Ordered Sequential-Superposition Cooperative Spectrum Sensing for Cognitive Radio Networks

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***Abstract*—Cognitive radio (CR) is a promising technology for improving usage of frequency band. In CR network, cognitive radio users (CUs) are allowed to use the bands without interference to operation of licensed users. Reliable sensing information about status of primary user (PU), who is assigned a licensed band, is a pre-requirement for CR network. Cooperative spectrum sensing (CSS) is able to offer an improved sensing reliability compared to individual sensing. However, when the number of CUs is large, the latency and network traffic for reporting sensing results to the Fusion Center (FC) become extremely large, which may result in an extended sensing time and collision in the control channel between Cognitive Users (CUs) and the FC. In this paper, we propose an ordered Sequential-Superposition Cooperative Spectrum Sensing (SSCSS) scheme for faster and more reliable spectrum sensing of CR network. Superposition CSS technique extends sensing time to the reporting slots of other CUs until their round of reporting. The proposed scheme estimates the required number of CUs needed to sense for satisfying the reliability requirement of the system. Furthermore, the scheme decides which CUs (and their orders of polling) will be chosen for the sensing process to maximize performance of the proposed scheme. The simulation results of the proposed scheme show the outstanding performance of the proposed scheme compared with the other conventional CSS.**

Keywords–cognitive radio; ordered sequential cooperative spectrum sensing; superposition cooperative spectrum sensing.

I. INTRODUCTION

Nowadays, more bandwidth and higher bit-rates have been required to meet usage demands due to an explosion in wireless communication technology. According to the Federal Communications Commission's spectrum policy task force report [1], the actual utilization of the licensed spectrum varies from 15% to 80%. In some cases, the utilization is only a few percent of the total capacity. Cognitive radio (CR) technology [2] has been proposed to solve the problem of ineffective utilization of spectrum bands. Both unlicensed and licensed users, termed the cognitive radio user (CU) and primary user (PU), respectively, operate in CR networks. In CR network, CUs are allowed to access the frequency assigned to PU when it is free. But CU must vacate the occupied frequency when the presence of PU is detected. Therefore, reliable detection of the PU's signal is a requirement of CR networks.

In order to ascertain the presence of a PU, CUs can use one of several common detection methods, such as matched filter, feature, and energy detection [2][3]. Energy detection is the optimal sensing method if the CU has the limited information about PU's signal (e.g., only the local noise power is known) [3]. In energy detection, frequency energy in the sensing channel is collected in a fixed bandwidth W over an observation time window T to compare with the energy threshold and determine whether or not the channel is utilized. However, the received signal power may fluctuate severely due to multipath fading and shadowing effects. Therefore, it is difficult to obtain reliable detection with only one CU. Better sensing performance can be obtained by allowing some CUs to perform cooperative spectrum sensing [4][5][6].

In CSS, because of the limitations of the control channel, CUs will report their sensing information to the FC one by one. Subsequently, in a CR network with a large number of CUs a very large number of reports will be transmitted through a control channel, which can make the sensing process sluggish and result in overhead traffic in the control channel. In order to solve those problems of CSS, SCSS scheme [8][9] has been proposed. In SCSS, the fusion center (FC) acts as the control center for the operation of CR network. The FC sends the "sensing request" message to CUs when it needs their sensing information, and randomly polls CUs one by one until the condition required to make a global decision is satisfied. The ordered SCSS can improve sensing performance by polling sensing results of CUs according to their order of reliability (i.e., signal-to-noise ratio (SNR) of sensing channel of the CU). The ordered SCSS can efficiently reduce the number of sensing report from the CUs. However, the conventional SCSS uses the same sensing time for all CUs. The superposition CSS [8] can solve this problem of conventional SCSS by extending sensing duration of CUs to the reporting time of other CUs.

In this paper, we propose an ordered sequential-superposition CSS for cognitive radio networks. The proposed scheme estimates the required number of CUs needed to poll for satisfying the reliability requirement of the system. Furthermore, through the proposed scheme we can decide which CUs will be chosen for the sensing process and their orders of polling to maximize sensing performance.

This paper is organized as follows. Section 2 describes and analyses the energy detection method. Section 3 gives a detailed explanation of the ordered sequential-superposition cooperative spectrum sensing scheme. Section 4 introduces simulation models and simulation results of the proposed scheme. Finally, Section 5 concludes this paper.

II. SYSTEM MODEL

In this paper, we consider a network consisting of N CUs. In addition, there is one PU occupying the observed band with

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a specific probability. If the CR network needs the sensing information, the FC will send the "request message" to the selected CUs with their order of polling. When the CU receives the "request message" from the FC, it will perform spectrum sensing (SS) and report sensing result to the FC according to its order of polling.

We assume that all CUs utilize energy detector for SS. Then at the i^{th} sensing interval, the received signal energy $E_j(i)$ of the j^{th} CU is given as:

$$E_j\left(i\right) = \begin{cases} \sum_{k=k_i}^{k_i+M_j-1} \left|n_j\left(k\right)\right|^2, & H_0 \\ \sum_{k=k_i}^{k_i+M_j-1} \left|h_j x\left(k\right)+n_j\left(k\right)\right|^2, & H_1 \end{cases} \quad (1)$$

where H_0 and H_1 correspond to the hypotheses of the absence and presence of the PU signal, respectively, $x(k)$ represents the signal transmitted from the PU, h_j denotes the amplitude gain of the channel, and $n(k)$ is the additive white Gaussian noise, $M_j = t_{sj} f_s$ is the number of samples over a sensing interval, t_{sj} is sensing time, f_s is sensing bandwidth and k_i is the time slot at which the i^{th} sensing interval starts.

In conventional CSS, when a CU sends sensing results to the FC, others will keep silent as shown in Fig. 1. In this case, all CUs have the same sensing time such that $t_{s1,C} = t_{s2,C} = ... = t_{sN,C} = t_s$. On the other hand, superposition CSS extends the sensing time of CUs to the reporting time of other CUs as shown in Fig. 2.

When M_j is relatively large (e.g., $M_j > 200$), E_j can be well approximated as a Gaussian random variable under both hypotheses as follows [7]:

$$\begin{aligned} &N\left(\mu_{j,H_0} = M_j, \sigma_{j,H_0}^2 = 2M_j\right) \\ &N\left(\mu_{j,H_1} = M_j\left(\gamma_j+1\right), \sigma_{j,H_1}^2 = 2M_j\left(2\gamma_j+1\right)\right) \end{aligned} \quad (2)$$

where $N(.)$ is Gaussian distribution, μ_{j,H_0} and μ_{j,H_1} are the mean of E_j under H_0 and H_1 hypothesis, respectively, σ_{j,H_0}^2 and σ_{j,H_1}^2 are the variance of E_j under H_0 and H_1 hypothesis, respectively, γ_j is SNR in the sensing channel between the j^{th} CU and the PU.

The local decision of the j^{th} CU at the i^{th} sensing interval can be made as the following rule:

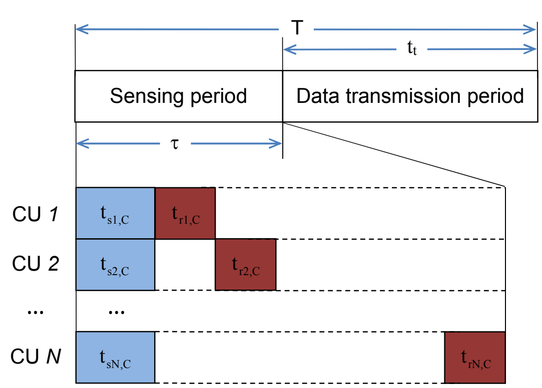

Figure 1. The time frame of conventional cooperative spectrum sensing

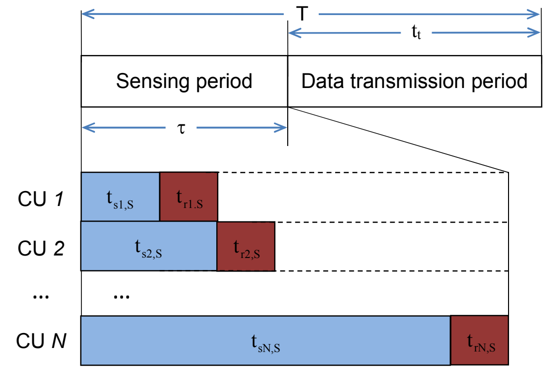

Figure 2. The time frame of superposition cooperative spectrum sensing

$$\begin{cases} G_j\left(i\right) = 1, \text{ if } E_j\left(i\right) \geq \lambda_j \\ G_j\left(i\right) = 0, \text{ otherwise} \end{cases} \quad (3)$$

where λ_j is the threshold for hard local decision of the j^{th} CU.

The average probability of detection and the average probability of false alarm of the j^{th} CU are given, respectively, by [11].

$$\begin{aligned} P_{d,j} &= \Pr\left(G_j\left(i\right) = 1 \middle| H_1\right) \\ &= Q_u\left(\sqrt{2\gamma_j}, \sqrt{\lambda_j}\right), \end{aligned} \quad (4)$$

$$\begin{aligned} P_{f,j} &= \Pr\left(G_j\left(i\right) = 1 \middle| H_0\right) \\ &= \frac{\Gamma\left(M_j, \frac{\lambda_j}{2}\right)}{\Gamma\left(M_j\right)}, \end{aligned} \quad (5)$$

where $\Gamma(a, x)$ is the incomplete gamma function which is given by $\Gamma(a, x) = \int_x^\infty t^{a-1} e^{-t} dt$, $\Gamma(a)$ is the gamma function, $Q_{M_j}(a, b)$ is the generalized Marcum Q-function which is given by $Q_{M_j}(a, x) = \frac{1}{a^{M_j-1}} \int_x^\infty t^{M_j} e^{-\frac{t^2+a^2}{2}} I_{M_j-1}(at) dt$, and $I_{M_j-1}(.)$ is the modified Bessel functions of the first kind and order $(M_j - 1)$.

With the requirement value of probability of detection, $P_{d,j}^*$, probability of false alarm can be calculated as follows:

$$P_{f,j}\left(P_{d,j}^*\right) = Q\left(\sqrt{2\gamma_j+1} Q^{-1}\left(P_{d,j}^*\right) + \sqrt{M_j}\gamma_j\right) \quad (6)$$

We define the reliability of CU as probability of false alarm $P_{f,j}\left(P_{d,j}^*\right)$. If all CUs have the same $P_{d,j}^*$ and M_j, the CU with lower value of $P_{f,j}\left(P_{d,j}^*\right)$ will be higher reliability.

III. The Ordered Sequential-Superposition Cooperative Spectrum Sensing Scheme

In conventional ordered based SCSS, the highest reliability CU (the CU with the highest SNR of sensing channel) should be polled first for fast SS. However, this technique gives good performance only for CSS with the same sensing time for

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all CUs. In this paper, we propose an ordered sequential-superposition CSS for cognitive radio network in which the the set of CUs will be selected to perform SS and each of selected CU will be assigned a suitable sensing time for the best sensing performance of sensing process.

In the initial stage, a requirement number of CUs, p, which is needed to perform SS, will be selected as $0 < p < N$. After that, FC will choose the set of p highest reliability CUs, $\Omega = [\mathrm{CU}_1, \mathrm{CU}_2, ..., \mathrm{CU}_\mathrm{p}]$. Set Ω is sorted according to the increasing order of reliability that is CU_1 is the lowest reliable CU and CU_p is the highest reliable CU. The CUs included in set Ω will be required to sense the signal from the PU.

We assume that all CUs have the same reporting time such that $t_{r1,S} = t_{r2,S} = ... = t_{rN,S} = t_r$. Then the sensing time for p CUs will be given as follows:

$$\begin{aligned} &t_{s1,S} = t_s \\ &t_{s2,S} = t_{s1,S} + t_r = t_s + t_r \\ &t_{s3,S} = t_{s2,S} + t_r = t_s + 2t_r \\ &... \\ &t_{sp,S} = t_{sp-1,S} + t_r = t_s + (p-1)\, t_r \end{aligned} \quad (7)$$

This means that the CU, who firstly reports sensing information to the FC, will have the shortest sensing time $t_{s1,S} = t_s$ and the CU, who is the last CU reporting sensing information to the FC, will have the longest sensing time $t_{sN,S}$. The time frame of the proposed scheme is shown in the Fig. 3.

In order to maximize sensing performance, in the proposed scheme the CU with higher reliability, CU_p, will be assigned to have the longer sensing time $t_{sp,S}$. Subsequently, the highest reliable CU CU_p is required to sense in $t_{sp,S}$ time and is the last CU reporting sensing information to the FC. On the other hand, the lowest reliable CU, CU_1, is required to sense in $t_{s1,S}$ time and firstly reports sensing information to the FC.

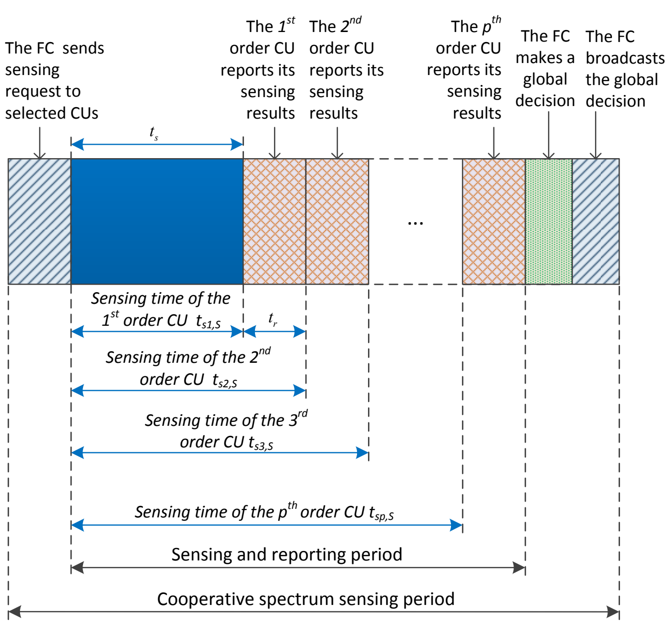

Figure 3. The time frame of the proposed scheme

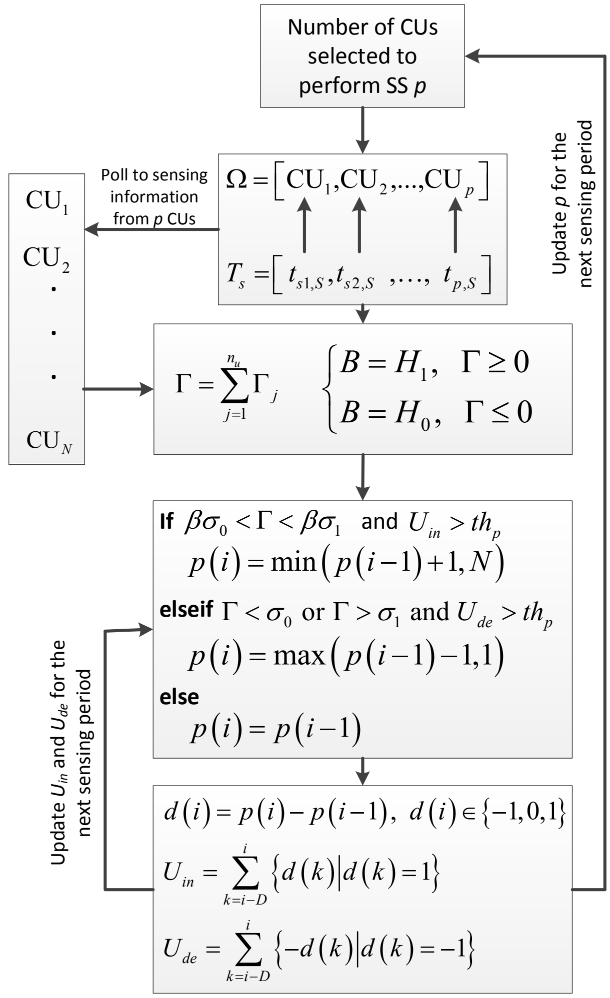

Figure 4. Flow-chart of the proposed scheme

In order to start the sensing process, FC will send the "sensing request" message and the order of reporting to the CUs in Ω. When CUs receive the "sensing request" message from the FC, they will sense the signal from the PU until their round of reporting. Each CU will make local decision as Eqn. (3) and report its decision to the FC. At the FC, the accumulated log-likelihood of p CUs will be calculated as [12]:

$$\Gamma = \sum_{j \in \Omega} \Gamma_j \quad (8)$$

where

$$\begin{aligned} &\Gamma_j = \log \frac{\mathrm{P_{d,j}}}{\mathrm{P_{f,j}}}, \ \text{ if } \mathrm{G_j} = 1 \\ &\Gamma_j = \log \frac{(1-\mathrm{P_{d,j}})}{(1-\mathrm{P_{f,j}})}, \ \text{ otherwise.} \end{aligned} \quad (9)$$

The global decision about status of the PU signal can be made as:

$$\begin{cases} B = H_1, \ \text{if } \Gamma \geq 0 \\ B = H_0, \ \text{otherwise} \end{cases} \quad (10)$$

Here, the value of accumulated log-likelihood of p CUs, Γ, is known as reliable level of sensing process. Then we utilize Γ as a criteria to update the required number of CUs for the

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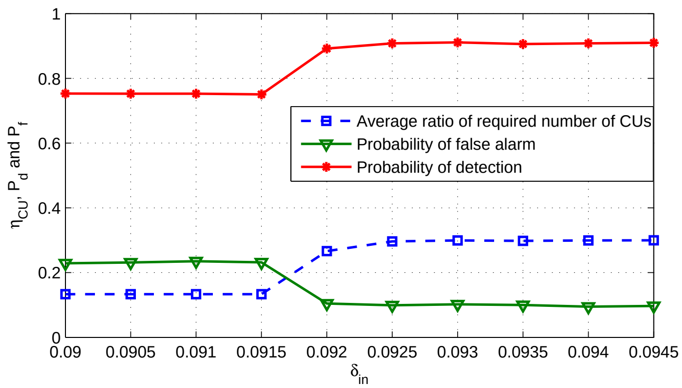

Figure 5. Performance of the proposed scheme versus "*reliable threshold*"

next sensing period. We define σ_1 and σ_0 as the "*reliable thresholds*" of sensing process. Those *reliable thresholds*" can be determined according to requirement of probability of detection, P_d^*, and false alarm, P_f^*, of CR system as [9]:

$$\sigma_0 = \log \frac{(1 - P_d^*)}{\left(1 - P_f^*\right)} \tag{11}$$

and

$$\sigma_1 = \log \frac{P_d^*}{P_f^*}. \tag{12}$$

We also define the "*fluctuate level*" of p as

$$U_{in} = \sum_{k=i-D}^{i} \{d(k) \, | d(k) = 1\} \tag{13}$$

and

$$U_{de} = \sum_{k=i-D}^{i} \{-d(k) \, | d(k) = -1\}, \tag{14}$$

where U_{in} and U_{de} show the number of times that p is increased and decreased in the considered window size D, and $d(i)$ can be calculated as

$$d(i) = p(i) - p(i-1), \;\; d(i) \in \{-1, 0, 1\}. \tag{15}$$

TABLE I. Initial Conditions for simulations

Parameter	Initial values
N	30
t_s	1ms
t_r	1ms
th_p	4
n	50000
D	200
U_{in}	5
U_{de}	5
δ_{in}	$\{0.0900, 0.0905, ..., 0.0945\}$
δ_{de}	$\{2.055, 2.070, ..., 2.190\}$

The value of p can be updated at each sensing interval according to values of "*reliable threshold*" and '*fluctuate level*" as $p(i) = \min(p(i-1) + 1, N)$, if $\beta\sigma_0 < \Gamma < \beta\sigma_1$ and $U_{in} > th_p$, where β is "*adjusting factor*" for "*reliable threshold*" and th_p is threshold for "*fluctuate level*". If $\Gamma < (2-\beta)\sigma_0$ or $\Gamma > (2-\beta)\sigma_1$ and $U_{de} > th_p$, the value of p will be updated as $p(i) = \max(p(i-1) - 1, 1)$. Otherwise, the value of p will be kept the same to that one of the previous sensing interval.

The flow-chart of the proposed scheme is shown in Fig. 4

IV. Simulation Results

In this section, simulation results of the proposed scheme and conventional SCSS with ordered and randomly polling are provided. The network includes 30 CUs with SNR of sensing channel varying from -14dB to -43dB and $t_s = t_r = 1$ms. In order to evaluate the performance in terms of reducing required number of CUs performing SS, we define η_{CU} as average ratio of required number of CUs,

$$\eta_{CU} = \frac{\sum_{i=1}^{n} p(i)}{nN} \tag{16}$$

where n_i is number of total sensing intervals.

The parameters for simulation are shown in Table I, where the "*reliable thresholds*" are considered as $\delta_{in} = -\beta\sigma_0 = \beta\sigma_1$ and $\delta_{de} = -(2-\beta)\sigma_0 = (2-\beta)\sigma_1$. Fig. 5 shows probability of detection, probability of false alarm and average ratio of required number of CUs, η_{CU}, of the proposed scheme, respectively.

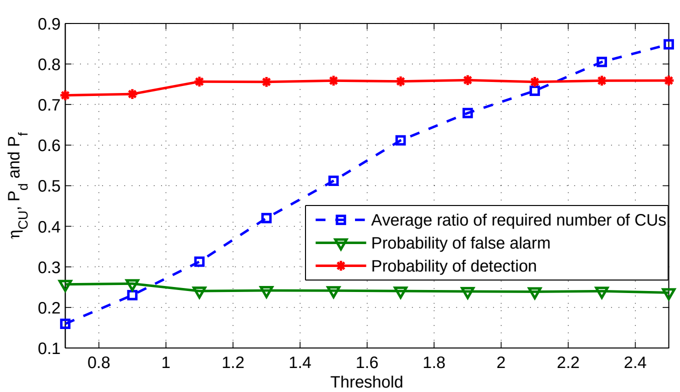

Figure 6. Performance of the conventional ordered SCSS.

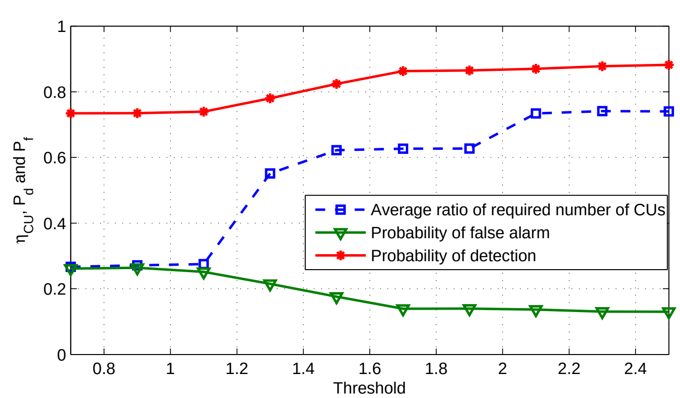

Figure 7. Performance of the conventional randomly polling SCSS.

The performance of reference schemes, conventional SCSS with ordered and randomly polling, are shown in Figs. 6 and 7, respectively. Both schemes consider superposition for assigning sensing time for each CU. The ordered SCSS polls sensing information from CUs according to their values of SNR in the sensing channel; the CUs with higher SNR will be polled sooner than the CUs with lower SNR. The randomly polling SCSS randomly choose the CUs to poll sensing information.

From Figs. 5, 6 and 7, it can be observed that the proposed scheme has the best performance. When $\eta_{CU} = 0.3$, the proposed scheme obtains the sensing performance of $P_d = 0.9$ and $P_f = 0.1$; however, the randomly polling SCSS and ordered SCSS obtains sensing performance of $P_d = 0.75$ and $P_f = 0.25$. The randomly polling SCSS can get the similar sensing performance to that of the proposed scheme when its required number of CUs is two time higher (i.e., $\eta_{CU} = 0.6$) than that of the proposed scheme. For the conventional ordered SCSS, most of high reliable CUs are polled to achieve good sensing performance at $P_d = 0.75$ and $P_f = 0.25$, and the performance cannot be improved even when the number of polled CUs is increased.

V. CONCLUSION

In this paper, an ordered sequential-superposition CSS is proposed for fast SS. The proposed scheme shows the algorithm to determine how many and which CUs are needed to sense the signal from PU and their corresponding sensing time for superposition CSS. The simulation results prove that the proposed scheme significantly improves performance of sensing process and can reduce 50% of required number of CUs to achieve the similar sensing performance to conventional SCSS.

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