Implementation of OFDM Receiver Using Rotating Circular Array Antenna for Vehicle Communications

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Abstract: - In high-speed mobile OFDM communication systems, the receiving characteristics are degraded badly by channel time variation. Our solution is to rotate a circular array antenna so as to decrease the speed of the receiving antenna relative to the ground. Moreover, the BER characteristics with the parameters of ISDB-T, which are a standard of Japanese digital terrestrial television broadcasting, were used in prior research to evaluate the performance of concept. Past studies indicated that the rotating circular array antenna is effective in high-speed mobile OFDM communications. However, the composition of an OFDM receiver with rotating circular array antenna was not fully elucidated. We conduct fundamental research on receiver construction.
In this paper, we evaluate the performance of the OFDM receiver with rotating circular array antenna, that employs error correction decoding. Additionally, we improve the performance of rotation speed control method by using a moving average filter. Simulation results show the effectiveness of the proposed method by using the parameters of ISDB-T Mode3.

Key–Words: - OFDM; Rotating Circular Array Antenna; ISDB-T; Doppler Effect

1 Introduction

OFDM (Orthogonal Frequency Division Multiplexing) offers efficient utilization of the frequency band, and maintains good performance in multi-path environments since a wideband signal is divided into a large number of orthogonal narrow-band subcarriers[1]. This technique has been adopted in digital terrestrial television broadcasting and broadband mobile wireless access (WiMAX etc). OFDM is expected to be a prime next-generation mobile communications technology. Unfortunately, the transmission characteristics of high-speed mobile OFDM communication systems are severely degraded by the channel time-variation. Therefore, accurate channel estimation that can match the time-variation of the channel state is essential. Some channel estimation methods based on pilot symbols have been proposed[2]-[4]. However, those techniques contain the serious problem that channel estimation accuracy falls as vehicle velocity increases. We have already proposed a solution[5]. The proposal improves the receiving characteristics by lowering the speed of the receiving antenna relative to the ground by using a rotating circular array antenna. Compared to conventional techniques based on interpolation, the proposed method physically reduces the effect of the channel time-variation.

In order to put the rotating circular array antenna into practical use, the following studies have been conducted.

1. Simulations were conducted using parameters characteristics of a practical OFDM system. The BER (Bit Error Rate) characteristics with the parameter of ISDB-T (Integrated Services Digital Broadcasting-Terrestrial) Mode3[6], which are a standard of Japanese digital terrestrial television broadcasting, were shown [7].
2. When the vehicle speed changes, the rotating circular array antenna needs to keep the optimum rotation speed. In order to solve this problem, we proposed a control method of the rotating circular array antenna. It uses the margin of MSE (Mean Square Error) of two successive symbols[8].

From these studies, we confirmed that the rotating circular array antenna improved the BER characteristics in high-speed mobile OFDM communications.

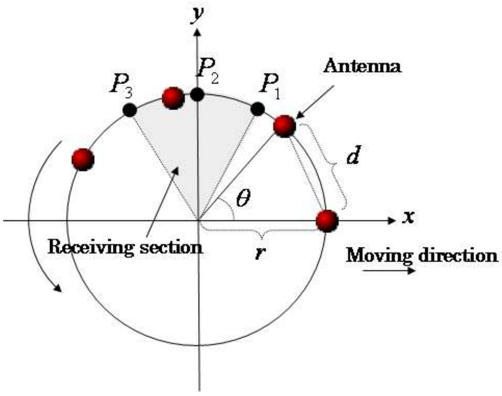

Figure 1: The receiving section of rotating antenna

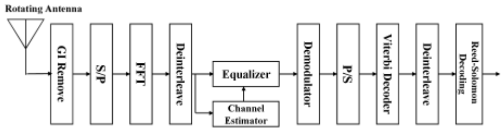

Figure 2: Receiver structure with rotating circular array antenna

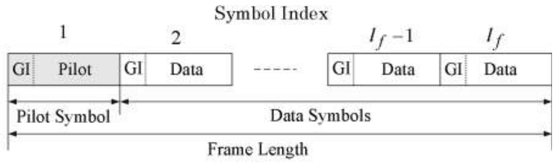

Figure 3: Frame construction

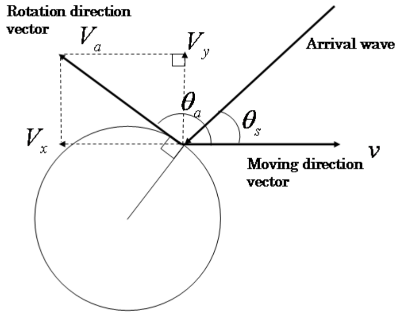

Figure 4: The receiving model of a vehicle with rotating antenna

They indicated that the rotating circular array antenna was effective in high-speed mobile OFDM communications. However, the composition of OFDM receiver using the rotating circular array antenna has been not examined enough. To create a fully functional mobile OFDM communication systems, this paper conducts fundamental research on receiver construction. Channel coding with error correcting code is adopted to improve mobile OFDM communication systems reliability. However, because error correction was not considered in past research, we introduce error correction decoding into the receiver. Additionally, we propose a new method to control rotation speed. In the case of the conventional approach, the performance of rotation speed control method drops because MSE characteristics are affected by AWGN and fading. In this paper, we improve the performance of rotation speed control method by using a moving average filter.

First of all, we confirm the effect of error correction from simulations based on the parameters of ISDB-T Mode3. RS (Reed-Solomon) and convolution code (encoding ratio $= 1/2$, Viterbi decoding) are adopted as error correcting codes. Moreover, the required C/N, i.e. C/N that obtains the BER performance of 2×10^{-4}[9], is examined. Simulation results indicate that the required C/N is improved compared to channel estimation based on pilot symbols. Then simulation results show the effectiveness of the proposed method to control rotation speed.

2 Rotating Circular Array Antenna

2.1 Construction of the Rotating Antenna

In this paper, we place n equally-spaced antenna elements on a circle. The section of $\frac{2\pi}{n}$[rad] that rotates $\frac{\pi}{2}$[rad] against the moving direction of the mobile is defined as the receiving section (see Fig.1). The antenna in this section receives the signal. When the receiving antenna reaches P_3, the receiving antenna is changed to the antenna at P_1. This iterative process yields physical compensation of the Doppler shift.

We assume that l_f OFDM symbols are received while the receiving antenna moves from P_1 to P_3. A frame is composed of l_f symbols. l_f is determined as;

$$l_f = \frac{1}{nRT_s} \tag{1}$$

where T_s is OFDM symbol duration, and R is rotation speed of the antenna. From (1), the frame length is defined from the rotation speed, OFDM symbol duration, and the number of antennas.

The rotation speed R[rps] (revolutions per second) that minimizes the effect of Doppler shift at P_2 is given as;

$$R = \frac{v}{2\pi r}. \tag{2}$$

From (2), the rotation speed is defined from the moving speed of the vehicle v[km/h] and the radius of the antenna r[m].

Fig.3 shows the frame structure. The pilot symbol is placed at the head of the frame to compensates the distortion of the following data symbol.

2.2 Doppler Frequency When Using a Rotating Antenna

When using a rotating circular array antenna in high-speed mobile communication systems, the Doppler frequency $f_d(t)$ of the signal arriving from the direction

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of θ_s relative to the moving direction of a vehicle is given by

$$f_d(t) = f_D \cos\theta_s + f_a(t) \tag{3}$$

where f_D is the maximum Doppler frequency which is written as v/λ (λ:wavelength of radio wave). $f_a(t)$ is the time function of Doppler shift offered by the rotating circular array antenna. $f_a(t)$ is calculated as follows. The position of the antenna is given by

$$x = r\cos(2\pi Rt + \theta_0) \tag{4}$$
$$y = r\sin(2\pi Rt + \theta_0) \tag{5}$$

where θ_0 is the initial phase of the antenna.

The speed of a tangent direction of the antenna at (x, y) is defined as V_a. V_a is given by V_x and V_y shown in Fig4.

$$V_a = \sqrt{(V_x)^2 + (V_y)^2} \tag{6}$$

V_x, V_y are defined by differentiating (4) and (5) with respect to time t as

$$V_x = -2\pi Rr\sin(2\pi Rt + \theta_0) \tag{7}$$
$$V_y = 2\pi Rr\cos(2\pi Rt + \theta_0). \tag{8}$$

Using (7) and (8), $f_a(t)$ is given by

$$\begin{aligned} f_a(t) &= \frac{V_a}{\lambda}\cos(\theta_a - \theta_s) \\ &= \frac{V_a}{\lambda}(\cos\theta_a\cos\theta_s + \sin\theta_a\sin\theta_s) \\ &= \frac{V_a}{\lambda}\left(\cos\theta_s\frac{V_x}{V_a} + \sin\theta_s\frac{V_y}{V_a}\right) \\ &= \frac{1}{\lambda}\left(V_x\cos\theta_s + V_y\sin\theta_s\right) \qquad (9) \end{aligned}$$

where θ_a is the angular difference between the rotation direction of the rotating antenna and moving direction of the vehicle. By substituting (7) and (8) into (9), $f_a(t)$ can be written as

$$f_a(t) = \frac{2\pi Rr}{\lambda}\sin\{\theta_s - (2\pi Rt + \theta_0)\}. \tag{10}$$

When using a rotating circular array antenna in mobile communication systems, the Doppler shift imposed on the arriving signal is given by

$$f_d(t) = \frac{v\cos\theta_s + 2\pi Rr\sin\{\theta_s - (2\pi Rt + \theta_0)\}}{\lambda}. \tag{11}$$

3 Control Rotation Speed of the Antenna

In mobile communication, the rotation speed of the antenna should be changed since vehicle speed is not constant. An iterative algorithm to estimate the optimal rotation speed is introduced here.

Table 1: Simulation parameters

Carrier frequency(f_c)	473.142 MHz
Modulation	64QAM
Number of subcarriers(N)	5617
Symbol duration($\frac{1}{f_0}$)	1008 μs
Guard interval(T_g)	126 μs
Sub-carrier spacing(f_0)	0.992 kHz
Number of antennas(n)	18

Table 2: Propagation model of GSM Typical Urban Area

Path Number	1	2	3	4	5	6
Delay [μs]	-0.2	0	0.3	1.4	2.1	4.8
Power [dB]	-3	0	-2	-6	-8	-10

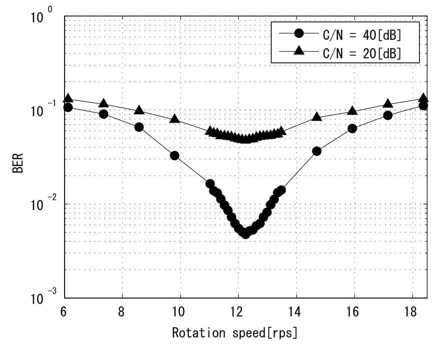

Figure 5: BER vs. Rotation speed, $v = 100$[km/h]

3.1 BER vs. Rotation Speed

Fig.5 shows the relationship between BER and rotation speed R[rps]. The simulation parameters are listed in Table1 and Table2; $v = 100$[km/m], C/N $= 20, 40$[dB], and number of antenna is 18. The BER vs. rotation speed curve is convex downward regardless of mobile speed and C/N. The minimal value of Fig.5 corresponds to the value obtained by entering the radius ($r = 0.36$[m]) and vehicle speed ($v = 100$[km/h]) into (2). Thus, the rotation speed calculated from (2) is regarded as the value which minimize BER.

3.2 Frame Construction

From (1), the number of received symbols, i.e. the frame length, decreases as of the rotation speed increases and vice versa. When the rotation speed increases, pilot symbols might not be received. On the other hand, several pilot symbols are received in a receiving section when the rotation speed decreases. If we define the pilot symbol interval from the maximum speed of the vehicle, the received signal will always includes a pilot symbol. Fig.6 shows a frame construction to control the rotation speed.

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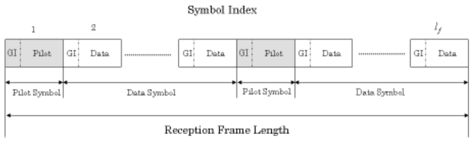

Figure 6: Proposed frame constructions

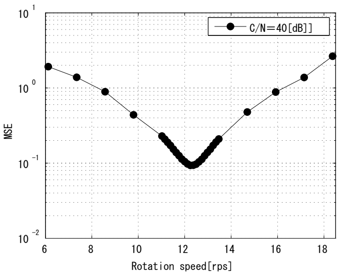

Figure 7: MSE vs. Rotation speed, v = 100[km/h], C/N = 40[dB]

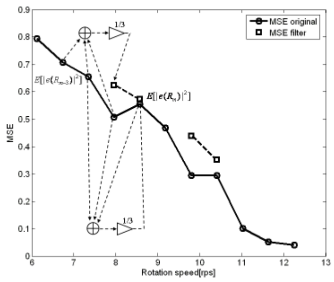

Figure 8: MSE after a moving average filtering

3.3 Algorithm to Control the Rotation Speed

When the vehicle speed changes, the rotating antenna needs to keep the optimum rotation speed to decrease the speed of the receiving antenna relative to the ground. Since the rotating antenna is installed in mobile communication systems, for example cars or trains and so on, the mobile speed is given by speedometer. However, considering a convenience and general versatility to introduce the system, the optimum rotation speed should be estimated automatically. Therefore, we propose a method which determines the optimum rotation speed by the method of steepest descent since the curve of BER vs. rotation speed is convex downwards (see Fig.5). However, since it is difficult to calculate BER in real systems, we employ MSE between before and after demodulated symbols instead of BER. MSE is defined as;

$$E\left[|e(R_m)|^2\right] = \frac{1}{N \cdot l_f} \sum_{k=0}^{l_f-1} \sum_{l=0}^{N-1} |X(k,l,R_m) - D(k,l,R_m)|^2 \quad (12)$$

where R_m is the rotation speed of the mth frame. $(N \cdot l_f)$ is the number of symbols in a received frame. $X(k,l,R_m)$ indicates a symbol before demodulation. This symbol is propagated by the lth subcarriers in the OFDM symbol. This OFDM symbol is received by a rotating antenna with rotation speed R_m at time k. $D(k,l,R_m)$ is the demodulated form of $X(k,l,R_m)$.

Fig.7 shows the relationship between rotation speed and MSE. The simulation parameters are listed in Table 1; vehicle speed is 100[km/m] and C/N is 40[dB]. From Fig.7, relationship between the rotation speed vs. MSE characteristic represents a convex downward. Thus the optimum rotation speed can be estimated by applying the method of steepest descent to the MSE of the symbols before and after demodulation instead of BER. The conventional method employs two rotating antennas to update the rotation speed. In order to achieve the iterative algorithm with single rotating antenna, we propose a new method which employs the margin of MSE between two successive symbols. In this situation, rotation speed R_{m+1} in the $(m+1)$th frame is determined as;

$$R_{m+1} = R_m - \mu\left(\frac{E\left[|e(R_m)|^2\right] - E\left[|e(R_{m-1})|^2\right]}{R_m - R_{m-1}}\right). \quad (13)$$

where μ is a step size parameter. In this algorithm, the margin between MSE and one before 1 frame is applied to determines the slope of the relationship between rotation speed and MSE.

However, Fig.7 is a averaged MSE characteristics. Each characteristic is not a smooth characteristic because of the influence of AWGN and fading. Fig.8 shows the appearance to which the MSE characteristics are smoothed with the moving average filter. In the proposed method, the MSE characteristics are smoothed by maintaining the data of M-frame in the buffer, and using M-point moving average filter. In this paper, we adopt three-point moving average filter. The stability of the system is maintained by this technique in the condition of $E\left[|e(R_m)|^2\right] < E\left[|e(R_{m-3})|^2\right]$.

3.4 Receiver Structure

Fig.9 shows a receiver structure that implements the proposed method. Signal, received by rotating antenna whose rotation speed is R_m, is subjected to guard interval removal, serial parallel conversion, and FFT. Channel estimation based on the pilot symbols is then performed at the equalizer, and distortion is compensated. Compensated symbols are then demodulated. The rotation speed is then updated by using the margin between MSE of the mth frame ($E\left[|e(R_m)|^2\right]$) and one of the $(m-1)$th frame which is held in buffer

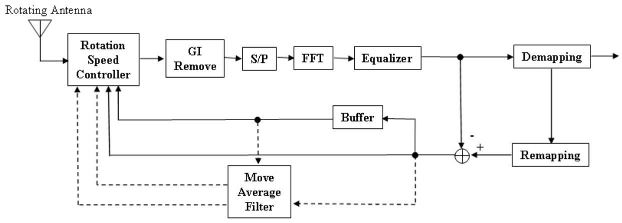

Figure 9: Receiver structure to control rotation speed

Table 3: Parameters of rotating antenna

Number of array elements(n)	18
Rotation speed(R)	12.25[rps]
Radius of antenna(r)	0.36[m]

($E\left[|e(R_{m-1})|^2\right]$) . In the case of $E\left[|e(R_m)|^2\right] - E\left[|e(R_{m-1})|^2\right] \geq 0$, the MSE characteristics are smoothed by using three-point moving average filter.

4 Simulation

4.1 BER vs. C/N based on ISDB-T Mode3

In this section, we indicate the effect of the error correction from the simulation result with the parameters of ISDB-T Mode3. The simulation parameters, taken from ISDB-T Mode3, are listed in Table 1. The carrier frequency is 473.142[MHz], one of the broadcasting channels of Japanese digital terrestrial television. Moreover, vehicle speed is 100[km/m], and pilot symbol interval is 4 symbols. This interval is adopted by reference to a interval of scattered pilot symbols in the time domain. Table 3 shows the parameters of the rotating circular array antenna. The propagation model is 6-path Rayleigh phasing transmission channel of GSM Typical Urban Area shown in Table 2. This model approximates the mobile receiving characteristics of UHF band in an urban area[10].

Fig.10 shows the BER vs. C/N characteristics. When we focus only on the data for BER = 10^{-3}, RS code improves the BER performance by about 1[dB]. On the other hand, convolution code improves the BER performance by about 9[dB]. Additionally, when the outer and inner codes are RS code and convolution code, respectively, the improvement in BER performance is about 10[dB].

These results indicate that error correction does improve the performance of an OFDM receiver with rotating circular array antenna.

4.2 Evaluation based on the required C/N

The C/N that yields the BER performance of 2×10^{-4} is defined as the required C/N. If the required C/N

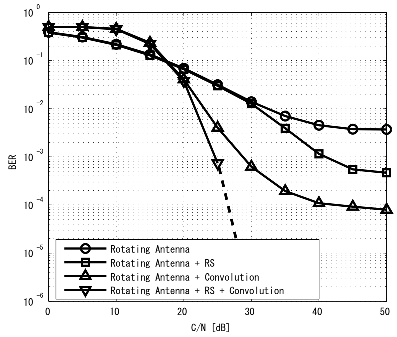

Figure 10: BER vs. C/N based on parameters of ISDB-T Mode3

Table 4: Required C/N[dB]
(Convolution code, Encoding ratio = 1/2)

	Required C/N[dB] (Convolution code)	
Modulation	Linear interpolation method	Rotating antenna
QPSK	22	18
16QAM	Error floor at BER = 2×10^{-3}	26
64QAM	Error floor at BER = 4×10^{-2}	35

is achieved after Viterbi decoding, the BER performance of 10^{-11} is obtained by RS decoding. The BER performance of 10^{-11} is considered to be quasi-error free. Even if the electric field strength drops, as long as the required C/N is kept, it is possible to receive digital terrestrial television broadcasts.

The simulation parameters and propagation model are the same as in Section 3.1. QPSK, 16QAM, and 64QAM are considered as modulation schemes. The performance of the interpolation estimation method (linear) is shown for comparison. Each required C/N is listed in Table 4. In the case of QPSK modulation, the rotating circular array antenna improves the required C/N by 4[dB] compared to channel estimation based on pilot symbols. When we focus on 16QAM and 64QAM, the BER of the linear interpolation method does not drop under 2×10^{-4}. Therefore, it is extremely difficult for the linear interpolation method to attain the required C/N.

These results confirm that the rotating circular array antenna is superior to the linear interpolation method as regards C/N performance.

4.3 Control the Rotation Speed

This section presents the computer simulation results that validate the proposed algorithm. In this paper, μ, which yields better performance of the proposed method, are calculated to show the effectiveness of the proposed algorithm empirically. The simulation parameters and a propagation model are the same as Section 3.1. The number of antennas is 18.

Fig.11 and Fig.12 plot the convergence characteristics when vehicle speed changes at a moment from 50[km/h] to 100[km/h]; the rotation speed should change

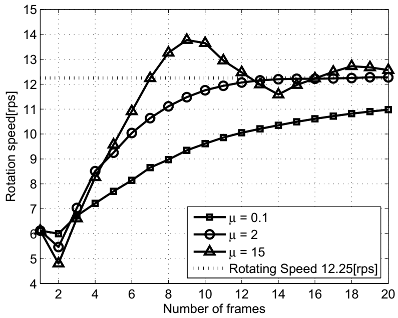

Figure 11: Rotation speed vs. Number of frames, $\mu = 0.1, 2, 15$, $n = 18$, C/N = 40[dB]

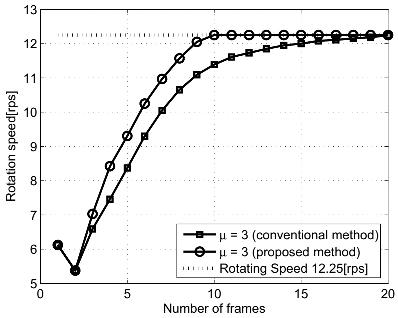

Figure 12: Rotation speed vs. Number of frames, $\mu = 3$, $n = 18$, C/N = 40[dB]

from 6.13[rps] to 12.25[rps]. The convergence characteristics of the rotation speed vs. the number of received frames with μ values of $0.1, 2$, and 15 are shown in Fig.11. In the case of $\mu = 15$, the rotation speed has an overshooting response for the desired rotation speed of 12.25[rps]. When the case of $\mu = 0.1$, the rotation speed increases gradually over 20 frames. On the other hand, the rotation speed is adequately estimated within 15 frames for $\mu = 2$. Fig.12 shows the convergence characteristics of the proposed method and a conventional method with μ values of 3. The convergence rate is improved by a moving average filter compared with the conventional method. From Fig.12, the rotation speed is estimated within 10 frames. This means that the desired rotation speed is calculated from 64.3 [msec] after the velocity changes. Considering the performance of general cars, the proposed method offers sufficient convergence rate. These results indicate that the proposed algorithm is effective in the tracking characteristics for vehicle speed variation.

5 Conclusions

We confirmed the effect of error correction as part of fundamental research on OFDM receiver construction. Simulation results indicated that error correction does improve the performance of an OFDM receiver with rotating circular array antenna. Moreover, we proposed the rotation speed control method using moving average filter. Simulations proved that the proposed method is effective in the tracking characteristics for vehicle speed variation compared with the conventional method.

Future work includes examining antenna characteristics of the rotating circular array antenna with a view to system implementation.

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