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Performance of Orthogonal Multi-Carrier FH-CDMA System in the Presence of Selective Fading and Nonlinear Amplification

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SUMMARY To improve frequency efficiency or user capacity in multi-path fading environments, we introduce and investigate an orthogonal multi-carrier frequency hopping-code division multiple access (FH-CDMA). These improvements are achieved by combining the orthogonal frequency division multiplexing (OFDM) and FH-CDMA schemes. The basic idea has been previously proposed by the authors. The aim of study in this paper is to evaluate the performance of this scheme in various environments. The theoretical analysis of bit error rate (BER) performance in this paper includes the effects of frequency selective fading in land mobile communications and of nonlinear amplification in satellite communications. A modified scheme of controlling transmission power to be controlled according to the number of simultaneously accessing users is also discussed. This modified scheme improves BER performance for frequency selective fading when the number of simultaneously accessing users in a cellular zone is small. Furthermore, an error-correcting code and its erasure decoding are applied in order to reduce errors due to hits in asynchronous FH/CDMA for reverse link as well as errors due to fading and noise.
key words: *frequency hopping, code division multiple access, orthogonal multi carrier, frequency selective fading, nonlinear amplification*

1. Introduction

The rapid growth of land-mobile communication services requires the use of frequency efficient schemes that can make better use of the available frequency spectrum. Recently, code division multiple access (CDMA) based on spread spectrum technology has been recognized as a viable alternative to frequency division multiple access (FDMA) and time division multiple access (TDMA) for cellular systems. The two main types are direct sequence (DS) spread spectrum and frequency hopping (FH) spread spectrum, and the combined scheme is DS/FH hybrid spread spectrum [1], [2]. The advantages of CDMA include (1) robustness against narrowband interference, (2) information security, (3) multiple access flexibility, and (4) software hand-off capability. The disadvantages of CDMA include (1) power control requirement, (2) degradation due to frequency selective multipath fading, and (3) pilot timing.

On the other hand, the orthogonal frequency division multiplexing (OFDM) technique has recently received considerable attention for land-mobile communications over frequency selective multipath fading channels [3], and for digital audio terrestrial/satellite broadcasting (DAB), as well as terrestrial digital television [4]. The OFDM scheme is based on the idea of transmitting the information bits in parallel streams, each at a low transmission rate, with mutually orthogonal carriers. The frequency difference between adjacent carrier is kept at 1/(symbol time). Therefore, highly efficient frequency utilization can be achieved, and the fading effect is spread out over many carriers.

Recently, various multi-carriers schemes combined with CDMA have been studied. For example, Tomisato et al. proposed coherent hybrid DS-FFH (CHYB-DS-FFH) CDMA [5], [6], which is derived from a hybrid of DS and fast FH CDMA, to improve the BER performance in Rayleigh fading channels by using interleaved frequency hopping. Sourour et al. studied orthogonal multi-carrier DS CDMA [7] in nonfading and slowly nonselective fading channels. Fiebig studied unconventional fast FH/multiple frequency shift keying (FFH/MFSK) system, where carrier frequencies are hopped faster than the symbol rate, provides frequency effective scheme [8]. In these schemes, the frequency efficiency is very good in the case of using orthogonal multi-carrier technique such OFDM.

In this paper, we study an orthogonal multi-carrier FH-CDMA scheme in the presence of frequency selective fading and nonlinear amplification. The basic idea of the orthogonal multi-carrier FH-CDMA scheme has been previously proposed by the authors [9], [10]. The main purpose of this paper is to evaluate the BER performance of this scheme in the presence of various degradation effects. As shown in Fig. 1, mutually orthogonal carriers are frequency-hopped according to a hopping pattern driven by orthogonal codes such as Walsh codes as in a FH CDMA. Since the previous study did not include the transmission power control and the forward error correction (FEC) capability, we will modify the previous scheme to evaluate these effects to improve the bit error performance in the presence of frequency selective fading. Moreover, we study

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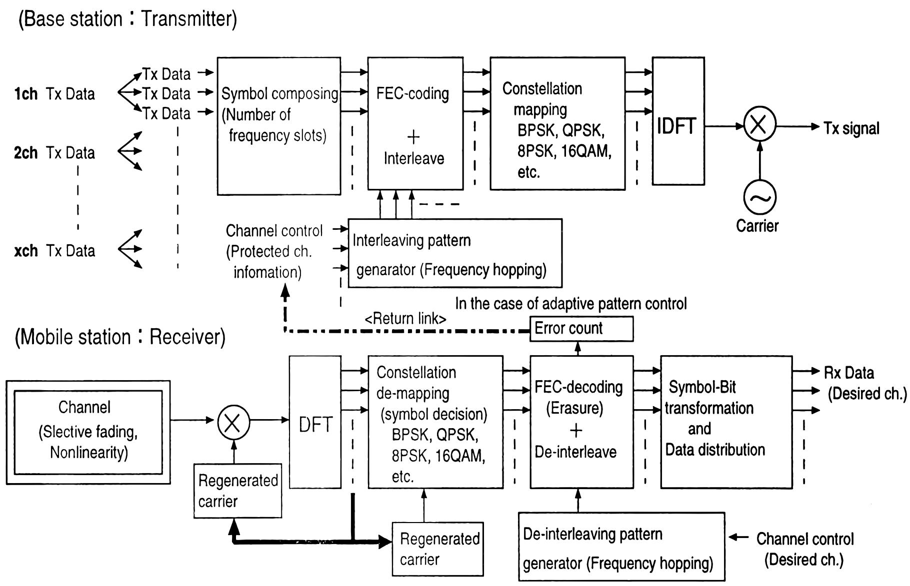

Fig. 2 Configuration of an orthogonal multi-carrier FH-CDMA system.

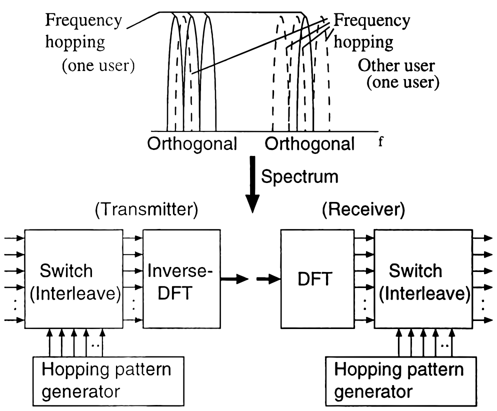

Fig. 1 Principle of an orthogonal multi-carrier FH-CDMA system.

performance degradation due to nonlinear amplification. In such multi-carrier schemes, intermodulation products due to nonlinear amplification, which occurs in satellite transponders or in cellular terminal's transmitter, will impair the bit error performance. In this paper, we present (1) the bit error rate (BER) performance in the presence of frequency selective fading, Rician fading, and nonlinear amplification, (2) the effect of a transmission power control applied according to the number of simultaneously accessing users, and (3) the effect due to FEC, which will reduce errors caused by collisions in asynchronous frequency hopping in a reverse link.

This Sect. 1 introduces the background and the aim of our study. Section 2 provides a system configuration of orthogonal multi-carrier FH-CDMA scheme. Section 3 presents the advantages of the orthogonal multi-carrier FH-CDMA scheme. In Sect. 4, the BER performance of the modified FH-CDMA scheme, which include the FEC and the transmission power control capabilities, is analyzed in the presence of frequency selective fading. Section 5 is also the analysis of the BER performance in the presence of nonlinear amplification for applications of satellite communications. Section 6 describes the analysis results and evaluations of the performance mentioned in Sects. 4 and 5. Section 7 concludes our study.

2. Orthogonal Multi-Carrier FH-CDMA

Figure 2 shows a system model for the orthogonal multi-carrier FH-CDMA system, which can be employed in a forward link of a cellular network of in a broadcasting link like DAB. Figures 3 and 4 show its power spectrum and a timing chart for the synchronous state, respectively. An advantage of this scheme is that it can reduce both intra-cell interference occurred in the same cell and inter-cell interference occurred among adjacent cells, although this requires synchronous timing control at the transmitter. A reverse link, access from a mobile station to a base station, needs a scheme (FDMA, etc.) such that signal quality is not degraded by frequency hopping hits from other frequency bands in the proposed system. In the reverse link, orthogonality cannot be expected to improve the frequency utilization efficiency. If an allowed value is established for this degradation and a channel from the mobile station to the base station is constituted, channels in both directions can be established in orthogonal multi-carrier FH-CDMA schemes.

Errors due to hits in a reverse link can be reduced by an error-correcting code and its erasure decoding.

The fundamental function of base and mobile stations will be described next.

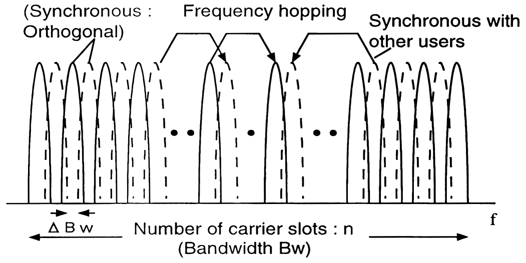

Fig. 3 Conceptual explanation of power spectrum for the orthogonal multi-carrier FH-CDMA system.

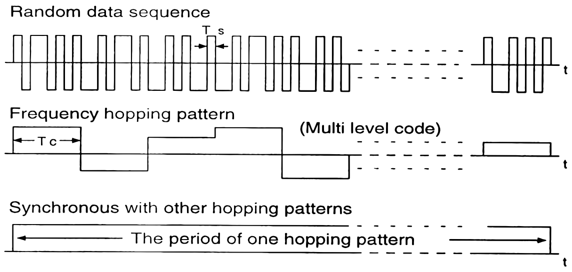

Fig. 4 Timing chart in synchronous orthogonal multi-carrier FH-CDMA.

2.1 Transmitter

It is assumed that serialy transmitted data is converted into n paths for multi-carriers. One carrier frequency is used for each path. The carrier frequency sets itself according to a time domain interleaving (it is equal to frequency domain hopping) pattern generator and it modulates the transmitted symbol data. Clock timing and frequency are completely controlled and the orthogonality between signals of adjacent carriers is maintained. The orthogonality of signals is realized by inverse discrete Fourier transform (IDFT). The modulation scheme is assumed here to be BPSK in land mobile communication and QPSK in satellite mobile communication, but it is possible to use any modulation order with high frequency efficiency. The slow FH scheme is used in which a chip hopping rate is slower than the data rate for one path. A chip hopping of the slow FH scheme is equivalent to symbol interleaving. In this slow FH scheme, the process in which a sequential symbol stream is spread into multi channels in the frequency domain is equivalent to the symbol interleaving process in the time domain. The interleave depth is equivalent to the number of carrier slots, and the symbol interval is equivalent to the chip interval.

2.2 Receiver

A mobile station receiver requires carrier recovery for multi-carrier. The demodulated signal by the carrier formed is transformed into a frequency domain by DFT and the received signal is divided into paths for the number of carriers. After the signals of each path are de-mapped to symbols and are decoded by an FEC decoder, the symbol sequence is recovered according to the interleaving (hopping) pattern generator. As in modulation, completely synchronous control occurs, such as coupling with other-frequency paths. The received data of each frequency path is composed and the data of the hoped user is then reconstructed.

If a possible bit rate is less than the coherent bandwidth of the propagation path, a bit rate of one user does not oblige channel division over multiple carriers. This scheme is valid for bit rates greater than the coherent bandwidth. The number of carriers is determined by examining the bit rate of a service and the coherent bandwidth of a propagation path.

3. Advantages of the Orthogonal Multi-Carrier FH-CDMA

3.1 Improvement in Frequency Utilization Efficiency

The orthogonal multi-carrier FH-CDMA scheme saves the guard frequency band due to the orthogonality among adjacent signals. This scheme reduces the effect of multi-path delay thanks to the using multi-carriers and the frequency diversity based on frequency hopping. Entire BER performance and frequency utilization efficiency can be improved.

3.2 Techniques to Improve the System Performance

In the orthogonal multi-carrier FH-CDMA systems, FEC, transmission power control, and adaptive control of the frequency hopping pattern can improve the BER performance in frequency selective fading channels. Since frequency hopping is performed symbol by symbol in the proposed system, a block coded FEC, such as one of the Read-Solomon (RS) codes, is suitable as error correction techniques. In reverse links, where hits between hopping carriers of different users may occur, erasure decoding of RS codes can be applied. When the number of users decreases in this scheme, transmission power control accompanied with RS codes can greatly improve the BER performance. The transmission power control technique and its effects will be described in the next subsection. Moreover, adaptive control of the hopping pattern in response to the frequency characteristic of frequency selective fading can also improve the frequency diversity effects of a multi-carrier scheme. The detailed analysis of the adaptive control will remain as future study and is not treated in this paper.

3.3 Practical Use of Transmission Power Control

The concept of transmission power control in the proposed scheme is shown in Fig. 5. When a mobile station

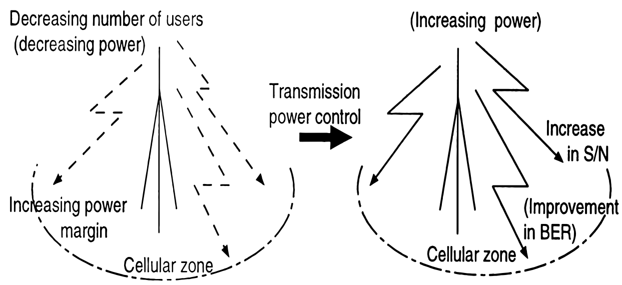

Fig. 5 Concept of transmission power control in a base station.

approaches a base station, the transmission power control system in land mobile communication systems using FDMA reduces the transmission power of the base station in that cell and surpresses the channel interference from neighboring cells. This is in contrast to IS-95 system in the USA, which employs DS-CDMA. This system is typically applied to solve the near/far problem by eliminating co-channel interference from other stations to the base station.

The transmission power control system for the new scheme is different. This scheme aims to improve signal quality for accessing users as the number of users in a cell decreases. When the number of users accessing a channel decreases, transmission power is controlled so as to maximize total bit rate capacity of accessing users. Thus, the user BER associated with the channel improves in a single cellular zone and becomes strong against frequency selective fading. Random FM degradation, difficult to reduce by frequency selective fading, cannot be compensated even if transmission power is controlled to increase S/N. However, it can be reduced by reduction of transmit power via transmission power control down the error floor.

The usual FDMA schemes always transmit carriers but do not hop them. Therefore, power flux density is not reduced and transmission power is not changed in the base station.

3.4 Adaptive Control of Hopping Pattern

An unbalance of fading frequency bandwidth for signal spectrum arises in frequency selective fading characteristics when a mobile station comes to a standstill. If bi-directional communication between a mobile station and a base station becomes possible so that adaptive hopping pattern can improve frequency diversity due to frequency characteristics, a diversity effect is further improved. Impartiality of bit rate capacity among users can be kept as important feature in this case. Adaptation waveform shaping or equalization to compensate for distortion in every channel becomes possible so that the BER improves through hopping pattern control keeping impartiality of each users.

4. Performance Analysis of Orthogonal Multi-Carrier FH-CDMA Scheme

4.1 Error Rate in a Frequency Selective Fading Environment

The BER performance of the proposed scheme can be analyzed in a manner similar to that used to analyze the performance of an OFDM scheme [11]–[14]. In this paper, we assume the multi-path Rayleigh distribution model with a delay quantity, τ, for several waves and a frequency shift relative to the Doppler frequency, f_d. The amplitude of these waves is expressed by the Rayleigh distribution.

The complex transmission signal, $s(t)$, in the proposed scheme, when all users transmit to all carriers, is expressed as

$$s(t) = \sum_{i=-\infty}^{\infty} \sum_{k=0}^{u-1} \mathrm{Real}[C_{ki} e^{j2\pi f_k (t-iT_s)}] f(t-iT_s)$$
$$f(t) = \begin{cases} 1 & 0 \le t \le T_s \\ 0 & t < 0 : t > T_s \end{cases}$$
$$f_k = f_0 + \frac{k}{T_s}, \tag{1}$$

where u is number of carriers, the T_s is symbol time, f_k is the carrier frequency, and C_{ki} is the complex amplitude for the i-th symbol of carrier k.

The received signal, $r(t)$, can be represented with the impulse response, $h(\tau;t)$, of the propagation path and Gaussian noise, $n(t)$, of the receiver as

$$r(t) = \int_{-\infty}^{\infty} s(t-\tau) h(\tau;t) d\tau + n(t). \tag{2}$$

The effect of the delay quantity, τ_l, is derived as follows. Using the analysis in Appendix A, the mean square value, $E[r_{mi} r_{mi}^*]$, of received power is given by

$$E[r_{mi} r_{mi}^*] = b_0 + \sigma_I^2 + \sigma_n^2$$
$$b_0 = \sum_{l=1}^{L} \left(\frac{T_s - \tau_l}{T_s} \right)^2 p_l$$
$$\sigma_I^2 = \sum_{l=1}^{L} \left(\frac{\tau_l}{T_s} \right)^2 p_l \cdot \left\{ \sum_{k=0}^{u-1} \mathrm{sinc}^2 \left(\frac{\pi (k-m) \tau_l}{T_s} \right) - \frac{1}{2} \right\}. \tag{3}$$

As the number of carriers increases in the above equation, the symbol time T_s becomes large for multi-path delay time τ_l. Thus, the symbol interference σ_I^2 due to multi-path decreases and the ratio of desired signal power to undesired signal power becomes advantage for BER performance.

Let us now analyse the effect of Doppler frequency shifts.

Using the analysis in Appendix B, average received power $E[r_{mi}r^*_{mi}]$ is given by

$$E[r_{mi}r^*_{mi}] = b'_0 + \sigma_c^2 + \sigma_n^2$$
$$b'_0 = 1 + \frac{(\pi f_d T_s)^2}{6}$$
$$\sigma_c^2 = \sum_{k=0,k\neq m}^{u-1} \frac{(f_d T_s)^2}{2(k-m)^2}. \quad (4)$$

As the number of carriers increases in the above equation, the symbol time T_s becomes large. In such a case, the channel interference σ_c^2 due to Doppler frequency shifts increases and the ratio of desired signal power to undesired signal power becomes disadvantages with respect to BER performance. Thus, for the proposed scheme the number of carriers should be selected so that the effect of multi-path delay time τ_l is dominant. In this paper, such propagation conditions are assumed.

Based on the variation due to drift in the parameters given by Eqs. (3) and (4), the variance of the ratio γ of the desired signal power to the undesired power is given by

$$\sigma^2 = \left\{ \left(\frac{b_0}{\sigma_n^2}\right)^{-1} + \left(\frac{b_0}{\sigma_I^2}\right)^{-1} + \left(\frac{b'_0}{\sigma_c^2}\right)^{-1} \right\}^{-1}. \quad (5)$$

The probability density function for γ is given here by the Rayleigh distribution. The probability of data errors due to frequency selective fading is described by the following error and probability density functions:

$$P(S/N) = \int_0^\infty \frac{1}{2}\mathrm{erfc}(\sqrt{\gamma})\frac{1}{\sigma^2}\exp\left(-\frac{\gamma}{\sigma^2}\right)d\gamma$$
$$S/N = \frac{b_0}{\sigma_n^2}. \quad (6)$$

4.2 Influence due to Hopping Pattern Hits

When the frequency hopping patterns of all the users are completely synchronized, there are no frequency hits among carriers. When frequency hopping patterns are asynchronous, there are frequency hits. In the new scheme, there will not, in principle, be any frequency hits because perfectly synchronous control of hopping patterns on the transmitter side is assumed to be achieved.

The frequency hit probability for hopping pattern, P_a, and that of no hit, P_s, are written as,

$$P_h = 1 - (1 - P_a, s)^{u-1} \quad (7)$$
$$P_a = \frac{1}{n}\text{(for hit)}$$
$$P_s = 0 \text{ (for no hit)},$$

where u is the number of carriers actually using carrier slots n. P_h is the frequency hit probability in the case of using the number of active carriers u in total number of carrier slots n. It is assumed that chip synchronization is completely achieved in Eq. (7) whenever the hopping pattern is asynchronous. When the hopping pattern is completely synchronous, $P_h = 0$ regardless of the value of u. However, because many mistakes are expected for asynchronous data recovery, the error rate in a chip is given by 0.5. A slow FH scheme permitted data for many binary digits to be contained in a chip. Thus, bit error rate due to hits P_c is

$$P_c = P_h \times 0.5. \quad (8)$$

When coherent detection is possible and a modulation scheme adopts QPSK, BER due to white noise and hopping pattern hit, is derived as follows. Degradation of BER performance usually caused by hopping pattern hits is minimized in the case of synchronization.

$$P_E = P_e + P_c \text{ (for hit and orthogonal)}$$
$$P_E = (1-2P_h)P_e + 2P_hP'_e + P_c$$
$$\text{(for hit and non orthogonal)}$$
$$P_E = P_e \text{ (for no hit and orthogonal)}$$
$$P_E = P'_e \text{ (for no hit and non orthogonal)}, \quad (9)$$

where P_e denotes the bit error probability that is a function of signal-to-noise ratio (S/N) in frequency selective fading. Thus,

$$P_e = P(S/N). \quad (10)$$

When orthogonality is not guaranteed, P'_e becomes a function of the spacing Δf between adjacent carrier frequencies as well. Let the influence of adjacent signal interference be A_d; then

$$P'_e = P'(S/N, \Delta f) = P(S/N/A_d). \quad (11)$$

The difference in the S/N ratio for non-orthogonal and orthogonal ($\Delta f = 1/T_s$) cases is assumed to be $A_d = 1$ dB for S/N and the performance is calculated in the section of results. Although the influence of adjacent-channel interference in non-orthogonal cases is large for the frequency interval $1/T_s$, degradation in the S/N ratio of BER becomes about 1 dB for a broad band somewhat larger than $1/T_s$. It is considered as an equivalent degradation of frequency efficiency.

4.3 Improvement Based on Transmission Power Control

Let us now discuss the improvement in signal quality brought about by transmission power control for a channel-accessing user. Figure 5 shows the concept of transmission power control (TCP) in a base station. We note that when the number of users decreases, the time average power spectrum density decreases, because the occurrence of signal power falling into a carrier slot due to frequency hopping decreases. This decreasing share of power makes up for the transmission gain achieved by the TPC which improves the signal quality of the accessing user. The ratio of carriers, u, actually becomes n at the maximum bit rate: $R_n = u/n$. This numerical ratio R_n is equivalent to the ratio of the decreasing power spectrum density. When σ_I^2 and σ_c^2, derived from the BER analysis described in Sect. 4.1, are weighted by R_n and the reciprocal of R_n is multiplied by the S/N, the signal BER under transmission power control can be calculated.

4.4 Improvement Based on Forward Error Correction

Furthermore, it expected that Forward Error Correction (FEC) codes will improve the BER of the proposed scheme in a frequency selective fading environment. Because the proposed scheme is that symbol sequence is interleaved per symbol, Reed Solomon (RS) FEC codes is selected as symbol error correction codes. Time interleaving or frequency hopping in the proposed scheme carry out a role of that it improve the effect of RS error correction in the case of convolutional and RS concatenated codes for instance.

The BER used block code like Reed-Solomon (RS) code is given by

$$P_{FEC} \approx \frac{q+1}{2q^2} \sum_{j=r+1}^{q} j \cdot \frac{q!}{(q-j)!j!} \cdot P_W^j (1-P_W)^{q-j}, \tag{12}$$

where $q = 2^b - 1$ is the block length (b is the number of bits in a symbol), p is information data length, and r is the number of correctable symbols ($q - p = 2r$) [15]. The symbol error rate P_W is written as

$$P_W = (2q)/(q+1) \cdot P_E. \tag{13}$$

In the presence of hits, the erasure decoding is very effective so that BER performance is improved [15]. Figure 6 shows a timing chart of hopping pattern with erasing hits in asynchronous. The error and erasure correcting capability of the RS code is

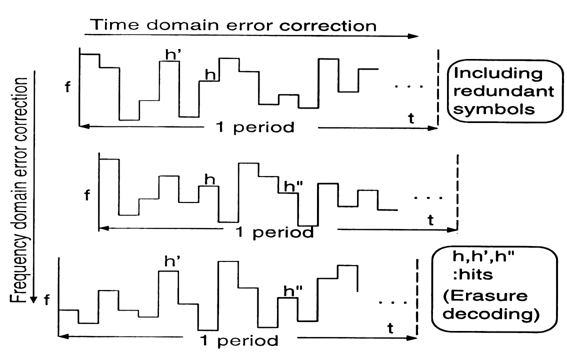

Fig. 6 Timing chart of hopping pattern with erasing hits in asynchronous.

$$2s + e + 1 \leq d, \tag{14}$$

where d is the minimum distance and s and e respectively denote the numbers of correctable errors and erasures. The BER obtained using RS code and erasure decoding is given by

$$P_{ER} \approx \frac{q+1}{2q^2} \sum_{s=0}^{q} \sum_{e=d-2s,e>0}^{q-s} \frac{q!}{(q-e-s)!e!s!} \left(s+\frac{e}{2}\right) \cdot P_h^e (P_W - P_h)^s (1-P_W)^{q-e-s}, \tag{15}$$

where ($q - p = d - 1$) is the maximum number of corrected symbols. The BER performance including erasure decoding is improved than only RS error correction so that it is shown above equation by decoding excepted symbol of hits.

5. Performance Analysis for Satellite Broadcasting Like System Including Nonlinear Amplification

We have described in previous section an analysis of the proposed scheme for frequency selective fading of land mobile communications. In this section, the analysis is applied for satellite broadcasting like system including nonlinear amplification. Satellite link is generally not multi-path condition of the Rayleigh distribution. In L, S band, it is expressed by Rice distribution. Therefore, it is expected fewer number of carrier are needed. In satellite link, the nonlinearity of the amplifier is problem. Influences of nonlinear amplification and Rice frequency selective fading are analyzed in this section.

5.1 Influence of Nonlinear Amplification

An amplifier used in satellite transponders is used to have amplitude and phase nonlinearities. Especially, in the case of satellite broadcasting, the satellite amplifier operates near its saturation point. Therefore, the signal quality degradates due to nonlinear distortion.

The output of this orthogonal multi carrier FH-CDMA scheme suffers from undesired intermodulation due to nonlinear amplification of multi carriers. This section shows the influence of third order intermodulation using third order equation as input vs. output characteristics.

If an orthogonal multi carrier FH-CDMA signal was represented as multi carriers that were not modulated, the input amplitude of nonlinear amplifier is expressed as

$$X(t) = \sum_{k=0}^{u-1} a_k \cos 2\pi f_k t, \tag{16}$$

where u is the total number of carriers, a_k and f_k denote the amplitude and frequency of the k-th carrier, respectively. Equation (16) was derived from Eq. (1)

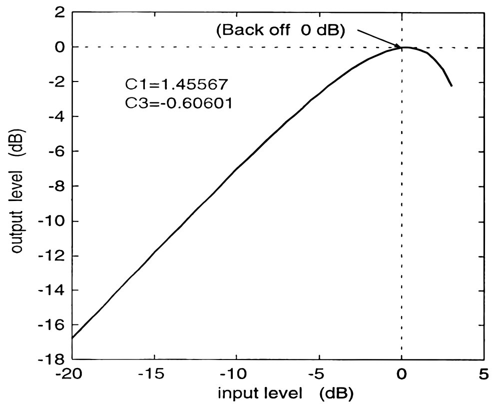

Fig. 7 Nonlinear characteristics of satellite transponder.

in the case of that multi carriers were not modulated. The factors, C_1, C_3, are set up considering up to third order.

$$Y(t) = C_1 X(t) + C_3 X(t)^3. \tag{17}$$

The output amplitude of amplifier, in the band of carriers, calculated using Eq. (16) and Eq. (17), is given by

$$\begin{aligned} Y(t) = \sum_{k=0}^{u-1} \left(C_1 a_k + \frac{3}{2} C_3 a_k \sum_{\substack{j=0 \\ (k \neq j)}}^{u-1} a_j^2 + \frac{3}{4} C_3 a_k^3 \right) \\ \cdot \cos 2\pi f_k t + \frac{3}{4} C_3 \sum_{\substack{p=0 \\ (p \neq q)}}^{u-1} \sum_{q=0}^{u-1} a_p^2 a_q \\ \cdot \cos 2\pi (2f_p - f_q) t + \frac{3}{4} C_3 \sum_{\substack{p=0 \\ (p \neq q, q \neq r, r \neq p)}}^{u-1} \sum_{q=0}^{u-1} \sum_{r=0}^{u-1} a_p a_q a_r \\ \cdot \cos 2\pi (f_p + f_q - f_r) t. \end{aligned} \tag{18}$$

The first term of this equation is the output of the desired carriers, the second and third terms are undesired intermodulation. The ratio of interference due to intermodulation and carrier power, (C/I), was calculated using above equation.

Figure 7 shows input vs. output power characteristics in the case of one carrier that calculated using Eq. (18). The back off denotes the operating point for saturation point (Back off 0 dB) of input level in Fig. 7.

5.2 Influence of Rice Frequency Selective Fading

The propagation characteristics of high frequency satellite communication are dominated by the influence of shadowing due to various obstacles. To make use good of the advantages of the orthogonal multi carrier FH-CDMA scheme for Rice frequency selective fading and multi-path delay, the use in S, L bands (about 1–4 GHz) is effective.

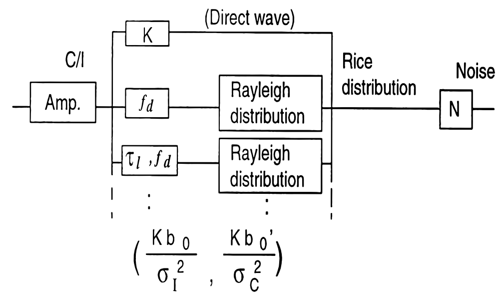

Fig. 8 Multi-path propagation model.

Figure 8 shows a model of multi-path propagation. The multi-path interference waves excepted of direct wave have Rayleigh distribution, and each waves have different delay quantity, τ_l, and the Doppler frequency shift, f_d. Total signal of direct wave and multi-path interference waves have Rice distribution, and the broadband signal suffer frequency selective fading given by delay quantity τ_l.

Applying the analysis in Sect. 4 to the Rice fading enviroment, the bit error rate of orthogonal multi carrier FH-CDMA scheme, P, is given by the following error probability functions:

$$\begin{aligned} P(N) &= \int_0^\infty \frac{1}{2} \mathrm{erfc} \left(\sqrt{\frac{\rho^2}{2N}} \right) \frac{\rho}{\sigma^2} \exp \left(-K - \frac{\rho^2}{2\sigma^2} \right) \\ &\quad \cdot I_0 \left[\frac{\rho \sqrt{2K}}{\sigma} \right] d\rho, \\ C/N &= \left\{ \left(\frac{2\sigma^2 \gamma}{N} \right)^{-1} - \left(\frac{C}{I} \right)^{-1} \right\}^{-1}, \end{aligned} \tag{19}$$

where $I_0[x]$ is the zero-th order modified Bessel function of the first kind.

The probability density function of desired signal envelope ρ is Rice distribution function, and K is the ratio of desired signal power to undesired signal power without frequency selective fading. C/I give intermodulation interference due to nonlinearty of amplifier to carrier power. σ^2 is total interference power.

The ratio of desired signal power to total undesired signal power, γ, is given by

$$\gamma = K \left\{ 1 + \left(\frac{b_0}{\sigma_I^2} \right)^{-1} + \left(\frac{b_0'}{\sigma_c^2} \right)^{-1} \right\}^{-1}, \tag{20}$$

where b_0 and b_0' are desired signal powers, σ_I^2 is symbol interference, and σ_c^2 is channel interference.

6. Results

6.1 Results for Frequency Selective Fading

BER performances in the absence of hits are shown in Fig. 9. The curves in this figure were calculated using

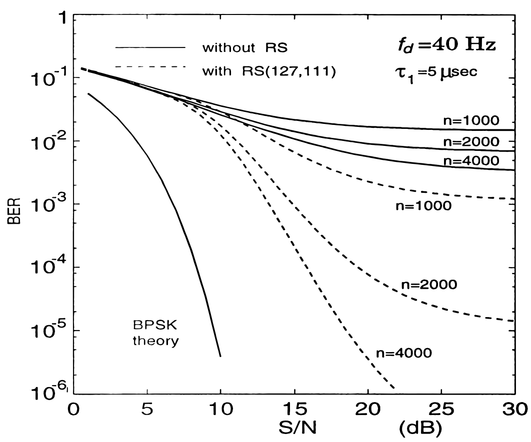

Fig. 9 BER vs. SNR in the absence of hits.

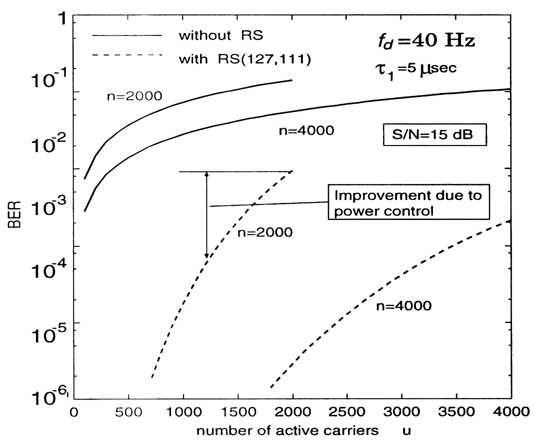

Fig. 10 BER vs. number of active carriers in the absence of hits.

Eq. (12). The bit rate in each carrier is $20/n$ (Mbps). The two wave model for the propagation path is assumed to have a maximum Doppler frequency, f_d, of 40 Hz and a delay time, $\tau 1$, of 5 μsec in 800 MHz frequency band. In this figure, the BER error floor, is less than 4×10^{-3} when the number n of carrier slots is 4000, but for 1000 slots it is 1.5×10^{-2}. Furthermore, in the case of using RS(127, 111), the BER characteristics improve remarkably such that the error floor is less than 10^{-6} when there are 4000 carrier slots. The block length and the information length of this FEC code are respectively 127 and 111 bytes. (Using RS code had long bit length that can correct burst error due to fading.) The BER is expected to improve when the number of carrier slots increases, thereby delay time effect for the symbol time decreases. Thus, because the propagation path is not frequency selective, the BER approaches the values for the Rayleigh fading environment.

Even if number of users decrease in the scheme being completely identical with OFDM scheme, all carriers continue to be transmitted. Therefore, the effect of frequency diversity degrades when the number of carriers used decreases due to a decrease in the number of users. When the number of users accessing a channel decreases in the proposed scheme, the total transmission power decreases in that band. This is because the carrier transmission not being used is stopped in the new scheme. Therefore, the signal quality for one user improves to that obtained with frequency selective fading of the propagation path when we adequately employ transmission power control in a cellular zone of a land mobile communication system.

Figure 10 shows the BER improvement of a channel accessing user brought about by the gain obtained through transmission power control without RS and with RS(127, 111) in the absence of hits. The curves in this figure were calculated using Eq. (12) and using the S/N weighted by $Rn = u/n$ in Sect. 4.3. Decreasing the number of users further improves the effect of transmission power control. This figure indicates improved BER for decreasing number of users at $S/N = 15$ dB. The BER characteristics of the modified scheme using transmission power control are compared with the error rate in the case when there is no transmission power control.

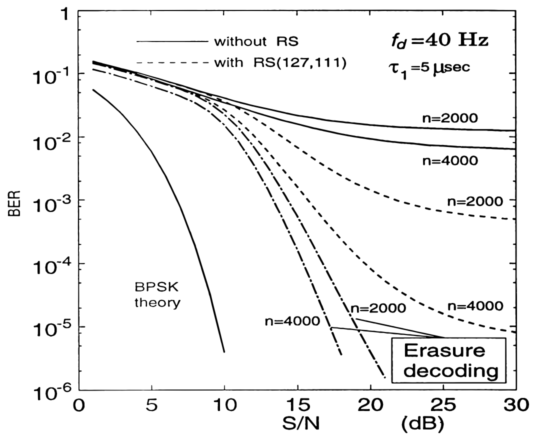

Fig. 11 BER vs. SNR in the presence of hits.

Transmission power control permits a BER of 10^{-2}. This is within the range of standard S/N in the absence of hits, even when the decrease factor of accessing carriers is comparatively low.

Transmission power control in the new scheme can clearly improve BER for users accessing in a frequency selective fading channel up to the error floor. We next need to design a system in which the reception S/N is adequate so that transmission power control can be effective.

Figure 11 shows the BER vs. SNR with RS error correcting code and erasure decoding in the presence of hits compared without FEC coding. The curves in this figure were calculated using Eq. (15). In the case of asynchronous hopping pattern, the BER due to hits can not be decreased much even if the number of user is restricted. Because the hits are regarded as erasures,

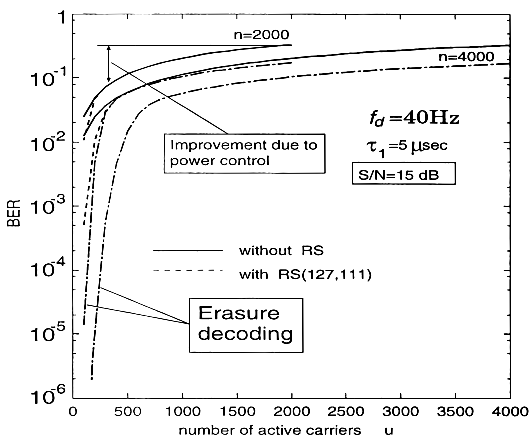

Fig. 12 BER vs. number of active carriers in the presence of hits ($Ad = 1$ dB).

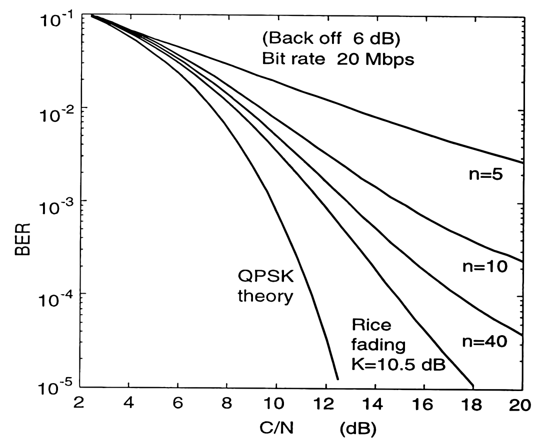

Fig. 13 BER vs. C/N performance (back off 6 dB, bit rate 20 Mbps).

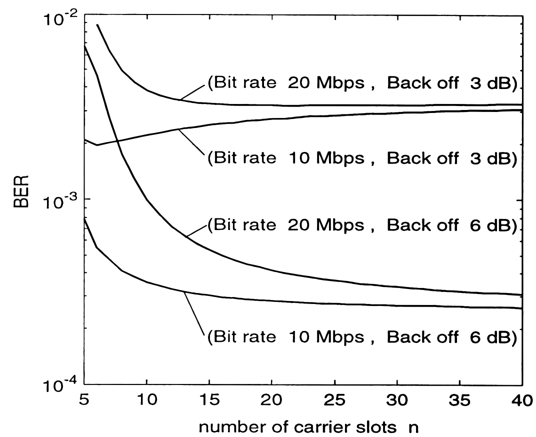

Fig. 14 BER vs. number of carrier slots performance.

the BER is improved by erasure decoding. In the figure, the BER improves from 1.5×10^{-2} without RS to 1.8×10^{-3} with RS, and furthermore it is noted that the BER can be improved from 1.8×10^{-3} with only FEC to 4×10^{-6} with FEC and erasure decoding in the carrier slot number $n = 2000$, the carrier number $u = 50$ used and $S/N = 20$ dB.

Figure 12 shows the BER improvement of power control when a channel accessing user are decreasing and the number of active carriers are decreasing. The curves in this figure were calculated using Eq. (15) and using the S/N weighted by $Rn = u/n$ as described in Sect. 4.3. In this case, the BER obtained with FEC and erasure decoding improves remarkably accoding to decrease the number of active carriers. The FEC and erasure decoding is very effective in the presence of hits like reverse link.

6.2 Results for Rice Frequency Selective Fading and Nonlinear Amplification

We calculated the BER performance of orthogonal multi-carrier FH-CDMA scheme in Rice fading and nonlinear amplification like satellite communication in the L band. The Rice fading factor, K, was assumed to be 10.5 dB so that it supposed a propagation in the L band. The delay, τ, of two waves model used a value of measurement in city, 0.4 msec. A maximum Doppler frequency shift f_d was supposed 80 Hz.

Figure 13 shows the BER vs. C/N performance with back off 6 dB of nonlinear amplifier in bit rate 20 Mbps. The curves in this figure were calculated using Eqs. (19) and (20). The number of carriers u was assumed to be equal to the number of carrier slots n. The BER improves according as the number of carrier slots n is increased from 5 to 40, and nearly performance in Rice fading. This result presents the effect of using multi-carrier in this scheme.

Figure 14 shows BER vs. the number of carrier slots in the back off 3 dB and 6 dB, the bit rate 10 Mbps and 20 Mbps. The curves in this figure were also calculated using Eqs. (19) and (20). The C/N setting is 15 dB. The BER performance is including intermodulation interference due to nonlinear amplification. Because this intermodulation interference plays a dominant role in the BER degradation at back off 3 dB, the effect to increase number of carrier slots is not much reflected in the improvement of BER. The back off should be set a effective value to multi-path with increasing number of carrier slots in link budget.

7. Conclusion

This paper has introduced an orthogonal multi-carrier FH-CDMA scheme in which the carrier signals have orthogonality with each other, as in OFDM, and hop on the frequency domain. The proposed scheme achieves high performance against multi-path and frequency-selective fading. It also provides privacy and efficient utilization of the frequency spectrum by combining the advantages of OFDM and FH-CDMA schemes. We theoretically analysed BER performance theoretically, including analysis of frequency selective fading and nonlinear amplification. In doing so, these analysis confirmed that this scheme is effective in frequency selective fading circumstances. Moreover, we have discussed a modified scheme in which that transmission power can be controlled according to the number of simultaneously accessing users. This modification improves BER performance in terms of frequency selective fading when the number of simultaneously accessing users in a cellular zone is small. Furthermore, performance improvement in reverse links is evaluated if an error-correcting code and its erasure decoding are applied. This research indicates that the proposed scheme will help to overcome the severe conditions of restricted frequency bandwidth in land mobile communication systems and satellite communication systems using the S and L bands.

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Appendix A: The Effect of Delay Qquantity, τ_l

Impulse response, $h(\tau;t)$, of the propagation is given by

$$h(\tau;t)=\sum_{l=1}^{L}h_l\delta(\tau-\tau_l). \tag{A$\cdot$1}$$

A sample of the demodulated signal of the m-th carrier at a given instant, derived from the above expression, is represented by

$$\begin{aligned}r_{mi}&=\frac{1}{T_s}\int_{iT_s}^{(1+i)T_s}r(t)e^{j2\pi f_m(t-iT_s)}dt\\&=C_{mi}\sum_{l=1}^{L}\frac{T_s-\tau_l}{T_s}h_le^{j2\pi f_m\tau_l}\\&\quad-\sum_{l=1}^{L}\sum_{k=0,k\neq m}^{u-1}\frac{\tau_l}{T_s}h_le^{j2\pi f_k\tau_l-j\pi(k-m)\tau_l/T_s}\\&\quad\times\mathrm{sinc}\left(\frac{\pi(k-m)\tau_l}{T_s}\right)C_{ki}\\&\quad+\sum_{l=1}^{L}\sum_{k=0}^{u-1}\frac{\tau_l}{T_s}h_le^{j2\pi f_k(\tau_l-T_s)-j\pi(k-m)\tau_l/T_s}\\&\quad\times\mathrm{sinc}\left(\frac{\pi(k-m)\tau_l}{T_s}\right)C_{k(i-1)}+n_{mi}.\end{aligned} \tag{A$\cdot$2}$$

When $|C_{ki}|=|C_{k(i-1)}|=1$, the mean square value, $E[r_{mi}r_{mi}^*]$, of received power is given by

$$\begin{aligned}E[r_{mi}r_{mi}^*]&=b_0+\sigma_I^2+\sigma_n^2\\b_0&=\sum_{l=1}^{L}\left(\frac{T_s-\tau_l}{T_s}\right)^2p_l\\\sigma_I^2&=\sum_{l=1}^{L}\left(\frac{\tau_l}{T_s}\right)^2p_l\\&\quad\cdot\left\{\sum_{k=0}^{u-1}\mathrm{sinc}^2\left(\frac{\pi(k-m)\tau_l}{T_s}\right)-\frac{1}{2}\right\}.\end{aligned} \tag{A$\cdot$3}$$

Appendix B: The Effect of Doppler Frequency Shifts

The symbol $g(t)$ represents a complex Gaussian random process. An impulse response, $h(\tau;t)$, of a propagation path of this type is shown by

$$h(\tau;t) = g(t)\delta(\tau). \qquad \text{(A}\cdot 4)$$

The correlation function $R(\tau)$ of $g(t)$ becomes a function of the maximum Doppler frequency f_d in land mobile propagation paths. Thus,

$$R(\tau) = \frac{1}{2}E[g(t+\tau)g(t)^*] = \alpha J_0(2\pi f_d \tau)$$
$$\simeq \alpha\{1-(\pi f_d \tau)^2\}, \qquad \text{(A}\cdot 5)$$

where $J_0()$ is the zero-th order Bessel function, α is the average of received power and $\alpha = 1$. Therefore,

$$r_{mi} = \frac{1}{T_s}\sum_{k=0}^{u-1} C_{ki}\int_0^{T_s} g(t)e^{-j2\pi(m-k)t/T_s}dt + n_{mi}. \qquad \text{(A}\cdot 6)$$

Average received power $E[r_{mi}r_{mi}^*]$ is given by

$$E[r_{mi}r_{mi}^*] = b_0' + \sigma_c^2 + \sigma_n^2$$
$$b_0' = \frac{1}{T_s^2}\int_0^{T_s}\int_0^{T_s} R(\xi-\eta)d\xi d\eta$$
$$= 1 + \frac{(\pi f_d T_s)^2}{6}$$
$$\sigma_c^2 = \sum_{k=0,k\neq m}^{u-1}\frac{1}{T_s^2}\int_0^{T_s}\int_0^{T_s} R(\xi-\eta)$$
$$\times e^{-j2\pi(m-k)(\xi-\eta)/T_s}d\xi d\eta$$
$$= \sum_{k=0,k\neq m}^{u-1}\frac{(f_d T_s)^2}{2(k-m)^2}. \qquad \text{(A}\cdot 7)$$

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