1. Introduction

In recent years, the demand for high capacity, high-reliability, and high quality has reached an astonishing level in wireless communication systems. UWB (Ultra Wide Band) wireless communications can transmit at the speed of several gigabits per second using a pulse with an extremely short time width [1], [2]. UWB is also applied to radar systems utilizing its wideband characteristics. An antenna that has wideband characteristics is required for the system because a very wide frequency band is utilized in UWB. However, it is difficult to obtain an antenna that has uniform characteristics in all UWB frequency bands [3].

Pre-distortion technology that is used to compensate for the distortion due to the antenna characteristics before transmission was proposed in [4] and [5]. To compensate for the distortion in the gain characteristics of the antenna, a method of inverse filtering was proposed [6], [7]. However, the compensation effect of the inverse filter was not sufficient when the distortion of the antenna gain characteristics was severe. It was reported that the compensation effect is improved by limiting the filter gain [8]. However, it is difficult to determine the appropriate limiting level because the surrounding environment varies the distortion of the antenna characteristics.

In this paper, we first propose a quasi-inverse filter (QIF) in order to improve the compensation effect for the transmitter antenna. The effectiveness of the proposed filter for severe distortion is verified by computer simulation.

Second, we describe a compensation method for the transmitter and receiver antennas, and the radio propagation characteristics using the QIF. The effectiveness of the compensation method for severe distortion is verified by computer simulation. Furthermore, we examine the required period for updating the filter coefficients in a dynamic propagation environment.

Finally, the proposed method is applied to a disc monopole antenna as a concrete example of a broadband antenna, and the compensation effect for the antenna is indicated.

2. Compensation Method for Distortion Using Pre-Distortion Filter and Its Problem

2.1 Concept of Compensation Using Pre-Distortion

In the case of a UWB radar system, it is important to compensate the distortion in the transmitted signal from the antenna. Thus, we first consider the compensation effect for the transmitter antenna.

Figure 1 shows the concept of using a pre-distortion filter to compensate for the distortion. To make the amplitude spectrum of the signal from the antenna constant, the gain characteristics of the conventional filter, \( G_{RF}(f) \), are set to the inverse of the antenna gain characteristics, \( H_a(f) \), as shown in Eq. (1) [6]. We assume that the pre-distortion filter comprises a transversal filter in the baseband and the process is achieved through digital signal processing. After the signal processing, the pre-distorted signal is up-converted to RF frequency and amplified before it is radiated from the transmitter antenna.

\[
G_{RF}(f) = 1/H_a(f),
\]

2.2 Problem Facing Conventional Inverse Filter

The conventional inverse filter cannot adequately compensate for the frequency distortion when the distortion of the gain characteristics of the antenna is severe [3]. This is because when the antenna gain is extremely low, the gain of
3. Proposed QIF

3.1 Frequency Characteristics of QIF

To avoid the extreme high gain characteristics of the inverse filter, we propose the application of the QIF. The gain characteristics of the filter, $G_{QIF}(f)$, are determined by Eq. (2).

$$G_{QIF}(f) = \frac{H_a(f)}{|H_a(f)|^2 + \alpha}, \quad \alpha : \text{Constant} \tag{2}$$

Here, $H_a(f)$ is the gain characteristics of the antenna, and $\alpha$ is a small constant coefficient to avoid the extreme high gain characteristics. Namely, the QIF has almost the same characteristics as the inverse-filter when gain $H_a(f)$ of an antenna is sufficiently high. On the other hand, the gain of the QIF becomes almost 0 in the band when $H_a(f)$ is very low as shown in Fig. 3. In the proposed filter, the small constant, $\alpha$, in Eq. (2) corresponds to a noise level in the Wiener filter [9].

3.2 Simulation Conditions

3.2.1 Input Signal to Filter

The spectrum of the output pulse from the signal generator in the computer simulation is shown in Fig. 4. It is assumed that the energy of the pulse is concentrated in the vicinity of the 3.1–10.6 GHz band. Both ends of the spectrum, 3.1 GHz and 10.6 GHz, are 3 dB cut-off frequencies, and the outskirts are regarded as Nyquist characteristics of the roll-off rate of 0.5. The sampling frequency is 32 Gsample/sec. The input pulse to the filter is obtained by performing an inverse Fourier transform of the spectrum shown in Fig. 4. The waveform of the pulse in the time domain is shown in Fig. 5.
3.2.2 Antenna Characteristics in Simulation

To evaluate the effect of the compensation filter on various antenna characteristics, the antenna gain characteristics in the simulation shown in Fig. 6 are determined using Eq. (3). Parameters $a_0$ and $a_1$ shown in Fig. 6 are the gain at the central frequency and the distortion coefficient of the gain characteristics, respectively [6]. It is assumed in this section that the antenna characteristics are known at transmission side.

$$H_d(f) = a_1 x + a_0, \quad x = \frac{2(f - f_0)}{f_H - f_L}. \quad (3)$$

3.2.3 Filter Composition and Evaluation Method

We assume that the pre-distortion filter comprises a transversal filter in the baseband and the process is achieved through digital signal processing [9]. The coefficients of the proposed filter are determined as the inverse Fourier transform of the objective frequency characteristics. The target characteristics herein are determined by Eq. (2).

RMSE (Root Mean Square Error) between the original signal indicated in Fig. 5 and radiated signal from the antenna are calculated for evaluation. We evaluate the effectiveness of the filter using the RMSE ratio, which is the ratio between the RMSE with the filter and the RMSE without the filter. The RMSE ratio is calculated using Eq. (4). If the RMSE ratio is a positive value, the filter is effective, and if the RMSE ratio is a negative value, then the filter is ineffective.

$$RMSE \text{ ratio} = 10 \log_{10} \left( \frac{\text{RMSE w/o filter}}{\text{RMSE with filter}} \right). \quad (4)$$

3.3 QIF Compensation Effect

3.3.1 Decision of QIF Coefficient

In the proposed QIF, the coefficient $\alpha$ in Eq. (2) may greatly affect the performance of the QIF. Thus, the effect of coefficient $\alpha$ is evaluated first. Figure 7 shows the variation in the RMSE ratio as a function of the value of $\alpha$ in the QIF. The parameters are the distortion coefficient, $a_1$, and the gain at the central frequency, $a_0$.

We can find in Fig. 7 that when $\alpha$ is approximately 0.01, the RMSE ratio almost reaches its peak except for the case of $a_1$ is 0.5. Although small value of $\alpha$ is better when $a_1$ is small, degradation of the RMSE ratio is very little when $\alpha = 0.01$. Therefore, we can say that the value of 0.01 is appropriate for the coefficient $\alpha$.

3.3.2 Comparison with Conventional Inverse Filter Based on Compensation Effect

Figure 8 shows a comparison of the effect of the filter as a function of distortion coefficient $a_1$. Coefficient $\alpha$ of the QIF is 0.01. The performance of conventional techniques such as the inverse filter [6], and the simple limiting gain filter [8], is shown for comparison. In case of the simple limiting gain filter, the values of filter coefficients are just limited for avoiding emanation of the filter coefficients.

Figure 8 shows that the QIF achieves a higher RMSE ratio compared to those for the conventional filters when $a_1$ is large. That is, the proposed method works well even if the distortion of the antenna characteristics is very severe.

4. Compensation Method for Wideband Communication System

In the previous section, we considered the compensation effect for the distortion of a transmitter antenna. In this chapter, we propose a method that compensates for the distortion in the frequency characteristics of both the transmitter and receiver antennas, in addition to the radio propagation characteristics using QIF. We examine the influence of the signal
to noise power ratio (SNR) at the receiver antenna, the desired wave to undesired wave power ratio (DUR) value of the arrival waves, the number of taps and bits for the compensation filter, and the feedback delay on compensation effect.

4.1 Compensation System Configuration for Communications

Figure 9 shows the configuration of the proposed compensation system using a pre-filter and a post-filter. In the figure, the total characteristics, $H_{\text{total}}(f)$, are expressed in Eq. (5). Here, $H_{\text{tx}}(f)$ represents the gain characteristics of the transmitter antenna, $H_{\text{rx}}(f)$ represents the gain characteristics of the receiver antenna, and $H_{\text{space}}(f)$ represents the propagation characteristics of the radio channel. In the following simulation, the total characteristics, $H_{\text{total}}(f)$, are estimated from the received signal.

$$H_{\text{total}}(f) = H_{\text{tx}}(f) \times H_{\text{space}}(f) \times H_{\text{rx}}(f).$$

To compensate the $H_{\text{total}}(f)$, gain characteristics in conventional inverse filter, $G_{\text{IF}}(f)$, and quasi-inverse filter, $G_{\text{QIF}}(f)$, are decided as follows.

$$G_{\text{IF}}(f) = \frac{1}{H_{\text{total}}(f)},$$

$$G_{\text{QIF}}(f) = \frac{H_{\text{total}}(f)}{|H_{\text{total}}(f)|^2 + \alpha}, \quad \alpha : \text{Constant.}$$

Here, we consider the following three types of configurations.

A) Only pre-filter

The frequency distortion is compensated before a signal is input to the transmitter antenna. The characteristics of the filters are set as shown in Eq. (8).

$$G_{\text{pre}}(f) = G_{\text{IF}}(f), \quad G_{\text{post}}(f) = 1.$$ 

Here, $G_{\text{pre}}$ and $G_{\text{post}}$ are the gain characteristics of the pre-filter and post-filter, respectively. $G_{\text{IF}}$ means gain characteristics of compensation filter decided by Eq. (6) or Eq. (7).

B) Only post-filter

The frequency distortion is compensated after receiving a signal at the receiver antenna. The characteristics of the filters are set as shown in Eq. (9). The post-filter corresponds to the conventional equalizers.

$$G_{\text{post}}(f) = G_{\text{flt}}(f), \quad G_{\text{pre}}(f) = 1.$$ 

C) Pre-filter and Post-filter

To compensate for the distortion using a pre-filter and post-filter, the characteristics of the filters are set as shown in Eq. (10).

$$G_{\text{pre}}(f) = G_{\text{post}}(f) = \sqrt{G_{\text{flt}}(f)}.$$ 

4.2 Propagation Model in Simulation

The propagation characteristics of a radio system are also distorted by frequency selective fading in a multi-path environment. We assume that two waves arrive at the receiving point. One is the desired wave, which is usually a direct wave. The other is an undesired wave, which is usually a reflected wave or diffracted wave. The frequency characteristics of the radio channel are expressed as Eq. (11).

$$|A_0(f, \tau)| = |A_D + A_U e^{j2\pi f \tau}|.$$ 

Here, $A_D$, $A_U$, and $A_0$ are the amplitude of the desired wave, the undesired wave, and the received signal, respectively. Term $f$ is the carrier frequency and $\tau$ is the delay time between two arriving waves. Since the amplitude of the received signal, $A_0$, depends on the frequency as shown in Eq. (11), the propagation characteristics are dependent on the frequency. The DUR in decibels is given in Eq. (12). We assumed that AWGN (Additive White Gaussian Noise) is added on received signal.

$$\text{DUR} = 20 \log_{10}(A_D/A_U).$$

4.3 Compensation Effects in Wideband Communication System

4.3.1 Compensation Method Comparison

Figure 10 shows the compensation effects of the filters as a function of distortion coefficient $a_1$, when the gain at the center frequency, $a_0$, is 1. The SNR is 50 dB, the DUR is 10 dB, and coefficient $\alpha$ of the QIF is 0.01. The horizontal axis indicates the distortion coefficients, $a_1$, in Eq. (3) and the vertical axis shows the RMSE ratio expressed as Eq. (4). When only the pre-filter or post-filter is used, the number of filter taps is 64. When the pre-filter and post-filter are used, the number of taps for the respective filters is 32. Namely, the total number of taps is 64 in any case.

In Fig. 10, the solid line represents the compensation effect using both the pre-filter and post-filter, and the dotted
line represents the results with only the pre-filter or post-filter. The compensation effects from the inverse filter and the QIF are shown in the figure.

Figure 10 shows that a higher RMSE ratio is obtained when using both a pre-filter and post-filter compared to that when using only the pre-filter or post-filter.

Since the configuration of the pre-filter and post-filter are the same, the performance of either case with only the pre-filter or post-filter are the same. However, the configuration of the case of pre-filter and post-filter is different from the others. That is, two filters with 32 taps are arranged in cascade. Since the filter with 32 taps has almost the same performance as shown in following section, it is thought that the better performance could be obtained when the pre-filter and post-filter are used than the other cases. More detailed discussion on the configuration is provided in Sect. 4.3.3.

The QIF is very effective compared to the inverse filter when distortion coefficient $a_1$ is large. That is, the proposed method with QIF works well even if the distortion of the transmission characteristics is very severe.

4.3.2 Influence of SNR and DUR

Figure 11 shows the influence of the noise level at the receiver antenna. As a reference, results in case of pre-filter and post-filter with 64 taps respectively is shown by thin line in the figure. We find that the compensation effect is almost the same as the case without noise when the SNR is greater than 20 dB, and the pre & post-filter compensation is the most effective. However, the pre & post-filter is less effective in case of low SNR. The performance degradation may be due to the configuration of the filter. That is, the number of taps in one side of the pre & post-filter is a half of that of pre-filter or post-filter. If both of the pre & post-filters has the same taps with pre-filter or post-filter, of course the better performance can be obtained even in case of low SNR.

The pre & post-filter method is effective in high SNR region. Thus, it can be said that the proposed method is effective in high speed mobile communication system because modulation techniques with high efficiency such as 64QAM are utilized in recent high speed mobile communication system. It is also preferable to improve the performance in low SNR situation, but the points are the future works.

In comparison between the only the pre-filter and only the post-filter, the post-filter has better performance. This is because that the noise at the receiver side can be suppressed by the post-filter, but the pre-filter cannot affect on the noise at the receiver side.

Figure 12 shows the relationship between the DUR value of the arriving waves and the compensation effect of the pre-filter & post-filter with quasi-inverse characteristics.

The horizontal axis indicates the DUR value. A large value on the axis indicates that the undesired wave is weak compared to the desired wave.

Figure 12 shows that the effect of the filter is almost the same as the case without multi-paths when the DUR is greater than 20 dB. We also find that when the delay time, $\tau$, is less than 0.01, the compensation effect does not depend on the value of the DUR and is slightly larger than the case without multi-paths. This is because the delayed wave is effectively combined with the desired wave when the delay is very short.

4.3.3 Influence of the Number of Taps and Its Resolution

It is assumed that the filters comprise transversal filter consist of tapped delay line. The number of taps greatly affects the cost in actualizing the system. Thus, we evaluate the effect of the number of taps on the compensation effect. Figure 13 shows the variation in the RMSE ratio with the number of taps when the pre-filter & post-filter are used. The number of taps indicated in the figure means the number of taps on one side. It is understood that the essential
performance are obtained by both the QIF and the inverse filter when the number of taps is more than 22.

When the filtering is achieved by digital signal processing, resolution of tap coefficients is also important parameter. Figure 14 shows the compensation effects when the number of taps and the number of the bits for the respective taps are varied. The vertical axis and horizontal axis indicate the number of taps in transversal filter and number of bit in individual taps, respectively. And the contour indicates the effect of the filter. As shown in Fig. 14, at least 22 taps are required for the filter and 5 bits for each taps are required to obtain a compensation effect.

In addition, there is a minimum required structure of the filters, e.g., 64 taps × 5 bits; 32 taps × 6 bits; and 22 taps × 7 bits, to obtain a compensation effect at the same level when there are many taps and bits. When the scale of the filter is considered, the number of operations of the digital filter can be roughly expressed as a product of the number of the taps and the number of the bits. So, the filter structure with 22 taps × 7 bits seems to be appropriate.

4.3.4 Influence of Feedback Delay

Figure 10 shows that the compensation effect using both pre-filter and post-filter is greater than when only the post-filter is used. However, the information pertaining to the propagation characteristics should be fed back from the receiving side to the transmission side. The propagation characteristics vary due to movement of the receiver antenna and the effect of the surrounding objects. The variation of the propagation characteristics may affect the performance of the compensation system. Therefore, the appropriate feedback period is very important in actualizing the system.

Thus, the effect of the feedback period on the compensation effect is evaluated. The results are shown in Fig. 15. The horizontal axis shows the product of the Doppler frequency $f_d$ of the arriving waves and feedback period $T$. Namely, the value on the axis indicates the variation in the phase of the arriving waves per feedback period.

Figure 15 shows that the RMSE ratio depends on feedback period $T$ when the value of DUR is small. Based on this result, we can say that the feedback period should be set to more than 10 times the Doppler frequency.

5. Applied Example on Broadband Antenna

In this section, the proposed method is applied to a disc monopole antenna as a concrete example of a broadband antenna, and the compensation effect for the antenna is verified.

5.1 Antenna Characteristics and Conditions

Figure 16(a) shows the structure of the disc monopole antenna [10]. The radiation element is mounted on a ground plane and it is fed from the back of the ground plane. The voltage standing wave ratio (VSWR) value of the antenna is below 2.0 in the frequency band from 0.5 to 10.6 GHz [11]. Radiation patterns of the antenna in the vertical plane are shown in Fig. 16(b). The patterns in Fig. 16(b) are calculated results based on the moment method. Since the radiation patterns depend on the frequency, we understand that the gain in a specific direction is distorted.

We applied a disc monopole antenna to both the transmission and reception sides and evaluated the compensation effect through computer simulation. Figure 17 shows the relative location of the antennas. We assumed that only direct wave arrives at the receiver antenna.

5.2 Compensation Effect for Wideband Disc Monopole Antenna

Figure 18 shows the frequency characteristics when the direction $\theta$ in Fig. 17 is 45 degrees which correspond to the direction of the maximum radiation of the antenna. The
gain characteristics of conventional inverse filter, $G_{IF}$, and the gain of QIF, $G_{QIF}$, are determined by Eq. (6) and Eq. (7), respectively. As we can see in the figure, the compensated characteristics by $G_{IF}$ are perfectly flat because $G_{IF}$ is just the inverse of $H_{total}$. However, noises must be enhanced in the frequency when the $H_{total}$ is very small. On the other hand, the peak of gain characteristics of QIF is reduced. Although the transmission characteristics are not compensated perfectly, the effect of noise enhancement might be reduced.

Figure 19 shows the compensation effect of the filters when the direction of the path is varied. The horizontal axis represents the direction of the direct path and the vertical axis indicates the RMSE ratio.

Figure 19 shows that the QIF achieves a higher RMSE ratio than that for the conventional inverse filter. The QIF greatly improves the RMSE ratio especially where angle $\theta$ is small. This is because the gain of the antenna at these angles is very small and greatly changes as shown in Fig. 16(b). Namely, the frequency characteristics are very severe and a significant compensation effect is obtained compared to the case of the conventional inverse filter.

6. Conclusion

In this paper, we proposed a method for compensating for the distortion in the frequency characteristics.

First, the compensation method for the transmitter antenna was proposed. In the method, the transmission signal was pre-distorted using the quasi-inverse characteristics of the antenna. Then, the compensation effect of the QIF was verified by computer simulation.

Next, the QIF was applied to compensate for the transmitter and receiver antennas, and the radio propagation characteristics. We found that a larger compensation effect is obtained when using both pre-filter and post-filter, compared to the case where only a pre-filter or a post-filter is used. We also found that the compensation effect is improved by the QIF compared to the case of the inverse filter, especially under severe conditions. The effect of the DUR of the radio environment on the compensation effect was evaluated. The results showed that the effect of the filter is almost the same as that without multi-paths when the DUR is greater than 20 dB.

The effects of the number of taps and feedback period of the propagation characteristics in the communication system were examined. The results showed that more than 22 taps and 5 bits for each tap are required to obtain the essential level of performance for QIF. The results also showed that the feedback period should be set to more than 10 times the Doppler frequency.

Finally, the proposed method was applied to a disc monopole antenna as a concrete example of a broadband antenna, and compensation effect for the antenna was verified.

References


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