IMPROVING INTERFERENCE IMMUNITY OF SPATIAL EVENT DETECTION SYSTEMUSING ARRAY ANTENNA

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Abstract: This paper proposes new techniques for improving the co-channel interference immunity of the event detection system which realizes indoor event detection scheme. Similar to the conventional methods the signal subspace-based approach sometimes suffers from interference in the same frequency band because the interference signals with different incident angles affect the signal subspace of the received signals at the receiving array antenna. Two types of new event detection methods are proposed to realize immunity against noise and interference in this paper. The first method proposed in this paper exploits the cyclostationarity of communication signals to distinguish the desired signal from the interference and suppresses noise and interfering signals without major hardware design changes. Another approach that improves immunity against co-channel interference is to utilize the transmission control scheme used for personal area network systems. In the proposed method of the study, carrier sense multiple access with collision avoidance (CSMA/CA) technique is utilized to distinguish the desired signal from the other transmitted signals. As a result of the detection of the presence of signals from other stations, the proposed system can avoid the transmitted interference signals from other systems. We are also developing an evaluation equipment to confirm the effectiveness of the proposed approach.

1 INTRODUCTION

We have been developing a new indoor event detection system which can detect events such as home or office intrusion by using signal subspace spanned by an eigenvector obtained by an array antenna, and delivers superior performance compared with conventional event detection methods based on received signal strengths (RSS) (Ikeda, Tsuji, and Ohtsuki, 2009)(Tsuji, Koshikawa, and Suzuki, 2011). Similar to the conventional methods, however, the signal subspace-based approach sometimes suffers from interference in the same frequency band because the interference signals with different incident angles affect the signal subspace of the received signals at the receiving array antenna. In this paper two types of new event detection methods are proposed to realize immunity against noise and interference of the event detection system, which realizes indoor event detection scheme by exploiting the cyclostationarity of the desired signal or the medium access control scheme defined in IEEE standard 802.15.4. The first method proposed in this paper exploits the cyclostationarity of communication signals to distinguish the desired signal from the interference that impinges on an array antenna and suppresses noise and interfering signals without major hardware design changes (Gardner, 1994)(Gardner, 1988). Another approach that improves immunity against co-channel interference is to utilize the transmission control scheme based on an IEEE 802 standard for personal area networks. Generally in the personal area networks the medium access control (MAC) enables the transmission of MAC frames through the use of the physical channel which is shared with other wireless systems. In the proposed method of the study, carrier sense multiple access with collision avoidance (CSMA/CA) technique, which realizes a wireless network multiple access method, is utilized to distinguish the desired signal from the other transmitted signals. As a result of the detection of the presence of signals from other stations, the proposed system can avoid the transmitted signals (interference) from other systems. We are also developing an evaluation equipment to confirm the effectiveness of MAC - based approach. In this paper, we first introduce the basic idea of the event.

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detection system using the signal subspace obtained by array antenna, and explain the ideas of the two approaches for improving the immunity interference. Finally, an evaluation equipment of the event detection system is introduced to realize the real-time event detection.

2 EVENT DETECTION METHOD USING SIGNAL SUBSPACE BY ARRAY ANTENNAS

2.1 Array Antenna Signal Model

First, we explain the principle of the original event detection system using the signal subspace obtained by array antennas.

The basic setup of the indoor event detection system consists of a pair of a transmitter and an array antenna receiver. Here, we consider an array of M sensors and a transmitter emitting a narrow band that impinges on the arrays from direction θ. The received signal at the array antenna can be modelled as

$$\boldsymbol{x}(t) = \boldsymbol{a}(\theta) s(t) + \boldsymbol{u}(t) \tag{1}$$

where $\boldsymbol{x}(t)$ is an $M\times 1$ vector of the complex envelopes of the observed signals, $\boldsymbol{a}(\theta)$ is the steering vector, $s(t)$ is the source signal, and $\boldsymbol{u}(t)$ is an $M\times 1$ vector of antenna measurement noises.

Next, in an environment of multipath propagation such as indoor environments, the above concept is expanded to a model describing the arrival of multiple narrow band coherent signals. Therefore, the received signal vector $\boldsymbol{x}(t)$ for multiple coherent signals is provided as below:

$$\begin{aligned} \boldsymbol{x}(t) &= \sum_{k=1}^{P} c_k \boldsymbol{a}(\theta_k) s(t) + \boldsymbol{u}(t) \\ &= \boldsymbol{a}' s(t) + \boldsymbol{u}(t) \\ \boldsymbol{a}' &\equiv \sum_{k=1}^{P} c_k \boldsymbol{a}(\theta_k) \end{aligned} \tag{2}$$

where P is the total number of coherent signals and c_k represents the complex attenuation of the k-th signal with respect to the first signal, $s(t)$.

Assume that the observation noise is Gaussian white noise with a variance of σ^2 having no correlation with the signal source, and the $M\times M$ covariance matrix of $\boldsymbol{x}(t)$ is provided as

$$\begin{aligned} \boldsymbol{R}_{xx} &= E\left\{\boldsymbol{x}(t)\boldsymbol{x}(t)^H\right\} \\ &= S\boldsymbol{a}'\boldsymbol{a}'^H + \sigma^2 \boldsymbol{I} \end{aligned} \tag{3}$$

where ^{H} indicates conjugate transposition and $S = E\{s(t)s(t)^H\}$. The event detection method studied in (Ikeda, Tsuji, and Ohtsuki, 2009) uses the signal subspace obtained by the covariance matrix of $\boldsymbol{x}(t)$. The covariance matrix $\boldsymbol{R}_{xx}$ in (3) can be decomposed by the spectral factorization as

$$\begin{aligned} \boldsymbol{R}_{xx} &= \boldsymbol{A}\boldsymbol{S}\boldsymbol{A}^H + \sigma^2 \boldsymbol{I} \\ &= \boldsymbol{V}\boldsymbol{\Lambda}\boldsymbol{V}^H \end{aligned} \tag{4}$$

where $\boldsymbol{V}$ is the unitary matrix and $\boldsymbol{\Lambda}$ is the diagonal matrix of the real eigenvalues λ_i, i=1,…,M having an order of $\lambda_1 \geq \lambda_2 \geq \ldots \geq \lambda_M$. Each matrix is expressed as

$$\boldsymbol{\Lambda} = \begin{bmatrix} \lambda_1 & 0 & 0 \\ 0 & \ddots & 0 \\ 0 & 0 & \lambda_M \end{bmatrix} \tag{5}$$

$$\boldsymbol{V} = \left[\boldsymbol{v}_1, \cdots, \boldsymbol{v}_M\right] \tag{6}$$

Here, the eigenvalue λ_i and eigenvector $\boldsymbol{v}_i$, satisfy the relationship $\boldsymbol{R}_{xx}\boldsymbol{v}_i = \lambda_i \boldsymbol{v}_i$. The eigenvalue-eigenvector pair can be used to separate the signal space and noise space. Since $S\boldsymbol{a}'\boldsymbol{a}'^H$ is a rank-one matrix in (3), span$\{\boldsymbol{v}_1\}$ is considered as the signal subspace. Then the signal subspace detection method studied in (Ikeda, Tsuji, and Ohtsuki, 2009) detects the event using the following criterion:

$$P(t) = \left|\boldsymbol{v}_{\text{no}}^H \boldsymbol{v}_{\text{ob}}(t)\right| \tag{7}$$

where $\boldsymbol{v}_{\text{no}}$ is the eigenvector $\boldsymbol{v}_1$ obtained in advance when no event occurs and $\boldsymbol{v}_{\text{ob}}(t)$ is the eigenvector associated with the largest eigenvalue obtained by the sensors during the period under observation. When no event occurs at time t, the value of the criterion in (7) is expected to be approximately one because the signal subspace spanned by $\boldsymbol{v}_{\text{no}}$ is expected to be almost the same as by $\boldsymbol{v}_{\text{ob}}(t)$. On the other hand, the value of the criterion becomes less than one if the signal subspace spanned by $\boldsymbol{v}_{\text{ob}}(t)$ varies due to the change of the radio propagation between the array antenna and the transmitter. The signal subspace detection method can therefore detect events by comparing the criterion with the specified threshold.

2.2 Experimental Results by Signal Subspace Detection

We confirmed the effectiveness of the event detection method discussed in (Ikeda, Tsuji, and Ohtsuki, 2009) through experimental results.

The experiment was conducted in a 7×9 m room, as shown in Figure 1. Since the room had metal walls, there was a very high possibility of generating numerous multipath signals between the transmitter and receiver. The array receiver was an 8-element uniform linear array with a half-wavelength element placed at a height of 2.52 m. The array receiver's location is indicated by Rx in Figure 1. Tx indicates the transmitter's location. The antenna height of the transmitter was 1 m and the center frequency of the transmitted signal was 2.335 GHz.

First, the vector $\boldsymbol{v}_{no}$ in (7) was obtained when no event occurred. As the blue line shows in Figure 2, we observed the constant values of the criteria given in (7) when no event occurred during the observation period. Next, the red line in Figure 2 shows the result of the changes of criteria when a person pulls the door B open and enters the room. Figure 3 shows the results when the door A or door B is opened. These indicate that the signal subspace event detection method discussed in (Ikeda, Tsuji, and Ohtsuki, 2009) can detect several events and also recognize the difference of the events via the experiment.

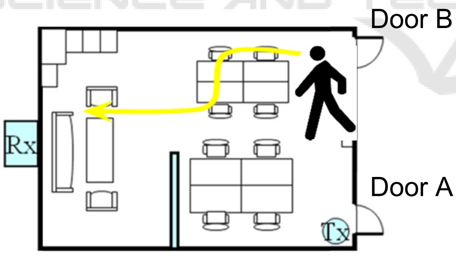

Figure 1: Layout of test area for event detection experiment.

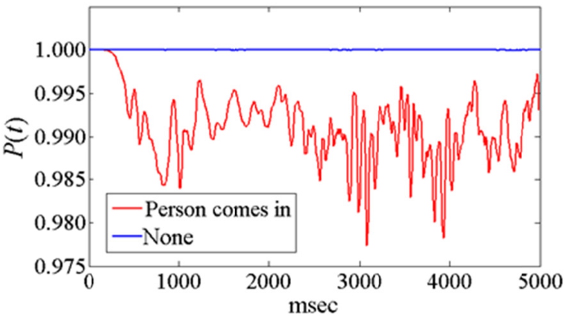

Figure 2: Changes of criteria when a person enters the room.

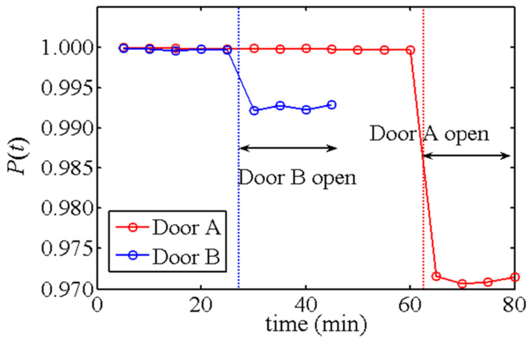

Figure 3: Changes of criteria when door is opened.

3 CYCLOSTATIONARY-BASED EVENT DETECTION METHOD

Similar to the conventional event detection methods, the approach of the signal subspace detection method in (Ikeda, Tsuji, and Ohtsuki, 2009) may make an incorrect decision if intentional or unintentional interference with the same frequency band impinges on array sensors. This is because the interference signals with different incident angles affect the signal subspace of the received signals at the array antenna. Therefore, mitigation techniques of unknown interference signals should be considered. One possible solution to deal with the problem is to apply a spread spectrum technique in order to separate the desired signals from the interference. This technique, however, may cause the circuit size to expand and drive up costs. Here, alternative approach that is computationally simple and offers good detection performance is proposed, using the signal's cyclostationarity (Tsuji, Koshikawa, and Suzuki, 2011).

3.1 Array Signal Cyclostationarity

Cyclostationarity indicates certain signal characteristics. Most modulation signals show cyclostationarity characterized by modulation scheme and speed. Such techniques as the SCORE algorithm and Cyclic MUSIC, which form beams by selecting signals and estimating the direction of signal arrival, have received attention in recent years (Gardner, 1994)(Gardner, 1988). These methods use statistics of up to the second rank. Thus, compared with conventional methods using higher rank statistics, the necessary calculation is rather limited. In addition, since signals can be selected according to differences in modulation scheme and modulation speed, this technique can be applied to signals of a frequency band in which a variety of modulation schemes and speeds exist. Here, we propose utilizing the cyclostationarity of the signal for the event detection system in order to improve performance in immunity against interference.

3.2 Cyclostationarity:

It is recognized that signal has a spectrum correlation with a cyclic frequency of α, unless the cyclic auto-correlation function of (8) is constantly zero.

$$r_{xx}^{\alpha}(\tau) = \left\langle x(t+\tau/2)\, x^*(t-\tau/2)\, e^{-j2\pi\alpha t} \right\rangle_\infty \qquad (8)$$

where $<\cdot>_\infty$ indicates infinite time averaging. The covariance matrix of the signal received by the array antenna can be defined as shown below, based on the cyclic correlation function:

$$\boldsymbol{R}_{xx}^{\alpha}(\tau) = \left\langle \boldsymbol{x}(t+\tau/2)\, \boldsymbol{x}^H(t-\tau/2)\, e^{-j2\pi\alpha t} \right\rangle_\infty \qquad (9)$$

As previously reported in multiple studies, most modulation signals (e.g., AM, PSK, PAM, FSK) feature $r_{xx}^{\alpha} \neq 0$ at a certain cyclic frequency α and lag τ, where the value of α changes with the modulation scheme and the modulation speed. Thus, even if other signals are included in the time and frequency areas of the received signal, the cyclic covariance function can be used to select the desired wave.
If we choose α to be a cyclic frequency of only the desired signal $s(t)$, then we have from (9)

$$\boldsymbol{R}_{xx}^{\alpha}(\tau) = r_{ss}^{\alpha}(\tau)\, \boldsymbol{a}'\boldsymbol{a}'^H \qquad (10)$$

$$r_{ss}^{\alpha}(\tau) = \left\langle s(t+\tau/2)\, s^*(t-\tau/2)\, e^{-j2\pi\alpha t} \right\rangle_\infty$$

The matrix (10) is obviously a rank-one matrix and the right (or left) eigenvector associated with its one eigenvector is $\boldsymbol{a}'$ (or $\boldsymbol{a}'^H$).

3.3 Cyclostationarity-Based Event Detection Method

The characteristics of the interference signals with the same frequency band are unknown. Meanwhile we can purposefully generate a transmitting signal as the desired signal with a specified cyclic frequency. As mentioned in 3.2, the cyclic frequency is determined with the modulation scheme and speed. This means we know the cyclic frequency of the desired signal in advance and the cyclic frequency can be used for discriminating between the desired signal and the interference. The proposed method's concept is simple. In the proposed method, the cyclic covariance function is used to distinguish the desired signal from the interference. The covariance matrix in (4) can be replaced by the cyclic covariance matrix in (10). Then the eigenvector of the cyclic covariance matrix is used to define the following new criterion for detecting events as

$$\tilde{P}(t) = \left| \tilde{\boldsymbol{v}}_{\text{no}}^H \tilde{\boldsymbol{v}}_{\text{ob}}(t) \right| \qquad (11)$$

where $\tilde{\boldsymbol{v}}_{\text{no}}$ is the eigenvector obtained in advance when no event occurs and $\tilde{\boldsymbol{v}}_{\text{ob}}$ is the eigenvector obtained by the signals during the period under observation, as in the original event detection method.

Even if the interference with different cyclic frequency than the desired signal impinges on the array, the signal subspace obtained from the cyclic covariance matrix remains the same. Therefore, the event detection method with the cyclostationarity of the desired signal is performed by comparing the value of the criterion in (11) with a specified threshold $\tilde{P}_{\text{th}}(t)$. Note that the criterion defined in (11) becomes identical to that in (7) if the cyclic frequency is set at zero.
Thus, the event detection method proposed here can be summarized as follows:

1. Choose α to be a cyclic frequency of the desired signal.
2. Calculate the eigenvector $\tilde{\boldsymbol{v}}_{\text{no}}$ of $\boldsymbol{R}_{xx}^{\alpha}(t)$ when no event occurs.
3. Update the value of $\tilde{P}(t)$ with $\tilde{\boldsymbol{v}}_{\text{ob}}$ obtained by the array.
4. If $\tilde{P}(t) < \tilde{P}_{\text{th}}(t)$, an event is to be expected.
5. Repeat steps 3 and 4.

3.4 Simulation Results

Numerical examples were performed to evaluate the proposed method's effectiveness. The linear array consists of eight isotropic sensors spaced uniformly, having half the carrier wavelength. Unless otherwise specified, signal power is given in dB SNR (signal-to-noise ratio) and the noise is additive white Gaussian noise (AWGN) uncorrelated from sensor to sensor. The source signal is a BPSK signal, which is filtered using a square root raised cosine filter with a roll-off factor of 0.5. The three total coherent signals with different angles (θ=10°, −60°, and 20°)

and SNRs (0dB, −10dB, and −10dB) impinge on the array, and an AM interference of compatible bandwidth arrives from −20° in the middle of the observation period (t=100). Each symbol rate of the BPSK signals is 0.2, which is normalized by the sampling frequency. Therefore, the cyclic frequency of the desired signal can be determined as 0.2. In this case, the interference has different cyclic frequency from the desired signals. The proposed method is conducted with $\alpha = 0.2$ and $\tau = 0$. The event detection method studied in (Ikeda, Tsuji, and Ohtsuki, 2009) is also performed for comparison with the proposed method.

In the first simulation example, the SNR of the interference is set at 5 dB. The resulting values of the criteria defined in (7) and (11) are shown in Figure 4. We observe that the value of the criteria given by (11) stays roughly constant during the observation period while the value obtained by (7) decreases slightly after the interference comes in at t =100.

In the second simulation, the SNR of the interference is set at 10 dB and the other simulation conditions are the same as in the first one. We observe that the interference provides significant change of the criterion in (7) but has little influence on the value in (11) in Figure 5.

These results show that the proposed detection method utilizing the cyclostationarity of the desired signal is effective for improving immunity against interference with different cyclic frequency.

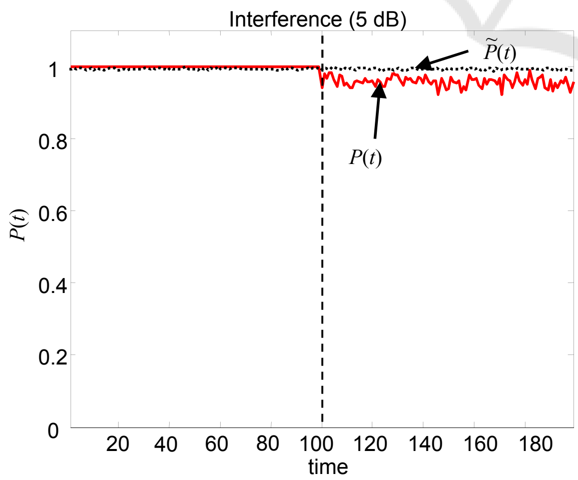

Figure 4: Changes of criteria (interference SNR=5dB).

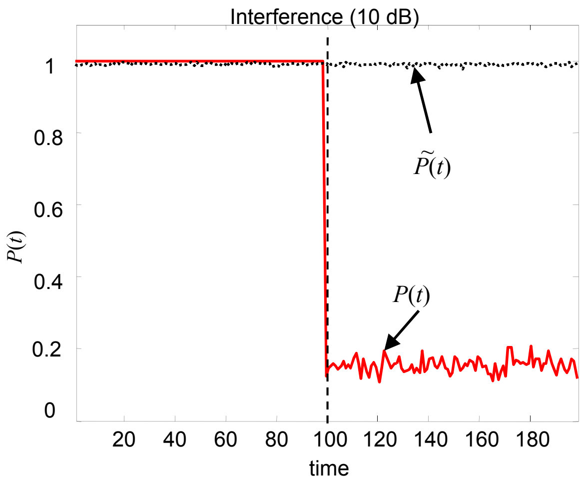

Figure 5: Changes of criteria (interference SNR=10dB).

4 UTILIZATION OF THE TRANSMISSION CONTROL SCHEME BASED ON SHORT RANGE WIRELESS SYSTEM

Here, another approach that is structurally-simple and offers good detection performance is proposed using the transmission control scheme based on an IEEE standard for short range wireless system.

We consider that CSMA/CA technique is of use in the differentiation between desired and interference signals. We take particular note of the IEEE 802.15.4 standard which uses CSMA/CA. The reason is that the systems based on the standard such as ZigBee has few analog stages and uses digital circuits wherever possible and that the software is designed to be easy to develop on small and inexpensive microprocessors. And that it is relatively easy to detect the timing of receiving of the desired signal from an IEEE 802.15.4 compliant RF transceiver chip.

Figure 6 shows a simplified block diagram of the equipment of the event detection system proposed here. The receiver with an array antenna is connected with a node terminal A, which receives the signal from the other node terminal B. The node terminal B knows the address of the node terminal A and sends packets periodically to the node terminal A. The array antenna of the receiver receives the signals from the node B and also may receive unknown interference occasionally. The node terminal A connected to the receiver gives the timing of the receiving period and the result of receiving the desired packets if the node terminal A receives the desired signal successfully without interference. As the result of implementing the scheme, the array antenna receiver can avoid the transmitted signals from the other systems.

4.1 Experimental Results

We are developing an evaluation equipment to confirm the effectiveness of MAC-based approach. The equipment has four received antenna elements and is connected to the receiving node terminal based on IEEE 802.15.4 standard. The receiving node terminal is programmed to set a bit when it receives a start of frame delimiter and to set another bit after the cyclic redundancy checksum (CRC) of the received signal is verified. Due to the limit of the paper, we show only a result of the behavior of the receiving node terminal when it receives the desired and interference signals where the transmitting node terminal sends a packet at 100 msec interval and meanwhile another transmitting node terminal as interference with different node address sends a packet at 48 msec interval.

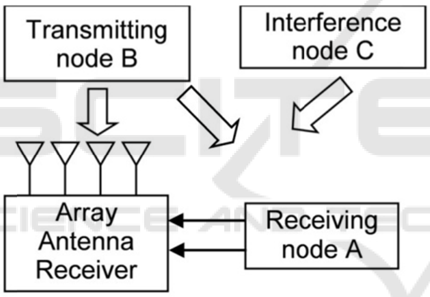

Figure 6: Block diagram of the equipment of the event detection system

As shown in Figure 7, we observed that the receiving node A outputted bits when the start of frame delimiters (F1, F2 and F3) were received and that it outputted a bit (C2) only if the start frame delimiter packet (F2) was received from the node B.

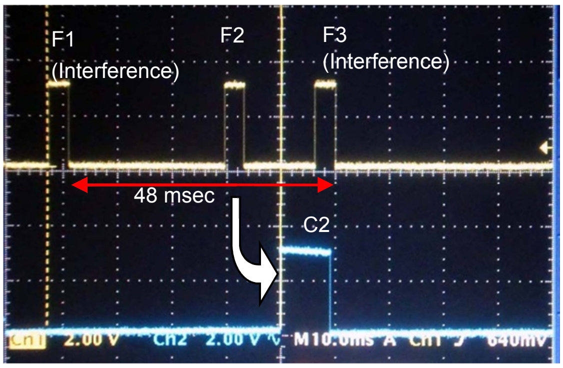

Figure 7: Start of frame delimiter bit and CRC bit

5 DEVELOPMENT OF EVENT DETECTION EQUIPMENT

An evaluation equipment of the event detection system was developed to realize the real-time event detection. The equipment was made smaller, and the real-time algorithm was implemented in the unit by introducing several kinds of efforts so that it would be possible to use with most engineers. The basic specifications of the equipment are summarized in Table 1, and the appearance of the equipment is shown in Figure 8. The equipment has four received antenna signal terminals and one output terminal which is used for the transmitting signal. The receiving circuit and the digital signal processor are also included in the unit. The unit also has a USB connection to control the digital signal processor and to take data from the unit by an external PC. One of the features of the equipment is that the unit can connect to the node receiving terminal which gives the start of frame delimiters information of the receiving transmitting signal and also the condition of the received signal to the equipment. This feature easily enables the implementation of several schemes of interference immunity.

6 CONCLUSIONS

This paper proposed new techniques for improving the co-channel interference immunity of the event detection system which realized indoor event detection scheme by exploiting the cyclostationarity of the desired signal or the medium access control scheme defined in wireless personal area network. The proposed methods could distinguish the desired signal from the interference that impinges on array antenna without major hardware design changes. In future work, some experiments will be conducted to confirm the effectiveness of the total performance of the equipment

Table 1: Specifications of the event detection equipment.

Frequency band	2400 MHz ISM band
Reception bandwidth	600 kHz
Reception level	-80 dBm to -20 dBm
Number of antenna input	4
Number of transmitting port	1
Interface	USB 2.0
Dimensions	200 (W) ×140(D) ×50(H) [mm]

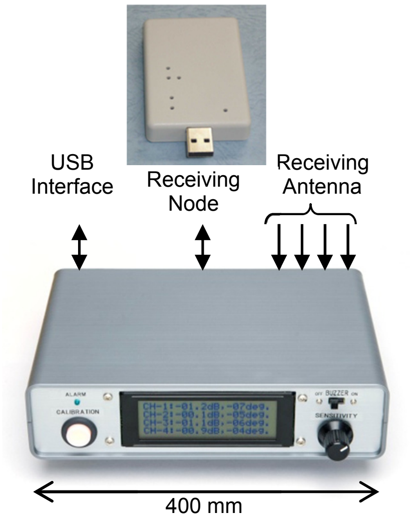

Figure 8: Appearance of the event detection equipment

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