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Orthogonal Time Hopping Multiple Access for UWB Impulse Radio Communications

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Abstract— **Recently, UWB technologies have been introduced for low rate wireless personal area networks (LR-WPANs). Since the energy level of the UWB impulse radio signals is very low, it is very hard to apply them to a carrier sensing multiple access with collision avoidance (CSMA/CA) scheme, which was adopted as the MAC protocol in IEEE 802.15.4 standard. In this paper, we propose an orthogonal time hopping multiple access (OTHMA) as a multiple access scheme for UWB impulse radio communications, and compare the MAC performance of the proposed scheme with that of CSMA/CA in terms of throughput, success probability, average delay, and user utilization. Simulation results show that the proposed scheme performs better than CSMA/CA as the number of users increases. Therefore, OTHMA can be applied as a multiple access scheme for low power, large scale, and low activity networks in UWB impulse radio communications.**

Index Terms— **UWB, Multiple Access, Statistical Multiplexing, IEEE 802.15.4 (LR-WPAN).**

I. INTRODUCTION

Ultra-wideband (UWB) technologies have attracted public attention in communications systems since FCC's approval in Feb. 2002. Since they use very short pulses with approximately one nano second, the signal energy is widely spread up to several GHz band. The signal may be overlaid with some conventional narrow band communications systems. To reduce the interference to other systems, we must strictly meet the FCC's rules for power limitation. However, because of high bit rate, low cost and low power implementation, location awareness with high resolution, and robustness for dense multipath environments, they have been investigated for a short range communications in Wireless Personal Area Networks (WPAN) and sensor networks [1].

Among the standardization communities, Low Rate Alternative PHY Task Group (TG4a) in IEEE 802.15 WPAN, which is defined as an amendment to IEEE 802.15.4 standard [2], has investigated high precision ranging (1 m accuracy and better), low data rate, low power, very low complexity, and large scalability for WPANs or sensor networks [3]. Especially, they consider UWB impulse radio technologies as good solutions for IEEE 802.15.4a standard due to their advantages.

Carrier Sensing Multiple Access with Collision Avoidance (CSMA/CA) was adopted as an IEEE 802.15.4 MAC protocol [2]. It requires a carrier sensing procedure, which performs a Clear Channel Assessment (CCA) function in the physical layer, to detect if the channel is busy or idle before transmitting data [2]. Since the energy level of the received UWB impulse signals is very low, it is very hard to detect the carrier signal in a very short time. The receiver must integrate the energy of UWB signals during CCA detection time, and determine the existence of signals. Since the detection time is very short as only 8 symbol period, as described in [2], the receiver cannot fully detect the carrier signals and it may cause longer delay and consume more power. Even if carrier sensing methods to detect a busy medium for UWB impulse radio were proposed in [4], [5], it is also hard to apply them to IEEE 802.15.4 or sensor networks due to hardware complexity and control overhead.

In order to overcome the difficulties in carrier sensing, we need a new multiple access scheme for low power, large scale, and low activity networks in UWB impulse radio communications.

Recently, an orthogonal code hopping multiplexing (OCHM) scheme has been proposed in order to support a large number of users in DS/CDMA systems [6], [7]. Since the code channels are shared by users with user-specific hopping patterns in the given code domain, the number of allocatable channels can be much larger than that of codes. This statistical multiplexing scheme may cause collisions when more than two users choose the same code during a symbol period. But, they can be partially recovered by the mitigating schemes such as the channel coding schemes. If the activity is low, the collision probability is low. Therefore, it can achieve a high statistical multiplexing gain for low activity user environments.

In this paper, we propose a multiple access scheme, that is called Orthogonal Time Hopping Multiple Access (OTHMA), employing a statistical multiplexing concept like the above mentioned OCHM in the time hopping multiple access (THMA) scheme, which is the conventional multiple access scheme of UWB impulse radio communications [1], [8]. We compare the performance of both the proposed scheme and CSMA/CA in IEEE 802.15.4 MAC protocol.

This paper is organized as follows. We briefly describe the IEEE 802.15.4 MAC protocol in Section II, and propose an orthogonal time hopping multiple access (OTHMA) in Section III. In Section IV, we introduce a simulation model and a data traffic model in order to compare the performance of the proposed OTHMA and CSMA/CA. In Section V, we compare the performance of OTHMA with that of CSMA/CA in terms of throughput, success probability, average delay, and user utilization. Finally, we present conclusions in Section VI.

II. IEEE 802.15.4 MAC Overview

IEEE 802.15.4 networks can be operated in a beacon-enabled mode or a non-beacon-enabled mode. In the non-beacon-enabled mode, users in a PAN communicate with each other based on the unslotted CSMA/CA. However, most of applications are expected to be operated in the beacon-enabled mode. In the beacon-enabled mode, a superframe structure that has an active period and an optional inactive period is used and its length is specified as beacon interval (*BI*), as shown in Fig. 1. The active period consists of a beacon period, a contention access period (CAP), and a contention free period (CFP), and its length is specified as superframe duration (*SD*). During the inactive period, the coordinator and nodes shall not interact with its PAN and may enter a low-power mode.

At the start of each superframe, a PAN coordinator transmits a beacon frame that has system parameters, such as beacon order (*BO*) that determines the length of beacon interval ($BI = aBaseSuperFrameDuration * 2^{BO}$), and superframe order (*SO*) that determines the length of superframe duration ($SD = aBaseSuperFrameDuration * 2^{SO}$).

In the CAP period, users communicate with a PAN coordinator and others using slotted CSMA/CA. When a user wants to transmit a message, it must attempt carrier sensing that is performed by clear channel assessment (CCA) in the physical layer before transmission. If the channel is idle, it transmits. If the channel is busy, it delays a random number of backoff periods that are limited up to $2^{BE}-1$ periods, where *BE* is the backoff exponent, and retries to do carrier sensing. For each retry, *BE* and *NB* are increased by one, where *NB* is the number of times that the CSMA/CA algorithm was required to backoff while attempting the current transmission. If *NB* is greater than *macMaxCSMABackoffs*(default value=4), the CSMA/CA algorithm shall be terminated with a channel access failure.

A frame transmitted with the acknowledgment request can be acknowledged by the recipient. If the intended recipient correctly receives the frame, it generates and sends an acknowledgment frame within t_{ack}, between *aTurnaroundTime* and (*aTurnaroundTime* + *aUnitBackoffPeriod*) after the reception of the last symbol of the data frame. If an acknowledgment frame is received by the sender within *macAckWaitDuration*, the transmission is considered successful. On the other hand, if an acknowledgment is not received within *macAckWaitDuration* and its timer ($T_{MaxAckWait}$) is expired, the sender can conclude that the single transmission attempt has failed and can try again a retransmission up to *aMaxFrameRetries* (default value=3).

In the CFP period, users use a time division multiple access (TDMA) protocol. If users require special QoS or dedicated bandwidth, they request one or more guaranteed time slots (GTS) to the PAN coordinator and the coordinator allocates the required number of GTSs. The PAN coordinator informs nodes of the allocation status of GTSs in this CFP through a beacon. Then, they transmit their messages in their allocated GTSs without contention.

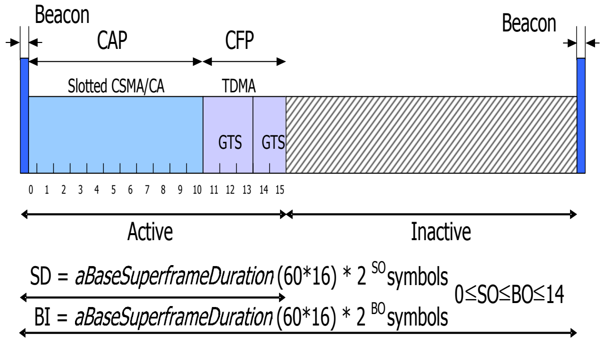

Fig. 1. An example of superframe structure for IEEE 802.15.4 MAC

III. Orthogonal Time Hopping Multiple Access

An Orthogonal Time Hopping Multiple Access (OTHMA) is based on the conventional time hopping multiple access scheme for UWB impulse radio communications. The time hopping format using M-ary pulse position modulation (PPM) of the k-th user with UWB impulse radio signal $s^{(k)}(t)$ is given by

$$s^{(k)}(t) = \sum_{j=-\infty}^{\infty} w(t - jT_f - c_j{}^{(k)}T_c - d^{(k)}(\lfloor j/N_r \rfloor)T_m), \quad (1)$$

where $w(t)$ is the transmitted monocycle waveform, and T_f is the pulse repetition time. $c_j{}^{(k)}$ is the pseudo random time hopping sequence of the kth user with period N_p and an integer in the range $0 \leq c_j{}^{(k)} < N_c$. It may be generated by PN sequences based on user's ID such as a device address. T_c is the chip duration, and N_c is the number of time hops (THs) in one T_f, that is, $T_f = N_c T_c$. $d^{(k)}(\cdot)$ is the data symbol sequence of the kth user, N_r is the number of repetitions, and T_m is the pulse bin width, where $T_c = MT_m$. To reduce the inter-symbol interference (ISI), we consider that the value of T_m is larger than the delay profile of UWB impulse radio, and it is approximately 200 (ns) in [9].

Since the number of THs in T_f is limited and the time hopping sequence for each user is mutually independent, some THs of two or more active users may be identical during T_f as shown in Fig. 2. Active users #3 and #5 have the same TH #11 in the $(n+2)$-th T_f. This event is called *collision*. Although users #4 and #5 have the same TH #12 in the $(n+3)$-th T_f, it is not a collision because user # 4 is inactive.

When collisions occur, the receiver can operate *perforation* or *synergy*. If the symbols of a colliding TH are different, the receiver does not know the transmitter of each symbol. Therefore, it can not detect the signal, that is, *perforation*. If the symbols of a colliding TH are identical, the receiver recognizes the symbol and operates the same as the case of no collision, that is, *synergy*. The damaged symbols by

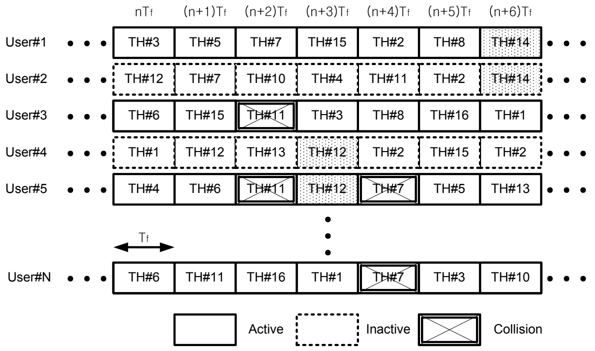

Fig. 2. Orthogonal Time Hopping Multiple Access

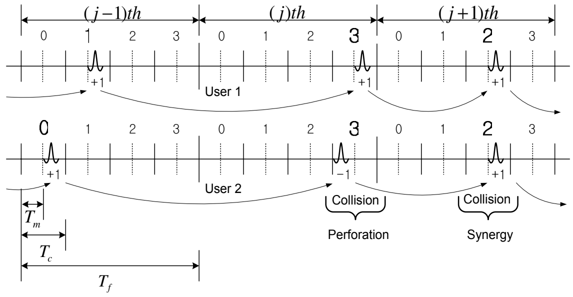

Fig. 3. An operating example of OTHMA

perforation can be recovered by repetitions or channel coding schemes.

The collision probability (P_c) in OTHMA is written as

$$P_c = 1 - (1 - \frac{\nu}{N_c})^{K-1}, \tag{2}$$

where ν is the user activity, and K is the number of users. The perforation probability (P_p) in OTHMA is expressed as

$$P_p = 1 - \sum_{i=0}^{M-1} \pi_i (1 - (1 - \pi_i)\frac{\nu}{N_c})^{K-1}, \tag{3}$$

where π_i is the probability of modulated symbol $i \in \{0, 1, \cdots, M-1\}$. For a given ν, the perforation probability increases as K increases.

If each symbol is repeated N_r times, the receiver can correctly determine that symbol except all perforations, that is, most perforated symbols can be recovered. Since the probability of i perforations among N_r symbol repetitions follows a binomial distribution

$$P(Y_{N_r} = i) = \begin{pmatrix} N_r \\ i \end{pmatrix} {P_p}^i (1 - P_p)^{N_r - i}, \tag{4}$$

where Y_{N_r} is a random variable representing the number of perforations among N_r symbol repetitions (*Bernoulli* trials), the symbol error rate (P_M) is given as

$$P_M = 1 - \sum_{i=0}^{M-1} \pi_i (1 - (1 - \pi_i){P_p}^{N_r}). \tag{5}$$

Fig. 3 shows an operating example of OTHMA that is based on a time hopping system with binary PPM. A TH sequence $c^{(1)}$ of user 1 is $\{\cdots, 1, 3, 2, \cdots\}$ and a TH sequence $c^{(2)}$ of user 2 is $\{\cdots, 0, 3, 2, \cdots\}$. There are two collisions at the j-th and the $(j+1)$-th T_f. In the case of the j-th T_f, the symbols of users 1 and 2 are '+1' and '-1', respectively. Since there are signals in the two positions of binary PPM, the receivers do not identify their desired symbol. Therefore, they decide that the symbol is '0' by perforation operation. In the case of the $(j+1)$-th T_f, the symbols of users 1 and 2 are '+1' and '+1', respectively. Since there is only one signal in one position of binary PPM, the receivers can simply identify their desired symbol. Therefore, they decide that the symbol is '+1' by synergy operation.

Based on the IEEE 802.15.4 MAC protocol, a superframe structure is divided into an active period which consists of a beacon period, a contention access period (CAP), and a contention free period (CFP), and an inactive period as mentioned in Section II. We apply the proposed multiple access scheme, called OTHMA, into CAP. Unlike CSMA/CA, users transmit data when they desire, that is, it allows users to simultaneously transmit the data. The receiver can distinguish the symbols of the sender by the user-specific time hopping sequence. The acknowledgement policy is the same as the IEEE 802.15.4 MAC protocol.

IV. Simulation Model

To evaluate the performance of multiple access schemes, we consider a star topology network that consists of a PAN coordinator and many users. Since most of applications are to collect data from users in low-rate WPANs, we focus on the CAP period. For simplification, we assume that users are time-synchronous according to the beacon of a PAN coordinator.

In data traffic models, the packet size and the inter-arrival time are taken into account. The size of a data packet L_{DATA} is fixed with $L_{DATA} = 22$ bytes and that of an ACK packet L_{ACK} is also fixed with $L_{ACK} = 11$ bytes [2]. A random variable τ of inter-arrival time follows an exponential distribution with mean $E[\tau] = \frac{1}{\lambda_\tau}$ and channel activity $\nu = \frac{T_{ON}}{T_{ON}+T_{OFF}}$, where $E[\tau] = T_{ON} + T_{OFF}$, and $T_{ON} = 13.95$ ms.

In OTHMA, the time hopping sequence for each user is independently generated by PN sequences.

Table I illustrates the input parameters for simulation. They are related to system parameters of the superframe structure and multiple access schemes as mentioned in Sections II and III.

Four performance measures are used in this paper. First, throughput [bps] is defined as the successfully transmitted bits per second. Second, the success probability is defined as the probability that a frame is successfully transmitted. The third, the average delay [s] is defined as the average sojourn time from the frame generation time to the reception time of an acknowledgement for successful frame transmission. The

TABLE I
INPUT PARAMETERS

Parameter	Value
Data Rate (R)	20 (kbps)
Bit Duration (T_{BIT})	0.05 (ms)
Beacon Interval (*BI*)	192 (ms)
Superframe Duration (*SD*)	96 (ms)
Beacon Period Duration (T_{BP})	6 (ms)
CAP Duration (T_{CAP})	60 (ms)
CFP Duration (T_{CFP})	30 (ms)
aTurnaroundTime (t_{ack})	0.6 (ms)
Max. waiting time for ACK ($T_{MaxAckWait}$)	6 (ms)
# of positions for PPM (M)	2 (binary)
Pulse Bin Width (T_m)	200 (ns)
# of hops (N_c)	8
# of repetitions (N_r)	16
User activity (ν)	10^{-2}

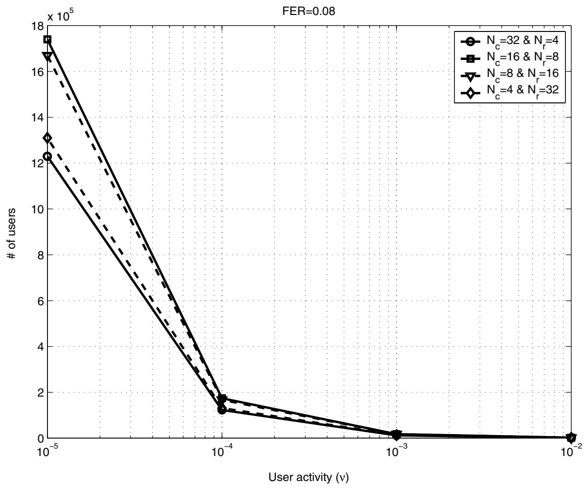

Fig. 4. The allowable number of users ($FER = 0.08$)

fourth, user utilization is defined as the ratio of user's active duration to transmit a frame out of the total simulation time.

V. SIMULATION RESULTS

We investigate the allowable number of users according to the user activity (ν) for OTHMA. Using the symbol error rate P_M, the maximum number of users that its frame error rate is smaller than or equal to 0.08, is illustrated for the case of $N_c = 32, 16, 8, 4$ and $N_r = 4, 8, 16, 32$, as shown in Fig. 4. These parameters can be set up to adjust a data rate R. Since lower activity causes lower P_M, the allowable number of users increases. The case of $N_c = 16$ and $N_r = 8$ shows the best. If N_c is larger, the resource pool which user chooses is larger and it is more preventive for collisions. If N_r is larger, the probability of recovery from collisions becomes higher. From the results, there is a tradeoff between the effect of the number of THs N_c and that of the number of repetitions N_r for mitigating collisions.

Fig. 5 compares the throughput of OTHMA and CSMA/CA for varying the number of users. OTHMA performs about 6 times better than CSMA/CA as the number of users increase. Under given simulation environments, OTHMA can support about 180 users and CSMA/CA can do about 30 users. Even if the channel is idle, users do not immediately transmit data by performing CCA for CSMA/CA. If one user occupies the channel, other users that want to transmit must wait until the channel is idle. There is a decrease in the resource efficiency and it causes low throughput. On the other hand, OTHMA can accommodate desired users to simultaneously transmit the data and mitigate a collision problem through perforation/synergy operations and symbol repetitions. Therefore, it can achieve high throughput.

Fig. 6 shows the success probability of OTHMA and CSMA/CA for varying the number of users. The performance of OTHMA is better than that of CSMA/CA. In the case of OTHMA, the success probability is almost 1.0 for up to 180 users and then decreases for more than 180 users. It is because the throughput increases for up to 180 users, as shown in Fig. 5. It is shown that OTHMA is capable of perfectly mitigating the collisions among 180 users under given simulation environments. On the contrary, in the case of CSMA/CA, the success probability rapidly decreases as the number of users increases. It is approximately reduced by a half for 40 users. As the number of users increases, more and more users cannot occupy one channel, and they discard more data frames by transmission failure.

Fig. 7 shows the average delay for OTHMA and CSMA/CA for varying the number of users. The performance of OTHMA is better than that of CSMA/CA, also. Since the success probability of OTHMA is almost 1.0 for up to 180 users, as shown in Fig. 6, the average delay keeps at a constant value and then increases due to limitation of its capacity for more than 180 users. It yields an increase in the average delay due to lower success probability and more retransmissions for more than 180 users. The average delay of CSMA/CA rapidly increases for up to 60 users since the success probability rapidly decreases, as shown in Fig. 6. It takes a relatively long time to successfully send the data and to successfully receive its acknowledgement due to more competitions and retransmissions. Since the number of retransmissions is limited to *aMaxFrameRetries* (default value=3), it yields to saturate the average delay for more than 60 users in the case of CSMA/CA.

Fig. 8 compares the performance of both systems in terms of user utilization for varying the number of users. User utilization indicates the duration that a user stays in the active state to transmit data. As it is higher, the amount of power consumption in active state is larger. The performance of OTHMA is about 5 times better than that of CSMA/CA for 150 users. It means that the battery lifetime for OTHMA is about 5 times longer than for CSMA/CA. It is because the user can transmit data in the case of OTHMA when he desires, without waiting for the next CSMA/CA procedures, such as performing CCA or backoff. As the number of users increases, user utilization of CSMA/CA rapidly increases due to competitions and retransmissions. If the number of

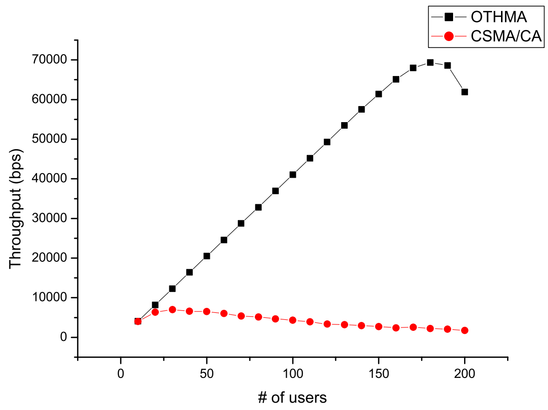

Fig. 5. Throughput for OTHMA and CSMA/CA

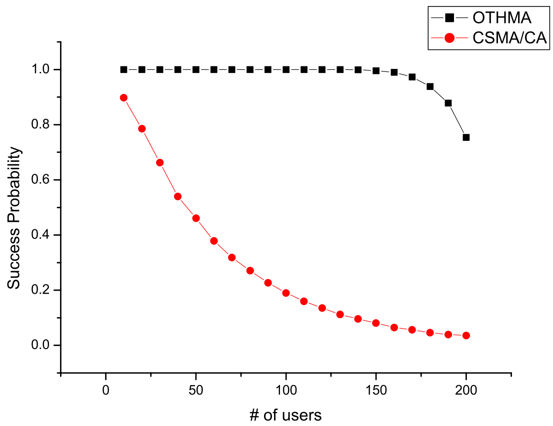

Fig. 6. Success probability for OTHMA and CSMA/CA

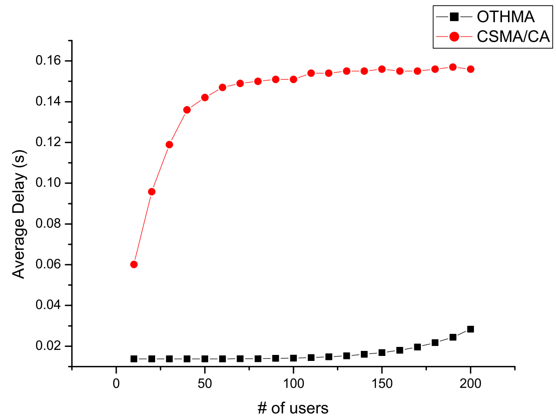

Fig. 7. Average delay for OTHMA and CSMA/CA

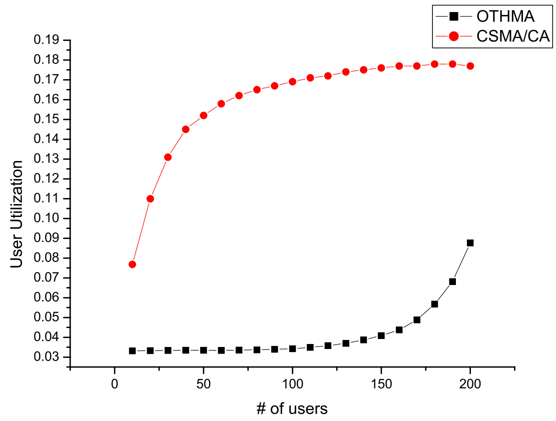

Fig. 8. User utilization for OTHMA and CSMA/CA

retransmissions exceeds *aMaxFrameRetries*, that transmission fails. Therefore, users may be in the active state, at the very most, until a data frame is discarded due to transmission failure. It causes to saturate the user utilization for a large number of users in the case of CSMA/CA, also.

VI. Conclusions

In this paper, we proposed an OTHMA as a multiple access scheme for UWB impulse radio communications and compared the performance of OTHMA and CSMA/CA in terms of throughput, success probability, average delay, and user utilization. Simulation results show that the performance of OTHMA is better than that of CSMA/CA. Since OTHMA allows active users to transmit data needless of performing CCA and mitigates a collision problem through perforation/synergy operations and symbol repetitions, it can achieve good performance. In addition, if the user's activity is lower, the collision probability is lower. Consequently, OTHMA can support a larger number of users due to a higher statistical multiplexing gain. Therefore, OTHMA can be applied as a multiple access scheme based on UWB impulse radio communications for low activity, large scale, and energy efficient networks.

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