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Effective cooperative DTV detection using the Goertzel algorithm

Selman KULAÇ[1,*], **Murat Hüsnü SAZLI**[2]
[1]Department of Electrical and Electronics Engineering, Düzce University, Konuralp, Düzce, Turkey
[2]Department of Electrical and Electronics Engineering, Ankara University, Gölbaşı, Ankara, Turkey

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Abstract: In digital TV (DTV) detection, to monitor the DTV spectrum, only pilot tone frequency values can be observed in order to achieve calculation and energy savings. These savings can be achieved using the Goertzel algorithm. However, more than one receiver sensor is needed in order to increase the detection quality. In this technique, the Goertzel algorithm is used for energy-efficient pilot tone detection and a new effective cooperative structure is proposed. There is no extra fusion center and more than one DTV band can be monitored with this OR rule-based cooperative structure. With this new cooperative structure, reaching the desired levels of ROC curves for probability of detection and probability of false alarm with the total energy efficiency is also demonstrated with detailed simulations for all DTV multipath profiles.

Key words: Cooperative diversity, spectrum sensing, cooperative spectrum sensing, DTV sensing, pilot tone detection, Goertzel algorithm

1. Introduction

The importance of energy efficiency has been increasing in all areas in recent years. Reducing energy consumption and using renewable (wind, solar) energy resources is being encouraged. Therefore, less energy consumption in wireless communication is targeted more effectively, too. Longer battery life for mobile devices used in mobile communications is one of the most prominent demands. Studies on the development of algorithms to improve battery life and usage of less energy with reduced complexity are on the increase.

Energy consumption efficiency has great importance in cognitive radio technology with the spectrum efficiency because it is thought that effective usage of sources (especially frequency sources) is aimed with the wider usage of this technology.

Cognitive radio technology aims at usage of optimum wireless channels [1]. In this technology, automatically detection of appropriate channels is needed before automatically changing the transmission and reception parameters. Detection of appropriate channels is an important part of the spectrum sensing technique. With this spectrum sensing technique, it is aimed to sense the licensed frequency bands that are out of usage. It is important to sense unused frequency bands of primary users strictly and therefore powerful spectrum sensing techniques are needed. In wireless communications, the cooperative spectrum sensing technique has been derived from the cooperative diversity technique. In the cooperative diversity technique, users can be either source (transmitter) or relay (repeater) to help each other with the advantages of mobile system dimensions, cost, and power consumption [2–4]. Implementing cooperative diversity in spectrum sensing also increases the performance of detection of unused licensed frequency bands [5–7].

*Correspondence: selmankulac@duzce.edu.tr

There is still a lot of underutilized space within the total use of the radio spectrum (especially observed for a long time in the countryside), which could be used by cognitive radio technologies [8]. The Federal Communications Commission, the communications authority in the United States, became aware of this situation years ago and then permitted unlicensed usage [9]. Therefore, the IEEE 802.22 working group was established and began the first cognitive radio study (development of IEEE 802.22 WRAN - Wireless Regional Area Network Standard).

It is planned to operate in TV bands with the IEEE 802.22 WRAN standard while ensuring that no harmful interference is caused for the TV receivers [10].

In cognitive radio, the geolocation technique is the other method of operating in licensed frequency bands. In this method, in order to find the existing spectrum resources through the TV white space database, the information about the CR transceiver's (BS or CPE) place needs to be known [11].

Pilot tone transmitting (also sine wave transmission) is used in some of the licensed broadcast systems and because of receiver synchronization. This pilot tone can be used for detection of broadcast signals in licensed frequency bands. In [12], a digital TV (DTV) pilot tone detection method was proposed for faster spectrum sensing implementation with no cooperation. The Goertzel algorithm was used in this pilot tone detection method. In [13], a cooperative pilot detection method was proposed with higher detection performance using an extra fusion center source and tested for only multipath profile B.

In this paper, an effective DTV detection method is proposed with a new cooperative structure. With this proposed method, total energy efficiency increases while not using an extra fusion center and spectrum sensing quality is also shown for all multipath profiles of the IEEE 802.22 WRAN standard.

The remainder of this paper is organized as follows. In Section 2, the spectrum sensing model that is suitable to our scenario and to the IEEE 802.22 WRAN standard is introduced. Section 3 describes DTV pilot tone detection using the Goertzel algorithm. In Section 4, proposed cooperative detection and performance evaluation are provided. Conclusions are given in the last section.

2. Spectrum sensing model

In this paper, the standard from [14] is referenced, as in other studies [15–18] for the IEEE 802.22 WRAN standard and the smallest distances calculated in [15] are used. Spectrum sensing model parameters are given in Table 1.

Table 1. Spectrum sensing model parameters.

Parameters	Value
TV transmitter (PU1) output power	60 dBW
TV transmitter (PU1) antenna height (HAAT)	300 m
WRAN base stations (SUs) antenna height (HAAT)	106 m
DTV transmission bandwidth	6 MHz
DTV transmission frequency	615 MHz
Interference protection distance	$\geq$ 23 km
WRAN cell radius	23 km
TV cell radius	134.2 km
PU1-SU4 distance	240 km

HAAT: Height above average terrain.

Based on this model, two big TV broadcast cells and four smaller IEEE 802.22 WRAN cells are used in Figure 1. There is one TV transmitter (Primary User, PU) and TV receivers distributed randomly in each TV broadcast cells. There is one base station (cooperation member) named the secondary user (SU) and users (CPE – customer premise equipment) distributed randomly in each IEEE 802.22 WRAN cell. Adequate interference protection distances ($\geq$23 km) are set free, because it is aimed that interference effects of users to the other cells of users be reduced with these protection distances.

SU2 behaves as a fusion center that it can take the other secondary users' decisions about PU1 and PU2 periodically and assess the two TV channels' occupancy. Here, PU1 monitoring is focused on. Since the model is symmetrical, the same thing is valid for PU2 monitoring. Thus, PU1 monitoring is adequate.

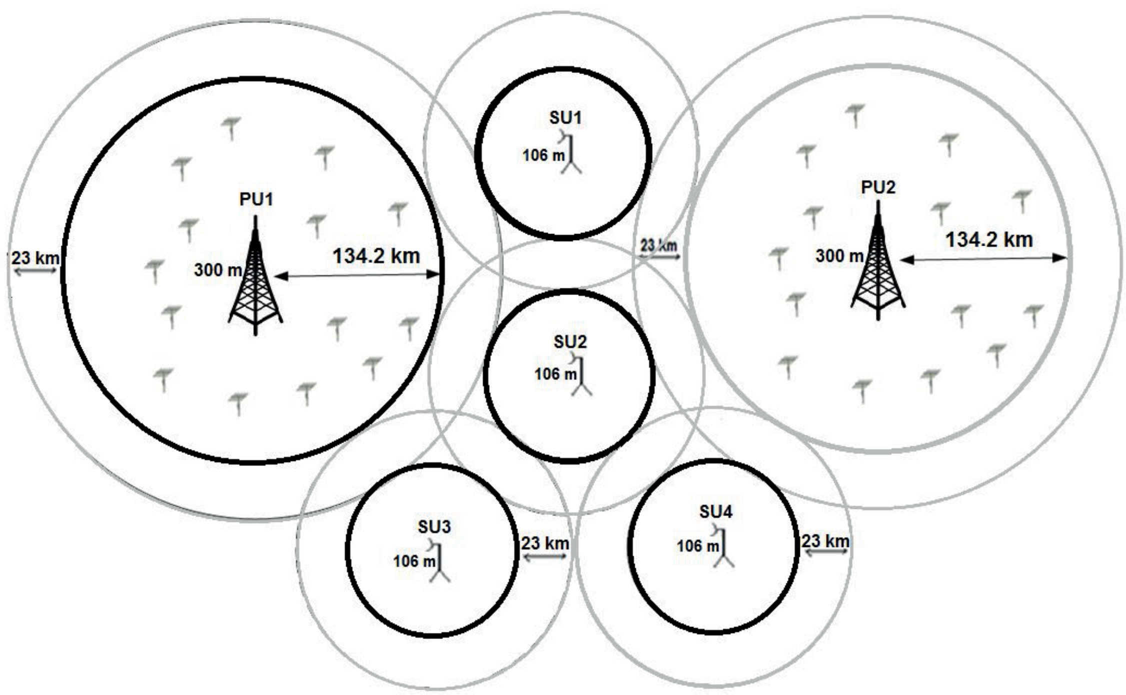

Figure 1. Spectrum sensing model.

The Okumura–Hata model is selected for the path loss model as in [19] with the assumption that base stations have isotropic antennas in the suburban areas.

Shadow fading variance is accepted as 5.5 dB. The multipath approach is evaluated in Rayleigh multipath fading channel profiles shown in Table 2. This channel model is recommended in [20] to test the proposed algorithms for WRAN cognitive radio systems. The profiles include 6 paths and the associated delays and amplitudes relative to the first path as well as the Doppler frequencies [21].

In this study, multipath effects were simulated for all profiles (Profile A, Profile B, Profile C, and Profile D) using [22]. Detected signals were obtained by adding additive white Gaussian noise (AWGN) to the multipath faded signals.

Table 2. Multipath profiles.

Profile A	Path 1	Path 2	Path 3	Path 4	Path 5	Path 6
Excess delay	0	3 μs	8 μs	11 μs	13 μs	21 μs
Relative amplitude	0	–7 dB	–15 dB	–22 dB	–24 dB	–19 dB
Doppler frequency	0	0.10 Hz	2.5 Hz	0.13 Hz	0.17 Hz	0.37 Hz
Profile B	Path 1	Path 2	Path 3	Path 4	Path 5	Path 6
Excess delay	–3 μs	0	2 μs	4 μs	7 μs	11 μs
Relative amplitude	–6 dB	0	–7 dB	–22 dB	–16 dB	–20 dB
Doppler frequency	0.1 Hz	0	0.13 Hz	2.5 Hz	0.17 Hz	0.37 Hz
Profile C	Path 1	Path 2	Path 3	Path 4	Path 5	Path 6
Excess delay	–2 μs	0	5 μs	16 μs	24 μs	33 μs
Relative amplitude	–9 dB	0	–19 dB	–14 dB	–24 dB	–16 dB
Doppler frequency	0.13 Hz	0	0.17 Hz	2.5 Hz	0.23 Hz	0.10 Hz
Profile D	Path 1	Path 2	Path 3	Path 4	Path 5	Path 6
Excess delay	–2 μs	0	5 μs	16 μs	22 μs	0 – 60 μs
Relative amplitude	–10 dB	0	–22 dB	–18 dB	–21 dB	–30 to +10 dB
Doppler frequency	0.23 Hz	0	0.1 Hz	2.5 Hz	0.17 Hz	0.13 Hz

3. DTV detection using periodogram and the Goertzel algorithm

The standard periodogram method is a direct method for pilot tone detection and frequency estimation. The standard periodogram is known as the square of the FFT amplitude. The periodogram for N point array is calculated as in the following equation [23]:

$$S_{x\_FFT}(f) = \frac{1}{N}\left|\sum_{n=0}^{N-1} x(n)\exp(-j2\pi n\frac{k}{N})\right|^2, \tag{1}$$

k = 0,1,. . . .,N – 1.

Our study was performed using a periodogram-like calculation that uses the Goertzel algorithm.

The Goertzel algorithm can be used to decrease calculation complexity more [24]. If L-point spectral values for the N-point input signal are sufficient when using the Goertzel algorithm, the computational load is proportional to N $\times$ L, but the computational load is proportional to $N(log_2 N)$ when FFT (N = 2^m – power of two FFT algorithm case) is used. In the event of $L < log_2 N$ proportionally, the Goertzel algorithm is considerably superior to ensure energy efficiency against the FFT with less computational load, since less computational load causes less energy consumption [25].

Energy calculation with the Goertzel algorithm, which needs only signal energy without phase information, using the previous input values is calculated as follows [26]:

$$|X_G(k)|^2 = Q_k^2(N-1) + Q_k^2(N-2)$$

$$-2\cos(2\pi\frac{k}{N}) \times Q_k(N-1) \times Q_k(N-2). \tag{2}$$

Here Q_ks are intermediate values that are formed when entering the x[n] input time signals in the Goertzel algorithm.

Our periodogram-like calculation with the Goertzel algorithm will be as follows using Eq. (3) in Figure 2.

$$S_G(f) = \frac{1}{N} \left| X_G(k) \right|^2 \tag{3}$$

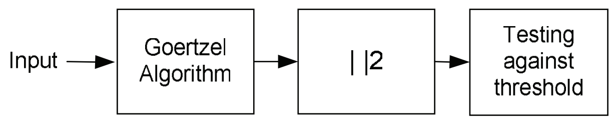

Figure 2. Block diagram of periodogram-like calculation used in energy detection with the Goertzel algorithm.

Frequency spectral density with the DFT calculation (FFT) method for the 6 MHz bandwidth received DTV signal can be obtained, but there is no need for the DFT calculation (FFT) method for the pilot signal of interest in the DTV signal and energy savings can be achieved with Goertzel algorithm calculation by filtering the DTV pilot signal [13,14,27]. In this study, the Goertzel algorithm is applied while taking into account 100,000, 200,000, 309,440.6, 400,000, 500,000, and 6,000,000 Hz frequency components (proportional to L = 6). The exact frequency of the DTV pilot frequency is 309.4406 kHz [28]. The frequency components (100,000, 200,000, 400,000, 500,000, 6,000,000) that are outside of the pilot frequency were chosen, because they are taken into account to form the sum of the energy components with the periodogram-like calculation method to ensure energy detection here.

In Figure 3, there is an example of the Goertzel spectrum of transmitted sinusoidal DTV pilot signal with a frequency of 309,440.6 Hz.

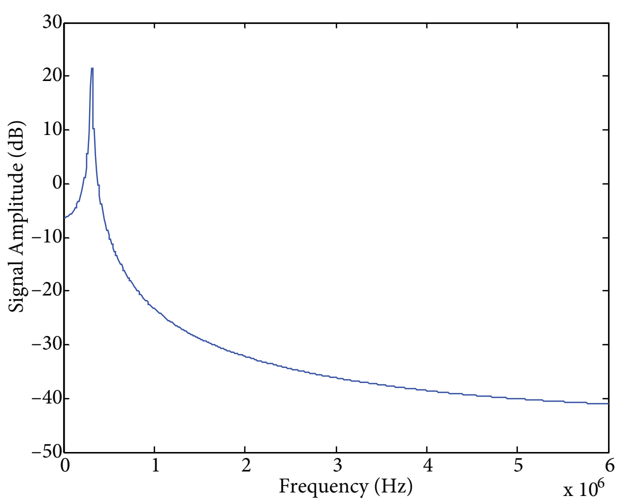

Figure 3. Goertzel spectrum of DTV pilot tone.

In Figure 4, there is an example of the Goertzel spectrum of a DTV pilot signal that is passed through the channel (with the path-loss, fading, and AWGN effects) and reaches the receiver.

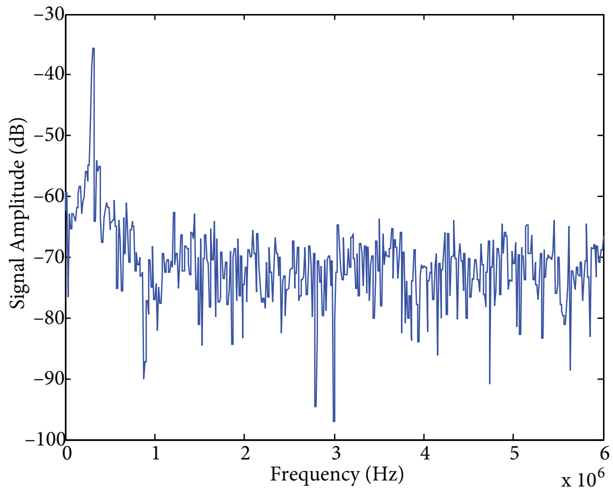

Figure 4. Goertzel spectrum of received DTV pilot signal.

The presence of the DTV signal that comes to a WRAN cell as in Figure 4 can be detected with the pilot signal energy detection method. However, more efficient detection can be done using forms of cooperative detectors instead of one detector.

4. Cooperative detection and performance evaluation

In this study, cooperative spectrum sensing simulation was carried out as specified in our model by sensors that are base stations of WRAN cells (SU1, SU2, SU3, and SU4) for all DTV multipath profiles. The simulation contained 100,000 iterations in each of the multipath profiles. For defining the probability of detection, there was a DTV signal on a channel subjected to one of multipath profiles in each of the 100,000 iterations and the same pilot signal was taken by all sensors for every threshold. Numbers of detection were formed by each of the sensors and the proposed cooperative structure using pilot energy detection according to the current threshold after the DTV pilot signal's 100,000 times of sending. For defining the probability of false alarm, there was no DTV signal on the channel in each of 100,000 iterations for every threshold. Numbers of detection were formed by each of the sensors and the proposed cooperative structure using pilot energy detection according to the current threshold 100,000 times for all the noisy receivers. The threshold was set to zero and increased step by step, and then probability of detection, P_d, and probability of false alarm, P_f, values were obtained. Both in terms of detection and false alarm state, care was taken that the number of iterations in which values were larger than the threshold was obtained. This number gives us the detection number according to one threshold.

In the literature, standard unfaded channel (AWGN channel) and different standard multipath channels (Rayleigh channels, Rician channels, Nakagami channel) according to the structure of the transmission channel have been formulated taking into account the probability of detection. The threshold (λ, used with FFT) in these probability of detection formulas is also a parameter [29]. In this study, IEEE 802.22 WRAN specific multipath fading channel profiles shown in Table 2 have been used and the Goertzel algorithm is implemented in the simulations. Here, when the threshold value is taken as minimum (i.e. zero), the probability of detection is high ($P_f > 0.9$), and but the false alarm probability (P_f) becomes high, too. After that, ROC graphics are created by increasing the threshold gradually and it also reduces P_f to the desired value.

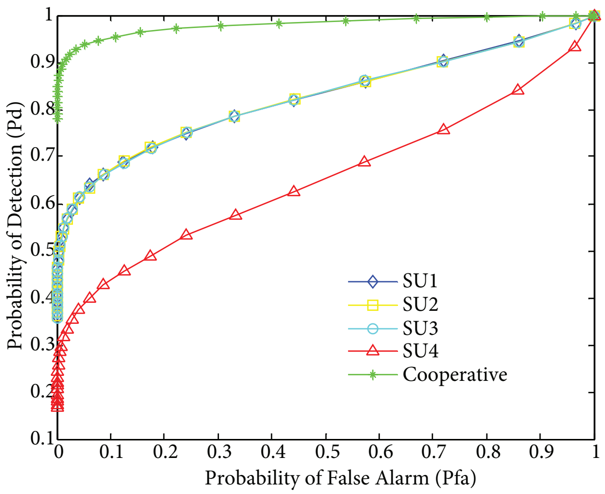

Figure 5. ROC curves for profile A.

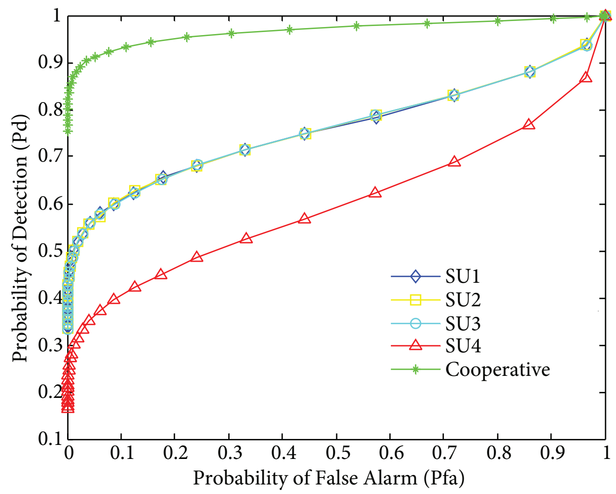

Figure 6. ROC curves for profile B.

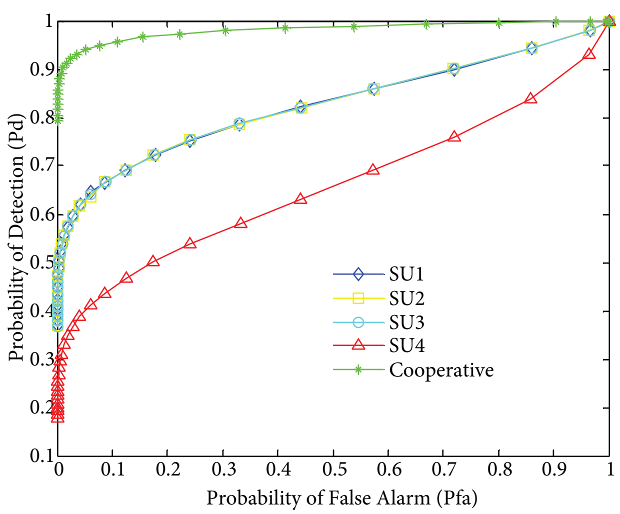

Figure 7. ROC curves for profile C.

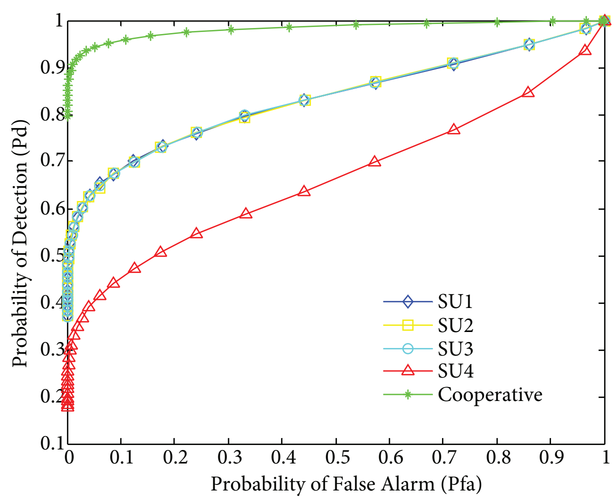

Figure 8. ROC curves for profile D.

As can be seen from Figures 5–8, the probability of detection for SU4 was at the lowest levels due to the longest distance from the DTV transmitter for all profiles. For the IEEE 802.22 WRAN standard, the requirements are probability of detection $P_d \geq 90\%$ and probability of false alarm $P_f \leq 10\%$ [10]. For each of the secondary users (SU1, SU2, SU3, and SU4), the desired level ($P_d \geq 90\%$ and $P_f \leq 10\%$) could not be reached for all profiles. The desired level of $P_d\,(\geq 90\%)$ and $P_f\,(\leq 10\%)$ could be reached with only the cooperative structure in Figures 5–8. It is understood that the highest detection level and lowest false alarm rate can be obtained with the proposed cooperative structure with implementation of the OR rule with at least one of the receiver's detections of any receiver in each iteration.

To detect the presence of TV signals in a channel is not easy at least 180 km away. As can be understood from the ROC curves, the SU4 curve remained far below according to the IEEE 802.22 WRAN probability requirements at a distance from the TV station of about 240 km. Therefore, at least one neighboring secondary user cell of the TV broadcasting cell is required.

In addition, in this study, for the input signal at 962 points in the Goertzel algorithm, by doing a calculation in each receiver according to the spectral values for L = 6 points, the 4 $\times$ L = 24 rate was reached with 4 cooperative sensors.

In the case of FFT, according to the N = 2^m rule, 1024 points of FFT input signal with the closest value to the 962-point were able to be used and it was possible to reach the $\log_2 1024 = 10$ ratio. In this case, the 4 $\times$ 10 = 40 rate with 4 receivers could be reached.

As described in Section 3, in the event of $L < log_2 N$ proportionally, the Goertzel algorithm was considerably superior to ensure energy efficiency against FFT with less computational load (24 < 40) that caused less energy consumption (40%) with four cooperative sensors implemented totally in pilot detection. Extra energy was not spent for an extra fusion center.

5. Conclusions

To monitor the DTV spectrum, pilot tone detection can be used. Only pilot tone frequency values are observed in order to achieve calculation and energy savings in DTV spectrum detection. These savings are achieved using the Goertzel algorithm. However, more than one sensor node is needed in order to increase detection quality. In this study, with an innovative approach, a new cooperative pilot detection technique is proposed. In this proposed technique, the Goertzel algorithm is used for energy efficient pilot detection and a new effective cooperative structure is proposed. There is no extra fusion center and more than one DTV band can be monitored with this OR rule-based cooperative structure. With this new cooperative structure, the reaching of the desired levels of ROC curves and total energy efficiency is also demonstrated with detailed simulations for all DTV multipath profiles.

Various combining schemes can be developed for both pilot-energy and pilot-location sensing. It is known that detection based on location can be robust against noise uncertainty since the position of the pilot can be pinpointed with accuracy even if the amplitude is low due to fading.

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