PAPER

A Novel Adaptive Array Utilizing Frequency Characteristics of Multi-Carrier Signals

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SUMMARY A novel algorithm for an adaptive array that is suitable for a multi-carrier transmission will be proposed in this paper. In an adaptive array, signals received by antenna elements are weighted and combined together. In the proposed algorithm, distortion of a spectrum of the combined signal is detected and weight coefficients for each antenna element are controlled so that the spectrum of the combined signal becomes flat. Concept of the proposed algorithm can be interpreted as the CMA which is applied to signals sampled in the frequency domain. Furthermore, a configuration of the adaptive array will be shown. Signals separated in a receiver of the multi-carrier transmission are utilized to detect the distortion of the signal spectrum. By adopting the proposed configuration, the spectrum of the multi-carrier signal can be easily detected. In order to investigate the performance of the proposed adaptive array, computer simulation has been carried out. Numerical results show that; 1) A desired wave is captured well even if an interference wave is narrow band signal and is stronger than the desired wave. 2) Suppression performance for a co-channel interference wave depends on both a symbol timing and SIR of arrival waves. If the symbol timing of the interference wave greatly differs from the timing of FFT window of the receiver, the desired wave can be captured even if the co-channel interference wave is stronger more than 10 dB compared with the desired wave. The conventional CMA adaptive array has a serious problem that the narrow band interference wave is captured when it is stronger than the desired wave. On the other hand, it is extremely rare that the proposed adaptive array captures the narrow band interference wave. Therefore, it can be said that the proposed adaptive array is a robust system compared with the conventional system.
key words: *adaptive array, mobile communication, multi-carrier, CMA*

1. Introduction

A data transmission rate of land mobile communication systems tends to be high-speed year by year. The most high-speed public system in Japan is PHS (Personal Handy phone System) with the rate of 384 kbps. In addition, the communication service with 2 Mbps will be provided on IMT-2000 (International Mobile Telecommunication system) from 2000. Furthermore, MMAC (multi-media mobile access) as one of more high-speed communication systems have been projected toward future. In mobile communication environment, however, as the data transmission rate is increased, there arise serious problems leading to deterioration of communication quality [1].

The deterioration of communication quality in land mobile communications is mainly caused by distortion of the received signal due to incidence of multi-path waves. To compensate the distortion and to improve the communication quality, various techniques such as adaptive arrays [2] and adaptive equalizers [1] have been studied. In recent years, also a multi-carrier transmission technique has been attracting much attention as a promising scheme to realize a high-efficiency and high-quality communication [3].

In the case of the multi-carrier transmission, the high-speed data to be transmitted are separated to multiple low-speed data, and each of these low-speed data is transmitted by use of the individual carrier (subcarrier). By decreasing the transmission rate per carrier, effect of the multi-path wave can be relieved. To realize the high-speed mobile communication with the multi-carrier system, however, several problems have to be solved. Especially, development of techniques to decrease the effect of the multi-path waves with a long delay and Doppler effect due to movement of mobile terminals is indispensable [4].

Adaptive arrays have been studied as a countermeasure to improve the communication quality of land mobile communications [2]. It has been clarified through the previous researches that the adaptive arrays can suppress the multi-path waves with the long delay. In most of conventional adaptive arrays, weight coefficients for the antenna elements are determined so as to minimize the distortion of the received signal. In the case of the multi-carrier transmission, however, detecting the distortion of the received signal is more difficult than the case of the single-carrier transmission.

In this paper, a novel algorithm for the adaptive array that is suitable for the multi-carrier transmission will be proposed. In the proposed system, a spectrum of the multi-carrier signal is detected from the outputs of the FFT and the obtained spectrum envelope is utilized to control a directional pattern of the array antenna. This leads to indirect utilization of the spectrum of the multi-carrier signal. Furthermore, a configuration of the adaptive array to detect the spectrum of the received multi-carrier signal will be provided.

The paper is organized as follows. In Sect. 2, a

Manuscript received April 28, 1999.
Manuscript revised September 6, 1999.
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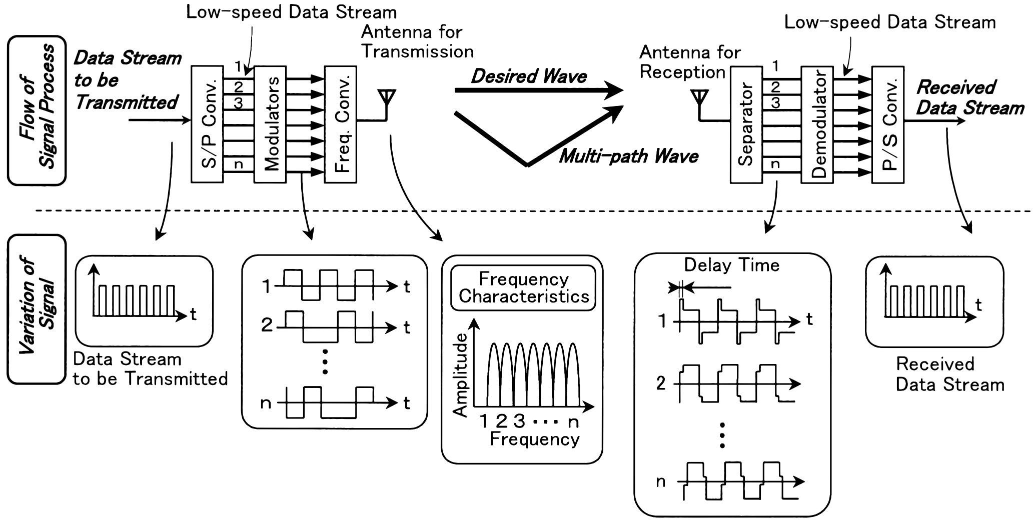


Fig. 1 Concept of multi-carrier transmission.

multi-carrier transmission scheme is described briefly. In Sect. 3, a configuration and principle of the proposed adaptive array are explained. In Sect. 4, results of computer simulation are shown and we discuss performances of the proposed adaptive array.

2. Multi-Carrier Transmission

The multi-carrier transmission has been proposed as a communication technique for high-speed transmission of a large amount of data [3]. Figure 1 shows conceptually a signal process flow of the multi-carrier transmission and variation of the signal with the process.

On the transmitting side, using a serial to parallel converter (S/P Conv.), a data stream to be transmitted is divided into multiple low-speed data streams which have a lower-speed transmission rate than that of the original data stream. The divided low-speed data streams are modulated and converted into high-frequency signals allocated to the different carrier frequencies, respectively. These high-frequency signals (sub-carriers) are combined and transmitted from the antenna for transmission.

On the receiving side, the transmitted data are reproduced through the reverse operation of the transmitting process. That is, the multi-carrier signal received by the antenna for reception is separated into the multiple signals using a separator. The respective separated signals are demodulated to obtain low-speed data streams. Using the parallel to serial converter (P/S Conv.), the low-speed data streams are converted into a high-speed data stream, thereby yielding a desired data stream. The effect of the multi-path is relieved because the transmission rates of the respective sub-carriers are decreased compared with the single-carrier transmission by using the multiple carriers.

The transmission technique in which the sub-carriers are allocated at orthogonal frequencies is called OFDM (Orthogonal Frequency Division Multiplexing). Since the signal process of the serial to parallel conversion and the frequency conversion of the OFDM are realized with discrete Fourier transform (DFT), the OFDM can be performed by a digital signal processing technique. Also, spectral efficiency of the OFDM system is better than that of the single-carrier transmission system. Hence, the OFDM is expected as a technique for realizing mobile communications with the features of both the high-speed and high-quality data transmission.

In the OFDM system, a guard period that is a replica of the last part of an information symbol (effective symbol) is inserted in the front part of each information symbol for combating against the distortion due to the multi-path waves. The deterioration of communication quality due to the multi-path waves is relieved as long as the delay of the multi-path waves is shorter than the duration of the guard period. Accordingly, the duration of the guard period must be set longer than the delay of the multi-path wave with the longest path. The deterioration of communication quality due to the multi-path waves can be avoided by setting the duration of guard period long enough. However, too long guard period reduces transmission efficiency because the guard period is a redundant part and they do not contribute to transmission of information.

On the other hand, adaptive arrays have been studied as a countermeasure to multi-path waves or interference waves. Through the previous studies, it is clarified that the multi-path wave with a long delay can be suppressed by the adaptive array. In most of the conventional adaptive arrays, the weight coefficients of antenna elements are determined so as to minimize the distortion of received signal in time domain. In the case of the multi-carrier transmission, the transmitted signal

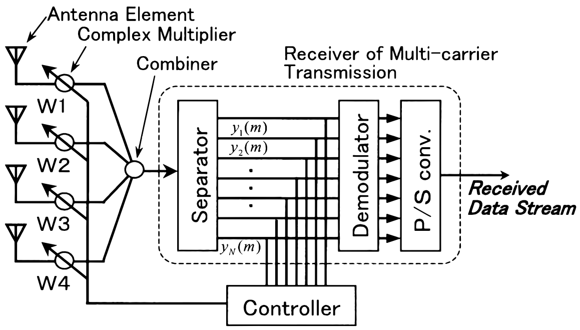


Fig. 2 Configuration of proposed adaptive array.

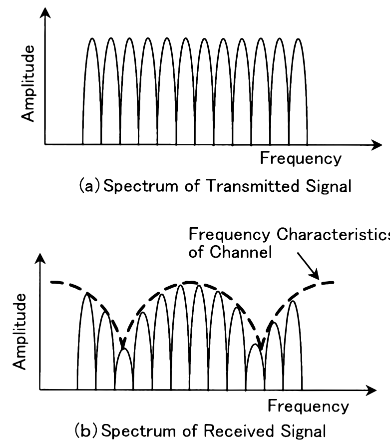


Fig. 3 Spectrum of multi-carrier signal.

is composed of the multiple sub-carriers and the respective frequencies are different from each other. Then, a waveform of the transmitted signal in time domain is much complex compared with the single-carrier signal. Namely, the amplitude of the multi-carrier signal has the Rayleigh distribution and the waveform of the signal is similar to the white gaussian noise [5]. Thus, in the case of the multi-carrier transmission, detecting the distortion in time domain of the received signal is much more difficult than the case of the single-carrier transmission.

3. Adaptive Array for Multi-Carrier Transmission

A novel algorithm of the adaptive array for the multi-carrier transmission is proposed in this section.

3.1 Configuration of Proposed System

Concept of the proposed algorithm can be interpreted as the constant modulus algorithm (CMA [6]) which is applied to signals sampled in the frequency domain.

A configuration of the proposed adaptive array is shown in Fig. 2. The signals received by the antenna elements are weighted by the complex multipliers and combined together. Then, the combined signal is inputted into the receiver of multi-carrier transmission. The combined signal is separated to the sub-carrier components and they are demodulated. The demodulated low-speed data are converted to the high-speed data by using the parallel serial converter. The signals separated to the sub-carrier components are also inputted to the controller to determine the weight coefficients.

3.2 Algorithm of Proposed System

Figure 3 shows the signal spectrum of the multi-carrier signal conceptually. When the desired wave and the multi-path waves are received together, the spectrum of the received signal is distorted due to the multi-path waves as shown in Fig. 3(b) even if all of the transmitted sub-carriers are the same in an amplitude as shown in Fig. 3(a). However, the signal spectrum of the combined signal is almost flat when deep nulls on a directional pattern are formed in the directions of the multi-path waves and only the desired wave is received. Thus, the weight coefficients for each antenna element should be controlled so that the spectrum of the combined signal becomes flat.

In order to detect the signal spectrum, in general, an additional tool such as a spectrum analyzer is needed. Here, instead of the spectrum analyzer, the signals outputted from the separator in the receiver are utilized in the proposed system. This is because the amplitude of each separated signal indicates intensity of the corresponding sub-carrier that is closely related to the spectrum of the combined signal. By adopting the configuration shown in Fig. 2, the distortion of the spectrum of the combined signal can be easily detected. Hence, the received multi-carrier signal, which is transmitted with the sub-carriers having the same amplitude, is separated and the weight coefficients are determined so that the separated signals become the same in the amplitude.

The control method of the weight coefficients is described as follows. Let $y_1(m)$ $y_2(m)$ $\ldots$ $y_N(m)$ represent the separated signals after m times of iteration and σ represent objective amplitude for each sub-carrier. The cost function $Q(m)$ of the proposed system is expressed as

$$Q(m) = \sum_{n=1}^{N} \left| |y_n(m)|^2 - \sigma^2 \right|^2 \tag{1}$$

Here, N indicates the number of sub-carriers. The cost function implies the distortion of frequency characteristics of the combined OFDM signal. When the cost function is minimized, all the amplitudes of sub-carriers become the same and then it is expected that nulls are formed in the directions of the multi-path waves on the directional pattern of the array antenna. To minimize the cost function, Marquardt method [7] is adopted in

Table 1 Conditions of simulation.

Number of Sub-carriers	10 (OFDM)
Modulation of Sub-carriers	Differential QPSK
Length of Guard Period	1/8T (T : Symbol Length)
Number of Arrival Waves	2 Waves
Directions of Arrival	0° (Desired Wave) 60° (Undesired Wave)
Intensity of Arrival Waves	0 dB (Desired Wave) -3 dB (Undesired Wave)
SNR of Desired Wave	20 dB
Number of Antenna Elements	4 Elements
Arrangement of Antenna Elements	Square Array
Distance of Antenna Elements	0.5 Wavelength
Algorithm	CMA
Optimizing Method	Marquardt Method [7]

the computer simulation of next section.

4. Computer Simulation

In this section, we investigate performances of the proposed system through a computer simulation.

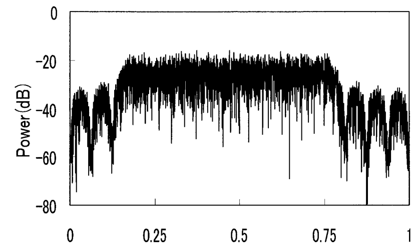
4.1 Condition of Simulation

The simulation is carried out on equivalent base-band systems. Conditions of the simulation are shown in Table 1. It is assumed that the desired wave and one undesired wave arrive at a receiving point. The desired wave is modulated with the OFDM. We consider following three types for the undesired wave.

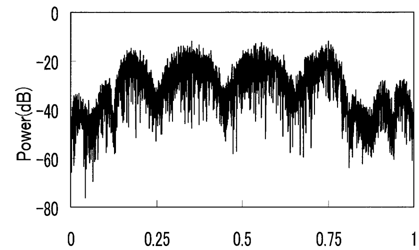
1) Case 1; The undesired wave originates from the same transmitting antenna as that for the desired wave, but has the different path from the desired wave. It is, so called, the multi-path wave.
2) Case 2; The undesired wave is transmitted from the antenna which is different from that for the desired wave and it is narrow band signal. Hereafter, we call this type of the interference wave "narrow-band interference wave."
3) Case 3; The undesired wave is transmitted from the different antenna from that for the desired wave, and it is an OFDM signal. Further, it has the same format (number of sub-carriers, frequency interval of sub-carriers, and so on) as that of the desired wave but it carries different information from the desired wave. Hereafter, we call this type of the interference wave "co-channel interference wave."

The OFDM signal is generated using IFFT (Inverse Fast Fourier Transform) with 16 points in the simulation. The IFFT is operated symbol by symbol and the guard period is inserted in the front part of each symbol after the operating the IFFT.

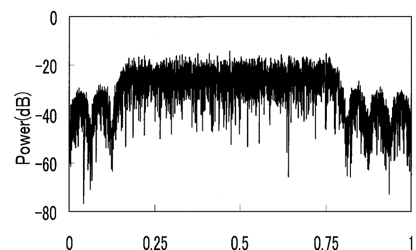
On the receiving side, the received signal is separated into the multiple sub-carrier components by using FFT. It is assumed in the simulation that a timing of FFT window synchronizes the symbol of the desired wave.



(a) Spectrum of Transmitted Signal



(b) Spectrum of Received Signal (1 Element)



(c) Spectrum of Combined Signal (Proposed system)

Fig. 4 Signal spectrum (simulation results).

We will compare performance of the proposed system with that of the conventional CMA adaptive array whose scheme is shown as follows:

- A single carrier signal modulated with differential QPSK is used.
- Weight coefficients are determined so as to minimize time variation of the amplitude of combined signal.

In this paper, DUR stands for the power ratio of the desired wave to the multi-path wave, SIR stands for the power ratio of the desired wave to the interference wave (narrow-band or co-channel), and the power of a multi-carrier signal means the sum of powers of all sub-carriers.

4.2 Suppression Performance for Multi-Path Wave (Case 1)

At first, the results of the signal spectrum in the simulation are shown in Fig. 4 in the case that the delay (τ) of the multi-path wave is 0.5 symbol length. Figures 4(a), 4(b) and 4(c) show the spectrums of the transmitted signal, the signal received by an omni-directional an-

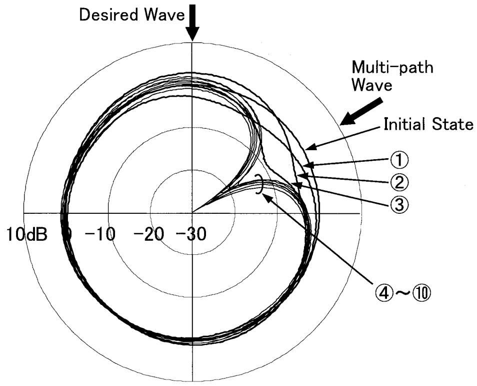


Fig. 5 Directional patterns.

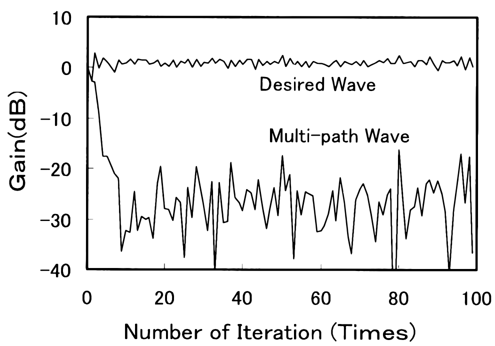


Fig. 6 Convergence properties.

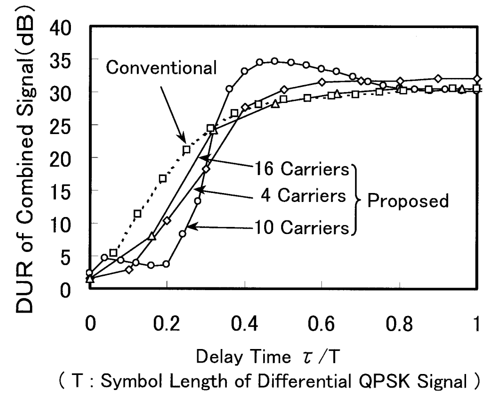


Fig. 7 Suppression performance for multi-path wave.

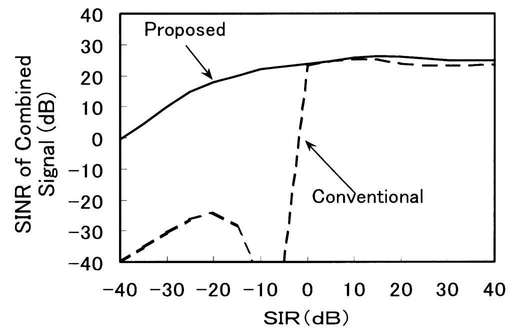


Fig. 8 Suppression performance for narrow-band interference wave.

tenna and the combined signal after iteration of 100 times in the proposed system, respectively.

In the case that the omni-directional antenna is used (Fig. 4(b)), it is clear that the spectrum of the received signal is distorted due to the multi-path wave. On the other hand, the spectrum of the combined signal (Fig. 4(c)) is almost flat similar to the spectrum of the transmitted signal.

Figure 5 shows the directional patterns of the array antenna. The thick arrows and the numbers in the figure indicate the directions of arrival and the numbers of iteration, respectively. It can be seen that a deep null is formed after several times of iteration and thus the multi-path wave is suppressed sufficiently.

Figure 6 shows convergence properties of the proposed system. The abscissa and ordinate denote the number of iteration and the gain in the direction of arrival, respectively. It can be seen from the figure that the multi-path wave is suppressed by approximately 20 dB or more in the steady state.

Furthermore, it is investigated how the delay of the multi-path wave affects performance of the proposed system. Figure 7 shows the DUR value of the combined signal after iteration of 100 times when the delay (τ) of multi-path wave is varied. For comparison, the DUR value of the conventional CMA adaptive array that minimizes time variation of the amplitude of combined signal is also shown by dashed line. The delay on the abscissa is normalized with a symbol length of the single carrier modulated with differential QPSK. The bit rates of all system in Fig. 7 are the same. It can be seen following results from Fig. 7.

1) The multi-path wave which has the long delay more than approximate 0.3 symbol length can be suppressed by the proposed system.
2) The suppression performance of the proposed system for the multi-path wave does not differ much from that of the conventional CMA adaptive array.

It is verified that the proposed system utilizing the spectrum of combined signal for the control of the directional pattern is an effective method to suppress the multi-path wave in the multi-carrier transmission system.

4.3 Suppression Performance for Narrow Band Interference Wave (Case 2)

In this subsection, the suppression performance for the narrow band interference wave will be shown. We assume that a continuous wave (CW) arrives as the interference wave besides the desired wave. The SINR (Signal to Interference plus Noise power Ratio) value of the combined signal after iteration of 100 times is shown in Fig. 8 when the SIR (Signal to Interference power Ratio) of the arrival waves is varied. It is shown that the SINR value of the conventional CMA adaptive array decreases when the interference wave is stronger than the desired wave (SIR < 0 (dB)). It is because that the strongest wave in the arrival waves is captured in the case of the conventional CMA adaptive array as already clarified [8]. In contrast with the above, the SINR value of the proposed system does not decrease so much even if the interference wave is stronger than the desired wave. These results are explained as follows.

In the proposed system, the weight coefficients are controlled so that the separated signals become the same in the amplitude. Unfortunately, the desired wave is suppressed and only the interference wave is received, then the amplitude of all the separated signals must decrease except for a separated signal which correspond to the frequency of the interference wave. In this case, all of the separated signals can not be the same in the amplitude.

4.4 Suppression Performance for Co-Channel Interference Wave (Case 3)

Finally, We discuss the suppression performance for the co-channel interference wave.

In this subsection, we assume that the signal format of the interference wave is the same as that of the desired wave. Namely, the carrier frequencies, the number of sub-carriers, the frequency interval of the subcarrier of the interference wave are the same as those of the desired wave. However, information to be transmitted is different between the arrival waves (the desired wave and the interference wave). As a matter of course, the direction of arrival, intensity and phase of each arrival wave are different from the other.

Figure 9 shows the SINR values of the combined signal after iteration of 100 times for the co-channel interference wave. The abscissa indicates the difference of symbol timing between the desired wave and the interference wave. The value of 0 on the abscissa implies the case that each wave arrives with the same symbol timing. It is assumed that the FFT window synchronizes the symbol of the desired wave as described before in the simulation.

It is found from Fig. 9 that

1) In the case that the desired wave is stronger than the interference wave (SIR = 4 dB), the SINR value is more than 20 dB.
2) In the case that the interference wave is stronger than the desired wave (SIR = −4 dB), the SINR value is approximately 20 dB when the absolute value of difference of the symbol timing is large. However, the SINR value decreases when the absolute value of difference of the symbol timing is small.

The above results are explained as follows.

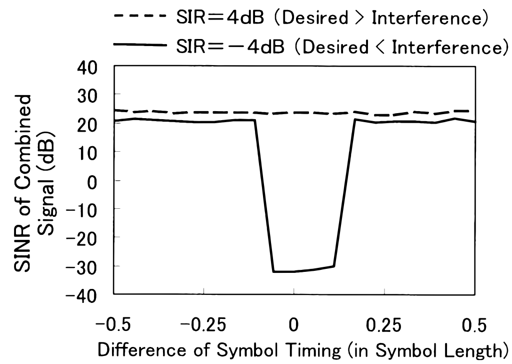


Fig. 9 Example of suppression performance for co-channel interference wave.

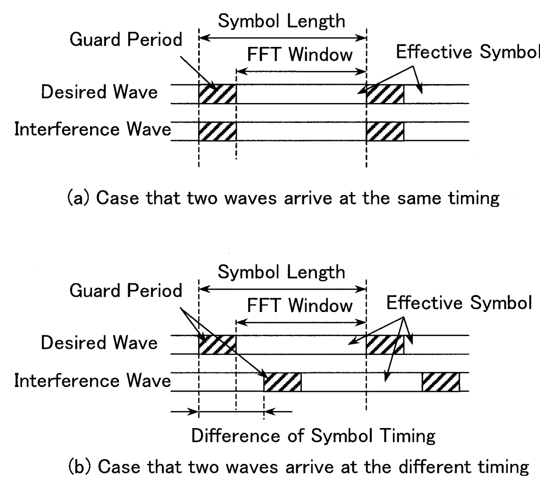


Fig. 10 Symbol timing of desired wave and co-channel interference wave.

If the symbol timings of both waves correspond to the FFT window as shown in Fig. 10(a), then the stronger wave is captured, as is the case with the conventional CMA adaptive array [8]. This is because the separated signals outputted from the FFT have the same value in the amplitude even if the interference wave is captured.

On the other hand, in the case that the symbol timing of the interference wave differs from the FFT window as shown in Fig. 10(b), the guard period and the different two symbols in both side of the guard period of the interference wave are included in one FFT window. Thus, the values of the amplitude of the separated signals outputted from the FFT are different from each other if the interference wave is captured. Therefore, in this case, the desired wave is captured even if the interference wave is stronger than the desired wave.

Figure 11 shows the SINR values of combined signal when the SIR of the arrival waves and the symbol timing vary. It is found from the Fig. 11 that the SINR value varies with not only the symbol timing but also the SIR of the arrival waves. In Fig. 11, the domain that the SINR value is larger than 0 dB corresponds to the

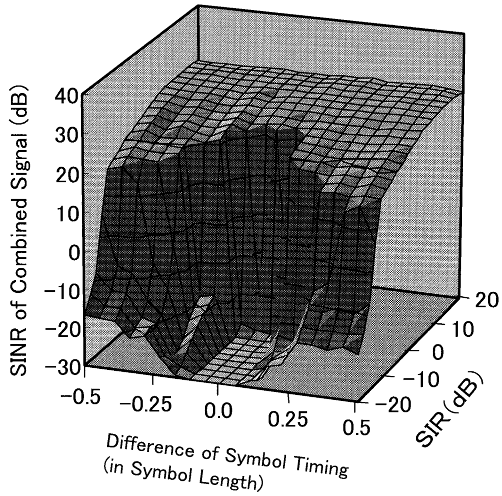


Fig. 11 Suppression performance for co-channel interference wave.

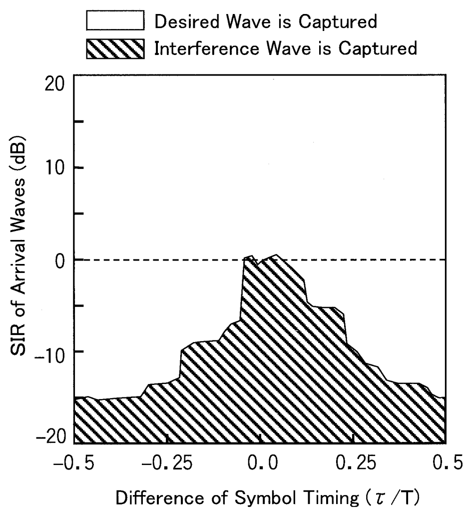


Fig. 12 Relationship between condition of arrival waves and captured wave.

case that the desired wave is captured. And the domain that the SINR value is smaller than 0 dB corresponds to the case that the interference wave is captured.

Figure 12 depicts a relationship between the condition of the arrival waves and the captured wave. In Fig. 12, the area with a shadow indicates the case that the interference wave is captured, and the area without the shadow indicates the case that the desired wave is captured. The dashed line, which is drawn in the center of the figure, shows the case that the intensity of the interference wave is equal to that of the desired wave. The conventional CMA adaptive array captures the interference wave in the region lower than the dashed line.

In the case of the proposed system, whether the desired wave is captured or not is depends on both the SIR of the arrival waves and the symbol timing. It is found from the figure that the desired wave can be captured when the symbol timing of the interference wave differs from the timing of the FFT window even if the interference wave is strong more than 10 dB compared with the desired wave.

5. Conclusion

A novel adaptive array that utilizes the frequency characteristics of multi-carrier signal has been proposed. In the proposed adaptive array, distortion of the signal spectrum of the received multi-carrier signal is detected and the directional pattern of the array antenna is controlled so that the spectrum of combined signal becomes flat. Furthermore, the configuration of the adaptive array has been shown. The signals separated in the receiver of the multi-carrier transmission are utilized to detect the distortion of the signal spectrum. By adopting the proposed configuration, the spectrum of the multi-carrier signal can be easily detected.

Next, in order to investigate the performance of the proposed adaptive array, computer simulation has been conducted. As a result, it is found that

1) The desired wave is captured well even if the interference wave is narrow band signal and is stronger than the desired wave.
2) Suppression performance for the co-channel interference wave depends on both the symbol timing and SIR of arrival waves. If the symbol timing of interference wave greatly differs from the timing of the FFT window, the desired wave can be captured even if the co-channel interference wave is strong more than 10 dB compared with the desired wave.

The conventional CMA adaptive array has a serious problem that the interference wave is captured when it is stronger than the desired wave. It can be said that reliability of the conventional CMA adaptive array is not enough because possibility of occurrence of the narrow band interference wave is not low. On the other hand, it is extremely rare that the proposed adaptive array captures the narrow band interference wave. Therefore, we can say that the proposed adaptive array is a robust system compared with the conventional system.

For the future study, we are planning to conduct the performance evaluation of the proposed adaptive array in more realistic environments by computer simulations and experiments.

Acknowledgments

The authors wish to acknowledge Dr. N. Itoh, Mr. N. Suzuki and other colleagues of the Communications Laboratory of Toyota Central Research & Development Laboratories, Inc. for their valuable discussions and supports throughout this work.

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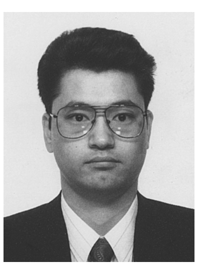

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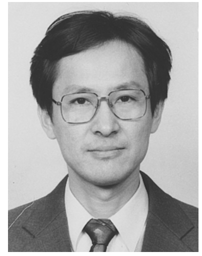

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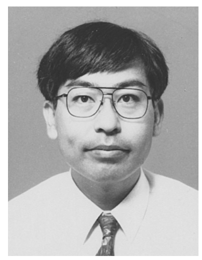

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