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Jammer Identification Technique based on a Template Matching Method

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ABSTRACT

GNSS has the disadvantage of being vulnerable to jamming, and thus, the necessity of jamming countermeasure techniques has gradually increased. Jamming countermeasure techniques can be divided into an anti-jamming technique and a jammer localization technique. Depending on the type of a jammer, applicable techniques and performance vary significantly. Using an appropriate jamming countermeasure technique, the effect of jamming on a GNSS receiver can be attenuated, and prompt action is enabled when estimating the location of a jammer. However, if an inappropriate jamming countermeasure technique is used, a GNSS receiver may not operate in the worst case. Therefore, jammer identification is a technique that is essential for proper action. In this study, a technique that identifies a jammer based on template matching was proposed. For template matching, analysis of a received jamming signal is required; and the signal analysis was performed using a spectral correlation function. Based on a simulation, it was shown that the proposed identification of jamming signals was possible at various JNR.

Keywords: spectral correlation, template matching, jammer identification

1. INTRODUCTION

Global Navigation Satellite System (GNSS) is a system that provides position, navigation and time services to users. Representative GNSS is the Global Positioning System (GPS), which was made in the early 1970s for military purposes in the United States. After GPS was made public for civilian purposes, it has been used around the globe due to wide service area and outstanding generality. Currently, it is being developed and operated by Russia, China, and Japan as well as the United States. With the expansion of the application fields of a satellite navigation system due to the development of technology, GPS has become an essential element of national infrastructure in Korea as well as in foreign countries. However, GNSS has the disadvantage of being vulnerable to jamming. In case of jamming, there is a possibility that confusion occurs in society at large, which leads to national loss. In addition, jamming signals have also developed in complicated and diverse forms (Mitch et al. 2011). Therefore, the necessity of jamming countermeasure techniques to cope with this has gradually increased. Based on this trend, studies on jamming countermeasure techniques are extensively performed in Korea and in foreign countries at present.

Jamming countermeasure techniques can be broadly divided into an anti-jamming technique and a jammer localization technique. The representative anti-jamming techniques that are applicable to array antennas include the space time adaptive process (STAP) (Godara 2004) and the space frequency adaptive process (SFAP) (Godara 2004); and the representative jammer localization techniques include the time difference of arrival (TDOA) localization technique (Smith & Abel 1987) and the angle of arrival (AOA) localization technique (Schmidt 1986). Each technique has inherent advantages and disadvantages; and depending on the type of a jammer, applicable techniques and performance vary significantly. If an appropriate

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jamming countermeasure technique is used, the effect of jamming on a GNSS receiver is not significant, and prompt action is enabled by finding a correct location in a short time when estimating the location of a jammer. However, if an inappropriate jamming countermeasure technique is used, the performance of the anti-jamming technique deteriorates, and the amount of algorithm calculation could increase beyond necessity. Also, in the worst case, the estimation of jammer location could fail or an incorrect location could be estimated. Thus, jammer identification is a technique that is essential for proper action against jamming. However, despite the importance, there have been relatively few studies on jammer identification techniques compared to those on jamming countermeasure techniques.

Therefore, in this study, a jammer identification technique was investigated, and a technique that identifies a jammer based on template matching was proposed. Each jamming signal has different spectral auto-correlation. By analyzing this in various aspects, the characteristic of each signal can be drawn. The obtained characteristic was used for generating templates for each jamming signal type. To define the similarity between an incident signal and each template, the Euclidean distance between a normalized spectral correlation result and a template depending on jamming signal type was drawn. Lastly, jammer identification was enabled by defining the jamming type of the received signal using the result of the similarity analysis. For the jammer identification technique proposed in this study, the performance was analyzed and the validity was verified using a software-based simulator.

2. JAMMING SIGNAL ANALYSIS

For jammer identification, the characteristic of each jamming signal needs to be analyzed and utilized. Thus, application of an appropriate signal analysis technique is required. Diverse signal analysis techniques were examined, and a signal analysis technique appropriate for this study was selected.

2.1 Jamming Signal

Jamming signals can be broadly divided into a narrowband jamming signal and a wideband jamming signal. To examine the applicability of the identification technique proposed in this study, a narrowband jamming signal (continuous wave (CW) signal) and a wideband jamming signal (sweep CW signal that has the bandwidth of a GPS signal) were considered as the representative examples, respectively. The model of a CW signal can be expressed as Eq. (1).

$$x_{cw}(t) = k\sin(\omega_c t) \tag{1}$$

where k is the amplitude of the signal, and ω_c is the frequency of the signal. On the other hand, the model of a sweep CW signal can be expressed as Eq. (2).

$$x_{sw}(t) = k\sin(\omega_c \int f_{sw}(t)dt) \tag{2}$$

where $f_{sw}(t)$ is the frequency change information of the sweep CW signal. In general, $f_{sw}(t)$ can be modeled as shown in Eq. (3).

$$f_{sw}(t) = \begin{cases} f_{sw}(t-T_s) + \dfrac{k_u}{f_s}, & n < t < n + T_{sw,u} \\ f_{sw}(t-T_s) + \dfrac{k_d}{f_s}, & n + T_{sw,u} < t < n + T_{sw,u} + T_{sw,d} \end{cases} \tag{3}$$

where f_s is the sampling frequency, T_s is the period of sampling, and k_u and k_d are the amount of frequency change for the rising frequency shift section and the falling frequency shift section, respectively. For a sweep CW signal, frequency shifts with time, and the characteristic of the signal is determined by the frequency change information depending on time. The amount of frequency change determines the frequency bandwidth of the sweep CW signal. In this study, this value was set to be identical to the bandwidth of a GPS signal. Also, depending on whether it is rising or falling, the characteristic of the signal changes; and depending on this, whether it can be removed changes. Therefore, three kinds of cases were considered: a sweep CW (rise) signal that has rising frequency, a sweep CW (fall) signal that has falling frequency, and a sweep CW (tri) signal that has the two changing trends at the same time.

2.2 Spectral Correlation Function (SCF)

For a signal analysis technique in a frequency domain, there are various techniques, and the representative method is the Fourier transform. However, this technique shows only the frequency component of a signal, and the changes in signal characteristics depending on time cannot be examined (Kamen & Heck 2000). Diverse signals can be regarded as a jamming signal, and the characteristics of several jamming signals could change with time. Accordingly, analyzing a jamming signal using only the Fourier transform would not be stable. Therefore, in this study, SCF was used for the analysis of signals.

Spectral correlation function (SCF) can analyze signal characteristics including cyclostationary characteristics. When the average and auto-correlation value of a specific target signal, $x(t)$, show periodic characteristics, it is said that $x(t)$ has cyclostationary characteristics. Eqs. (4) and (5) express the cyclostationary characteristics of the signal, $x(t)$ (Gardner 1986).

$$m_x\left(t+T\right) = m_x\left(t\right) \tag{4}$$

$$R_x\left(t+T, u+T\right) = R_x\left(t, u\right) \tag{5}$$

where m_x is the average of the signal, $x(t)$, and R_x is the auto-correlation value of the signal, $x(t)$. In this regard, it is assumed that m_x and R_x have a periodicity of T. As the auto-correlation value, R_x, of the cyclostationary signal, $x(t)$, has periodic characteristics, it can be expressed using a Fourier series, as shown in Eq. (6).

$$R_x\left(t+\frac{\tau}{2}, t-\frac{\tau}{2}\right) = \sum_{\alpha} R_x^{\alpha} e^{i2\pi t} \tag{6}$$

where R_x^{α} is the Fourier coefficient and can be expressed as Eq. (7).

$$R_x^{\alpha}(\tau) = \lim_{Z\to\infty} \frac{1}{Z} \int_{-T/2}^{T/2} R_x\left(t+\frac{\tau}{2}, t-\frac{\tau}{2}\right) e^{-j2\pi\alpha t} dt \tag{7}$$

In this regard, the coefficient of the Fourier series, R_x^{α}, is called a cyclic auto-correlation function (CAF) of the signal, $x(t)$, and α is called a cyclic frequency (Gardner 1986). This CAF shows auto-correlation characteristics in the frequency domain of the signal. For cross-correlation in the frequency domain, a frequency shift of the signal is required. The signals that are obtained through the frequency shift of the signal, $x(t)$, by $+\alpha$ and $-\alpha$ can be expressed as Eqs. (8) and (9), respectively.

$$U(t) = x(t)e^{-j\pi\alpha t} \tag{8}$$

$$V(t) = x(t)e^{j\pi\alpha t} \tag{9}$$

The average value of the cross correlation of the signals, $U(t)$ and $V(t)$, can be expressed as Eq. (10). This is identical to Eq. (7), which is the result of CAF.

$$\left\langle R_{UV} \right\rangle(\tau) = \lim_{Z\to\infty} \frac{1}{Z} \int_{-Z/2}^{Z/2} E\left\{ U\left(1+\frac{\tau}{2}\right) V\left(1+\frac{\tau}{2}\right)^{*} \right\} dt = R_x^{\alpha} \tag{10}$$

SCF is the frequency domain analysis of the CAF result. Thus, the SCF result of the equation, $x(t)$, can be obtained from the Fourier transform of R_x^{α} as Eq. (11).

$$S_x^{\alpha}(\tau) = \frac{1}{T} \int_{-\infty}^{\infty} R_x^{\alpha}(\tau) e^{-j2\pi f\tau} d\tau \tag{11}$$

SCF shows waveforms with different characteristics depending on the modulation method of an incident signal. Based on this, the frequency characteristics and correlation characteristics depending on the type of a jamming signal can be examined. Using the frequency component parameters (e.g., number and amplitude) of a jamming signal that is above a threshold value, which can be obtained from the SCF application result, it is possible to draw the characteristics depending on each modulation method (Gardner 1986).

3. JAMMER IDENTIFICATION TECHNIQUE

Considering the characteristics of a signal, the identification of the signal can be defined as a problem of finding the characteristics of the signal in time and frequency domains. In this study, SCF was used to analyze the characteristics of a signal. Considering that this result is two-dimensional, template matching is thought to be an appropriate technique. Therefore, in this study, a jammer identification technique based on template matching using an SCF analysis technique was proposed for jamming signal identification. As mentioned earlier, each jamming signal has different spectral auto-correlation characteristics, and a jammer can be identified through template generation and matching based on the result of the analysis. Fig. 1 shows the flow diagram of the proposed

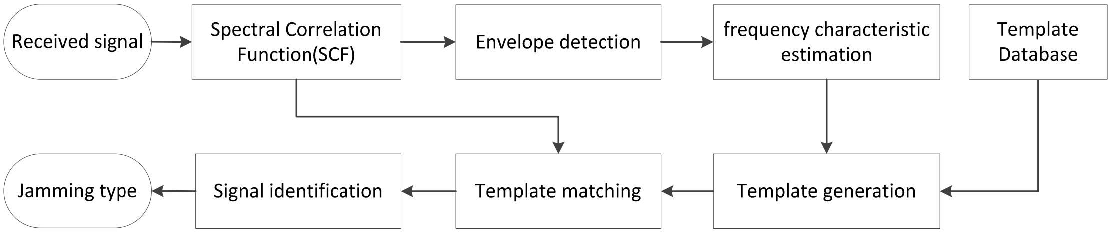


Fig. 1. Flow diagram of the proposed identification technique.

identification technique.

First, using SCF, the characteristics of a received signal are analyzed. Then, using the obtained characteristics, various templates depending on the template database are generated. The generated templates can be compared with the SCF result of the received signal. Similarity is drawn through template matching, and the template with the highest similarity can be defined as the type of the incident signal.

3.1 Analysis Of Signal Characteristics

By applying SCF to an incident received signal, the correlation characteristics depending on the frequency and time of the signal can be examined. Using the main lobe position of the SCF result, the center frequency of CW and Sweep CW jamming signals can be obtained; and using the side lobe located around each main lobe, the rate of frequency change depending on the time of the sweep CW jamming signal can be obtained. In addition, using the relative size of each main lobe that occurs in the SCF function, the increasing or decreasing trend of the frequency can also be obtained. Using the main lobe position, the center frequency and cyclic frequency can be obtained. In theory, cyclic frequency is twice the center frequency. Thus, the validity of the SCF result can be judged using the two values. On the other hand, noise is included in a received signal, and thus, there is a possibility that proper frequency characteristics cannot be obtained when the signal power is low. Therefore, envelope detection that can draw characteristics more easily and accurately is required. In this study, envelope detection was performed using two-dimensional LPF. After the envelope detection, for template generation, the result of the signal characteristic analysis is sent to the template generation part.

3.2 Template Generation

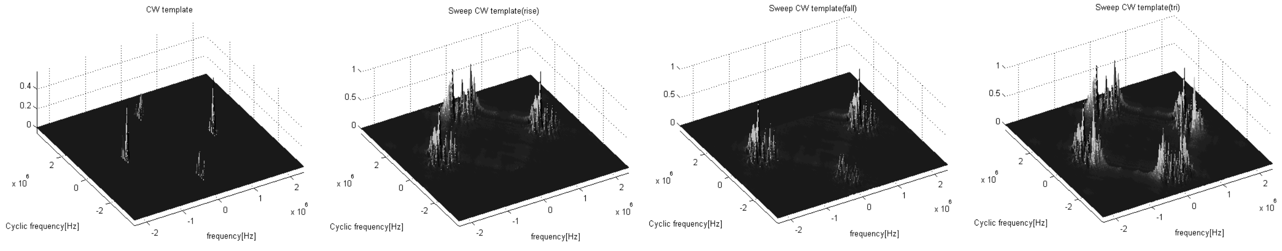
To identify a jammer, the generated template is used for performing template matching with a received signal. In this study, for jamming identification, CW and three types of sweep CW jamming signals were generated, and the template generation method was determined depending on the characteristics of each signal. The CW jamming signal has a very narrow main lobe bandwidth. Thus, a template can be generated using the value of only the main lobe of the center frequency obtained earlier as the effective value and assuming the other values as 0. For the sweep CW jamming signal, the relative value of each main lobe changes depending on the frequency increase direction. Thus, the templates of each type of sweep CW jamming signals can be generated by assuming the remaining values excluding a specific main lobe as the effective values. In the case of the sweep CW (rise) signal, the main lobe in a low cyclic frequency band has a lower value than other main lobes. In contrast, in the case of the sweep CW (fall) signal, the main lobe in a high cyclic frequency band has a lower value. The templates for each jamming signal type were generated based on the above characteristics. The four templates generated during the incidence of the sweep CW (tri) signal are as follows.

In this study, templates were defined as shown in Fig. 2. However, there is no standardized template generation method. Therefore, a template generation method should be flexibly determined depending on the type of the signal to be detected.

3.3 Template Matching and Identification

Template matching is performed by comparing the similarity between the generated template and the received signal. As a tool for comparing similarity, the Euclidean distance was used. The process for obtaining the Euclidean distance between the received signal, $x(t)$, and the template, $y(t)$, can be expressed as Eq. (12) (Deza & Deza 2009).

$$d(X,Y)=\sqrt{\sum_{i=1}^{N}\sum_{j=1}^{M}(x_{i,j}-y_{i,j})^2} \quad \begin{array}{l} i=1,2,\cdots,N \\ j=1,2,\cdots,M \end{array} \tag{12}$$



(a) CW template (b) Sweep CW (rise) template (c) Sweep CW (fall) template (d) Sweep CW (tri) template

Fig. 2. Templates generated during the reception of the sweep CW (tri) jamming signal.

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where $d(X,Y)$, is the Euclidean distance between the received signal and the template. x_{ij} is the normalized SCF result of the received signal for the *i*-th cyclic frequency and the *j*-th spectral frequency; and y_{ij} is the template value for the *i*-th cyclic frequency and the *j*-th spectral frequency. In this regard, the length of the horizontal axis of the template, *N*, and the length of the vertical axis of the template, *M*, are defined by the cyclic frequency interval and spectral frequency interval of the SCF function, respectively.

A short Euclidean distance indicates high similarity between the received signal and the template. The template that has the shortest Euclidean distance to the received signal can be defined as the template whose type is the most similar to that of the received signal. However, there could be similarity between noise and the template. Therefore, by setting a certain threshold value, jammer identification needs to be performed only when the similarity is higher than the threshold value. To select an appropriate threshold value, false alarm depending on the threshold value was drawn. In this technique, the false alarm was defined as the probability of making the identification success judgment for an arbitrary template when there is no incident jamming signal. Also, the detection probability was defined as the probability that the type of the selected template would be identical to that of the received jamming signal. The detection probability could vary depending on the false alarm. The false alarm, P_f and the detection probability, P_d are as follows.

$$P_d = P\left[D_e \le \lambda \mid H_1\right] \tag{13}$$

$$P_f = P\left[D_e \le \lambda \mid H_0\right] \tag{14}$$

where D_e is the Euclidean distance between the SCF result of the received signal and the generated template, and λ is the threshold value. The problem of signal identification decision can be assumed as a binary problem. H_0 that corresponds to an initial condition is the null hypothesis, and indicates a condition where there is no jammer in the identification range. The other condition, H_1, indicates a condition where the selected template is identical to the jamming signal. Therefore, Eq. (13) indicates that the probability that the template would be identical to the jamming signal and be smaller than the threshold value is defined as the detection probability. Also, Eq. (14) indicates that an identification success judgment is made because the Euclidean distance is smaller than the threshold value although there is no jammer in the identification range. Based on this, the threshold value depending on the desired false alarm can be experimentally determined, and the detection probability depending on this threshold value can be obtained.

4. PERFORMANCE ANALYSIS

To verify the performance of the identification technique proposed in this study, software-based jamming signals were generated (Kraus et al. 2011). The center frequency of the generated signal was assumed to be 1575.42 MHz, which is identical to the frequency of the GPS L1 C/A signal. The IF frequency was assumed to be 1.4 MHz, and the sampling frequency was assumed to be 47.14 MHz. Also, during the generation of sweep CW signals, the range of frequency change was set to 1 MHz, and the sweep time, which determines the rate of frequency change, was set to 10 . The noise was assumed to be AWGN, and the simulation for determining the performance was repeated 1000 times for each JNR.

Signal identification threshold values at false alarms of 0.001, 0.01, and 0.1 were obtained by repeated experiments. Fig. 3 shows the resultant detection probabilities for the CW jamming signal. As shown in Fig. 3, the detection probability varied depending on the JNR; and as the JNR increased, the i detection probability increased. When the JNR was -4 dB, the detection probability for the CW signal showed reliable performance at all the false alarms. Also, after -3 dB, identification was possible in every case. The results of the analysis of the detection probabilities for the three types of sweep CW signals in the same experimental environment are as follows.

In Figs. 4~6, the detection probabilities for the jamming signals depending on the type of the sweep CW jamming signal and the false alarm can be examined. For the CW jamming signal shown earlier, identification was relatively easier than the other signals, and stable identification performance was observed for all the false alarms. Therefore,

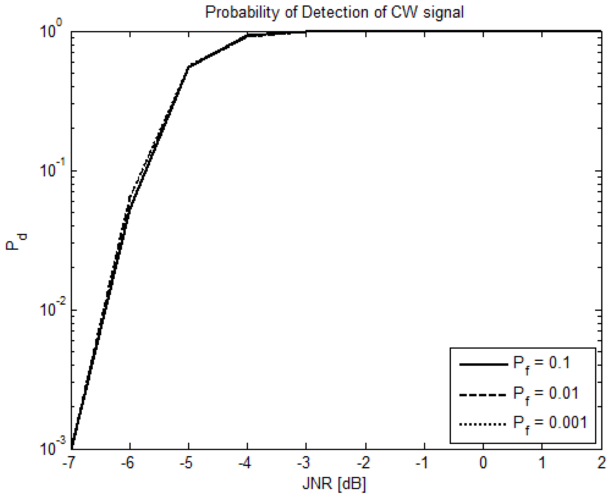

Fig. 3. Detection probability of CW signal vs. JNR.

performance difference depending on the false alarm was insignificant. However, for the sweep CW jamming signals, performance difference depending on the false alarm was distinct. It is noteworthy that as the false alarm decreased, the detection probability also decreased. This indicates that trade-off between the two performance indices is required to obtain desired performance. On the other hand, the detection probability also varied depending on the type of the sweep CW jamming signal. For the sweep CW (rise) and sweep CW (fall) signals, which have only one trend between frequency rise or fall, usable identification performance was obtained when the JNR was above -1 dB. The signal type that showed the lowest identification performance was the sweep CW (tri) type. When the power was low (below -1 dB), it showed unstable identification performance compared to the other types.

For all the jamming signals, the detection probability increased as the JNR increased. For the signals excluding the sweep CW (tri) jamming signal, an detection probability of 100% was obtained when the JNR was above 0 dB. Also, for the sweep CW (tri) signal, identification was successful when the JNR was above 1 dB. These results showed that the jammer identification technique proposed in this study was effective, and was implemented properly.

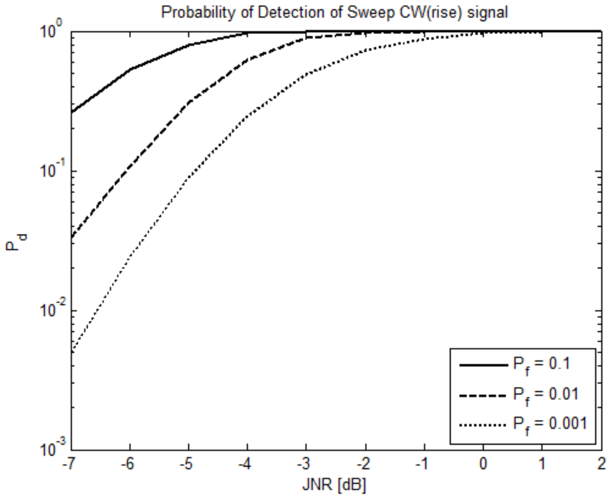

Fig. 4. Detection probability of Sweep CW (rise) signal vs. JNR.

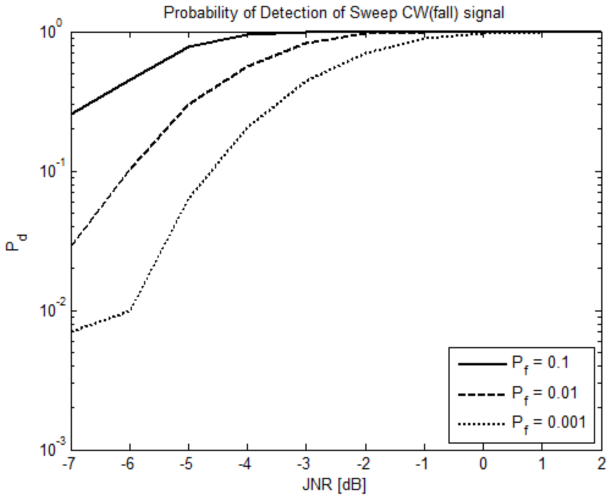

Fig. 5. Detection probability of Sweep CW (fall) signal vs. JNR.

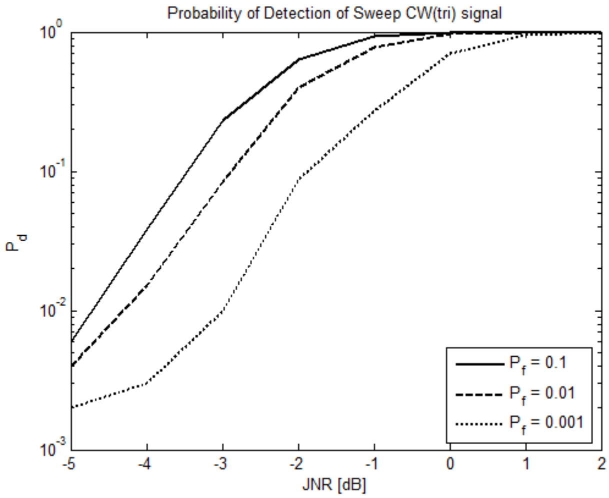

Fig. 6. Detection probability of Sweep CW (tri) signal vs. JNR.

5. CONCLUSIONS

The performances of an anti-jamming technique and a jammer localization technique vary significantly depending on the type of a jammer. Therefore, the importance of a jammer identification technique for applying an appropriate anti-jamming technique has increased. In this study, a jammer identification technique based on template matching was proposed. Using SCF, the spectral correlation and frequency characteristics of each jamming signal were analyzed; and based on this, the matching between the template generated for jammer identification and the received signal was performed. Based on a simulation, the difference in the jammer identification performance depending on the false alarm could be examined, and it was found that trade-off between the detection probability and the false alarm is required to obtain desired performance. Also, it was shown that the proposed identification technique was valid at a low power, and jamming identification could be performed using this. The technique proposed in this study can be applied to other types of jamming signals in addition to the jamming signals presented in this paper. For this purpose, research can be expanded by the additional analysis of the power of signals.

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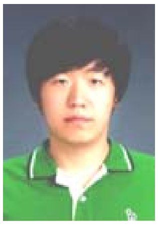

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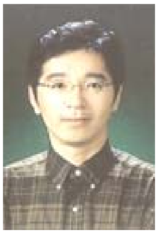

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