

Trial Study of SC-FDE Wireless Transmission System for Television Program Contribution using Microwave Band

Hotaka Ogawa†, Yusei Minowa†, Hiroyuki Hamazumi††(member) and Tomohiko Kimura†(member)

Abstract This paper describes a single carrier-frequency domain equalization (SC-FDE) wireless transmission method for microwave frequency-domain (FPU) systems.

This paper describes the results of a technical study on applying SC-FDE to a field pick-up unit (FPU). The transmission parameters of the SC-FDE method for microwave FPUs are examined, and the nonlinear and fading resistance characteristics are evaluated using OFDM (Orthogonal Frequency Division Multiplexing).

This paper quantitatively compares the OFDM and SC-FDE systems and discusses the usefulness of microwave FPUs using the SC-FDE system. The FPU operation applications are classified into three types: fixed transmission, quasi-mobile transmission, and mobile transmission, and the gain of SC-FDE relative to OFDM is calculated by adding the input back-off value of the transmitting amplifier and the required C/N of the receiver. The results show that in the case of fixed transmission, SC-FDE is advantageous, in the case of quasi-mobile transmission, the OFDM system and SC-FDE system are almost equivalent, and in the case of mobile transmission, OFDM system is advantageous.

Keywords: Micrometer Waveband, Microwave Link, OFDM, SC-FDE, Nonlinear Distortion, Fading

1. Introduction

Portable program material wireless transmission devices for television broadcasting (FPU: Field Pick-up Unit) are important radio equipment that is essential for live broadcasts of sports and news programs. The frequencies used by FPUs include the 1.2/2.3 GHz band, microwave (7-10 GHz) band, and millimeter wave (42 GHz) band. The 1.2/2.3 GHz band is mainly used for mobile transmission such as road race broadcasts, the microwave band is mainly used for medium- to long-distance transmission, and the millimeter wave band is used for short-distance transmission such as wireless cameras; different bands are used according to the nature of the radio waves¹⁾.

Microwave band FPU has a wide range of applications, from medium- to long-distance (up to 50 km) fixed transmission to short-distance transmission for wireless cameras. For this reason, two types of FPU are available: the Single Carrier (SC) type, which is resistant to nonlinear distortion and has the advantage of being compact and low-power for transmitters, and the OFDM type, which has excellent multipath resistance and is advantageous for mobile transmission. Both the Orthogonal Frequency Division Multiplexing (OFDM) method³⁾ and the Orthogonal Frequency Division Multiplexing (OFDM) method⁴⁾ have been standardized, and they are used according to the purpose.

This is becoming more and more common.

In recent years, with advances in technology, the Single Carrier-Frequency Domain Equalization (SC-FDE) method, which can improve multipath resistance by combining the SC method with frequency domain equalization technology on the receiving side, has attracted attention, and there have been reports of wireless cameras⁵⁾ ⁶⁾ that use the SC-FDE method in the millimeter wave band.

On the other hand, effective use of radio frequencies is also important. The SC-FDE system has the advantage of being able to configure a decode and forward relay (DF) that decodes and re-encodes the received data before retransmitting it. The authors have demonstrated that the SC-FDE system can relay signals without signal degradation when using a booster to relay signals on the same frequency.⁷⁾ In this context, there is an increasing need to clarify the potential of the SC-FDE radio system for microwave band FPUs.

There have been no reports examining SC-FDE radio systems that can be applied to FPUs. It has never happened before.

In this paper, we present the results of a technical study on the application of the SC-FDE wireless transmission method to microwave-band FPUs.

We investigate the transmission parameters of the SC-FDE scheme for microwave band FPU and quantitatively compare it with OFDM scheme in terms of its nonlinear and fading resistance characteristics. Based on the comparison results, we discuss the usefulness of microwave band FPU using SC-FDE scheme.

2. OFDM method

2.1 System Configuration of OFDM System Figure 1

(a) shows the transmitting block of the OFDM system used in this study, and Figure 1 (b) shows the receiving block diagram. On the transmitting side, convolutional coding (FEC Encoder) is performed as forward error correction, and modulation (QAM Mod.) is performed, followed by time interleaving (Time Interleave) and frequency interleaving (Frequency Interleave). The pilot signal for estimating the transmission path on the receiving side is the continual 2K full mode of ARIB STD-B714) as shown in Figure 2.

Using the Pilot (CP) arrangement, every eight subcarriers of OFDM are

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マイクロ波帯FPU用SC-FDE無線伝送方式の試行的検討

Trial Study of SC-FDE Wireless Transmission System for Television Program Contribution using Microwave Band

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あらまし 本論文は、SC-FDE (Single Carrier-Frequency Domain Equalization) 無線伝送方式をマイクロ波帯FPU (Field Pick-up Unit) に適用するための技術的検討を行った結果を述べている。マイクロ波帯FPU用SC-FDE方式の伝送パラメータを検討するとともに、耐非線形特性や耐フェージング特性に関してOFDM (Orthogonal Frequency Division Multiplexing) 方式と定量的な比較を行い、SC-FDE方式を用いたマイクロ波帯FPUの有用性について考察している。FPU運用の用途ごとに固定伝送、準移動伝送、移動伝送の三つに分類し、送信側増幅器の入力バックオフ値と受信機の所要C/Nを加算することでOFDMに対するSC-FDEの利得の値を求めた。その値を評価した結果、固定伝送の場合はSC-FDEが有利となり、準移動伝送の場合はOFDM方式とSC-FDE方式はほぼ同等となり、移動伝送の場合はOFDM方式が有利となる結果が得られた。

キーワード：マイクロ波, FPU, OFDM, SC-FDE, 非線形歪, フェージング

1. ま え が き

テレビジョン放送用可搬型番組素材無線伝送装置 (FPU : Field Pick-up Unit) は、スポーツや報道番組などの中継に必須となる重要な無線機材である。FPUが利用している周波数には、1.2/2.3 GHz帯、マイクロ波 (7~10 GHz) 帯、ミリ波 (42 GHz) 帯がある。1.2/2.3 GHz帯は、主にロードレース中継などの移動伝送の用途に、マイクロ波帯は主に中・長距離の伝送の用途に、ミリ波帯はワイヤレスカメラなど近距離伝送の用途と、電波の性質に応じた使い分けがなされている¹⁾。

マイクロ波帯FPUの用途は、中・長距離 (~50 km) の固定伝送からワイヤレスカメラの近距離伝送まで多岐にわたる。このため、非線形歪に対する耐性があり送信機の小型・低消費電力化に優位性を持つSC (Single Carrier) 方式²⁾と、マルチパス耐性に優れ移動伝送に優位性を持つOFDM (Orthogonal Frequency Division Multiplexing) 方式^{3) 4)}の両方の標準規格化が行われ、用途に応じた使い分けがなされてきている。

近年、技術の進歩に伴いSC方式に受信側での周波数領域等化技術を組み合わせることでマルチパス耐性を向上できるSC-FDE (Single Carrier-Frequency Domain Equalization) 方式が注目され、ミリ波帯を利用したSC-FDE方式のワイヤレスカメラ^{5) 6)}の報告もされている。

一方、電波の周波数の有効利用も重要である。SC-FDE方式には、受信データの復号、再符号化を行い再送信する再生中継 (DF: Decode and Forward relay) を構成できるという特長がある。筆者らは、プースターによる同一周波数リレー中継を行う際、SC-FDE方式は信号劣化がない中継ができることを明らかにしてきた⁷⁾。このような背景のもと、マイクロ波帯FPUにおいてもSC-FDE無線方式の可能性を明らかにする必要性が高まっているが、マイクロ波帯FPUに適用できるSC-FDE無線方式を検討した報告は、これまでになかった。

そこで本論文では、SC-FDE無線伝送方式をマイクロ波帯FPUに適用するための技術的検討を行った結果を述べる。マイクロ波帯FPU用SC-FDE方式の伝送パラメータを検討するとともに、耐非線形特性や耐フェージング特性に関して、OFDM方式と定量的な比較を行う。比較結果に基づき、SC-FDE方式を用いたマイクロ波帯FPUの有用性について考察する。

2. OFDM方式

2.1 OFDM方式のシステム構成

図1(a)に検討に用いたOFDM方式の送信側のブロックを、図1(b)に受信側のブロック図を示す。送信側では、前方誤り訂正として畳み込み符号化 (FEC Encoder) を行い、変調 (QAM Mod.) した後、時間インタリーブ (Time Interleave)、周波数インタリーブ (Frequency Interleave) を行う。受信側の伝送路推定を行うためのパイロット信号は、図2に示すようにARIB STD-B71⁴⁾の2KフルモードのContinual Pilot (CP) の配置を使って、OFDMの8サブキャリアごとに

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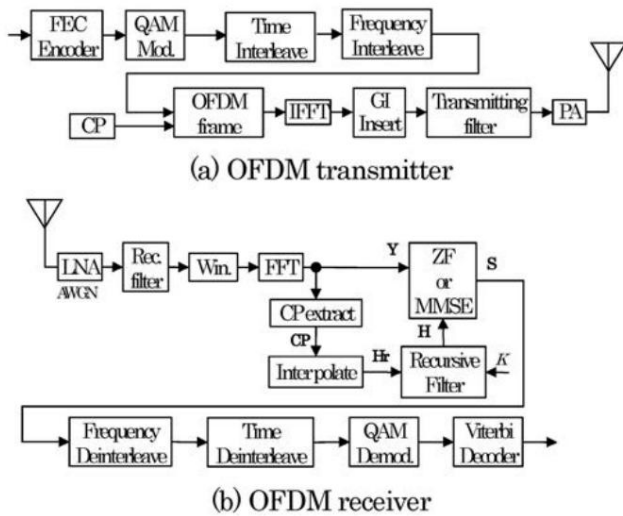


Figure 1 Block diagram of OFDM system

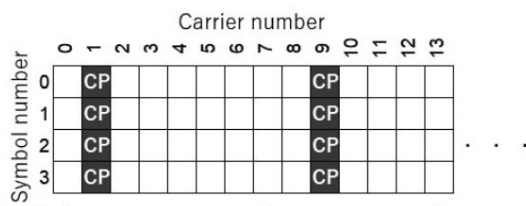


Fig. 2 Arrangement pattern of CP

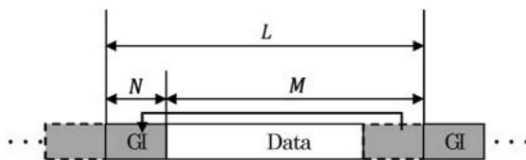


Figure 3 OFDM signal format

The OFDM frame components are arranged in a continuous format in the symbol direction.

(OFDM Frame). Next, the inverse fast Fourier transform

The signal is converted from the frequency domain to the time domain by IFFT (IFFT), and a guard interval (GI) is added before the data.

As shown in Figure 3, the latter half of the data is copied as GI and added before the effective symbol, and then transmitted through the transmitting filter. This transmitting filter directly affects the transmission spectrum mask. Out-of-band radiation is suppressed using a 256-tap equivalent low-pass FIR filter designed using the equiripple method with a normalized frequency of 0.410 in the passband and 0.443 in the stopband.

The received signal passes through a receiving filter, and the data of the FFT size is cut out by a window. Then, the time domain signal is transformed into frequency domain by a fast Fourier transform (FFT).

Next, the CPs distributed in the data symbols are extracted (Pilot Extract), the data portion is interpolated, and the receiving transmission path characteristics of all subcarriers are calculated.

Since H_r contains noise, a recursive filter is used to suppress the noise and obtain the transmission line characteristic H .

The recursive filter is shown in equation (1).

$$H(i) = K \cdot H(i-1) + (1-K) \cdot H_r(i) \quad (1)$$

Here, i is the OFDM symbol number and K is the noise suppression coefficient, which takes the value $0 \leq K < 1$. A value close to 1 results in greater noise suppression, but the ability to track time-varying transmission paths decreases.

When $K = 0$, no noise suppression is performed.

Next, the obtained transmission line characteristic H is used to perform frequency domain equalization according to the following equation. In the case of ZF (zero-forcing), it is expressed as equation (2). The signal-to-noise ratio is calculated using equation (3).

(2), and in the case of MMSE, Y is the input signal to the ZF or MMSE calculation unit, and S is the output signal from the calculation unit.

$$S = \frac{Y}{H} = \frac{H^* \cdot Y}{|H|^2} \quad (2)$$

$$S = \frac{H^* \cdot Y}{|H|^2 + \left(\frac{1}{\sigma}\right)^2} \quad (3)$$

Furthermore, frequency deinterleaving, time deinterleaving, and demodulation (QAM demodulation) are performed. Finally, Viterbi decoding is performed to decode the convolutional coding. For Viterbi decoding in the OFDM system, soft decision is used to decode using channel information obtained by channel estimation.

2.2 Transmission parameters of the OFDM system

Table 1 shows the transmission parameters of the OFDM system. Assuming the application of a microwave FPU, the values of the 2K full mode of ARIB STD-B713) were used as reference. Error correction is performed using convolutional coding and Viterbi Decoding was used, the coding rate was 1/2, and the constraint length was 7.

In order to improve the tolerance to burst errors that occur over time on the transmission line, we used the convolutional time interleaving shown in Figure 4. The parameter I is the number of shift registers, and the larger I is, the stronger the tolerance to long burst errors becomes.

The parameter SR is the number of register length steps.

To match the delay time of the SC-FDE method and the interleaving method, the number of shift registers is set to 119 and the number of register length steps is set to 52. The delay time of the time interleaving is calculated using Equations (4) and (5).

$$N_{sample} = I \times SR \times (I-1) \quad (4)$$

$$T_{delay} = N_{sample} \times T_{sample} \quad (5)$$

Here, the sample time T_{sample} is $1 / (f_{sym} \times M/L) \approx 94.3$ ns in the case of the SC-FDE method described later, where f_{sym} is the symbol rate of SC-FDE, L is the number of samples in one block, and M is the number of data samples.

On the other hand, the sample time T_{sample} in the OFDM system is $T_s / N_{dc} \approx 78.9$ ns, where T_s is the OFDM symbol length (time) and N_{dc} is the number of data carriers.

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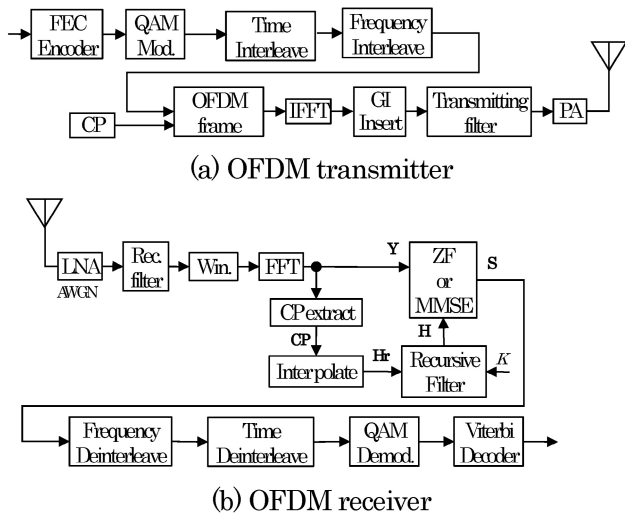


図1 Block diagram of OFDM system

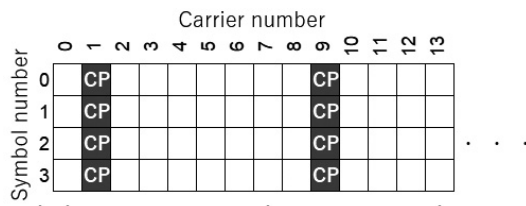


図2 Arrangement pattern of CP

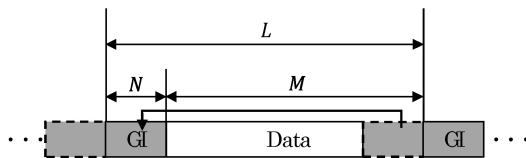


図3 OFDM signal format

シンボル方向に連続的な形式にて、OFDM フレーム構成部 (OFDM Frame) で挿入した。次に、逆高速フーリエ変換 (IFFT) により周波数領域から時間領域に変換し、データの前にガードインターバル (GI: Guard Interval) を付加 (GI Insert) する。図3に示すように、データの後半部分をGIとしてコピーしたものを有効シンボルの前に付加した後に、送信フィルタ (Transmitting filter) を通して送信する。この送信側フィルタは、送信スペクトルマスクに直接影響を与える。正規化周波数を通過域0.410、阻止域0.443として等リップル法にて設計した256タップの等価低域系のFIRフィルタを用い帯域外輻射を抑圧している。

受信信号は受信フィルタ (Receiving filter) を経て、窓 (Win.) によりFFTサイズのデータの切り出しを行った後、高速フーリエ変換 (FFT) により時間領域の信号が周波数領域の信号に変換される。次に、データシンボルに分散しているCPを抽出 (Pilot extract) して、データ部分の内挿 (interpolate) を行い、全サブキャリアの受信伝送路特性 $\mathbf{H}_r$ を得る。 $\mathbf{H}_r$ には雑音が含まれているので、再帰型フィルタ (Recursive filter) により雑音を抑圧し伝送路特性 $\mathbf{H}$ を得る。再帰型フィルタを (1) 式に示す。

$$\mathbf{H}(i) = K \cdot \mathbf{H}(i-1) + (1-K) \cdot \mathbf{H}_r(i) \quad (1)$$

ここに i は OFDM のシンボル番号、 K は雑音抑圧係数で、 $0 \leq K < 1$ の値をとる。1に近い値をとれば雑音抑圧が大きくなるが時変伝送路への追従性は低下する。 $K=0$ の場合は雑音抑圧が行われない。

次に得られた伝送路特性 $\mathbf{H}$ を用いて下式による周波数領域等化を行う。ZF (zero-forcing) の場合は (2) 式、MMSE の場合は σ を信号対雑音比として (3) 式による演算を行う。ここに $\mathbf{Y}$ は ZF もしくは MMSE の演算部の入力信号で、 $\mathbf{S}$ は演算部の出力信号である。

$$\mathbf{S} = \frac{\mathbf{Y}}{\mathbf{H}} = \frac{\mathbf{H}^* \cdot \mathbf{Y}}{|\mathbf{H}|^2} \quad (2)$$

$$\mathbf{S} = \frac{\mathbf{H}^* \cdot \mathbf{Y}}{|\mathbf{H}|^2 + \left(\frac{1}{\sigma}\right)^2} \quad (3)$$

さらに、周波数デインタリーブ (Frequency Deinterleave)、時間デインタリーブ (Time Deinterleave)、復調 (QAM Demod.) を行う。最後に、畳み込み符号化の復号としてビタビ復号 (Viterbi Decoder) を行う。OFDM 方式のビタビ復号の判定には、チャネル推定で得られたチャネル情報を活用して復号する軟判定⁸⁾を行っている。

2.2 OFDM方式の伝送パラメータ

表1にOFDM方式の伝送パラメータを示す。マイクロ波FPUの適用を前提として、ARIB STD-B71の2Kフルモードの値³⁾を参考にした。誤り訂正は畳み込み符号とビタビ復号を用い、符号化率は1/2、拘束長は7とした。

伝送路上で時間的に発生するバースト誤りに対する耐性を向上させるため、図4に示す畳み込み型の時間インタリーブを用いた。パラメータ I はシフトレジスタの数で、 I が大きいほど長いバースト誤りに対する耐性が強くなる。パラメータ S_R はレジスタ長ステップ数である。後述するSC-FDE方式とインタリーブの遅延時間を合わせるため、シフトレジスタ数119を、レジスタ長ステップ数を52とした。時間インタリーブの遅延時間は、式 (4)、式 (5) で求められる。

$$N_{\text{sample}} = I \times S_R \times (I-1) \quad (4)$$

$$T_{\text{delay}} = N_{\text{sample}} \times T_{\text{sample}} \quad (5)$$

ここで、サンプル時間 T_{sample} は、後述するSC-FDE方式の場合は、 $1/(f_{\text{sym}} \times M/L) \approx 94.3 \text{ ns}$ である。ただし f_{sym} はSC-FDEのシンボルレート、 L は1ブロック全体のサンプル数、 M はデータサンプル数である。

一方、OFDM方式の場合のサンプル時間 T_{sample} は、 $T_s/N_{dc} \approx 78.9 \text{ ns}$ である。ここに T_s はOFDMのシンボル長 (時間)、 N_{dc} はデータキャリア数である。

Table 1 OFDM transmission parameters

	OFDM
Carrier modulation	QPSK ($M_{th} = 2$) 16QAM ($M_{th} = 4$) 64QAM ($M_{th} = 6$) 256QAM ($M_{th} = 8$) 1024QAM ($M_{th} = 10$)
Error correction code	Convolutional code Viterbi decoding
Occupied band width [MHz]	17.21 (99%)
Carrier spacing [kHz]	99.9
FFT clock frequency [MHz]	20.450743
Number of Carrier	1723
Number of Carrier (Data)	1428
Number of GI symbols	256
FFT points	2048
Symbol length T_s [μ s]	112.66
Pilot format	CP: Continual Pilot
Total number of CP	216
CP boost ratio	1.0
Transmission bit rate [Mbps]	25.4 (QPSK) 50.7 (16QAM) 76.1 (64QMA) 101.4 (256QAM) 126.8 (1024QAM)
Rows of Shift Registers I	119
Register Length Step S_R	52

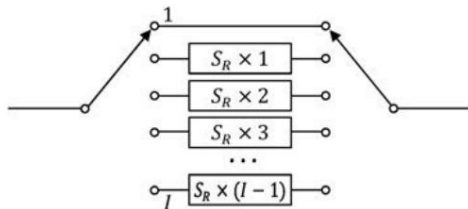


Fig. 4 Image of Time Interleave

The values of I and S_R were set so that the delay time T_{delay} of SC-FDE and OFDM was almost the same (approximately 58 ms).

3. SC-FDE method

3.1 System Configuration of SC-FDE Method

A block diagram of the transmitter side of the SC-FDE scheme is shown in Figure 5(a), and that of the receiver side is shown in Figure 5(b). SC-FDE is a scheme that transmits information using single-carrier modulation and performs frequency-domain equalization on the receiver side using a reference signal that is inserted in advance on the transmitter side.

On the transmitting side, convolutional coding (FEC Encoder) is performed as forward error correction, modulation (QAM Mod.) is performed, and then time interleaving is performed.

Then, as shown in Figure 6, a unique word (UW) of the reference signal is inserted before and after the data, and the data is transmitted through a transmitting filter. The transmitting filter uses a 256-tap equivalent low-pass FIR filter designed using the equiripple method with a normalized frequency of 0.53 in the passband and 0.57 in the stopband, and filters the out-of-band signals.

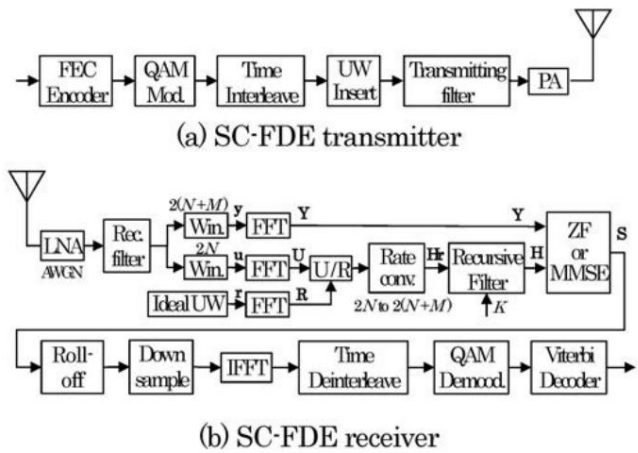


Figure 5 Block diagram of SC-FDE system

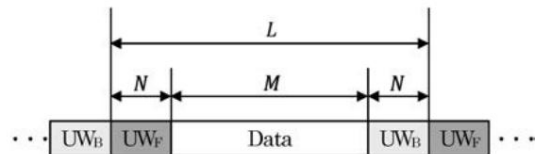


Figure 6 SC-FDE signal format

Radiation is suppressed.

The UW has the role of processing the signal so as not to interfere with the signal block received later, and uses the Zadoff-Chu code, which has a constant amplitude and excellent autocorrelation characteristics.

The number of data symbols is M , the number of UW symbols is M , and the number of UW symbols is B .

Let N be the number of block symbols and L be the number of block symbols.

On the receiving side, after passing through the LNA, the signal is sampled at twice the symbol rate and passes through the receiving filter. The main line window (Win.) extracts a $2(N+M)$ point signal y from the received signal, and the UW window (Win.) extracts a $2N$ point signal u from the received signal. Then, a fast Fourier transform (FFT) is performed to convert the time domain signal to the frequency domain, and signals Y and U are obtained. On the receiving side, a signal R , which is a Fourier transform of an ideal UW, is pre-sampled.

In order to obtain the transmission line characteristic, the signal is prepared for the transmission line and the U/R is calculated. Furthermore, a sampling rate conversion (Rate conv.) from $2N$ to $2(N+M)$ is performed to obtain the receiving transmission line characteristic H_r . As with OFDM in the previous section, noise is suppressed using equation (1) to obtain H , and frequency domain equalization is performed using equations (2) and (3). Furthermore, the frequency characteristic of a raised cosine roll-off with a roll-off rate of 0.1 is multiplied in the frequency domain. In this system, the roll-off characteristic is not allocated to the transmitting side, and the receiving side has a full roll-off characteristic (Figure 7). For this reason, the passband of the transmitting filter is set up to the frequency where the roll-off characteristic becomes zero, which reduces the deterioration of the transmission line characteristic estimation accuracy due to the S/N ratio drop in the roll-off part, and improves the accuracy of the high-order. This avoids BER degradation.

3.2 Consideration and proposal of transmission parameters

Table 2 shows the transmission parameters for the SC-FDE method. Assuming the application of microwave FPU, we have newly designed parameters with reference to the OFDM method so that the allowable delay time is equivalent.

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表1 OFDM Transmission parameters

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Error correction code	Convolutional code Viterbi decoding
Occupied band width [MHz]	17.21 (99%)
Carrier spacing [kHz]	99.9
FFT clock frequency [MHz]	20.450743
Number of Carrier	1723
Number of Carrier (Data)	1428
Number of GI symbols	256
FFT points	2048
Symbol length T_s [μ s]	112.66
Pilot format	CP: Continual Pilot
Total number of CP	216
CP boost ratio	1.0
Transmission bit rate [Mbps]	25.4 (QPSK) 50.7 (16QAM) 76.1 (64QMA) 101.4 (256QAM) 126.8 (1024QAM)
Rows of Shift Resistors I	119
Register Length Step S_R	52

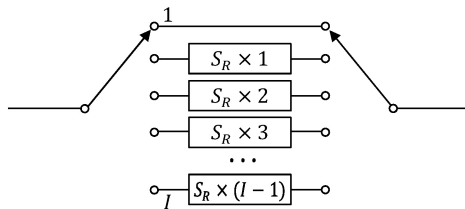


図4 Image of Time Interleave

SC-FDE と OFDM の遅延時間 T_{delay} が、ほぼ同等 (約 58 ms) になるよう、 I および S_R の値を設定した。

3. SC-FDE 方式

3.1 SC-FDE 方式のシステム構成

図5 (a) に SC-FDE 方式の送信側、図5 (b) に受信側のブロック図を示す。SC-FDE 方式は、単一キャリア変調を用いて情報を送信し、あらかじめ送信側で挿入された基準信号を用いて受信側で周波数領域等化を行う方式である。

送信側では、前方誤り訂正として畳み込み符号化 (FEC Encoder) を行い、変調 (QAM Mod.) した後、時間インターリーブ (Time Interleave) を行う。そして、図6のようにデータの前後に基準信号のユニークワード (UW: Unique Word) を挿入 (UW Insert) し、送信フィルタ (Transmitting filter) を通して送信する。送信側フィルタは、正規化周波数を通過域 0.53、阻止域 0.57 として等リップル法にて設計した 256 タップの等価低域系 FIR フィルタを用いて帯域外

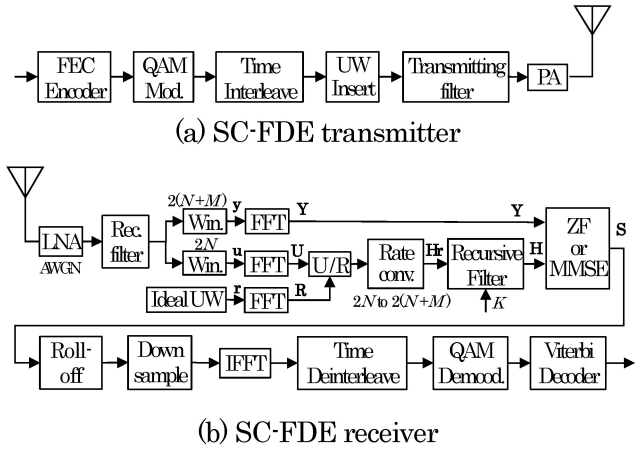


図5 Block diagram of SC-FDE system

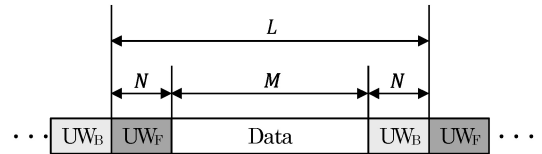


図6 SC-FDE signal format

輻射を抑圧した。

UW には、遅れて受信した信号ブロックと干渉しないように処理する役割があり、振幅が一定で自己相関特性に優れる Zadoff-Chu 符号を用いた⁹⁾。UWF と UW_B は同一の符号を用いるが、前後の区別をつけるために F と B の添え字をつけている。データシンボル数を M 、UW シンボル数を N 、ブロックシンボル数を L とする。

受信側は、LNA を経た後、シンボルレートの 2 倍でサンプリングされ、受信フィルタ (Receiving filter) を通過する。受信信号から $2(N+M)$ 点の信号 $\mathbf{y}$ を切り出す本線系の窓 (Win.) と、 $2N$ 点の信号 $\mathbf{u}$ を切り出す UW 系の窓 (Win.) を経て、それぞれ時間領域の信号を周波数領域に変換する高速フーリエ変換 (FFT) を行い、信号 $\mathbf{Y}$ 、 $\mathbf{U}$ を得る。受信側には理想 UW (Ideal UW) をフーリエ変換した信号 $\mathbf{R}$ を予め準備しておき、 $\mathbf{U}/\mathbf{R}$ の演算を行う。さらに $2N$ to $2(N+M)$ のサンプリングレート変換 (Rate conv.) を行い、受信伝送路特性 $\mathbf{H}_R$ を得る。前節の OFDM と同様、式 (1) を用いて雑音を抑圧して $\mathbf{H}$ を得るとともに、式 (2)、(3) を用いて周波数領域等化を行う。さらに、ロールオフ率が 0.1 のレイズドコサインロールオフの周波数特性を周波数領域で乗算する。今回のシステムでは送信側にロールオフ特性の配分をせず、受信側をフルロールオフ特性としている (図7)。このため送信フィルタの通過域はロールオフ特性がゼロになる周波数までとし、ロールオフ部分の S/N 低下による伝送路特性推定精度の低下を軽減し、高次変調時の BER 劣化を回避している。

3.2 伝送パラメータの検討と提案

表2に SC-FDE 方式の伝送パラメータを示す。マイクロ波 FPU の適用を前提として、OFDM 方式を参考に、遅延の許容時間が同等となるようなパラメータを新たに設計した。

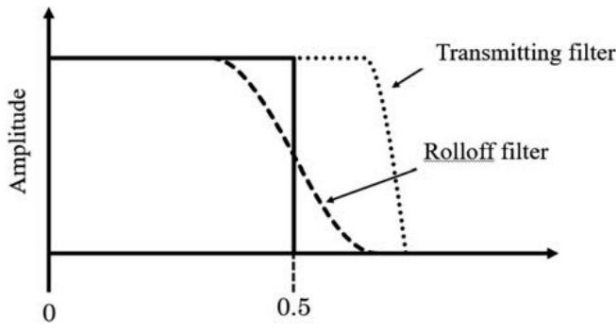


Fig. 7 Image of filter design

Table 2 SC-FDE Transmission parameters

	SC-FDE
Carrier modulation	QPSK ($M_{th} = 2$) 16QAM ($M_{th} = 4$) 64QAM ($M_{th} = 6$) 256QAM ($M_{th} = 8$) 1024QAM ($M_{th} = 10$)
Error correction code	Convolutional code Viterbi decoding
Roll-off factor	0.1
Occupied band width [MHz]	16.79 (99%)
Symbol rate [MHz]	15.5
Number of Carrier	1
Number of Data symbols	1664
Number of UW symbols	384 + 384
FFT points	2048
Block length T_s [μ s]	156.9
UW boost ratio	1.0
Transmission bit rate [Mbps]	21.2 (QPSK) 42.4 (16QAM) 63.6 (64QMA) 84.8 (256QAM) 106 (1024QAM)
Rows of Shift Registers I	128
Register Length Step S_R	38

The allowable delay time range for OFDM and SC-FDE systems was calculated by computer simulation using a two-path model. The horizontal axis is the delay time difference of the two-path, the vertical axis is the BER, and the amplitude ratio of the two paths is the BER.

The D/U was set to 20 dB. It can be confirmed that the range of delay tolerance is the same for OFDM and SC-FDE. This delay tolerance is proportional to the length of the reference signal, and is realized by setting the UW length of the SC-FDE method to 384. Time interleaving reduces the delay time that occurs during interleaving as described above.

In order to obtain a delay time T_{delay} (approximately 58 ms) almost equivalent to that of OFDM, the number of shift registers I is set to 128 and the number of register steps S_R is set to 38.

The signal is then downsampled by 1/2 and converted back to a time domain signal by an inverse fast Fourier transform (IFFT), after which it is time deinterleaved and QAM demodulated.

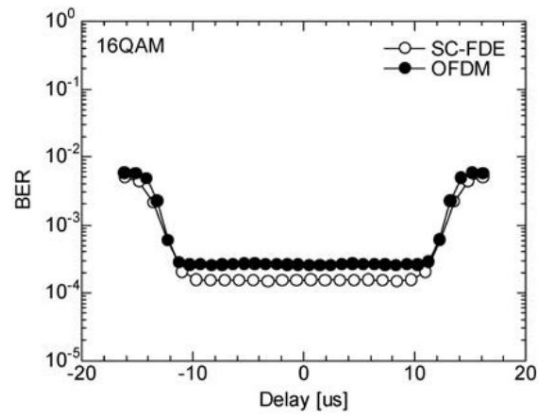


Figure 8 Delay vs BER

Finally, the convolutional coding is decoded using Viterbi decoding.

(Viterbi Decoder) is used.

4. Evaluation of nonlinear characteristics of the transmitting amplifier

Amplifiers have nonlinear characteristics that cause the output to saturate when an input above a certain level is applied. In particular, the transmitting amplifier requires high output power, so nonlinear distortion cannot be ignored. To avoid this, the amplifier is given a power amount lower than a specific value, and amplification is performed using a region where the input and output are linear. The input power value at the point 1 dB below the straight line where the input/output characteristics are linear is used as the reference.

The value that indicates how much lower the input power is used for amplification from that value is called Input Back Off (IBO). In this section, we evaluate the nonlinear characteristics of the transmitting amplifier.

4.1 Evaluation using the Rapp model

The model used to represent the nonlinear characteristics of the amplifier is the Rapp model shown in equation (6). Note that g_{in} is the input signal, u is the amplitude scaling coefficient, O_{sat} is the output saturation point, and S is the smoothness coefficient. The parameters used were set to 6 for the smoothness coefficient S and 0.5 for O_{sat} , simulating the performance of an actual device¹⁰⁾.

$$F_{AMAM}(u) = \frac{(g_{in} \times u)}{\left(1 + \left(\frac{g_{in} \times u}{O_{sat}}\right)^{2S}\right)^{\frac{1}{2S}}} \quad (6)$$

Figure 9 shows the results of computer simulation of the input/output characteristics of a sine wave, SC-FDE, and OFDM. This figure shows the input/output power values normalized based on the position of the linear line when the input/output characteristics of a sine wave are 1 dB lower than the linear line. The horizontal axis is the normalized power value on the input side, and the vertical axis is the normalized power value on the output side. The input/output characteristics of the theoretical values of the Rapp model based on Equation (6) are also shown. It is.

In the computer simulation, phase characteristics that cannot be expressed by the Rapp model are also taken into consideration, and are added with reference to reference 11). The phase characteristics used are also shown in Figure 9.

The results in Figure 9 confirm that the SC-FDE system is closer to the theoretical curve than the OFDM system and is less affected by nonlinear distortion.

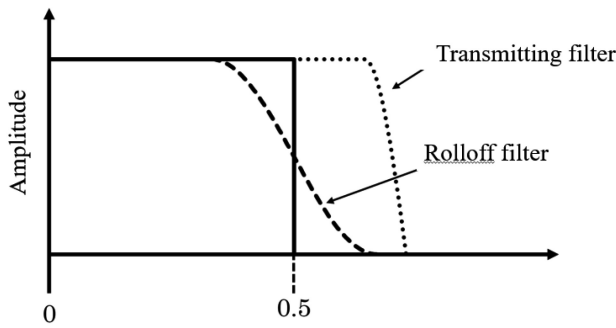


図7 The image of filter design

表2 SC-FDE Transmission parameters

	SC-FDE
Carrier modulation	QPSK ($M_{th} = 2$) 16QAM ($M_{th} = 4$) 64QAM ($M_{th} = 6$) 256QAM ($M_{th} = 8$) 1024QAM ($M_{th} = 10$)
Error correction code	Convolutional code Viterbi decoding
Roll-off factor	0.1
Occupied band width [MHz]	16.79 (99%)
Symbol rate [MHz]	15.5
Number of Carrier	1
Number of Data symbols	1664
Number of UW symbols	384 + 384
FFT points	2048
Block length T_s [μ s]	156.9
UW boost ratio	1.0
Transmission bit rate [Mbps]	21.2 (QPSK) 42.4 (16QAM) 63.6 (64QMA) 84.8 (256QAM) 106 (1024QAM)
Rows of Shift Registers I	128
Register Length Step S_R	38

OFDM方式とSC-FDE方式の遅延の許容時間の範囲を、2波マルチパスモデルを用いて計算機シミュレーションによって求めた結果を図8に示す。横軸は2波のマルチパスの遅延時間差、縦軸はBERであり、2波の振幅比であるD/Uは20 dBとした。OFDM方式とSC-FDE方式で遅延の許容時間の範囲が同等であることが確認できる。この遅延の許容時間は基準信号の長さに比例しており、SC-FDE方式のUW長を384とすることで実現している。時間インターリーブは、インターリーブで発生する遅延時間を前述のOFDMとほぼ同等の遅延時間 T_{delay} (約58 ms) になるよう、シフトレジスタ数 I を128、レジスタステップ数 S_R を38とした。

さらに、1/2のダウンサンプルを行い逆高速フーリエ変換 (IFFT) により時間領域の信号に戻し、時間デインターリーブ (Time Deinterleave), QAM復調 (QAM Demod.)

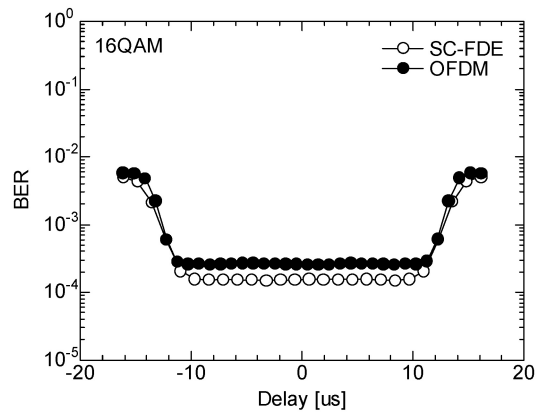


図8 Delay vs BER

を行う。最後に、畳み込み符号化の復号としてビタビ復号 (Viterbi Decoder) を行っている。

4. 送信側増幅器の非線形特性の評価

増幅器は、ある一定以上の入力を与えると出力が飽和する非線形特性を有する。特に送信側増幅器は、高い出力電力が必要になるため非線形歪が無視できない。これを回避するため、増幅器には特定の値より低い電力量を与え、入出力が線形となる領域を用いて増幅を行う。入出力特性が線形となる直線より1 dB下がった箇所の入力電力値を基準として正規化し、その値からどれだけ低い入力電力を用いて増幅したのかを表す値をInput Back Off (IBO) と呼ぶ。本章では送信側増幅器の非線形特性を評価する。

4.1 Rapp モデルを用いた評価

増幅器の非線形特性を表現するモデルは、式 (6) に示す Rapp モデルを用いた。なお、 g_{in} は入力信号、 u は振幅スケール係数、 O_{sat} は出力飽和点、 S は平滑度係数である。使用するパラメータは実際のデバイスの性能¹⁰⁾を模擬して、平滑度係数 S を6、 O_{sat} を0.5とした。

$$F_{AMAM}(u) = \frac{(g_{in} \times u)}{\left(1 + \left(\frac{g_{in} \times u}{O_{sat}}\right)^{2S}\right)^{\frac{1}{2S}}} \quad (6)$$

正弦波、SC-FDE、OFDMの入出力特性を計算機シミュレーションにより求めた結果を図9に示す。この図は、正弦波の入出力特性が線形直線から1 dB減少した時の線形直線の位置を基準として正規化された入出力電力値を示している。横軸は入力側、縦軸は出力側の正規化電力値で、(6)式に基づく Rapp モデル理論値の入出力特性も併せて示している。

計算機シミュレーションにおいては、Rapp モデルでは表現できない位相特性も考慮し、文献¹¹⁾を参考に位相特性を加えている。使用した位相特性を図9に併せて示す。

OFDM方式よりもSC-FDE方式の方が理論値の曲線に近く、非線形歪の影響が小さいことが図9の結果より確認できる。

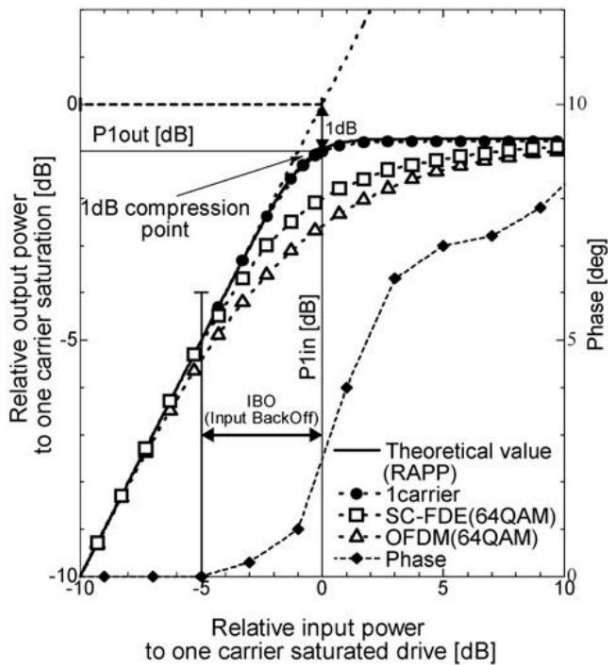


Figure 9 Rapp model input-output relation

4.2 Required IBO by Spectral Mask In this section, we

describe the results of an investigation using a transmission spectrum mask on the IBO (required IBO) that allows out-of-band radiation to be used as an FPU for both OFDM and SC-FDE systems. To be used as an FPU, the out-of-band power value based on the power value in the required frequency band must be below -37 dB₂ (-4). Here, we investigated the IBO in dB with a 3 dB margin in mind. We investigated the power value of out-of-band radiation relative to the in-band power value when the IBO was changed from 3 dB to 12 dB for each modulation format: QPSK, 16QAM, 64QAM, 256QAM, and 1024QAM. The results are shown in Figure 10.

As the IBO increases, the amount of power of out-of-band radiation relative to the in-band tends to decrease, and it has been confirmed that the SC-FDE method can reduce the out-of-band radiation power at a lower IBO value than the OFDM method.

It can be acknowledged.

In the SC-FDE system, the IBO value at which the out-of-band radiation relative to the in-band radiation is about -40 dB varies depending on the modulation order, and it is clear that the higher the modulation order, the larger the IBO must be.

On the other hand, in the OFDM system, the bandwidth varies depending on the modulation order.

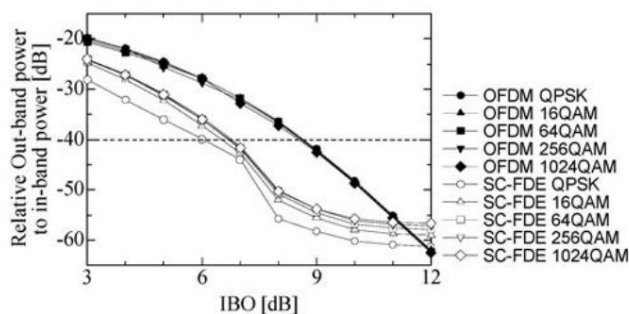


Figure 10 Relative Out-band power to in-band power for OFDM/SC-FDE system

Table 3 Required IBO that power radiated from in-band to out-of-band is -40 dB or less

Carrier modulation	OFDM [dB] ①	SC-FDE [dB] ②	Difference [dB] ③=①-②
QPSK	8.65	6.02	2.63
16QAM	8.63	6.51	2.12
64QAM	8.62	6.69	1.93
256QAM	8.51	6.78	1.73
1024QAM	8.45	6.72	1.73

No significant change was observed in the IBO, where the in-band radiation relative to the outside is -40 dB.

Table 3 shows the required IBO required to keep out-of-band radiation below -40 dB relative to in-band radiation for SC-FDE and OFDM at each modulation order, as well as the difference between the two systems. Comparing $\bar{\gamma}$ and $\bar{\gamma}_i$, it can be seen that the difference between OFDM and SC-FDE tends to become smaller as the modulation order increases. As shown in $\bar{\gamma}$, the sign of the difference is positive for all modulation orders, which shows that when OFDM and SC-FDE are transmitted using the same amplifier, SC-FDE can achieve higher output power than OFDM.

We will now explain a specific example of a spectrum mask. First, we compare the OFDM system and the IBO = 100 dB condition, which is free from the effects of nonlinear distortion. The calculated transmission spectrum of the SC-FDE system is shown in Figure 11. It can be seen that the transmission spectrum is shaped by the transmission filter and out-of-band radiation is suppressed.

Next, we consider the spectrum for each modulation order of the OFDM and SC-FDE systems. The spectrum mask is shown in Figure 12. This spectrum mask uses the required IBO required to keep the out-of-band radiation to the in-band radiation below -40 dB, as determined in Table 3. In standards 2) to 4), the required frequency band is within ± 9 MHz (18 MHz width) shown by the dotted line in each spectrum.

It is stipulated that the out-of-band emissions must be within the range of -40 dBm for both systems.

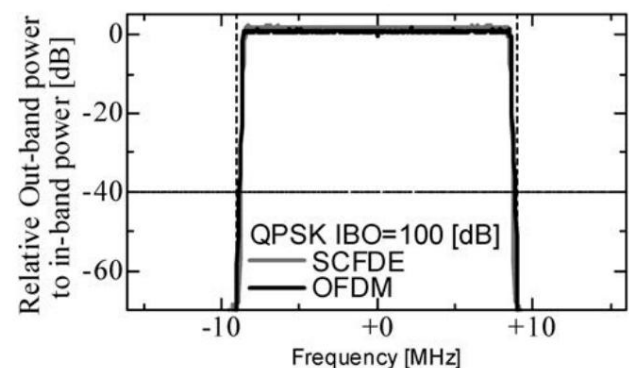


Fig. 11 OFDM/SC-FDE Spectrum Mask (IBO = 100 dB)

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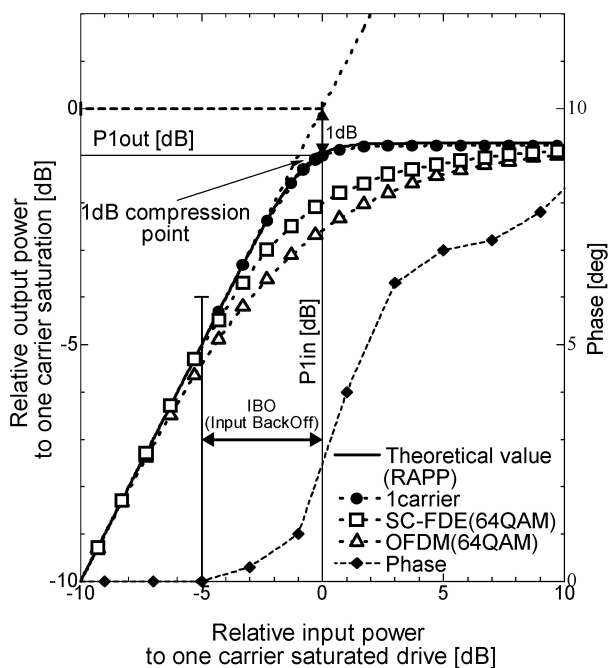


図9 Rapp model input-output relation

4.2 スペクトルマスクによる必要IBO

本節では、OFDM方式とSC-FDE方式の双方において、帯域内に対する帯域外輻射がFPUとして利用できるIBO(所要IBO)について、送信スペクトルマスクを用いて調査した結果を述べる。FPUとして利用するためには、必要周波数帯域内の電力値を基準とした帯域外の電力値が -37 dB を下回らなければならない^{2)~4)}。ここでは 3 dB のマーゼンを見込んで dB となるIBOを調査した。QPSK, 16QAM, 64QAM, 256QAM, 1024QAMの各変調方式について、IBOを 3 dB から 12 dB まで変化させた時の帯域内に対する帯域外輻射の電力値について調査した。結果を図10に示す。

IBOが増加するほど帯域内に対する帯域外輻射の電力値が減少する傾向があり、SC-FDE方式がOFDM方式よりも低いIBOの値で帯域外輻射電力を減少させられることが確認できる。

SC-FDE方式では、変調次数に依存して帯域内に対する帯域外輻射が -40 dB 程度となるIBOの値が変化し、変調次数が大きいほどIBOを大きくする必要があることがわかる。一方、OFDM方式では、変調次数の違いによって帯域

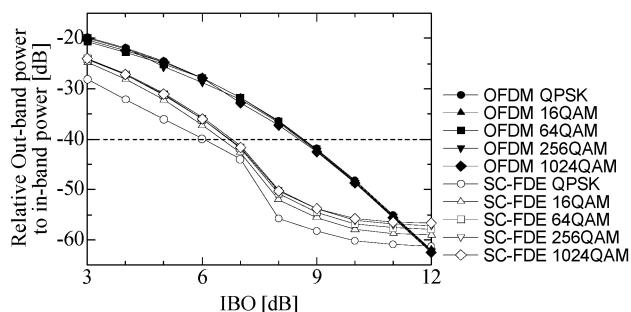


図10 Relative Out-band power to in-band power for OFDM/SC-FDE system

表3 Required IBO that power radiated from in-band to out-of-band is -40 dB or less

Carrier modulation	OFDM [dB] ①	SC-FDE [dB] ②	Difference [dB] ③=①-②
QPSK	8.65	6.02	2.63
16QAM	8.63	6.51	2.12
64QAM	8.62	6.69	1.93
256QAM	8.51	6.78	1.73
1024QAM	8.45	6.72	1.73

外に対する帯域内輻射が -40 dB となるIBOに大きな変化は見られなかった。

SC-FDE方式とOFDM方式の各変調次数において、帯域内に対する帯域外輻射が -40 dB を下回るために必要な所要IBOと両システムの差分を表3に示す。①と②を比較すると、変調次数が大きくなるほどOFDM方式とSC-FDE方式の差が小さくなる傾向が確認できる。③に示すように、すべての変調次数において差の値の符号は正であることから、OFDM方式とSC-FDE方式で同じ増幅器を用いて送信を行う場合、OFDM方式よりもSC-FDE方式のほうが出力電力を大きくできることがわかる。

スペクトルマスクの具体例について述べる。まず、非線形歪の影響がないIBO = 100 dB の条件にてOFDM方式とSC-FDE方式の送信スペクトルを計算した結果を図11に示す。送信フィルタにより送信スペクトルが整形され、帯域外輻射が抑圧されている様子が確認できる。

次に、OFDM方式とSC-FDE方式の変調次数ごとのスペクトルマスクを図12に示す。このスペクトルマスクは、表3で求めた、帯域内に対する帯域外輻射が -40 dB を下回るために必要な所要IBOを用いている。標準規格^{2)~4)}において所要周波数帯域はそれぞれのスペクトルに所要周波数帯域を点線で示している $\pm 9\text{ MHz}$ (18 MHz 幅)に収められなければならないと規定されている。両システムにおいて、帯域外輻射が -40 dB 程度となっていることがスペクトルマスクから確認できる。

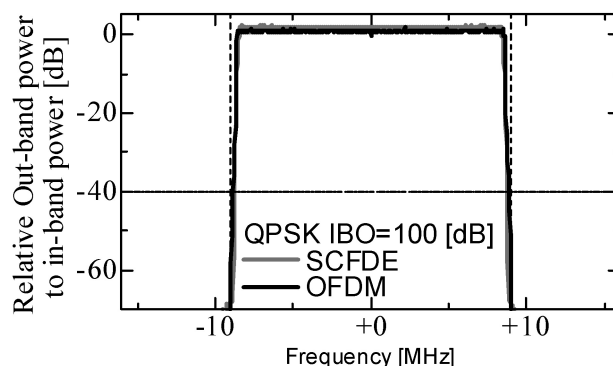


図11 OFDM/SC-FDE Spectrum Mask (IBO = 100 dB)

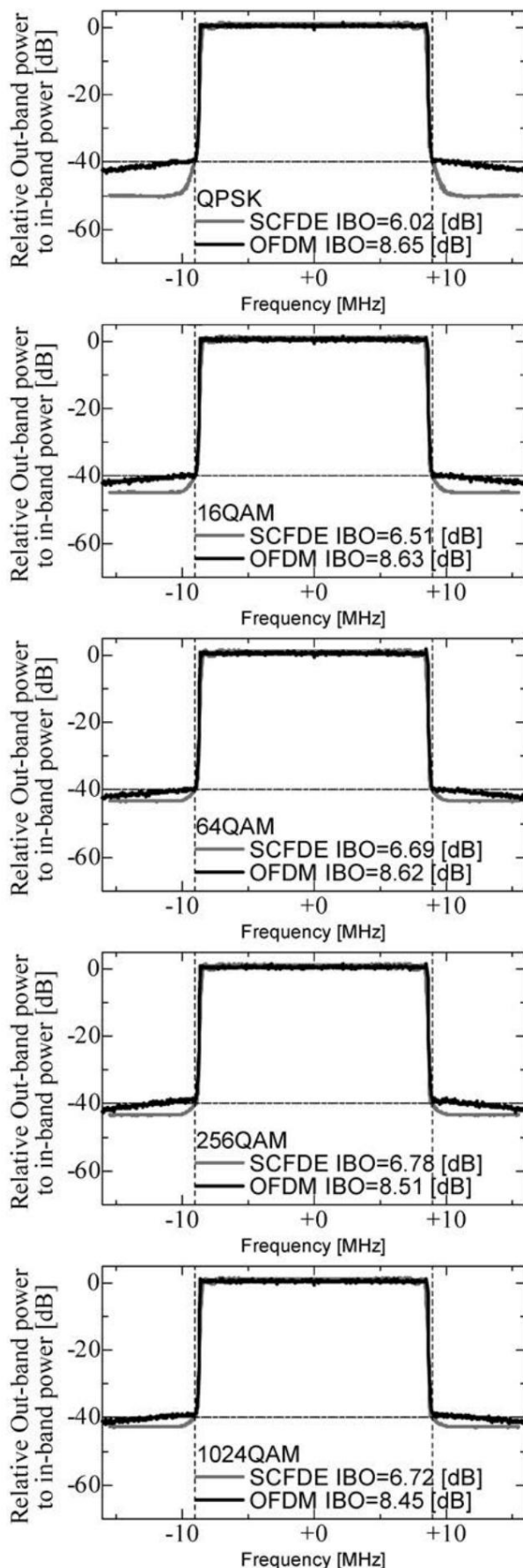


Fig. 12 OFDM/SC-FDE Spectrum Mask

5. Evaluation of receiver bit error rate

In this section, we present the results of computer simulations of the bit error rate characteristics of a receiver under the conditions including the nonlinear characteristics described in the previous section.

We first describe the results using an AWGN channel, then the results using a two-path multipath model. We then describe the results of evaluating fading associated with movement, using the Rice channel as a line-of-sight mobile propagation model and the Rayleigh channel as a non-line-of-sight mobile propagation model.

5.1 AWGN Transmission Path

Using the required IBO conditions described in Table 3, additive white Gaussian noise was added to the receiver input for OFDM and SC-FDE systems, and the bit error rate was calculated as shown in Figure 13. Calculations were performed for carrier modulation formats of QPSK, 16QAM, 64QAM, 256QAM, and 1024QAM. The BER (w/o) when decoding was performed without error correction, and the BER (Soft) when decoding was performed after error correction using the soft decision of the Viterbi decoding method are shown.

A floor is observed in the characteristics of SC-FDE with FEC for higher order modulation (64QAM, 256QAM, 1024QAM). The reason for this is that the required IBO for SC-FDE, which is calculated with an out-of-band radiation of -40 dB relative to the in-band radiation from the viewpoint of uniformity of conditions, affects the performance as nonlinear distortion in the case of higher order modulation.

In wireless systems, error correction is performed doubly by using a concatenated code consisting of an outer code (Reed-Solomon) and an inner code (convolutional code). Since evaluation including the outer code is extremely difficult due to the calculation time involved, the required C/N is calculated using the inner code BER = 2×10^{-4} , which is error-free when the outer code is applied.

In this case, the effect of nonlinear distortion on the Soft value after error correction is not so great. In Sections 5.1 and 5.2, the deviation of the BER from the theoretical value of synchronous detection was also confirmed, so the evaluation was performed using the ZF method of Equation (2) with the noise suppression coefficient $K = 0.93$ of the recursive filter for estimating the transmission path characteristics for both OFDM and SC-FDE. 5.2 Two-path transmission path Figures 14 and 15 show the results of

calculating the bit error rate for a two-path

transmission path that fluctuates relatively slowly under the required IBO conditions described in Table 3. Both figures show the results for the microwave over-the-sea transmission.

Considering the propagation delay, the evaluation was performed with $FdTs = 0.001$ (see Section 5.3 below). The delay time difference between the two waves is 64.5 ns for SC-FDE and 97.8 ns for OFDM. Figure 14 shows the amplitude ratio D/U of the two-wave multipath at 10 dB, while Figure 15 shows D/U at 6 dB. In terms of the characteristics of w/o FEC without error correction, when the C/N ratio is large, SC-FDE has a lower error rate, but under low C/N conditions, OFDM has a slight advantage.

The results are as follows.

5.3 Fading in Mobile Transmission Fading during

mobile transmission is a phenomenon in which radio waves of multiple paths interfere with each other, causing the strength of radio waves to change dramatically.

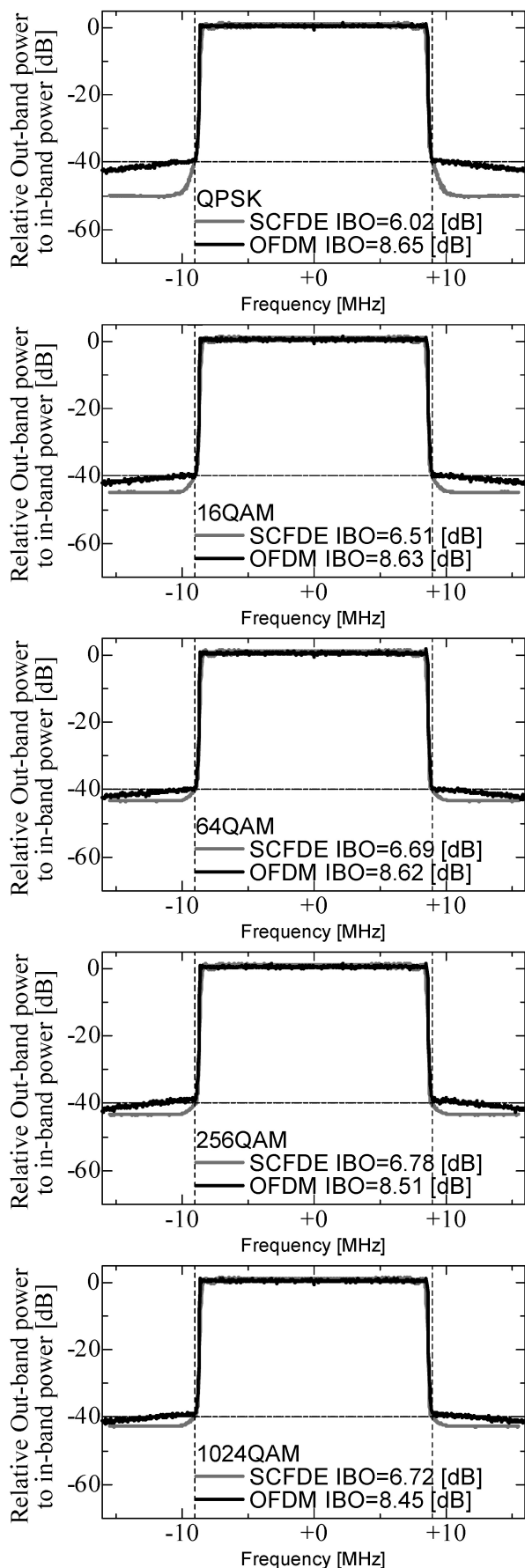


図12 OFDM/SC-FDE Spectrum Mask

5. 受信機のビット誤り率の評価

本章では、前章で述べた非線形特性を含んだ条件で受信機におけるビット誤り率特性を計算機シミュレーションによって求めた結果を述べる。まず、ガウス雑音のみのAWGN伝送路を用いた結果について述べ、次に2波マルチパスモデルを用いた結果を述べる。さらに、移動に伴うフェージングの評価として、見通し内移動伝搬モデルとしてライス伝送路、見通し外移動伝搬モデルとしてレイリー伝送路を用いて評価した結果を述べる。

5.1 AWGN伝送路

表3で述べた所要IBOの条件を用いて、OFDMとSC-FDE方式の受信機入力に相加性白色ガウス雑音を付加し、ビット誤り率を計算した結果を図13に示す。QPSK, 16QAM, 64QAM, 256QAM, 1024QAMのキャリア変調方式にて計算した。誤り訂正を行わずに復号した場合のBER (w/o) と、ビタビ復号法の軟判定を用いた誤り訂正を行った後に復号を行った場合のBER (Soft) をそれぞれ示した。

SC-FDEの高次変調(64QAM, 256QAM, 1024QAM)のw/o FECの特性にフロアの発生が認められる。この理由は、条件統一の観点から帯域内に対する帯域外輻射を-40dBとして求めたSC-FDEの所要IBOが、高次の変調の場合に非線形歪として影響を与えたことに起因している。実際の無線システムでは、誤り訂正は外符号(リードソロモン)と内符号(畳み込み符号)の接続符号を用い、二重に誤り訂正が施される。外符号を含めた評価は計算時間の関係から極めて困難となるので、外符号を適用した場合にエラーフリーとなる内符号のBER = 2×10^{-4} を用いて所要C/Nを評価する。この場合、誤り訂正後のSoftの値においては非線形歪の影響はそれほど大きくない。なお、5.1節および5.2節では、BERの同期検波の理論値からの乖離も併せて確認できることから、OFDM, SC-FDEともに伝送路特性推定の再帰型フィルタの雑音抑圧係数 $K=0.93$ として、(2)式のZF法を用いて評価した。

5.2 2波マルチパス伝送路

表3で述べた所要IBOの条件で、比較的緩やかに変動する2波マルチパス伝送路のビット誤り率を計算した結果を図14および図15に示す。両図ともマイクロ波帯の海上伝搬を考慮し、 $FdTs = 0.001$ (後述5.3節)にて評価した。2波の遅延時間差は、SC-FDEが64.5 ns, OFDMが97.8 nsである。図14は2波マルチパスの振幅比のD/Uが10 dBで、図15はD/Uが6 dBである。誤り訂正なしのw/o FECの特性において、C/N比が大きい場合はSC-FDEの方が誤り率が低いが、低C/Nの条件においてはOFDMが若干有利な結果となっている。

5.3 移動伝送のフェージング

移動伝送時のフェージングは、マルチパスの電波が互いに干渉し、電波の強さが激しく変化する現象である。このフェージングのモデルには、直接波が存在する仲上ライス

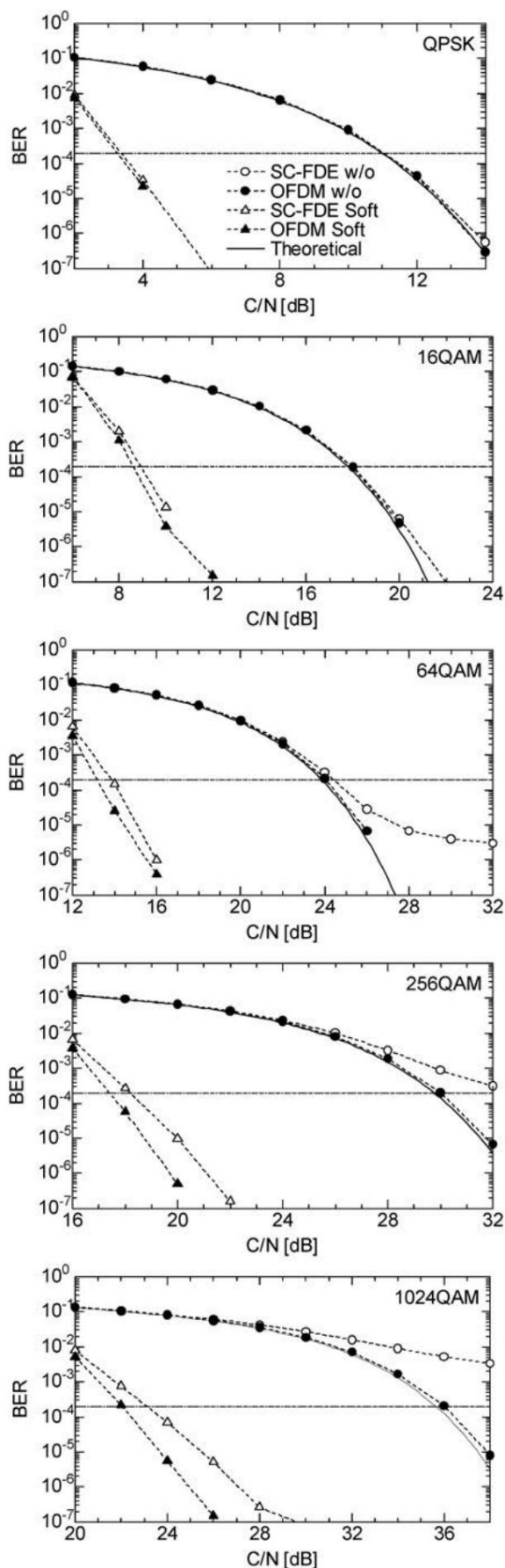


Fig. 13 BER vs. C/N (in AWGN channel)

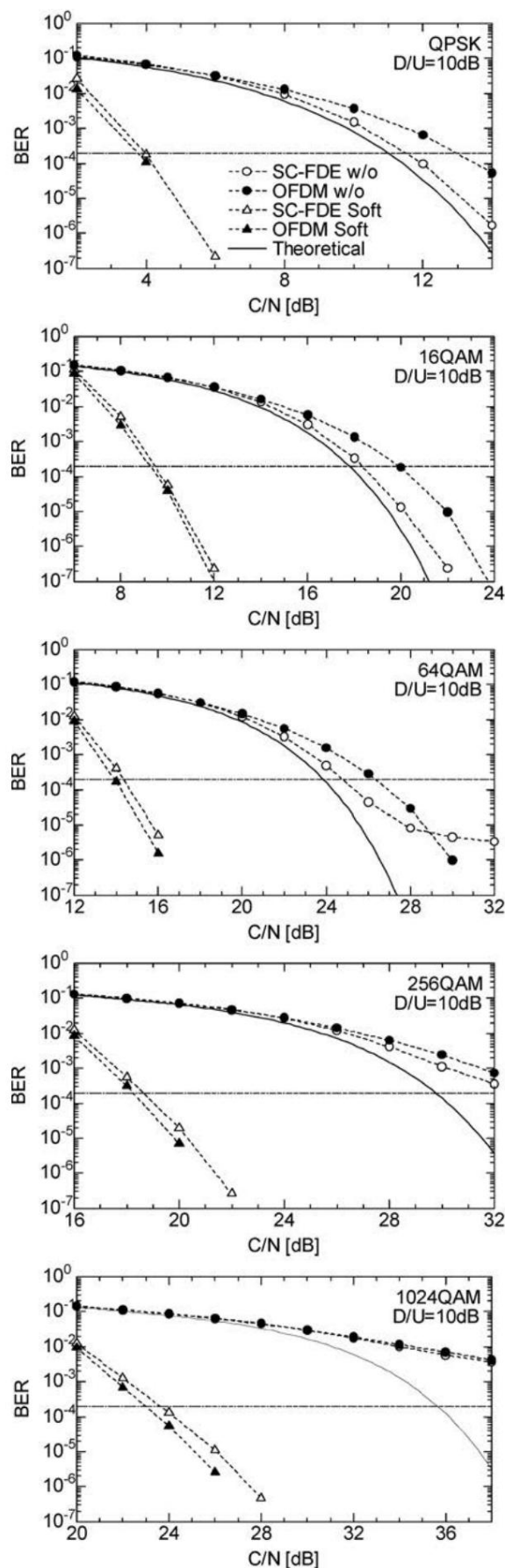


Figure 14 BER vs. C/N (in two path channel 10 dB)

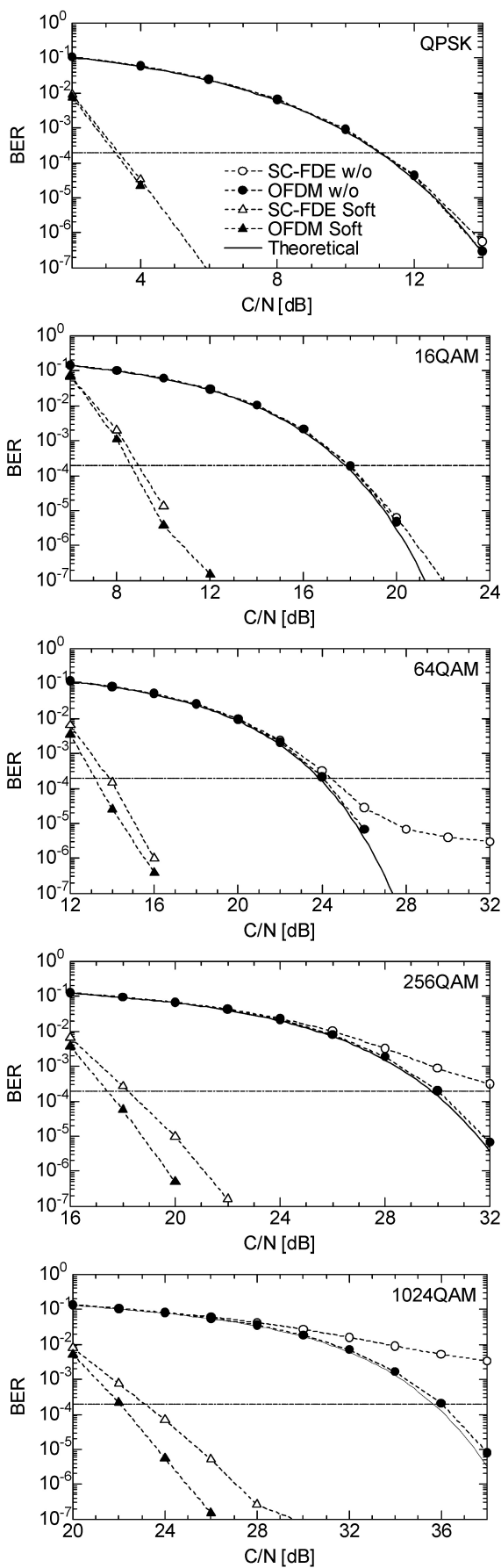


図13 BER vs. C/N (in AWGN channel)

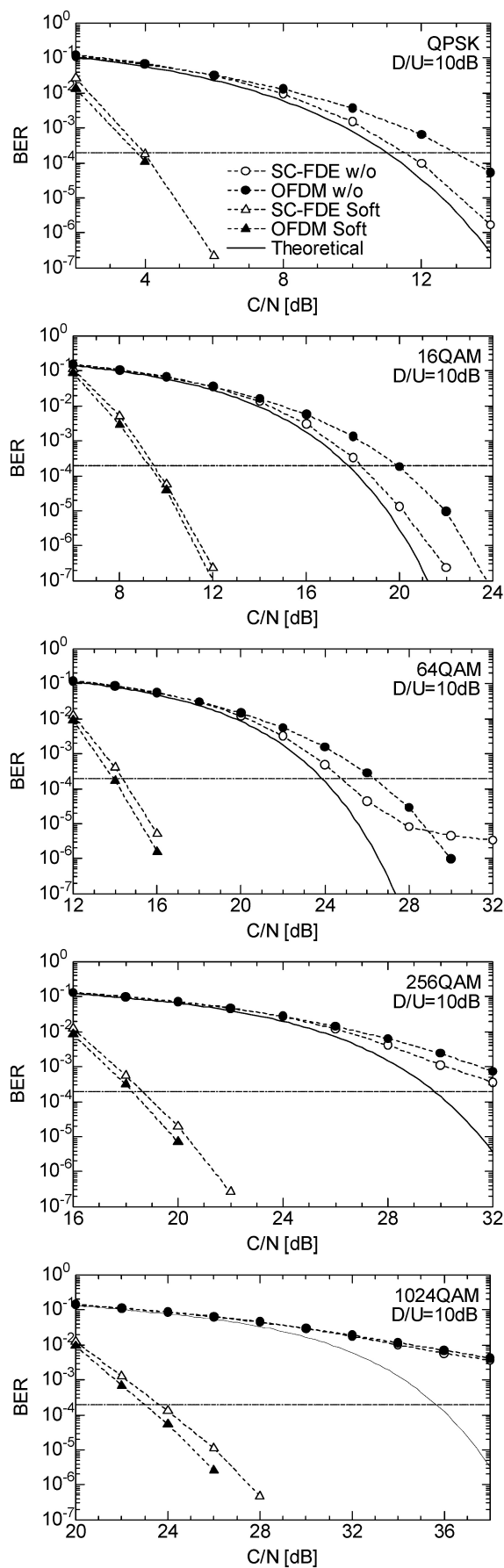


図14 BER vs. C/N (in two path channel 10 dB)

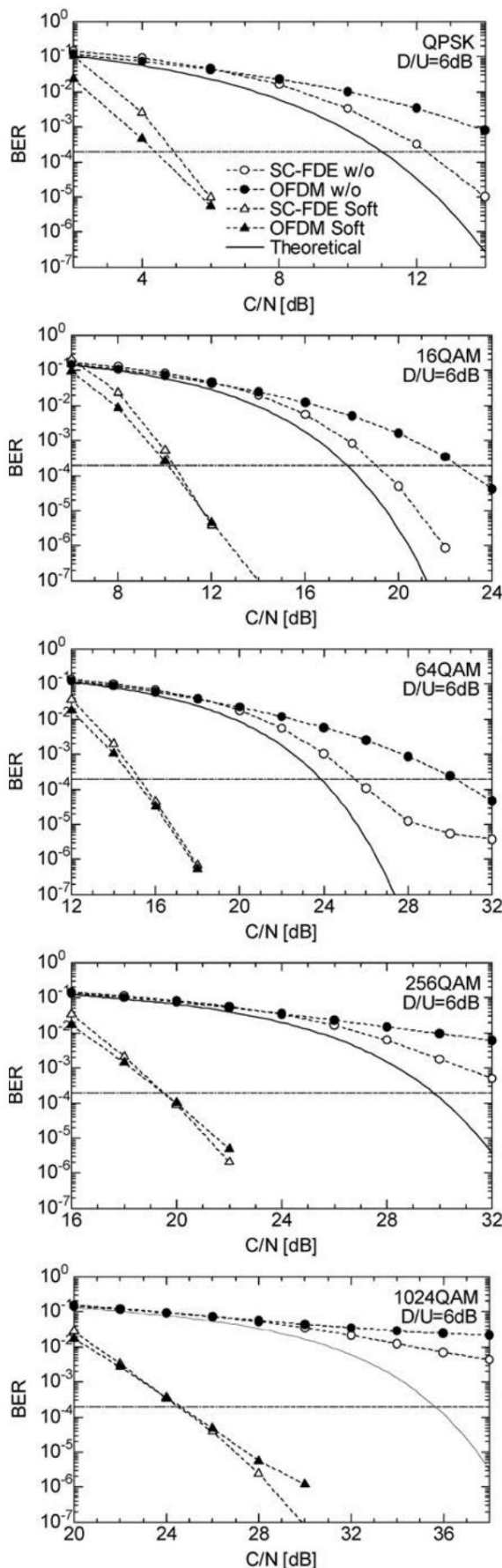


Figure 15 BER vs. C/N (in two path channel, 6 dB)

There are two types of fading: direct fading, which occurs when there is no direct wave and the propagation path is made up of only multipath waves reflected by mountains and buildings, and Rayleigh fading, which occurs when there is no direct wave and the propagation path is made up of only multipath waves reflected by mountains and buildings.

In general, FPU are used within line of sight.

An image of Nakagami-Rice fading is shown in Figure 15, and Rayleigh fading is shown in Figure 16. In mobile

transmission in a multipath environment, interference waves are reflected by moving objects, causing the Doppler effect, which causes the frequency to fluctuate.

The fluctuation frequency can be calculated using formula (7). The fluctuation frequency is F_d , the moving speed is v , the transmission frequency is f_c , and the speed of light is $c (= 3.0 \times 10^8)$ [m/s].

$$F_d = \frac{v \times f_c}{c} \quad (7)$$

When comparing the different wireless systems of SC-FDE and OFDM, it is difficult to select parameters that match the block length T_s of the SC-FDE system and the symbol length T_s of the OFDM system. For this reason, in this paper, we used the normalized Doppler frequency $F_d T_s$ normalized by T_s to enable comparative evaluation independent of T_s . $F_d T_s$ can be calculated using the following equation (8).

$$F_d T_s = F_d \times T_s \quad (8)$$

Table 4 shows the relationship between moving speed and normalized Doppler frequency.

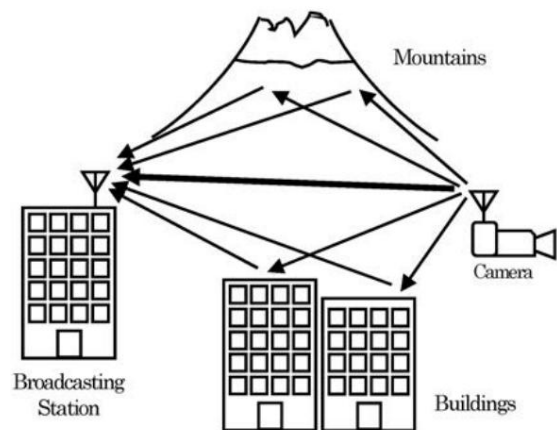


Figure 16 The image of Rician Fading

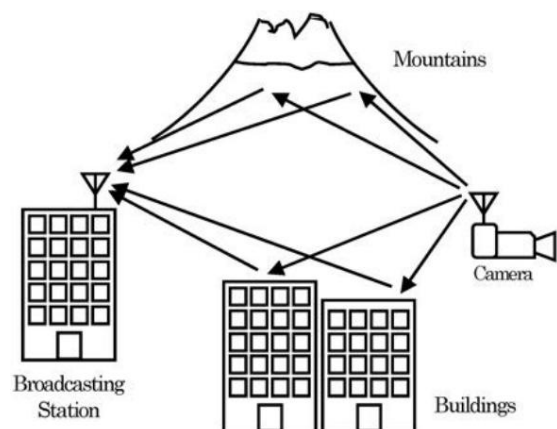


Figure 17 The image of Rayleigh Fading

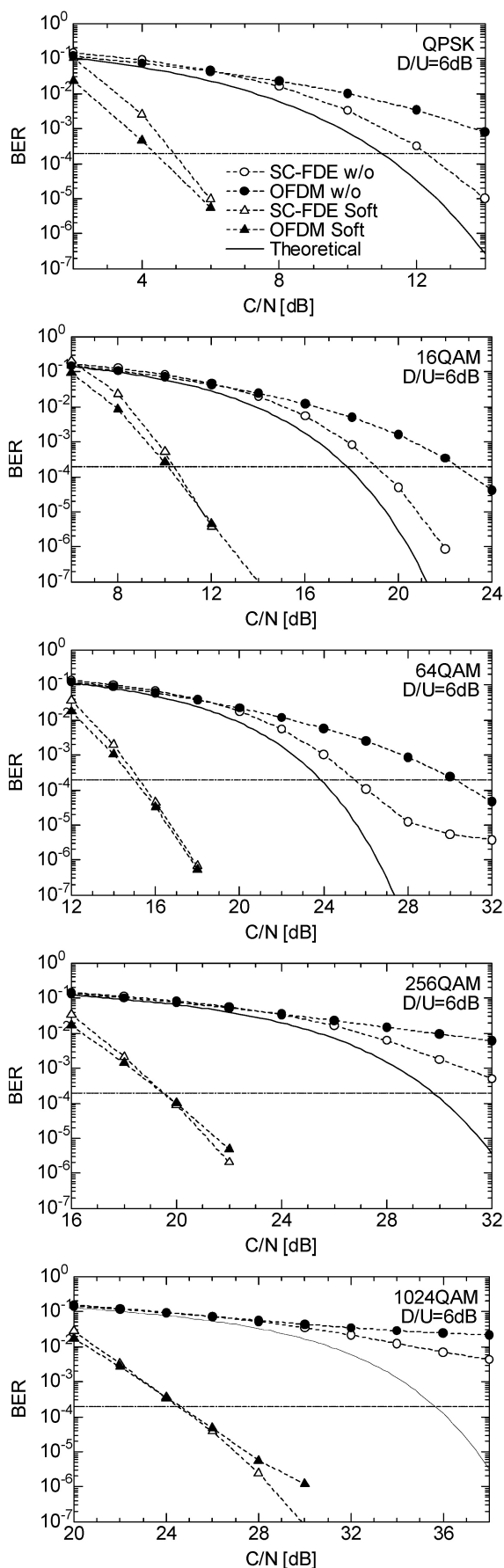


図15 BER vs. C/N (in two path channel, 6 dB)

フェージングと、直接波がなく山や建物に反射するマルチパスのみで伝搬路が構成されるレイリーフェージングがある。マイクロ波帯は1.2/2.3 GHz帯よりも電波の直進性が強く、FPUを見通し内で使用することが一般的である。図16に仲上ライスフェージング、図17にレイリーフェージングのイメージ図を示す。

マルチパス環境の移動伝送においては、妨害波が移動体などに反射してドップラー効果が生じ周波数が変動する現象が発生する。その変動周波数は、式(7)を用いて算出できる⁷⁾。変動周波数を F_d 、移動速度を v 、送信周波数を f_c 、光速を $c (= 3.0 \times 10^8)$ [m/s] とする。

$$F_d = \frac{v \times f_c}{c} \quad (7)$$

SC-FDE方式とOFDM方式という異なる無線システムを比較するにあたり、SC-FDE方式の1ブロック長 T_s と、OFDM方式の1シンボル長 T_s を一致させたパラメータを選定することは困難である。このため本論文では、 T_s に依存しない比較評価を行えるよう T_s で規格化した正規化ドップラー周波数 $F_d T_s$ を用いた。 $F_d T_s$ は以下の式(8)で求められる。

$$F_d T_s = F_d \times T_s \quad (8)$$

移動速度と正規化ドップラー周波数の関係を表4に示す。

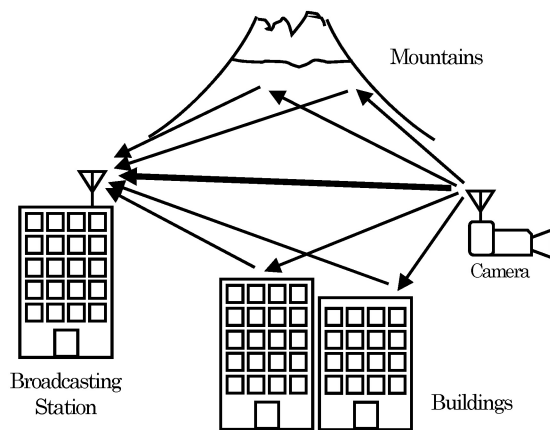


図16 The image of Rician Fading

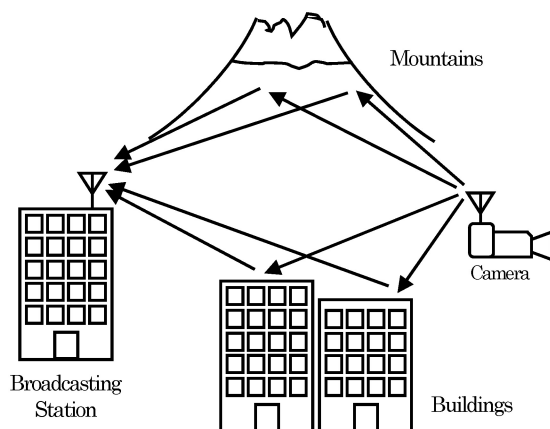


図17 The image of Rayleigh Fading

Table 4 Relationship between moving speed (v) and normalized Doppler frequency

		FdTs	
system		OFDM	SC-FDE
T_s [μ s]		112.66	156.9
v [km]	1	0.001	0.001
	10	0.010	0.015
	30	0.031	0.044

Table 5 Fading parameters

Model	Rician		Rayleigh	
	Delays [ns]	Gains [dB]	Delays [ns]	Gains [dB]
Path	0	0	0	0
	244	-3	244	-3
	489	-6	489	-6
	733	-9	733	-9
	978	-12	978	-12
	1222	-15	1222	-15
	1467	-18	1467	-18
K-factors	2		—	

An exponential delay profile [12] was used as a model for the mobile transmission environment, and an example of fading parameters with six delayed waves is shown in Table 5. In addition, the Rice factor (K-factors), defined as the ratio of the power of the stationary component used in Nakagami-Rice fading to the average power of the irregular component, was set to 2.

In this section, the evaluation of fading in mobile transmission is. Since the time fluctuation of the channel is large, the noise suppression coefficient of the recursive filter for estimating the channel characteristics was set to no noise suppression ($K = 0$) for both OFDM and SC-FDE, and the MMSE method of Eq. (3) was used for evaluation.

5.3.1 Rician fading channel

A simulation was performed using the Rice model to determine the BER when the C/N ratio was changed. The normalized Doppler frequency FdTs was set to 0.01 and 0.015, and the Rice factor (K-factors), defined as the ratio of the power of the stationary component to the average power of the irregular component, was set to 2. The results are shown in Figures 18 and 19. The OFDM system achieved the required BER for all modulation orders, but the SC-FDE system did not reach the required BER for 64QAM with FdTs=0.015.

Next, the normalized Doppler frequency FdTs corresponding to a moving speed of 30 km/h was set to 0.031 and 0.044 for the OFDM and SC-FDE systems, respectively, and the K-factor of the Rice model was set to 2.

The results of calculating the BER versus C/N are shown in Figure 20. The OFDM system achieved the required BER for all modulation orders, but the SC-FDE system did not reach the required BER for 16QAM and 64QAM.

Furthermore, the horizontal axis is the normalized Doppler frequency and the vertical axis is the BER.

The results of calculations using the Rice model are shown in Figure 21.

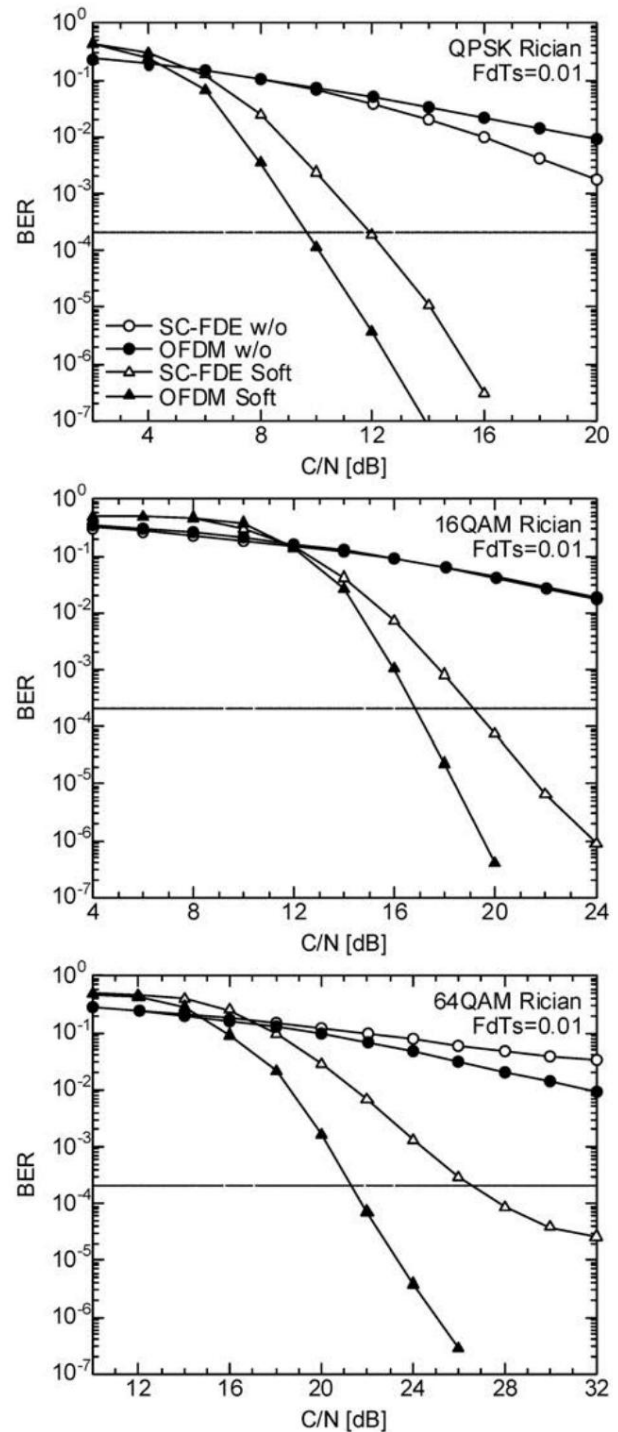


Figure 18 BER vs. C/N (Rician, FdTs = 0.01)

The C/N ratio was set to 20 dB for QPSK. For 16QAM, which has four times the number of symbols and half the symbol distance, the noise power was set to 26 dB, half that of QPSK, and similarly for 64QAM it was set to 32 dB. It can be seen that when FdTs is large, that is, when the moving speed is fast, the BER after error correction is better with the OFDM system. 5.3.2 Rayleigh fading transmission path A simulation was performed using the Rayleigh model to

determine the BER when the C/N ratio is changed. The normalized Doppler frequency

The results for wave numbers FdTs = 0.01 and 0.015 are shown in Figures 22 and 23.

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表4 Relationship between moving speed (v) and normalized Doppler frequency

		FdTs	
system		OFDM	SC-FDE
T_s [μ s]		112.66	156.9
v [km]	1	0.001	0.001
	10	0.010	0.015
	30	0.031	0.044

表5 Fading parameters

Model	Rician		Rayleigh	
	Delays [ns]	Gains [dB]	Delays [ns]	Gains [dB]
Path	0	0	0	0
	244	-3	244	-3
	489	-6	489	-6
	733	-9	733	-9
	978	-12	978	-12
	1222	-15	1222	-15
	1467	-18	1467	-18
K-factors	2		—	

移動伝送環境のモデルとして指数関数型遅延プロファイル¹²⁾を用い、遅延波を6波としたフェージングのパラメータの一例を表5に示す。また、仲上ライスフェージングで使用する定常成分の電力と不規則成分の平均電力の比で定義されるライスファクタ (K-factors) は2とした。

本節の移動伝送のフェージングの評価においては、伝送路の時間変動が大きいことから、OFDM, SC-FDEともに伝送路特性推定の再帰型フィルタの雑音抑圧係数を雑音抑圧なし ($K=0$) とし、(3) 式のMMSE法を用いて評価した。

5.3.1 ライスフェージング伝送路

C/Nを変化させたときのBERについて、ライモデルを用いてシミュレーションを行った。正規化ドップラー周波数FdTs=0.01, 0.015とし、定常成分の電力と不規則成分の平均電力の比で定義されるライスファクタ (K-factors) は2とした。その結果を図18, 図19に示す。OFDM方式は、すべての変調次数で所要BERに達したが、SC-FDE方式は、FdTs=0.015の64QAMにおいて所要BERに達しなかった。

次に、時速30 kmの移動速度に相当する正規化ドップラー周波数FdTsを、OFDM方式とSC-FDE方式でそれぞれ0.031, 0.044とし、ライモデルのK-factorを2としてC/Nに対するBERを計算した結果を図20に示す。OFDM方式は、すべての変調次数で所要BERに達したが、SC-FDE方式は16QAM, 64QAMにおいて所要BERに達しなかった。

さらに、横軸を正規化ドップラー周波数とし縦軸をBERとしてライモデルを用いて計算した結果を図21に示す。

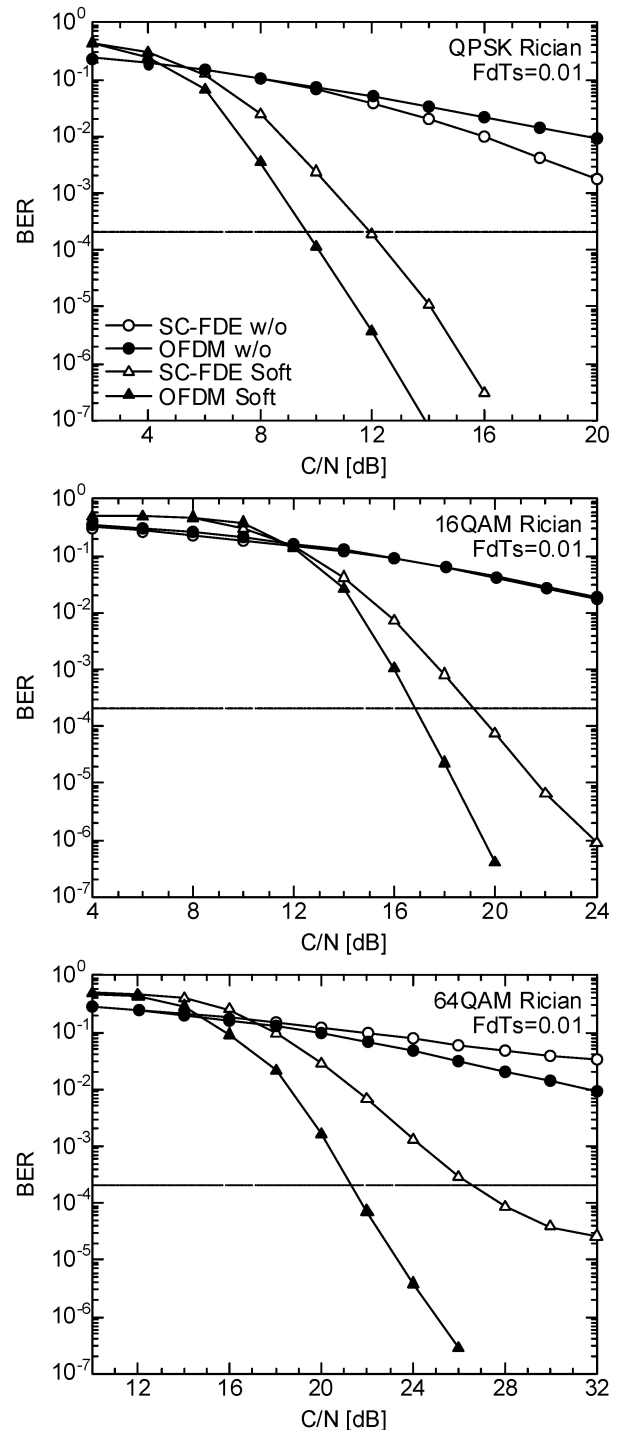


図18 BER vs. C/N (Rician, FdTs=0.01)

C/Nは、QPSKで20 dBとした。なお、シンボル数が4倍、シンボル間距離が1/2となる16QAMでは、雑音電力がQPSKの1/2となる26 dBに、同様に64QAMでは32 dBとした。FdTsが大きい場合、すなわち移動速度が速い場合の誤り訂正後のBERはOFDM方式の方が良好であることが確認できる。

5.3.2 レイリーフェージング伝送路

C/Nを変化させたときのBERについて、レイリーモデルを用いてシミュレーションを行った。正規化ドップラー周波数FdTs=0.01, 0.015とした結果を図22, 図23に示す。

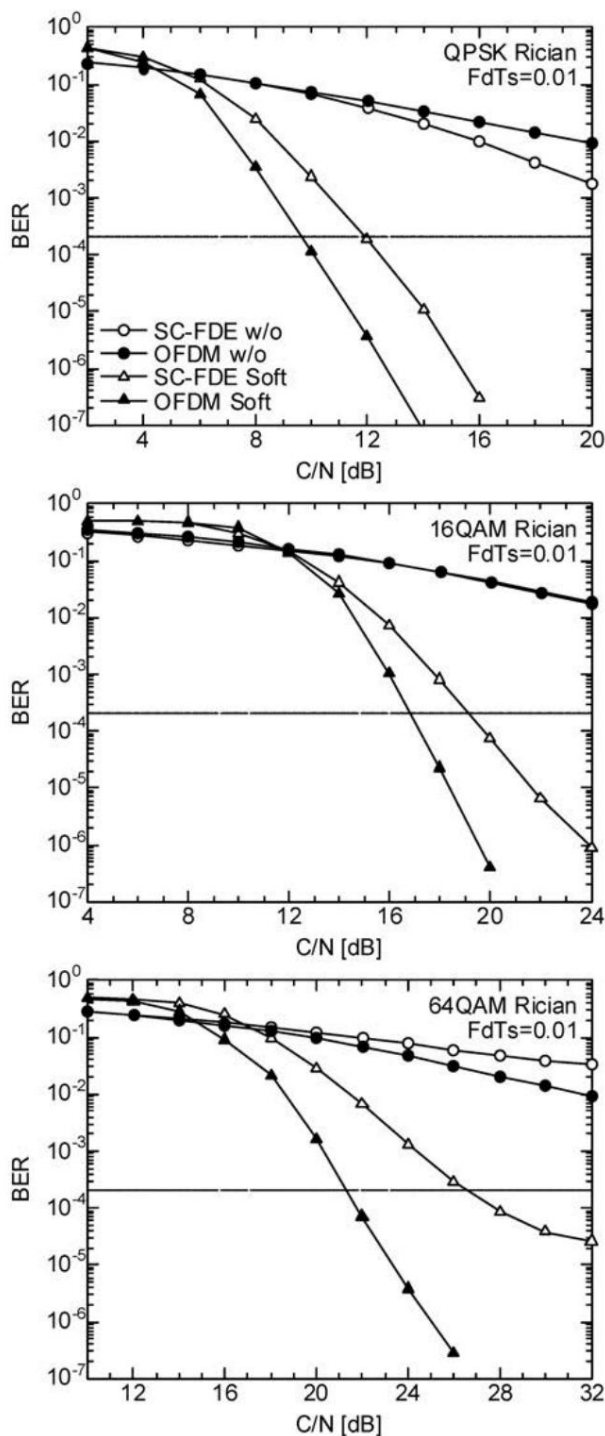


Figure 19 BER vs. C/N (Rician, $FdTs = 0.015$)

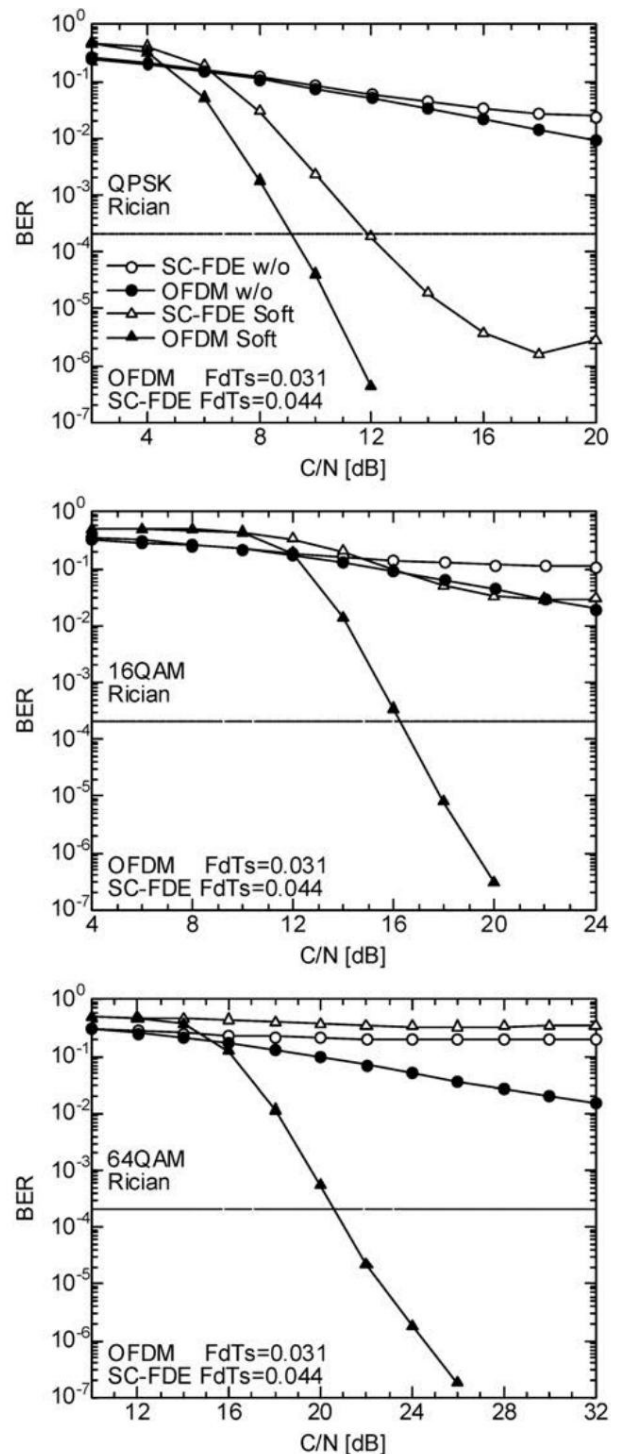


Fig. 20 C/N vs. BER (Rician, $v = 30$ km/h)

The OFDM method achieved the required BER for all modulation orders, but the SC-FDE method only achieved the required BER for 64QAM with $FdTs = 0.015$. The BER was not reached.

Next, the normalized Doppler frequency $FdTs$ corresponding to a moving speed of 30 km/h was calculated for the OFDM and SC-FDE systems, respectively. The BER versus C/N ratio was calculated using a Rayleigh fading model with the C/N ratios set to 0.031 and 0.044, and the results are shown in Figure 24. As with the results of the Rice model, the OFDM system achieved the required BER for all modulation orders, but the SC-FDE system did not achieve the required BER for 16QAM and 64QAM.

Furthermore, the results of calculations using the Rayleigh model with the horizontal axis being the normalized Doppler frequency and the vertical axis being the BER are shown in Figure 25. As with the Rice model, the C/N is 20 dB for QPSK and the BER after error correction is 26 dB for 16QAM and 32 dB for 64QAM. When $FdTs$ is large, that is, when the moving speed is fast, the BER is

It can be seen that OFDM is better.

6. Evaluation of wireless links

In this section, we assume that the same transmission amplifier is used for both OFDM and SC-FDE.

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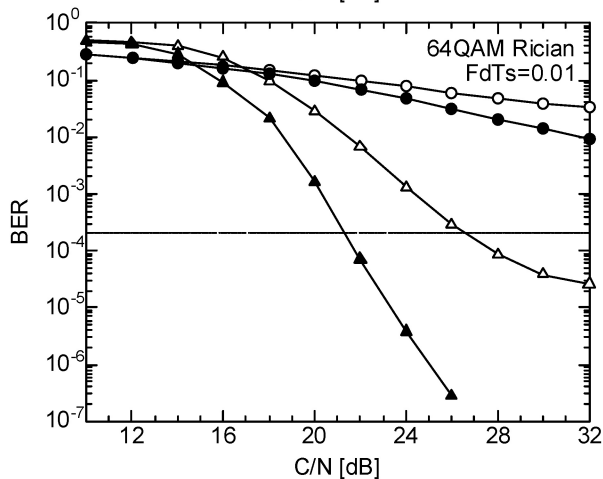
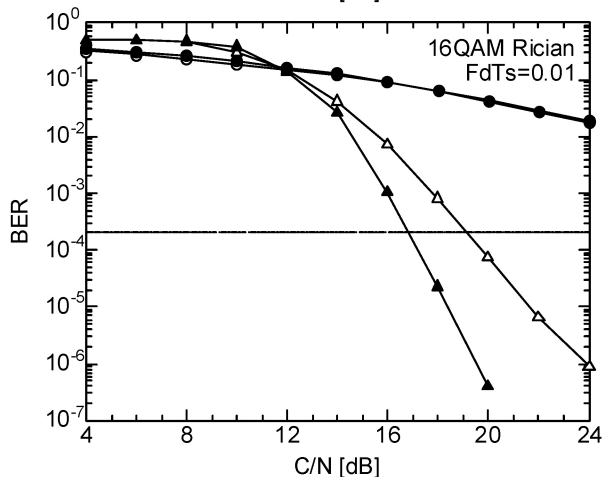
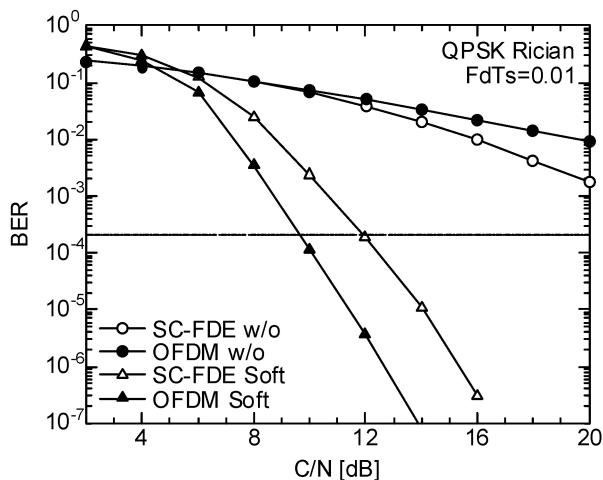


図19 BER vs. C/N (Rician, $FdTs=0.015$)

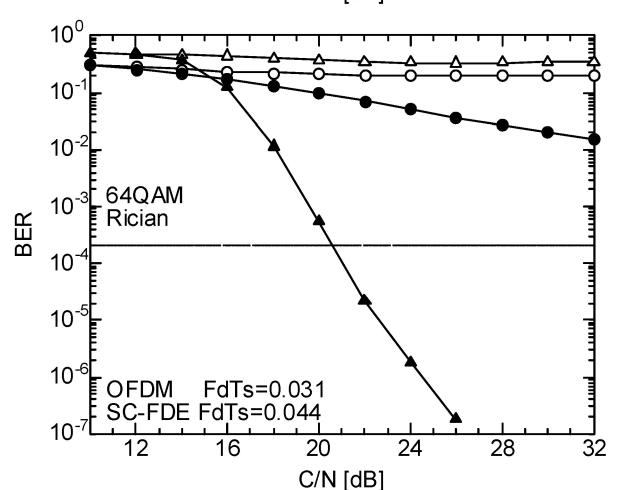
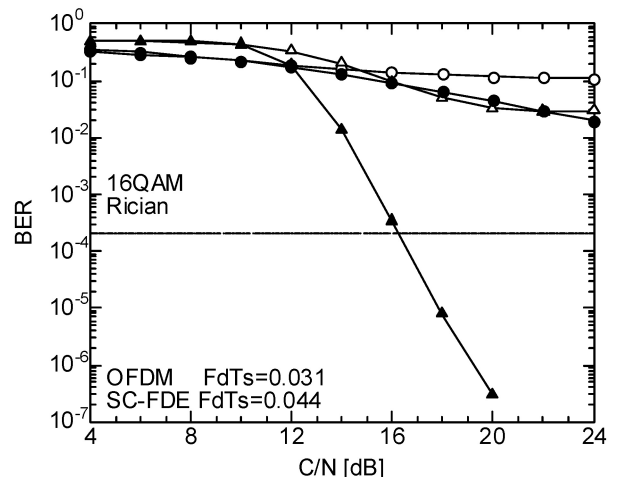
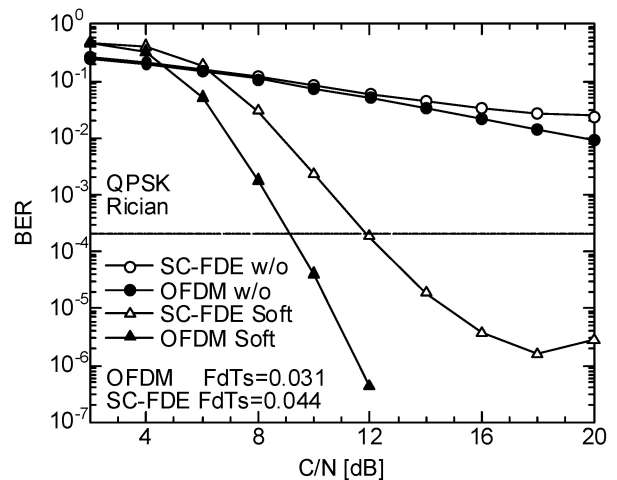


図20 C/N vs. BER (Rician, $v=30$ km/h)

OFDM方式は、すべての変調次数で所要BERに達したが、SC-FDE方式は、 $FdTs=0.015$ の64QAMにおいて所要BERに達しなかった。

次に、時速30 kmの移動速度に相当する正規化ドップラー周波数 $FdTs$ を、OFDM方式とSC-FDE方式でそれぞれ0.031, 0.044とし、レイリーフェージングのモデルを用いてC/Nに対するBERを計算した結果を図24に示す。ライスモデルの結果と同様、OFDM方式は、すべての変調次数で所要BERに達したが、SC-FDE方式は16QAM, 64QAMにおいて所要BERに達しなかった。

さらに、横軸を正規化ドップラー周波数とし縦軸をBERとしてレイリーモデルを用いて計算した結果を図25に示す。ライスモデルと同様に、C/NはQPSKで20 dB, 16QAMで26 dB, 64QAMで32 dBとした。 $FdTs$ が大きい場合、すなわち移動速度が速い場合の誤り訂正後のBERはOFDMの方が良好であることが確認できる。

6. 無線回線の評価

本章では、OFDM方式とSC-FDE方式の両方式において、同一の送信用増幅器を用いることを想定し、OFDM方式と

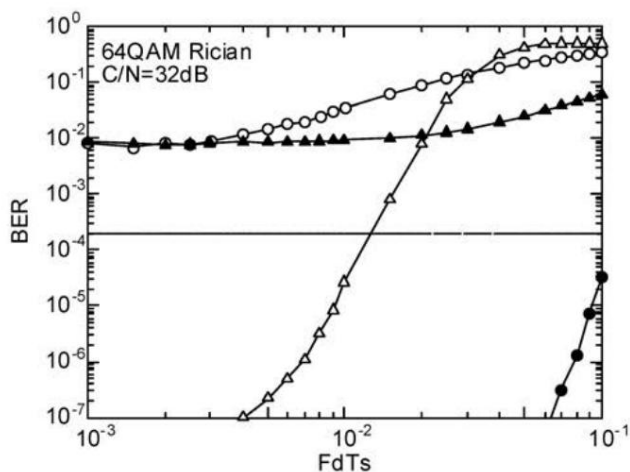
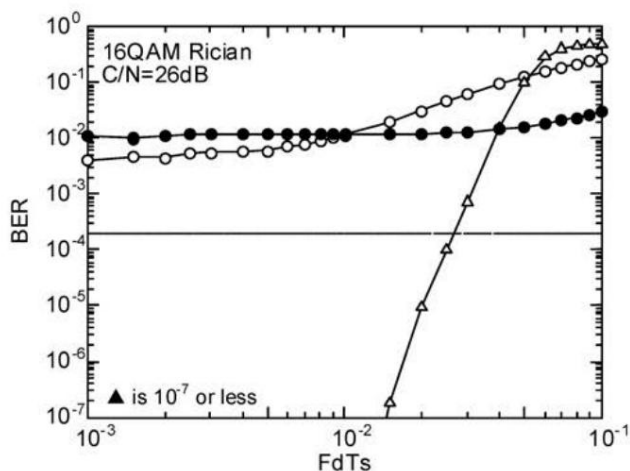
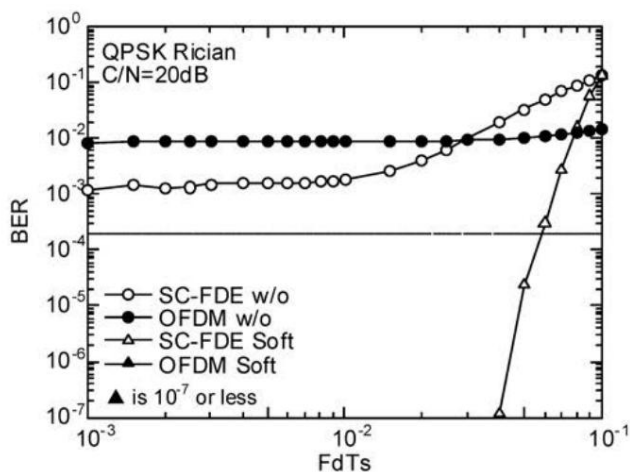


Figure 21 FdTs vs. BER (Rician)

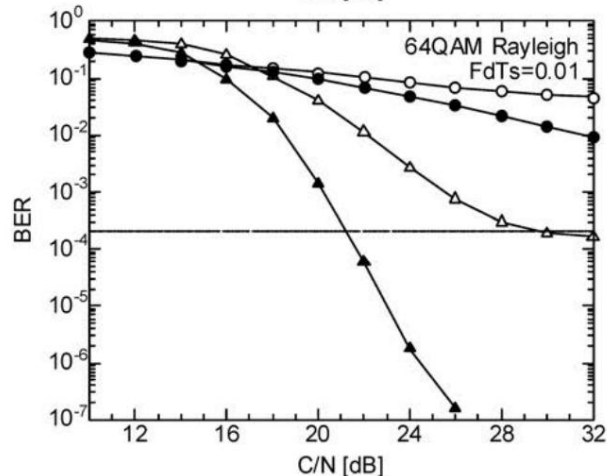
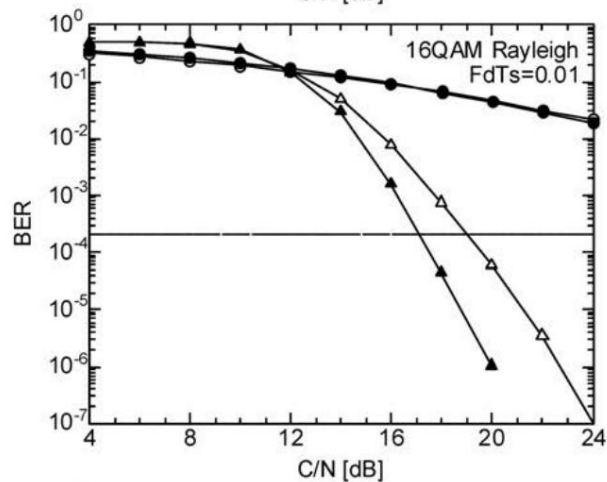
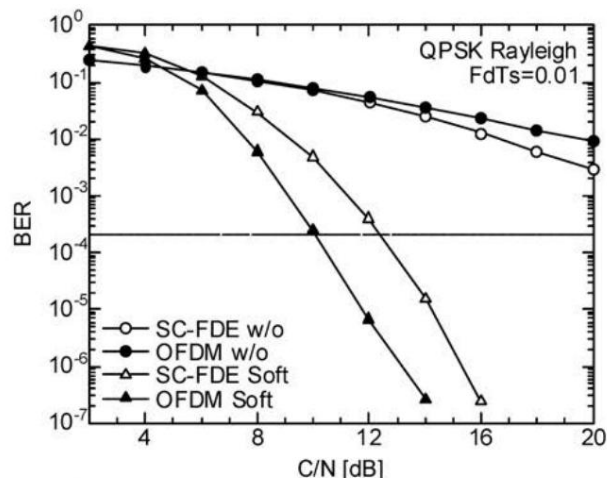


Figure 22 BER vs. C/N (Rayleigh, FdTs = 0.01)

We compare SC-FDE methods. We evaluate by adding and canceling the difference in the required IBO of the transmitting amplifier described in Chapter 4 and the difference in the required C/N of the receiver described in Chapter 5. We perform three evaluations: fixed transmission, quasi-mobile transmission, and mobile transmission.

6.1 Evaluation of fixed transmission

In this section, we perform an evaluation assuming fixed transmission where the transmitting and receiving antennas are line of sight and do not move. We describe the results using an AWGN transmission path with no multipath, and a two-path model in which the multipath seen in marine propagation fluctuates relatively slowly.

AWGN transmission path described in Section 5.1 and the two-wave model described in Section 5.2

The difference in required C/N between the OFDM system and the SC-FDE system was calculated using the values of γ , and the results are shown in Table 6.

The value of the SC-FDE method is subtracted, and if the value is positive, the SC-

A positive value means that the FDE system has an advantage, and a negative value means that the OFDM system has an advantage. In terms of the required C/N, the OFDM system has a slight advantage. Next,

the power gain of the SC-FDE system over the OFDM system was calculated by adding the value $\bar{\gamma}$ of the power difference in the required IBO of the transmitting amplifier described in Table 3 in Chapter 4 and the value $\bar{\gamma}$ of the power difference in the required C/N of the receiver shown in Table 6, as shown in Table 7. When this power gain is positive,

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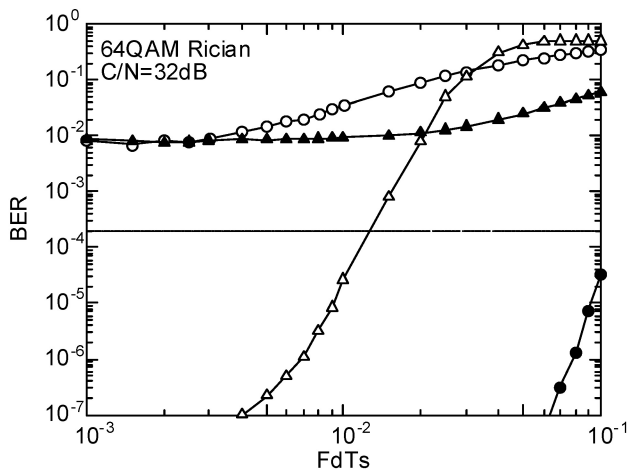
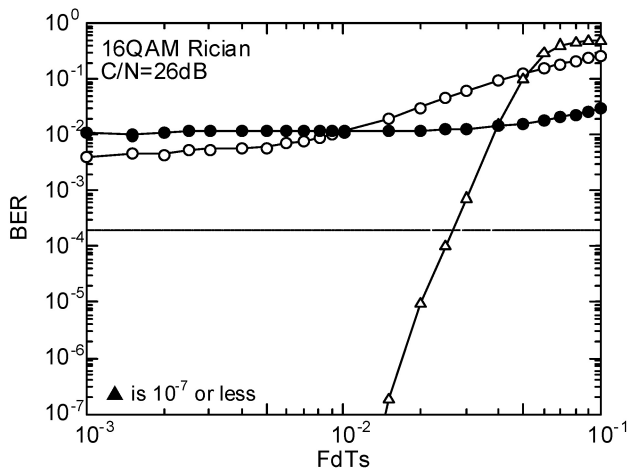
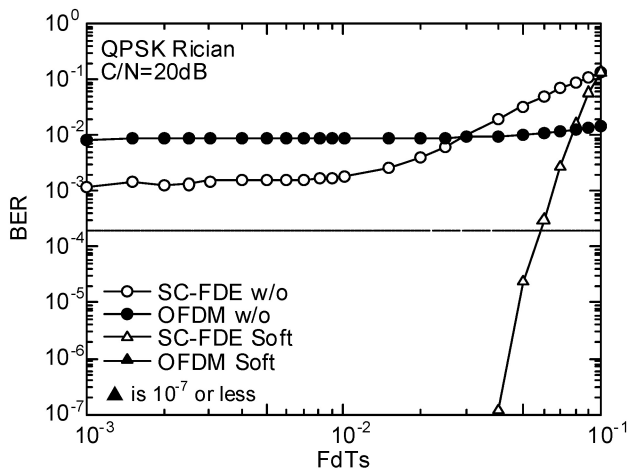


図21 FdTs vs. BER (Rician)

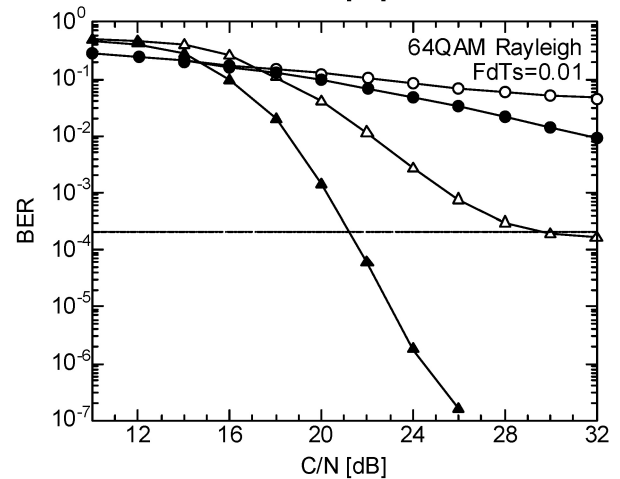
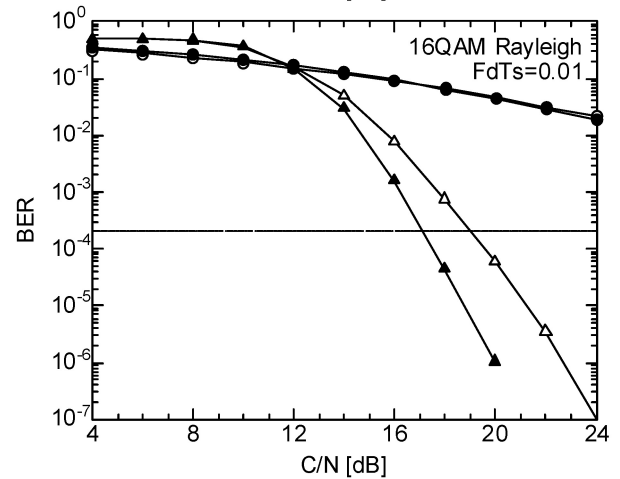
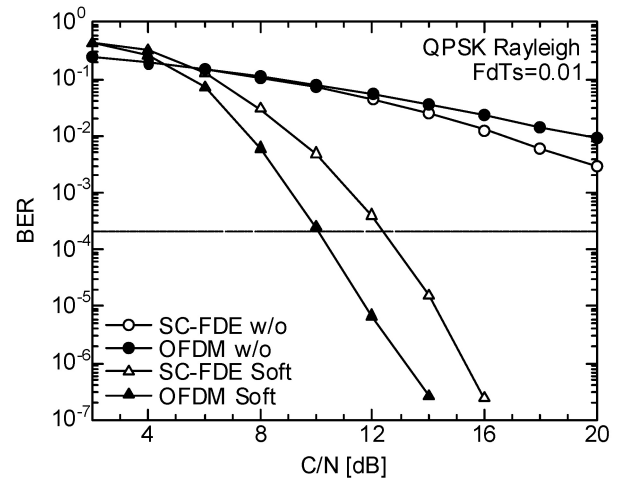


図22 BER vs. C/N (Rayleigh, FdTs = 0.01)

SC-FDE方式の比較を行う。4章で述べた送信側増幅器の所要IBOの差の値と、5章で述べた受信機の所要C/Nの差の値を加算して相殺することで評価する。固定伝送、準移動伝送、移動伝送の3通りの評価を行う。

6.1 固定伝送の評価

本節では、送受のアンテナが見通しで移動しない固定伝送を想定した評価を行う。マルチパスがないAWGN伝送路と、海上伝搬などにみられるマルチパスが比較的緩やかに変動する2波モデルを用いた結果を述べる。

5.1節で述べたAWGN伝送路と5.2節で述べた2波モデル

の値を用いてOFDM方式とSC-FDE方式の所要C/Nの差を求めた結果を表6に示す。差の値⑥は、OFDM方式からSC-FDE方式の値を引き算しており、値が正の場合はSC-FDE方式が有利、負の場合はOFDM方式が有利となることを意味する。所要C/Nの観点では、OFDM方式が若干有利となる。

次に、4章の表3で述べた送信側増幅器の所要IBOの電力差の値③と、表6に示した受信機の所要C/Nの電力差の値⑥を加算することで、OFDM方式に対するSC-FDE方式の電力利得を求めた結果を表7に示す。この電力利得が正の

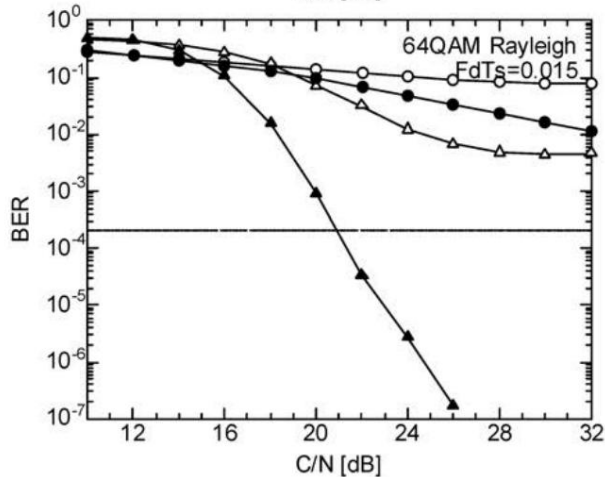
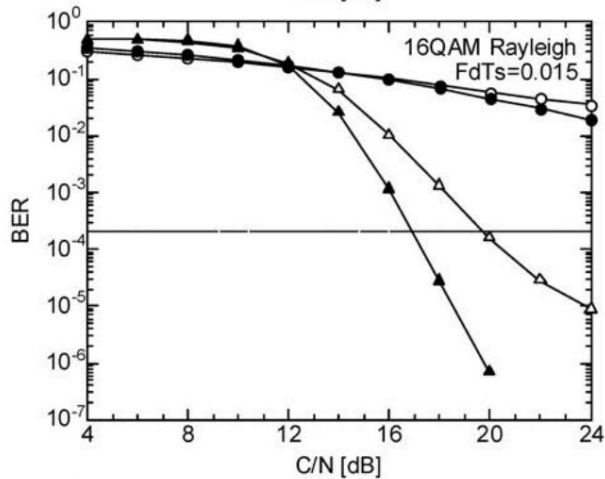
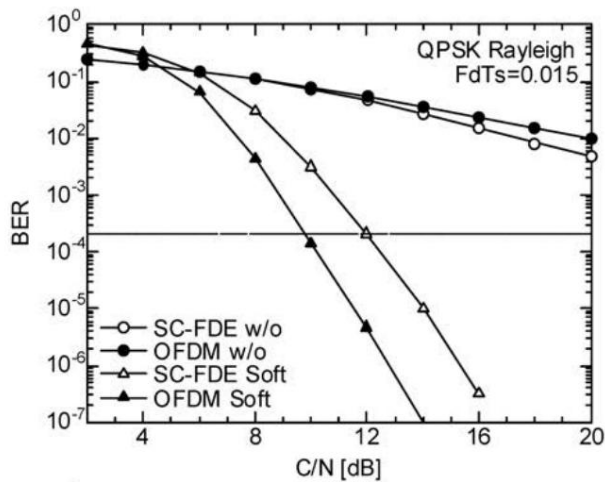


Figure 23 BER vs. C/N (Rayleigh, $F_d T_s = 0.015$)

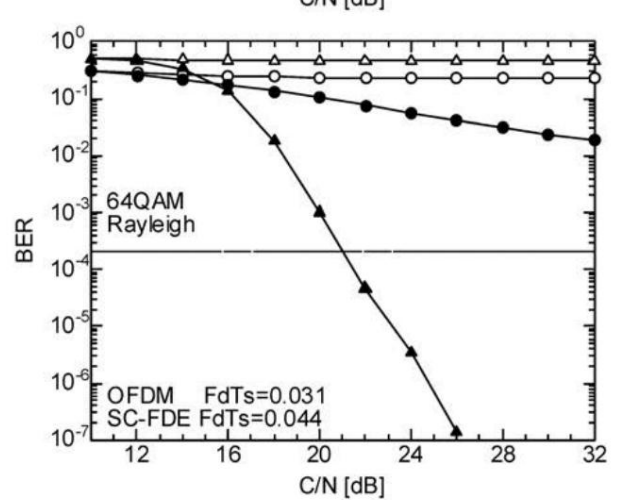
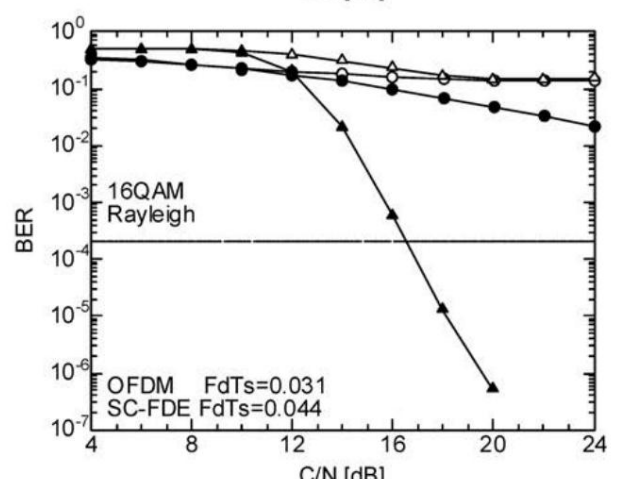
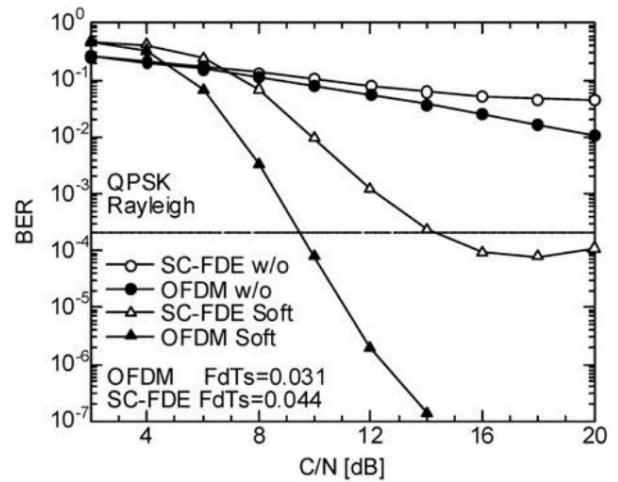


Figure 24 C/N vs. BER (Rayleigh, $v = 30$ km/h)

In the case of positive, the SC-FDE system is advantageous, and in the case of negative, the OFDM system is advantageous. All the results in Table 7 are positive, and it can be seen that in the case of fixed line-of-sight transmission, the SC-FDE system is advantageous.

6.2 Evaluation of Quasi-Mobile

Transmission In this section, we assume quasi-mobile transmission from wireless cameras and describe the results of evaluation using Ricean and Rayleigh fading models.

Using the required C/N value for fading described in Section 5.3,

The difference in required C/N between OFDM and SC-FDE systems is shown below.

The results are shown in Table 8. The transmission frequency is 10 GHz and the moving speed is 10 km/h. In this case, $F_d T_s$ is 0.015 for the SC-FDE method and 0.01 for the OFDM method. In terms of the required C/N, the OFDM method is more advantageous.

Since the value for 64QAM did not reach the required BER, a "-" is entered in the table.

Next, the power gain of the SC-FDE system against the OFDM system was calculated by adding the power difference value γ of the required IBO of the transmitting amplifier described in Table 3 of Chapter 4 and the power difference value γ of the required C/N of the receiver shown in Table 8. The results are shown in Table 9.

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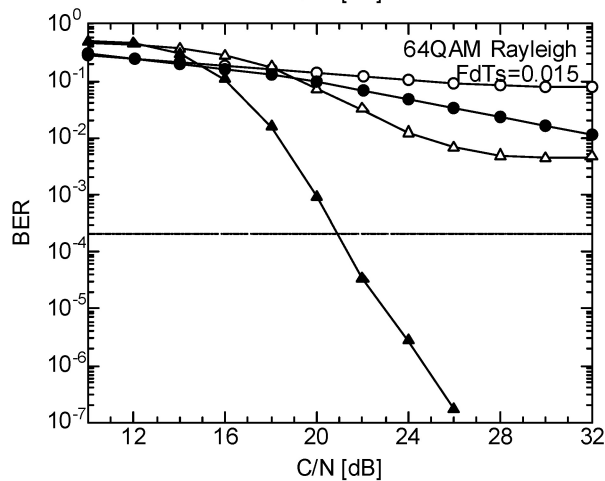
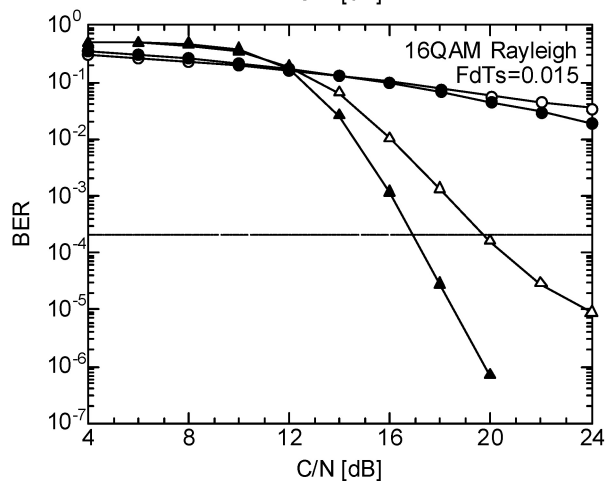
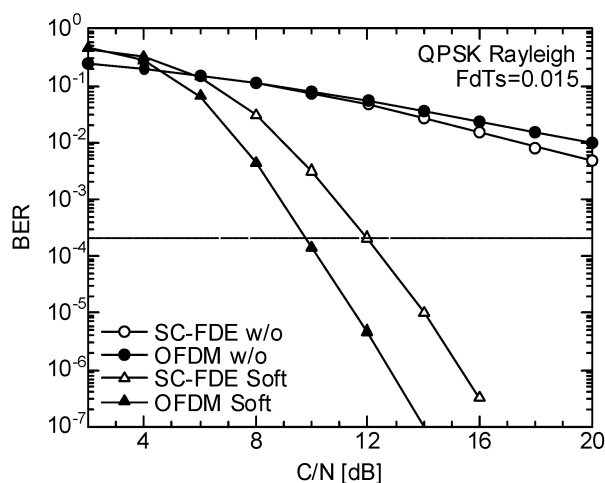


図23 BER vs. C/N (Rayleigh, $FdTs = 0.015$)

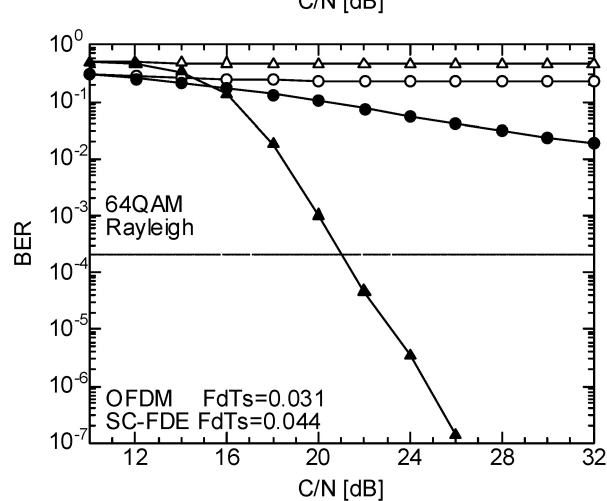
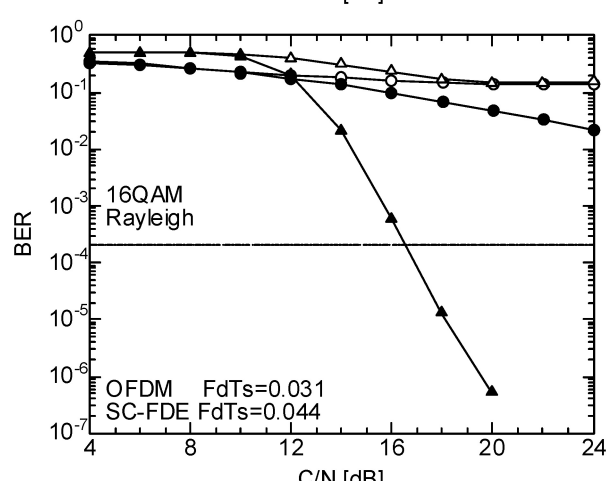
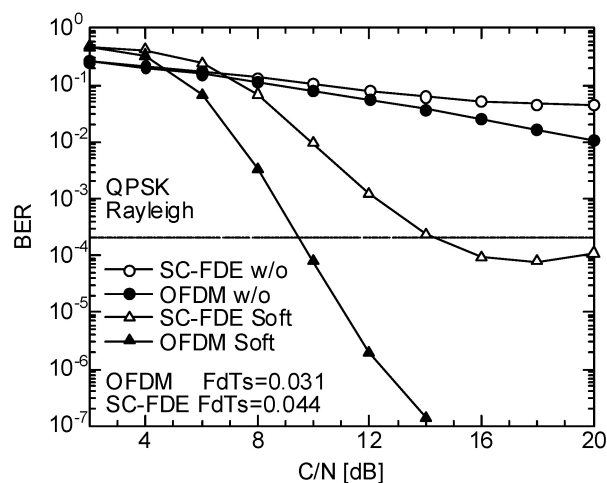


図24 C/N vs. BER (Rayleigh, $v = 30$ km/h)

場合はSC-FDE方式が有利、負の場合はOFDM方式が有利となる。表7の結果はすべて正の値となり、見通し内の固定伝送の場合は、SC-FDE方式の方が有利となることがわかる。

6.2 準移動伝送の評価

本節では、ワイヤレスカメラなどの準移動伝送を想定し、ライスおよびレイリーフェージングのモデルを用いて評価した結果を述べる。

5.3節で述べたフェージングの所要C/Nの値を用いてOFDM方式とSC-FDE方式の所要C/Nの差を求めた結果を

表8に示す。送信周波数は10 GHzとし移動速度は時速10 kmとした。この場合の $FdTs$ は、SC-FDE方式が0.015、OFDM方式が0.01となる。OFDM方式の場合所要C/Nの観点ではOFDM方式の方が有利となる。SC-FDE方式の64QAMの値は所要BERに達しなかったため、表中“-”を記載している。

次に、4章の表3で述べた送信側増幅器の所要IBOの電力差の値③と、表8に示した受信機の所要C/Nの電力差の値⑨を加算することで、OFDM方式に対するSC-FDE方式の電力利得を求めた結果を表9に示す。前節と同様、この電

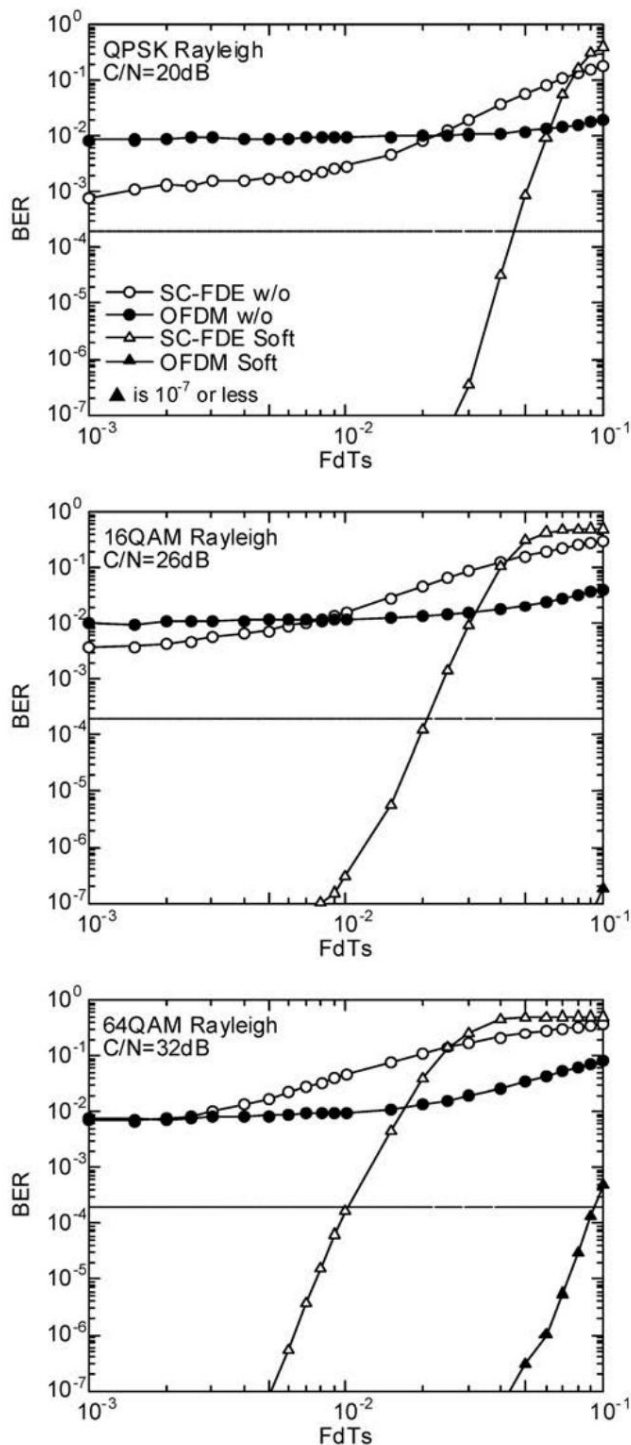


Figure 25 FdTs vs. BER (Rayleigh)

If the power gain is positive, the SC-FDE method is advantageous, and if it is negative,

The OFDM method is advantageous.

In the case of QPSK, the SC-FDE method has an advantage,

In the case of 16QAM, the results are almost the same, and in the case of 64QAM,

Table 9 shows that OFDM is advantageous.

6.3 Evaluation of mobile

transmission In this section, we describe the results of using a fading model that assumes mobile transmission, such as that seen in road race broadcasts, using a car.

Using the C/N value, the required C/N ratio for OFDM and SC-FDE systems is calculated.

Table 6 Difference of required C/N in fixed channel

Chan- nel	Carrier modulation	OFDM [dB] ④	SC- FDE [dB] ⑤	Difference [dB] ⑥=④-⑤
AWGN	QPSK	3.25	3.36	-0.11
	16QAM	8.60	8.92	-0.32
	64QAM	13.16	13.84	-0.68
	256QAM	17.40	18.19	-0.79
	1024QAM	22.05	23.11	-1.07
Two paths	QPSK	3.75	3.97	-0.21
	16QAM	9.25	9.44	-0.19
	64QAM	13.93	14.32	-0.40
	256QAM	18.24	18.62	-0.38
D/U= 10 dB	1024QAM	22.98	23.61	-0.64
	QPSK	4.38	4.92	-0.54
	16QAM	10.13	10.39	-0.27
	64QAM	14.97	15.22	-0.26
D/U= 6 dB	256QAM	19.48	19.50	-0.02
	1024QAM	24.58	24.50	+0.08

Table 7 Power gain between OFDM and SC-FDE with nonlinear Distortion in fixed channel

Carrier Modulation	Power gain ③ + ⑥		
	AWGN	Two paths D/U=6 dB	Two paths D/U=10 dB
QPSK	+2.52	+2.09	+2.42
16QAM	+1.80	+1.85	+1.93
64QAM	+1.25	+1.67	+1.53
256QAM	+0.94	+1.71	+1.35
1024QAM	+0.67	+1.81	+1.10

Table 8 Difference of required C/N in fading channel

Carrier mod- ulation	Fading	OFDM [dB] ⑦	SC- FDE [dB] ⑧	Difference [dB] ⑨=⑦-⑧
QPSK	Rician	9.61	11.75	-2.14
16QAM		16.68	19.00	-2.32
64QAM		21.29	—	—
QPSK	Ray- leigh	10.04	12.03	-1.99
16QAM		17.13	19.79	-2.66
64QAM		21.01	—	—

The results of the difference are shown in Table 10. The normalized Doppler frequency FdTs, which is an index of the speed of movement, is 0.044 for the SC-FDE system and 0.031 for the OFDM system. As in the previous section, the OFDM system has the advantage.

Next, the difference in the power of the required IBO of the transmitting amplifier described in Table 3

of Chapter 4 (y) and the difference in the power of the required C/N of the receiver shown in Table 10 are

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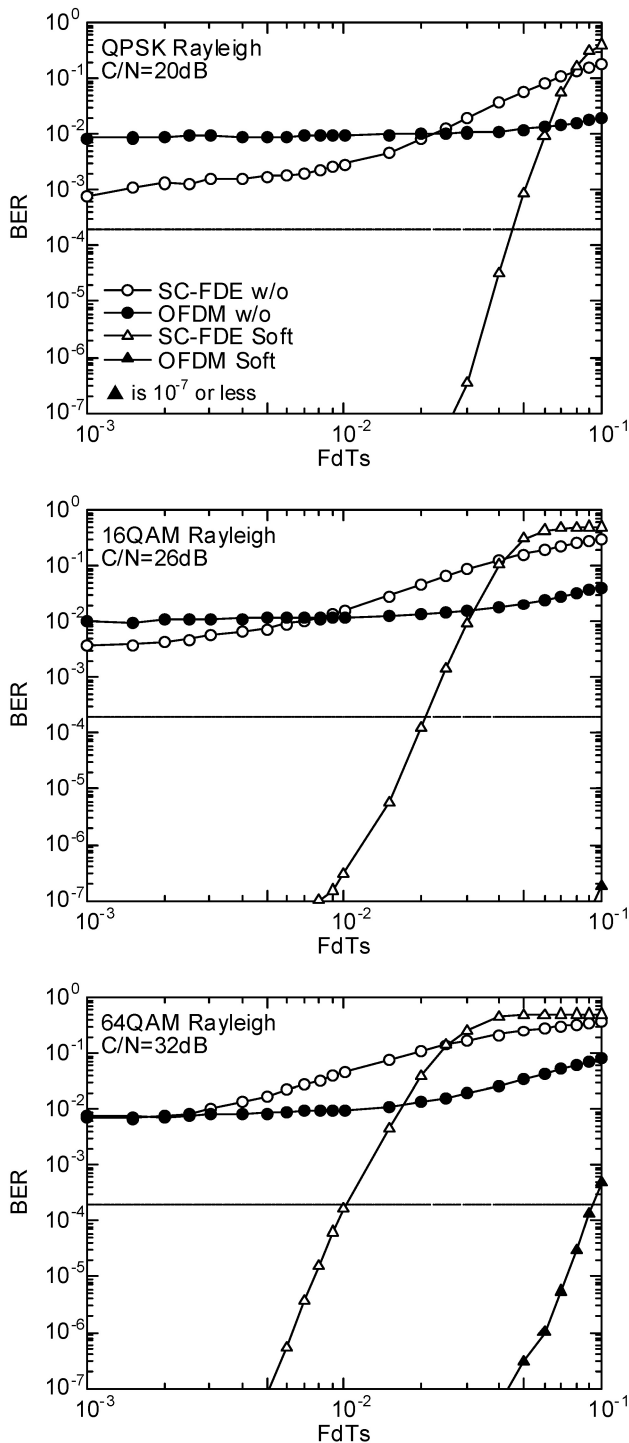


図25 FdTs vs. BER (Rayleigh)

力利得が正の場合はSC-FDE方式が有利、負の場合はOFDM方式が有利となる。

QPSKの場合はSC-FDE方式の方に優位性があるが、16QAMの場合はほぼ同等になり、64QAMの場合はOFDMが有利になることが表9より確認できる。

6.3 移動伝送の評価

本節では、ロードレース中継にみられるような車による移動中継などの移動伝送を想定したフェージングモデルを用いた結果を述べる。5.4節で述べたフェージングの所要C/Nの値を用いてOFDM方式とSC-FDE方式の所要C/N

表6 Difference of required C/N in fixed channel

Chan- nel	Carrier modulation	OFDM [dB] ④	SC- FDE [dB] ⑤	Difference [dB] ⑥= ④-⑤
AWGN	QPSK	3.25	3.36	-0.11
	16QAM	8.60	8.92	-0.32
	64QAM	13.16	13.84	-0.68
	256QAM	17.40	18.19	-0.79
	1024QAM	22.05	23.11	-1.07
Two paths	QPSK	3.75	3.97	-0.21
	16QAM	9.25	9.44	-0.19
	64QAM	13.93	14.32	-0.40
	256QAM	18.24	18.62	-0.38
D/U= 10 dB	1024QAM	22.98	23.61	-0.64
	QPSK	4.38	4.92	-0.54
	16QAM	10.13	10.39	-0.27
	64QAM	14.97	15.22	-0.26
D/U= 6 dB	256QAM	19.48	19.50	-0.02
	1024QAM	24.58	24.50	+0.08

表7 Power gain between OFDM and SC-FDE with nonlinear distortion in fixed channel

Carrier Modulation	Power gain ③ + ⑥		
	AWGN	Two paths D/U= 6 dB	Two paths D/U= 10 dB
QPSK	+2.52	+2.09	+2.42
16QAM	+1.80	+1.85	+1.93
64QAM	+1.25	+1.67	+1.53
256QAM	+0.94	+1.71	+1.35
1024QAM	+0.67	+1.81	+1.10

表8 Difference of required C/N in fading channel

Carrier mod- ulation	Fading	OFDM [dB] ⑦	SC- FDE [dB] ⑧	Difference [dB] ⑨=⑦-⑧
QPSK	Rician	9.61	11.75	-2.14
16QAM		16.68	19.00	-2.32
64QAM		21.29	—	—
QPSK	Ray- leigh	10.04	12.03	-1.99
16QAM		17.13	19.79	-2.66
64QAM		21.01	—	—

の差を求めた結果を表10に示す。移動の速度の指標である正規化ドップラー周波数FdTsは、SC-FDE方式が0.044、OFDM方式が0.031となる。前節と同様、OFDM方式の方が有利となる。

次に、4章の表3で述べた送信側増幅器の所要IBOの電力差の値③と、表10に示した受信機の所要C/Nの電力差の

Table 9 Power gain between OFDM and SC-FDE with nonlinear distortion in Fading channel

Carrier modulation	Power gain ③ + ⑨	
	Rician	Rayleigh
QPSK	+0.49	+0.64
16QAM	-0.20	-0.54
64QAM	-	-

Table 10 Difference of required C/N in fading channel ($v = 30$ km/h)

Carrier modulation	Fading	OFDM [dB] ⑩	SC-FDE [dB] ⑪	Difference [dB] ⑫=⑩-⑪
QPSK	Rician	9.22	11.94	-2.72
16QAM		16.17	-	-
64QAM		20.54	-	-
QPSK	Rayleigh	9.51	14.36	-4.85
16QAM		16.58	-	-
64QAM		21.03	-	-

Table 11 Power gain between OFDM and SC-FDE with nonlinear distortion in Fading channel

Carrier modulation	Power gain ③ + ⑫	
	Rician	Rayleigh
QPSK	-0.09	-2.22
16QAM	-	-
64QAM	-	-

By adding value $\bar{\gamma}$, the power gain of the SC-FDE system compared to the OFDM system was calculated, and the results are shown in Table 11. It can be seen from Table 11 that the OFDM system is advantageous.

7. Conclusion

We have investigated an SC-FDE radio system for microwave band FPU and quantitatively clarified its resistance to nonlinearity and fading through computer simulations.

FPU operation was classified into three types according to the purpose: fixed transmission, quasi-mobile transmission, and mobile transmission. The power value was calculated by adding the input back-off value of the transmitting amplifier and the required C/N of the receiver, and compared with the OFDM system. As a result, the SC-FDE system was found to be advantageous in the case of fixed transmission. In addition, a comparison was made using an example of an exponential delay profile as a propagation model, and the results showed that the OFDM system and the SC-FDE system were almost equivalent in the case of quasi-mobile transmission, and the OFDM system was advantageous in the case of mobile transmission.

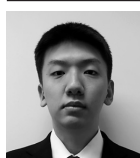
The SC-FDE method provides a single-frequency network with no signal degradation when using a booster to relay signals on the same frequency.

In the future, we would like to tackle the research topic clarified in this paper, "Improving the reception performance of SC-FDE during mobile transmission."

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表9 Power gain between OFDM and SC-FDE with nonlinear distortion in Fading channel

Carrier modulation	Power gain ③ + ⑨	
	Rician	Rayleigh
QPSK	+0.49	+0.64
16QAM	-0.20	-0.54
64QAM	-	-

表10 Diffrence of required C/N in fading channel ($v = 30 \text{ km/h}$)

Carrier modulation	Fading	OFDM [dB] ⑩	SC-FDE [dB] ⑪	Difference [dB] ⑫=⑩-⑪
QPSK	Rician	9.22	11.94	-2.72
16QAM		16.17	-	-
64QAM		20.54	-	-
QPSK	Rayleigh	9.51	14.36	-4.85
16QAM		16.58	-	-
64QAM		21.03	-	-

表11 Power gain between OFDM and SC-FDE with nonlinear distortion in Fading channel

Carrier modulation	Power gain ③ + ⑫	
	Rician	Rayleigh
QPSK	-0.09	-2.22
16QAM	-	-
64QAM	-	-

値⑨を加算することで、OFDM方式に対するSC-FDE方式の電力利得を求めた結果を表11に示す。OFDM方式が有利であることが表11より確認できる。

7. む す び

マイクロ波帯FPU用SC-FDE無線方式の検討を行うとともに、耐非線形特性や耐フェージング特性を計算機シミュレーションにより定量的に明らかにした。

FPU運用の用途ごとに固定伝送、準移動伝送、移動伝送の三つに分類し、送信側増幅器の入力バックオフ値と受信機の所要C/Nを加算した電力値を求め、OFDM方式と比較した。その結果、固定伝送の場合はSC-FDE方式が有利となる結果が得られた。また、伝搬モデルとして指数関数型遅延プロファイルの一例を用いて比較を行った結果、準移動伝送の場合はOFDM方式とSC-FDE方式はほぼ同等となり、移動伝送の場合はOFDM方式が有利となる結果が得られた。

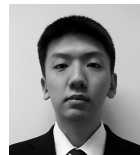
SC-FDE方式には、ブースターによる同一周波数リレー中継を行う場合、信号劣化がない単一周波数ネットワーク

が構築できる利点がある。今後は、本論文で明らかになった研究課題「SC-FDE方式の移動伝送時の受信性能の向上」に取り組んでいきたい。

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