of the transmitter and the receiver in this system model. The k-th user's transmitted signal $s_k(t)$ is,

$$s_k(t) = \sqrt{2P} \sum_{i=-\infty}^{\infty} \{b_{k,i'} a_{k,i} \cos(\omega_c t + \theta_k)\} \qquad (7)$$

$$\text{where} \quad i' = \left[\frac{i}{N}\right]$$

where P is the signal power of k-th user, ω_c is the carrier angular frequency, and θ_k is the initial phase relative to the k-th user's signal, $b_{k,i'}$ is the i'-th information symbol and $a_{k,i}$ is the i-th element of k-th user's signature sequence, and N is the period of k-th user's signature sequence of elements of $\{+1, -1\}$. Received signal $r(t)$

at the base station is expressed as

$$r(t)=\sum_{k=1}^{K}\sum_{i=-\infty}^{\infty}\{A_k b_{k,i'} a_{k,i}\cos(\omega_c t+\phi_k)\}+n(t) \tag{8}$$

where $\phi_k=\theta_k-\omega_c T_{a_k}$ and $n(t)$ is the channel noise process which we assume to be white and Gaussian process with two-sided spectral density $N_0/2$. And A_k shows k-th user's received signal amplitude.

In this paper, because of the packet transmission, it is difficult for each user to respond instantaneous variation of signal level. However, the open loop power control based on average received level may be achievable. We assume, therefore, that the average signal power $\overline{P_k}$ of each user is equal so that $\overline{P_k}=\overline{P}$ for $k=1,\cdots,K_{sys}$.

The correlator output Z is

$$Z=\left(Z_d+\sum_{\substack{k=1\\(k\neq d)}}^{K} Z_k\right)+Z_{noise} \tag{9}$$

$$Z_d=\frac{A_d}{2}b_{d,i}$$

$$Z_k=\frac{1}{N}\sum_{j=-\infty}^{+\infty}\sum_{n=0}^{N-1}\left[\frac{A_k}{2}a_{k,j}b_{k,j'}a_{d,n}\cos\phi_k\right].$$

where Z_d is the desired signal component, Z_k is the interference component and Z_{noise} is the noise component.

When K users transmit simultaneously, bit error rate $P_b(K)$ of desired signal is,

$$P_b(K)=\frac{1}{2}\mathrm{erfc}\left\{\sqrt{\frac{E_b}{N_0}}\left(Z_d+\sum_{\substack{k=1\\(k\neq d)}}^{K} Z_k\right)\right\}. \tag{10}$$

Where E_b is the bit energy, and $E_b=\overline{P}T_b$.

4. Performance Analysis of QS-CDMA S-ALOHA System

In this section, we will derive the throughput and the delay performance of QS-CDMA S-ALOHA System. The throughput S is defined as the average number of packets that are transmitted with error free per slot. The delay D is defined as the average number of slots which corresponds to the total time delay of a packet.

In this system, the total number of users K_{sys} equals to the number of employing spreading sequences, that is this system would be finite population system. Therefore, the probability that m packets will be generated in a slot can be assumed to be given by the binomial distribution, because K_{sys} users will transmit or not transmit their own packet aiming at a slot. So the probability is shown as below

$$P(m)=\binom{K_{sys}}{m}\lambda^m(1-\lambda)^{K_{sys}-m}. \tag{11}$$

Using Eq. (10), the throughput of QS-CDMA S-ALOHA system is,

$$S(G)=\sum_{m=1}^{K_{sys}} m\cdot P(m)\cdot(1-P_b(m))^L. \tag{12}$$

Therefore, the probability that a packet will be received successfully is

$$Q_s(G)=\frac{S(G)}{G}. \tag{13}$$

The delay time normalized by a slot time T_{slot} is then given by

$$\begin{aligned}D(G)&=\frac{1}{T_{slot}}\{0\cdot Q_s(G)+\Delta(1-Q_s(G))Q_s(G)\\&\quad+2\Delta(1-Q_s(G))^2Q_s(G)+\cdots\\&\quad+q\Delta(1-Q_s(G))^qQ_s(G)+\cdots\}\\&=\frac{1}{T_{slot}}\cdot\frac{\Delta}{Q_s(G)}(1-Q_s(G))\end{aligned} \tag{14}$$

where the time between the second reception and the first reception of packet $\Delta=T_{slot}+T_{ack}+T_w+2T_d$.

5. Numerical Examples

Figure 6 shows the maximum throughput versus the standard deviation of access timing error for QS-CDMA S-ALOHA system employing QS(OG-3) ($N=64$, $K_{sys}=16$) and CDMA S-ALOHA system employing orthogonal Gold sequences ($N=64$, $K_{sys}=64$) over AWGN channel. The signal amplitude is $A_k=\sqrt{2P}$ for all the users. We set $E_b/N_0=10$ [dB], $L=1000$ [bits]. It follows from Fig. 6 that for small access timing error ($\sigma<0.5$), CDMA S-ALOHA system with orthogonal Gold sequences has greatly high throughput performance.

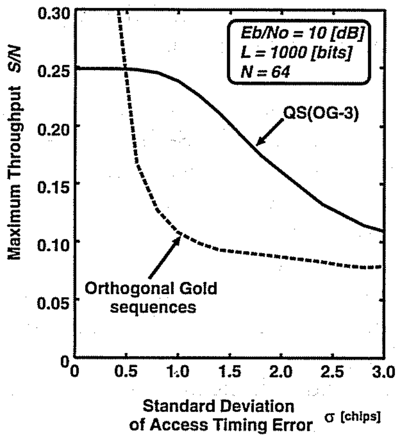

Fig. 6 Maximum throughput versus standard deviation of access timing error.

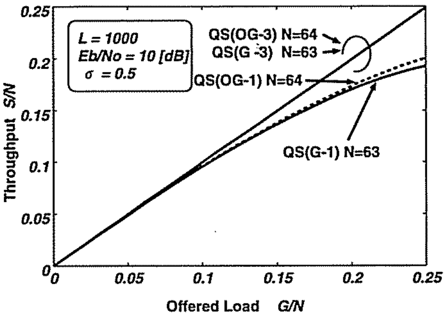

Fig. 7 Throughput performance of QS-CDMA S-ALOHA system over AWGN channel.

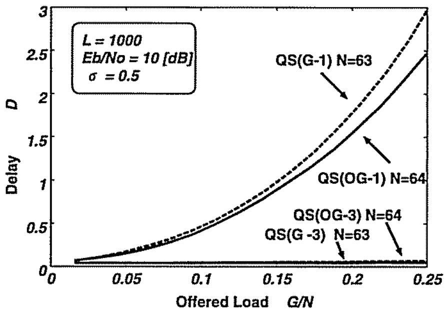

Fig. 8 Delay performance of QS-CDMA S-ALOHA system over AWGN channel.

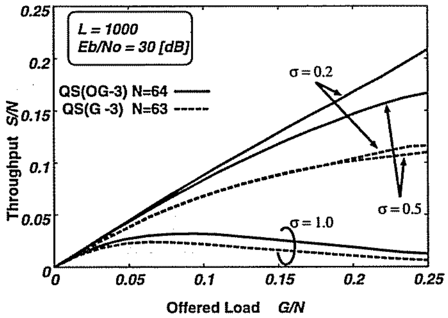

Fig. 9 Throughput performance of QS-CDMA S-ALOHA system over flat fading channel.

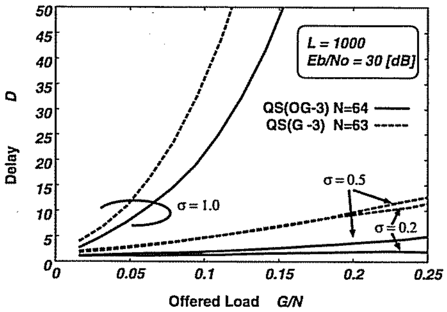

Fig. 10 Delay performance of QS-CDMA S-ALOHA system over flat fading channel.

However, for larger access timing error, QS-CDMA S-ALOHA system with QS(OG-3) shows better throughput than the other. Especially, that system can achieve over 20% of throughput, even if there exists access timing error for $\sigma < 1.5$ [chips]. This is because QS(OG-3) have cross correlation value 0 for 3 chips around the access timing, but orthogonal Gold sequences have it only at the access timing. In this case, the improvement of the throughput will be expected for $\sigma > 0.5$. However, judging from the cross correlation property of QS(OG-3), the improvement will be achieved for $\sigma < 1.0$, even if the channel is noisy. When $\sigma = 0$, the maximum throughput of the system using QS(OG-3) is about 0.25. This is because the number of users in that system is 16 and the sequence length is now 64, so the maximum normalized throughput is 0.25 at most.

In Figs. 7 and 8, we show the throughput and the delay performance of QS-CDMA S-ALOHA system with QS(OG-3), QS(OG-1) (sequence lengths and the number of users are the same in Fig. 6) and with conventional QS-sequences (QS(G-3) ($N = 63$, $K_{sys} = 16$), QS(G-1) ($N = 63$, $K_{sys} = 64$)) over AWGN channel. In these figures, we set $\sigma = 0.5$ [chips]. The values of the throughput and the offered load are normalized by the processing gain N.

Figures 7 and 8 indicate that better performance can be obtained by using QS(OG-3) and QS(G-3) than the case of QS(OG-1) and QS(G-1). The throughput and delay performance of using QS(OG-3) is almost same as using QS(G-3) in this situation. From these figures, even if the number of sequences are small, using QS-sequences that have wide range of allowance of access timing error can obtain higher throughput and small delay in CDMA S-ALOHA system.

Figures 9 and 10 indicate the throughput and the delay performance of QS-CDMA S-ALOHA system using previous four QS-sequences over the flat Rayleigh fading channel. The signal amplitude of each user is affected by the fading, so A_k is distributed as Rayleigh distribution of average $\sqrt{2P}$. In this system, the path model is the single path model. In these figures, we set $\sigma = 0.2, 0.5, 1.0$ [chips] and $E_b/N_0 = 30$ [dB]. For all the cases of access timing error, using QS(OG-3) performs better than using QS(G-3). This difference may be caused by the property of cross correlation of each QS-sequence. In the fading channel, if there exists a little cross correlation, fluctuation of amplitude, the fading may greatly degrade the probability of successful transmissions which will result in the long delay. Concerning r or sequence length N, the difference generally exists. Therefore, the performance of the system using QS(OG-r) may be superior to QS(G-r).

In these figures, even though $\sigma = 1.0$, the performance is considerably degraded due to the access timing error and the fading. Over the fading channel, because of the variation of signal to noise ratio, the throughput and the delay improvement won't be expected like AWGN channel. In this case, better performance may be obtained when $\sigma < 0.5$.

6. Conclusions

In this paper, we have proposed new QS-sequences for CDMA S-ALOHA system. The sequences which have been selected from orthogonal Gold sequences have robustness for access timing error, therefore even if the number of sequences are smaller than full set of orthogonal Gold sequences, using the sequences performs better throughput and delay performance in that situation.

Moreover, QS-CDMA S-ALOHA system using the new QS-sequences can show higher throughput and better delay over flat Rayleigh fading channel than using conventional QS-sequences. This may be because the new QS-sequences have cross correlation value 0 for a few chips near the access timing. On AWGN channel, this property is not so much greater than the property that the conventional QS-sequences have, however, on fading channel, using new QS-sequences may not be so affected by the amplitude fluctuation of fading and using conventional QS-sequences could not keep the correlation value small.

By using the QS(OG-τ), QS-CDMA S-ALOHA system can show available throughput and delay over AWGN or flat Rayleigh fading channel, even if access timing error exists.

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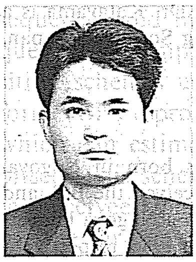

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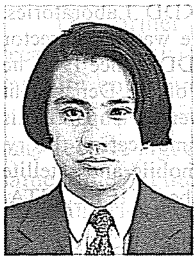

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