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# Digital Terrestrial Television Transmission over OFDM/FM Using Satellite Communications System

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## SUMMARY

The new digital terrestrial television transmission signals use the OFDM system. This system has the fundamental problem that the peak power to average power ratio (PAPR) of the signal is significant. In this paper, a satellite communication system is proposed as a supplemental network for digital terrestrial broadcasting. It is shown that effective use of the satellite power becomes possible at a large PAPR by using the FM system with a constant signal envelope as the secondary modulation, so that the problem can be resolved. It is shown analytically that a larger FM gain can be obtained by limiting the peak voltage of the OFDM signal by clipping. The degradation of the BER caused by clipping is derived by simulation and the system is optimized with regard to the degree of clipping. Taking the size and operational cost of the receiving station into account, channel design is performed assuming a real satellite channel. The overall transmission characteristics such as the transmission capacity of the satellite repeater and the channel quality are discussed. © 2007 Wiley Periodicals, Inc. Electron Comm Jpn Pt 2, 90(11): 74–84, 2007; Published online in Wiley InterScience (www.interscience.wiley.com). DOI 10.1002/ecjb.20385

**Key words:** digital television transmission; OFDM; FM; PAPR; satellite communication.

## 1. Introduction

Since the end of 2003, digital terrestrial television broadcasting has started in major cities of Japan. It is planned to expand the system to the entire country by 2006. Further, all analog broadcasting is scheduled to cease in 2011. Due to the public nature of broadcasting, the service area is required to cover the entire territory Japan, including remote locations such as islands and mountain regions. Accomplishing such a goal is difficult if only terrestrial broadcasting is used. To resolve the problem, various methods have been discussed in which remote relaying is performed by optical fibers and satellite communications, followed by rebroadcasting [1]. In this paper, a relay system based on satellite communications is proposed and its effectiveness is presented. In this case, the system must not affect the configurations of existing broadcasting transmitters and widely used television receiver sets. Transparency of the satellite relay sections must be maintained.

The modulation scheme at the wireless frequency for digital terrestrial television broadcasting is OFDM (Orthogonal Frequency Division Multiplexing) [2]. In this scheme, high-speed data signals are divided into many carriers for transmission. Therefore, the transmission speed per wave becomes lower and the scheme has a frequency diversity effect. Another advantage is that it is tolerant to multipath fading. In contrast, since the signal is formed by superposition of many synchronized carriers, large peaks appear in the waveform, so that the so-called PAPR (peak-to-average power ratio) becomes very large. This is not a significant problem for the transmitters used in terrestrial broadcasting, because a high-power amplifier can be used. But when this signal is transmitted by a satellite repeater with limited power, deterioration of the transmission characteristics and spreading of the output spectrum occur due to waveform distortion. To suppress these effects, sufficient backoff is needed, so that the power efficiency of the satellite is significantly degraded. Much research has recently been conducted on reduction of the PAPR of OFDM signals, including research by the present authors, Carrier Interferometry (CI)/OFDM [3, 4], and Fourier Spreading (FS/OFDM) [5–7]. But these methods cannot be used because they cannot align to the systems in operation. The reason is as follows. In CI/OFDM, the information on each symbol of the input data is distributed to all carriers. Therefore, the transmitter configuration is different from that in the conventional OFDM scheme, in which each symbol of the data is distributed to each carrier. As a result, the configuration of a receiver with the inverse functionality is substantially different from that used in commercially available digital terrestrial television receivers.

To transmit digital television signals via satellite, it is conceivable to use transmission with PSK modulation in the satellite section to allow the use of many channels, then to retransmit (broadcast) on the receiving side in a remote area after conversion to OFDM. In that case, however, the remotely located station must be equipped with a broadcasting setup for retransmission, such as a PSK demodulator and OFDM modulator, so that the size and configuration of the station become larger and more complicated. In this paper, to simplify and miniaturize ground station and the configuration of rebroadcast setups in disadvantaged remote locations, an FM system with a constant signal envelope is used in secondary modulation for the modulation scheme in the satellite section, and the signal is reconverted to OFDM on the receiver side. There have been previous investigations of the OFDM/FM system [8–11], but there is no research on the transmission characteristics in a system with nonlinearity in the transmission side. The system proposed in this paper, which has no amplitude components, can be used up to the saturation region of the satellite repeater. However, even with this system, the bandwidth of the FM signal is increased by the peak of the OFDM signal if the OFDM signal is directly applied to the FM modulator. Therefore, the peak of the OFDM signal is limited by clipping. In this case, the deterioration of the BER of the OFDM signal increases as the degree of clipping is deepened. Also, in the FM system, the overall transmission characteristics are determined by the bandwidth of the FM signals, which depends on that of the satellite repeater, and by the modulation index of the FM signals. Therefore, it is necessary to optimize the system by a trade-off of these factors.

In this paper, the relationship between the degree of clipping and the BER of the OFDM signals is derived and the FM gain, derived from the bandwidth of the OFDM signal and the bandwidth of the FM signals considering clipping, is computed. In this way, an optimum clipping level is derived. In the conventional theoretical calculation of the FM gain, the input signal is often assumed to be a sinusoidal wave with a small PAPR (3 dB) [12]. However, it is considered inappropriate to apply this approach directly to OFDM signals with a large PAPR, so that most of the power is concentrated at or below the average value. In this paper, the concept of the PAPR of the OFDM baseband signal is introduced into the calculation of the FM gain. It is shown that the FM gain becomes larger even with the same bandwidth if the PAPR is reduced. First, in Section 2 the configuration of the proposed system is described. The relationship between the peak voltage of the OFDM signal and the bandwidth of the FM signal is shown. In Section 3, the PAPR when the OFDM signals are clipped is derived by simulation and the spectral spreading of the OFDM signals due to clipping and the BER characteristics are evaluated. In Section 4, the transmission characteristics of the FM modulation scheme for a signal with large PAPR are theoretically analyzed. In Section 5, optimization of the clipping is discussed in terms of the FM gain determined from the bandwidth of the FM signal and the peak voltage of the OFDM signals. Also, in Section 6, channel design assuming a real satellite is performed for both the OFDM/FM system proposed in this paper and the direct transmission of the OFDM, and the two are compared. Conclusions are provided in Section 7.

## 2. System Configuration

The proposed system configuration is shown in Fig. 1(a). On the transmitter side, the output of the existing OFDM modulator is applied to the FM modulator. The relay section is the satellite channel using FM signals. At the receiving ground station, the secondary modulation is removed by FM demodulation and then the signal is broadcast by the terrestrial broadcast network. Hence, in the present system, the path from FM modulation to FM demodulation via the satellite channel is transparent in function, although a certain effect on the overall transmission characteristics is permitted.

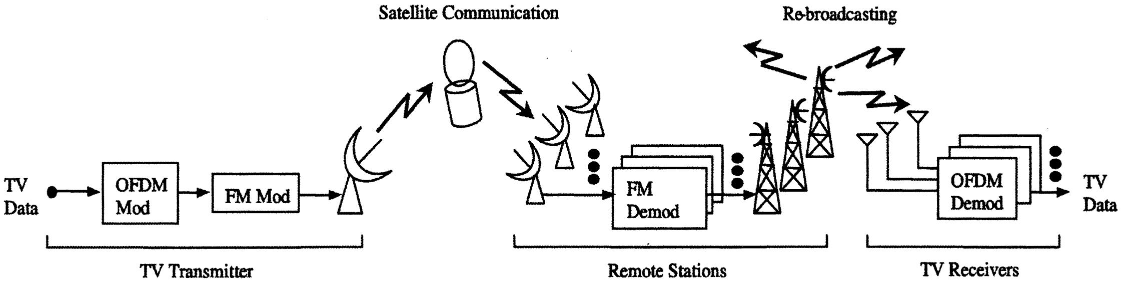
In Ref. 2, the bandwidth of the OFDM signals is specified as 5.572 to 5.575 MHz. Here, it is assumed to be 6 MHz. The bandwidth of the FM signals in the present system depends on the peak voltage of the OFDM signal or the PAPR. The one-side maximum frequency shift of the FM signal is expressed as follows [12]:

$$\Delta f = V_{max} \times \frac{k_f}{2\pi} \tag{1}$$

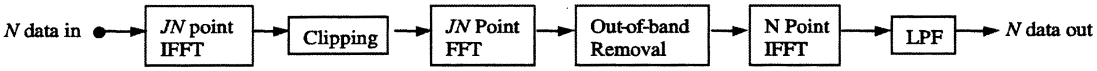
Here $V_{max}$ is the peak voltage of the OFDM signal within one symbol and $k_f$ is a system parameter. The relationship between $V_{max}$ and the PAPR is given by

$$PAPR_{(0 \le t < T)} = \frac{P_{max}}{P_{avg}} = \frac{V_{max}^2}{\sigma^2} \tag{2}$$

$$V_{max} = \sigma \times \sqrt{PAPR} \tag{3}$$



(a) OFDM/FM transmission over satellite communications system



(b) OFDM clipping with oversampling factor of $J$ and filtering

Fig. 1. OFDM/FM television over satellite transmission system.

Here $T$ denotes one symbol length of the OFDM and $\sigma$ is the rms (root mean square) value of the OFDM signal. From Eqs. (1) and (3), we obtain

$$\Delta F = \sigma \times \sqrt{PAPR} \times \frac{k_f}{2\pi} \tag{4}$$

Equation (4) states that the maximum frequency shift of the FM signals is proportional to the rms amplitude of the OFDM signals and the square root of the PAPR. Next, let us describe the clipping of the OFDM signals. Figure 1(b) shows a configuration using filtering to produce out-of-band spectral suppression, and clipping by oversampling (with a sampling factor of $J$). When the PAPR of the analog signal is derived, the peaks to be clipped between the sample intervals may be overlooked if the number of samples is too small. Therefore, it is necessary to make this value as large as possible in realization. If $J$ is large, the PAPR in the presence of clipping can be evaluated accurately. Hence, the PAPR of the clipped OFDM signals depends on the magnitude of the oversampling factor $J$. For instance, if $J = 1$, this becomes sampling at the Nyquist frequency [13, 14]. In Fig. 1(b), $N$ denotes the number of carriers of the OFDM signals. After taking the inverse fast Fourier transform (IFFT) with $J \times N$ points, clipping is applied. Since clipping is a nonlinear operation, the spectra of the signal broaden. Therefore, the results are reconverted by the fast Fourier transform (FFT) with $J \times N$ points. Then these components are suppressed by filtering.

## 3. PAPR of OFDM Signals and Transmission Characteristics

### 3.1. PAPR

If the OFDM signal is $s[n] = r[n]e^{j\phi[n]}$, the amplitude components after clipping with a voltage $A_{max}$ are

$$\begin{aligned} r_c[n] &= r[n], \text{ for } r[n] \leq A_{max} \\ &= A_{max}, \text{ for } r[n] > A_{max} \end{aligned} \tag{5}$$

Hence, the $n$-th sampled value of the clipped signal is given by $s_c[n] = rc[n]e^{j\phi[n]}$. In this paper, a soft limiter in which phase rotation can be neglected is assumed as the element for clipping [14]. Also, as the degree of clipping, the clipping ratio (CR) is defined as

$$CR = \frac{A_{max}}{\sigma} \tag{6}$$

where $\sigma$ is the mean square value of the OFDM signal level.

For instance, CR = 1.4 denotes the case in which the maximum level of the clipped signal is about 3 dB higher than the average level. As described in Section 3.2, a bandpass filter is used after the clipping to suppress the out-of-band spectrum caused by clipping. Therefore, a peak larger than the clipping level appears due to the waveform response. Although clipping can reduce the PAPR, the PAPR of the filter output signal is larger than the value determined from CR.

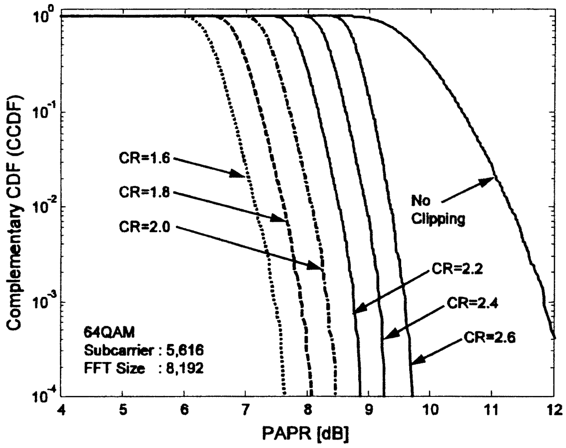
Table 1 lists the parameters used in the computer simulation carried out for evaluation of various charac-

Table 1. Simulation conditions

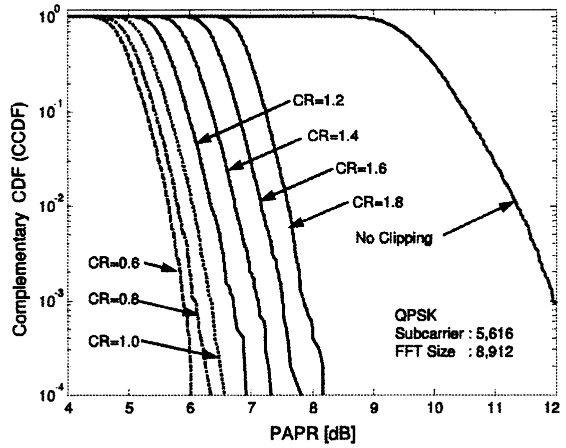
| Parameters | Values |
|---|---|
| Modulation | QPSK, 64QAM |
| FFT Size | 8,912 |
| Number of Subcarriers | 5,616 |
| Oversampling Factor (J) | 1,4587 |
| Length of Guard Interval (GI) | 702 (ISDB-T Mode 3) |
| Channel Model | AWGN |
| Clipping Ratio (CR) | 0.8~2.6 |
| BW of Sat. Transponder | 36 MHz |
| BW of OFDM for Dig. TV | 6 MHz |

teristics of the PAPR and those after clipping. As the modulation format for the OFDM signals, the 64QAM reference in the specification of the digital terrestrial broadcast services in Japan and the QPSK for comparison are used.

The PAPR after clipping and filtering is calculated by Eq. (2). Figure 2(a) shows the CCDF (Complementary Cumulative Distribution Function) of the PAPR for the case of 64QAM for several values of CR. Also shown in Fig. 2(a) is the PAPR distribution in the absence of clipping. As a sampling factor $J$, we use the commonly employed value of $J = 1.4587$. As the clipping becomes deeper, the PAPR can be made smaller. Since the amplitude components contain information in QAM format, increased degradation of the BER is expected due to signal distortion. This will be discussed later. Figure 2(b) shows the PAPR values when QPSK is used as a modulation format. Since the amplitude components are smaller in QPSK than in QAM, it is possible to use deeper clipping (with a smaller CR) and a substantial improvement of the PAPR is expected.



(a) PAPR Performance of 64QAM for various CR



(b) PAPR Performance of QPSK for various CR

Fig. 2. Relationship between PAPR and clipping ratio (CR).

### 3.2. Out-of-band radiated power

By the nonlinear operation of clipping, the spectrum of the OFDM signal is spread outside the bandwidth (spectrum broadening), and the signal power within the bandwidth is decreased accordingly. Figure 3 shows the signal spectrum power densities immediately after clipping and after filtering. From Fig. 3, it is found that the out-of-band power density increases to 33 dB at maximum. When FM modulation is considered as secondary modulation, as in the present system, the bandwidth spread of the OFDM signal, which is the first modulated wave, equivalently decreases the FM modulation index and the FM gain is reduced. For suppression of the out-of-band power, use of an FIR (Finite Impulse Response) time domain filter with 103 taps is assumed in Ref. 13. It is likely that the structure will be complicated in practice. On the other hand, the method used in this paper is to suppress the out-of-band components by filtering (FDF: Frequency Domain Filtering [15], with an FFT size of 8192). Since the ideal filter is difficult to be realized and the FFT size is finite in real computations, the power components outside the bandwidth still remain. However, the spectrum density almost identical to that without clipping can be obtained.

### 3.3. BER performances

The transmission characteristics of the present system must be evaluated by the entire path sequence in the receiving system with OFDM-clipping, and FM modulation and demodulation. Of these, FM modulation and demodulation are essentially linear with regard to the amplitude of the transmit signals. The BER degradation due to the distorted signals can be evaluated by the effect of clipping in the OFDM signal. The effect of FM modulation

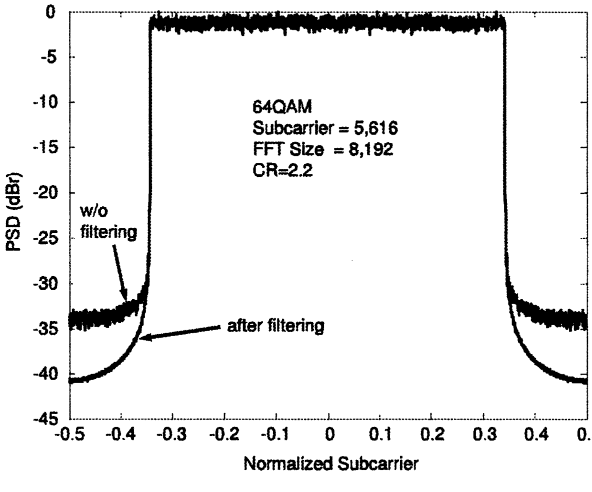
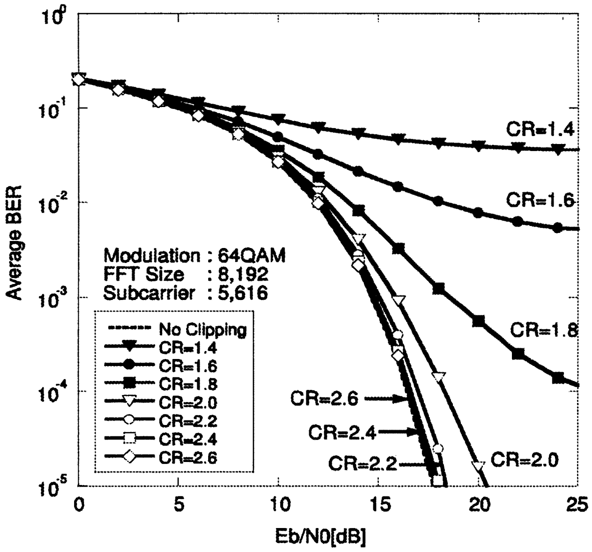


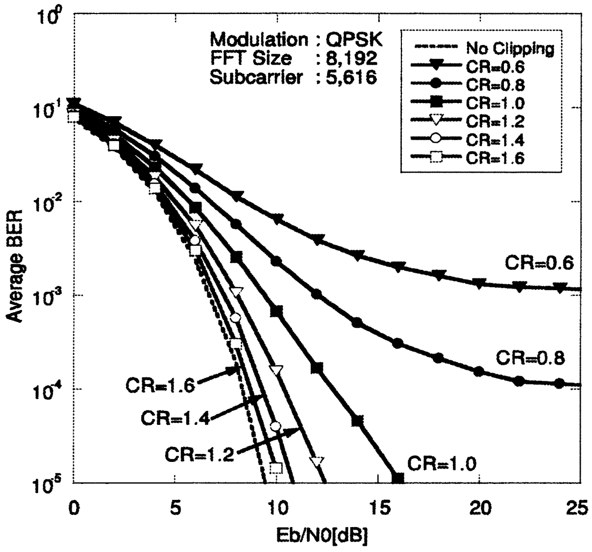
Fig. 3. Power spectrum density of clipped OFDM.

is evaluated, as noted later, from the relationship between the received C/N (carrier-to-noise ratio) in the wireless channel and the S/N (signal-to-noise ratio) of the FM demodulator.

The OFDM signal is subject to waveform distortion that causes BER degradation as well as an increase in the out-of-band spectrum by clipping. Further, additional degradation is caused by filtering. The BER characteristics are derived for several values of CR and the results are shown in Fig. 4. Figure 4(a) presents the results for 64QAM and (b) the results for QPSK. From Fig. 4(a), it is seen that the effect of clipping is significant in 64QAM, as expected. The degradation of the BER is very substantial when CR is less than 2.0. On the other hand, it is found from Fig. 4(b) that CR can be reduced to 1.4 in QPSK. This is because QAM contains much information in its amplitude.



(a) BER performance of 64QAM



(b) BER performance of QPSK

Fig. 4. BER performance of 64QAM and QPSK with various clipping ratios.

## 4. FM Modulation and Demodulation

### 4.1. S/N at FM demodulator

Figure 5 shows an example of the waveform and instantaneous power when clipping is applied or not applied to the OFDM signal. In Fig. 5, A indicates the waveform with CR = 0.5, B indicates that with CR = 1.5, and C indicates that without clipping. As described above, the maximum frequency shift of the FM signal is dependent on the voltage peak of the input signal. According to Eq. (4.75) in Ref. 12, if the modulation signal is $m(t)$, the power of the demodulated signal is given by

$$S_0 = \left(\frac{k_f}{2\pi}\right)^2 \overline{m^2(t)} \tag{7}$$

Here $k_f$ is the system constant of the FM modulator.

When the baseband signal is assumed to be sinusoidal, the signal power in the FM demodulator output is as follows, according to Eq. (4.91) of Ref. 12:

$$S_0 = \frac{\Delta F^2}{2} \tag{8}$$

However, in the case of a waveform which has impulsive peaks, as in the OFDM, it is difficult to use Eq. (8) directly, and the following treatment is considered. With reference to Eq. (4.90) in Ref. 12, in which the modulation signal is treated as a sinusoidal wave, it is considered that the following equation holds in general for nonsinusoidal waves such as that of the OFDM as a modulation signal.

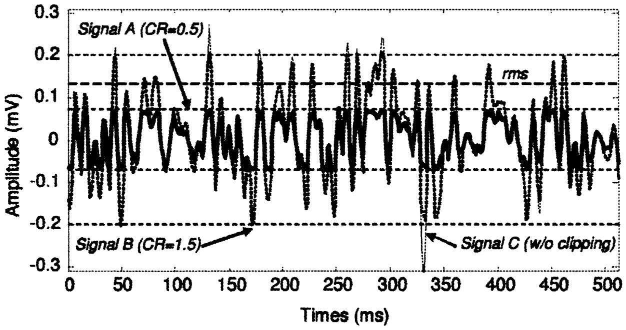


Fig. 5. Waveform of OFDM signals with and without clipping.

Let us replace $\cos 2\pi f_m t$ on the right-hand side of Eq. (4.90) in Ref. 12 with $A(t)$, obtaining

$$\frac{k_f}{2\pi} m(t) = \Delta F \times A(t)$$

$$\text{that is,}\ \ m(t) = \left(\frac{2\pi}{k_f}\right) \Delta F \times A(t) \tag{9}$$

Here $A(t)$ is an OFDM modulation signal. Hence, the average power of the FM demodulated signal is obtained from Eqs. (7) and (9) as

$$\begin{aligned} S_{0OFDM} &= \left(\frac{k_f}{2\pi}\right)^2 \overline{m^2(t)} \\ &= \Delta F^2 \times \overline{A^2(t)} \end{aligned} \tag{10}$$

From the definitions of the average power and peak power of the OFDM signal and the PAPR, we have

$$\overline{A^2(t)} = \frac{1}{PAPR} \tag{11}$$

Here the peak voltage of $A(t)$ is assumed to be normalized to 1.0. Therefore, by Eq. (10),

$$S_{0OFDM} = \Delta F^2 \times \frac{1}{PAPR} \tag{12}$$

If it is taken into account that the PAPR of the sinusoidal wave is 2, Eq. (12) may be considered as a generalization of Eq. (8) that is derived with the modulation signal as a sinusoidal wave. From Eqs. (12) and (4.88) of Ref. 12, the S/N of the OFDM signal of the FM demodulator output is

$$\begin{aligned} \left(\frac{S}{N}\right) &= \left(\frac{3B}{f_m^3}\right)\left(\frac{\Delta F^2}{PAPR}\right)\left(\frac{C}{N}\right) \\ &= \left(\frac{3 \times 2(\Delta F + f_m)}{f_m^3}\right)\left(\frac{\Delta F^2}{PAPR}\right)\left(\frac{C}{N}\right) \\ &= \frac{6}{PAPR}\beta^2(\beta+1)\left(\frac{C}{N}\right) \end{aligned} \tag{13}$$

where $\beta$ is the modulation index, such that $\beta = \Delta F/f_m$, where $f_m$ is the bandwidth of the OFDM. Also, the bandwidth $B$ of the FM signal is obtained from Eq. (4.46) in Ref. 12 as

$$B = 2(\Delta F + f_m) \tag{14}$$

The above can easily be predicted physically from the power distribution of the OFDM signal. However, in contrast to the conventional analysis of the FM gain using sinusoidal waves, which are easily treated, the present method considers the PAPR, so that the method is effective for quantitative evaluation of the FM gain for arbitrary signals, such as OFDM.

### 4.2. Satellite occupancy bandwidth and the received S/N

For ground stations installed on remote islands, it is desirable to make this size as small as possible for economy of operation. Also, if the high C/N required for the 64QAM-OFDM demodulation is considered, the system is expected to be power-limited. Under this assumption, secondary modulation by FM is used because it can increase the power by the use of the bandwidth. The case of using the total bandwidth of the satellite repeater per channel to make the FM gain greater is compared with the case in which half the bandwidth is used.

In the FM modulation format, the modulation index can be made larger by taking a frequency shift that is larger with respect to the bandwidth of the input signal. In this way, a larger FM gain can be obtained.

On the other hand, the bandwidth $B$ of the FM signal is expressed by Eq. (14). Therefore,

$$\Delta F = \frac{B}{2} - f_m \tag{15}$$

The allowable FM bandwidth $B$ is determined by the use conditions of the satellite repeater. If the bandwidth of the satellite repeater is 36 MHz and one FM signal wave is transmitted with the entire bandwidth of the repeater (Case 1), $B$ = 36 MHz. If half the bandwidth is used (Case 2), $B$ = 18 MHz. Therefore, $\Delta F$ is 12 MHz in Case 1 and 3 MHz in Case 2. Hence, the modulation index for each case is

$$\begin{aligned} \beta &= 12/6 = 2\ (\text{ case } 1) \\ \beta &= 3/6 = 0.5\ (\text{case } 2) \end{aligned} \tag{16}$$

When the input C/N is sufficiently large (more than 10 dB), the relationship between the S/N in the FM demodulator output and the input CN ratio is shown above as being given by Eq. (13). From Eqs. (16) and (13), the relationships between the S/N and the C/N for Cases 1 and 2 above are

Case 1:

$$\begin{aligned} \left(\frac{S}{N}\right)_1 &= \frac{72}{PAPR} \times \frac{C}{N} \\ &= \left(\frac{C}{N}\right)_{dB} + 18.6 - PAPR(\text{dB}) \end{aligned} \tag{17}$$

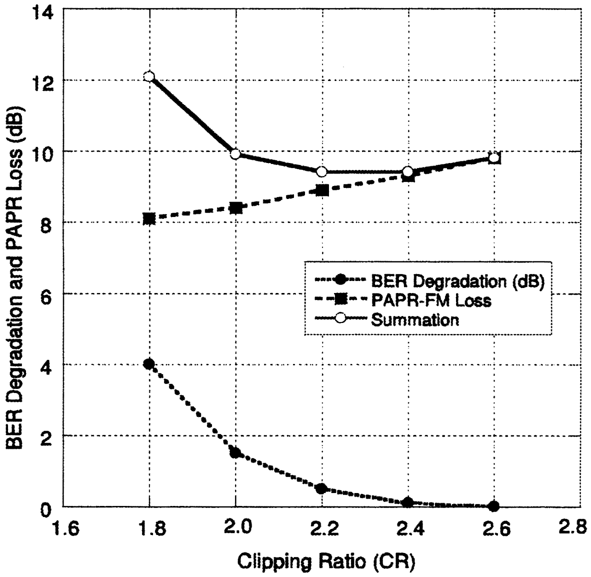
Case 2:

$$\begin{aligned} \left(\frac{S}{N}\right)_2 &= \frac{2.25}{PAPR} \times \frac{C}{N} \\ &= \left(\frac{C}{N}\right)_{dB} + 3.5 - PAPR(\text{dB}) \end{aligned} \tag{18}$$

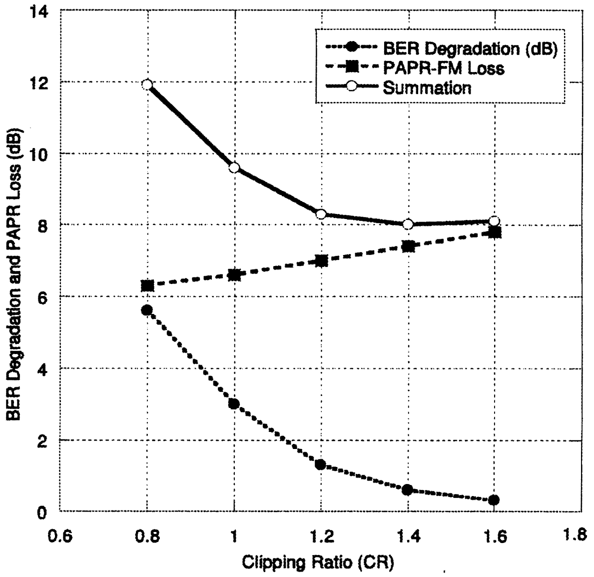
From Eqs. (17) and (18), it is found that the S/N at the FM demodulator output, namely, the S/N of the OFDM receiver signal, is smaller by the magnitude of the PAPR in this system. Also, a difference of about 15 dB is noticed in different use conditions of the bandwidth of the satellite receiver, namely, one wave/transponder, or one wave/half transponder. The ratio of (C/N) and (S/N) given by Eq. (17) or (18) is the FM gain in the proposed system.

## 5. System Optimization

In Section 3, the variations of the PAPR in the presence of the clipping to the OFDM signal and the degradation of the BER due to the waveform distortion are derived. It is found that the degradation of the BER is more significant, and the PAPR is improved, if the clipping is deeper (or the CR is smaller). The effect is more significant in 64QAM than in QPSK. Further, in Section 4, the relationship between the output S/N of the FM demodulator and the PAPR is presented. It is shown that the S/N is reduced by the PAPR (called S/N loss and PAPR-FM loss). From these relationships, it is demonstrated that the magnitude of clipping is in contradiction with the BER and S/N characteristics.



(a) 64QAM



(b) QPSK

Fig. 6. BER degradation and PAPR-FM loss as a function of CR.

Let us discuss how to select the CR for the entire system. Figures 6(a) and 6(b) show the BER degradation, the S/N loss by the PAPR, and their sum for 64QAM and QPSK as functions of CR. As the BER degradation, that of the equivalent $E_b/N_0$ is used at a BER of $10^{-3}$, which is the threshold value of the bit error rate before error correction that is widely used for OFDM reception and mobile communication demodulation. First, it is found from Fig. 6(a) that the sum of the two quantities almost always tends to decrease with an increase in the CR up to the vicinity of CR = 2.4 in 64QAM. As Fig. 6(b) shows, the sum approaches the minimum at about CR = 1.4 for QPSK. Hence, in each system, CR = 2.4 is chosen for the former and CR = 1.4 for the latter for the minimum total degradation. Then, the value of the PAPR directly affecting the FM gain described in Section 4 is about 9.3 dB for 64QAM and 7.4 dB for QPSK. When these values are assigned in Eqs. (17) and (18), the FM gain for Case 1 is 9.3 dB for 64QAM and 11.2 dB for QPSK, while they are –5.8 dB for 64QAM and –3.9 dB for QPSK for Case 2.

The degradation of the BER is 0.1 dB for 64QAM and about 0.5 dB for QPSK for their optimum CR values.

## 6. Channel Design (Noise Budget)

By using the results up to Section 5, channel design was performed for an OFDM/FM system transmitting over a satellite channel and its effectiveness was verified. The channel design was performed only for 64QAM, which is actually used for digital terrestrial broadcasting. The satellite used for channel design was assumed by way of example to be JCSAT-1B. The case of one-wave transmission of OFDM/FM wave in the bandwidth of 36 MHz (Case 1 in Section 4) and the case of two-wave transmission (Case 2) were studied. In addition, channel design was performed for an OFDM signal transmitted directly without FM modulation (Case 3). Three cases were compared from the operational point of view. In order to perform comparison under the same conditions, the aperture of the transmitting antenna of the ground station was 4.5 mϕ and the receiving antenna aperture was 3.6 mϕ for all cases. With regard to the location of the station in the channel design, studies are needed for various locations over the country, including remote islands, based on the antenna beam shape and rainfall data. In the present design, calculations were performed for a transmitting station in Tokyo and a receiving station at Hachijojima Island as an example.

On the other hand, the satellite repeater amplifier can be operated at its saturation point by taking advantage of the constant amplitude for the FM signals in Case 1. Also, for Case 2, half the satellite power (–3 dB) is assigned per wave. In order to reduce intermodulation due to multiple carrier transmission, a further backoff of 3 dB (with a total output backoff of 6 dB per wave) was assumed. Further, for Case 3, the output backoff was assumed to be that of the PAPR value (9.3 dB at CCDF of $10^{-4}$) of the OFDM signal after clipping. Note that in Case 3 the bandwidth of the repeater is only 6 MHz. The total power other than the backoff was assigned. There are two conceivable ways to set the operating point of the satellite amplifier. In one approach, the satellite receiving power is made constant while the gain of the satellite amplifier is varied. In the other, the transmitting power of the ground station is reduced. Here, the latter method, which can be controlled for each carrier, was applied. Also, in this method, the transmitted power of the ground station can be made smaller at the time of backoff.

Table 2 shows the distribution of the signal power and the noise power from transmission at the ground station to reception by another ground station via a satellite. The present distribution is in accordance with the usual channel design method for satellite communications [17]. The upper portion of Table 2 indicates the uplink C/N, the middle portion shows the downlink C/N, and the lower portion presents the overall C/N and the S/N of the OFDM demodulator. Also shown in ②, in the lower portion, is the downlink rainfall margin (according to the ITU-R Recommendation) needed to guarantee a nonoperational rate of 0.05% (in terms of time, a total of about 4 hours in which the rain attenuation exceeds the specified margin over the year). The

Table 2. Comparison between three systems through satellite communications

| | 1) OFDM-FM Carrier /Transponder | 2) OFDM-FM Carrier /Half Transponder | 3) OFDM Carrier /Transponder |
|---|---|---|---|
| Uplink | | | |
| ① ES. TX Power (dBW) | 16.0 | 5.0 | 4.0 |
| ② ES. TX Losses (dB) | −2.9 | −2.9 | −2.9 |
| ③ ES.Ant. Gain (dB) | 56.4 | 56.4 | 56.4 |
| ④ Uplink Loss (dB) | −206.9 | −206.9 | −206.9 |
| ⑤ SAT G/T (dB/K) | 12.2 | 12.2 | 12.2 |
| ⑥ Bandwidth (dB-Hz) | −75.6 (36 MHz) | −72.6 (18 MHz) | −67.8 (6 MHz) |
| ⑦ Boltzmanns Const (dBW) | 228.6 | 228.6 | 228.6 |
| ⑧ Uplink C/N (dB) | 27.8 | 19.8 | 23.6 |
| Downlink | | | |
| ① SAT. Power (dBW) | 20.0 | 20.0 | 20.0 |
| ② Sat. Ant. Gain (dB) | 36.0 | 36.0 | 36.0 |
| ③ Output Backoff (dB) | 0 | −6.0 | −9.3 |
| ④ Downlink Losses (dB) | −205.8 | −205.8 | −205.8 |
| ⑤ ES.G/T (dB/K) (3.6 m) | 23.4 | 23.4 | 23.4 |
| ⑥ Bandwidth (dB-Hz) | −75.6 | −72.6 | −67.8 |
| ⑦ Boltzmanns Const (dBW) | 228.6 | 228.6 | 228.6 |
| ⑧ Downlink C/N (dB) | 26.6 | 23.6 | 25.1 |
| ① Total C/N | 24.1 | 18.4 | 21.3 |
| ② Rain Attenuation (0.05) (at Hachijojima) | −4.5 | −4.5 | −4.5 |
| ③ FM Gain | 9.3 | −5.8 | - |
| ④ FM Output S/N | 28.9 | 8.1 | - |
| ⑤ OFDM S/N | 28.9 | 8.1 | 16.8 |
| ⑥ BER degradation due to Clipping (CR = 2.4) | 0.1 | 0.1 | 0.1 |
| ⑦ Required S/N for $10^{-3}$ | 22.6 | 22.6 | 22.6 |
| ⑧ Margin | 6.3 | × | × |

- Satellite: JCSAT1B, Ku-band (Up-link 14.25 GHz, Down-link 12.5 GHz)
- Earth Station Antenna : TX $4.5\,\mathrm{m}\phi$, RX $3.6\,\mathrm{m}\phi$
- Satellite Power Usage: 1) Saturation with one FM carrier, 2) 6 dB output back-off with one FM carrier in half transponder, 3) 9.3 dB output back-off with OFDM carrier
- Satellite Bandwidth: 1) 36 MHz, 2) 18 MHz, 3) 6 MHz

rain attenuation of the uplink is assumed to be compensated by the usual uplink power control.

In ③ in the lower portion, FM gain considering the PAPR of the OFDM signal is presented. Further, in ⑥ in the lower portion, the BER degradation of a 64QAM/OFDM signal due to clipping as derived in Section 3 is presented. ⑦ shows the necessary S/N to obtain a BER of 64QAM with allowable degradation in ⑥. ⑧ shows the overall margin corresponding to the values of ④ to ⑦. For the present channel design, the following are found. (1) The scheme that enables transmission under the above conditions is limited to the case of one-wave/(all bandwidth of the repeater) with the OFDM/FM system. (2) Since the FM gain is small and the satellite power is 1/4 in the two-wave transmission scheme, transmission is not possible by itself. For transmission, a performance of at least 15 dB is needed. This is unrealistic from the point of view of ground station size. (3) The OFDM direct transmission system has a large PAPR, so that the power use efficiency of the satellite repeater is poor (with a large backoff). The receiving S/N is about 12 dB lower than that in the proposed system. Hence, the secondary modulation system using the FM proposed in this paper is found to be highly effective for a system in which signals with a large PAPR such as OFDM are transmitted through a nonlinear amplifier.

## 7. Conclusions

As a supplemental network for the digital terrestrial television broadcasting, use of a satellite is proposed. Although the OFDM signals used for television signals are very resistive to fading and have excellent characteristics for use in terrestrial transmission systems, the transmission efficiency for a power controlled satellite receiver is decreased if they are transmitted directly due to the large PAPR values of the waveform. In this paper, the OFDM television signals are subjected to secondary modulation by the FM format and the constancy of the signal envelope is used. Thus, efficient transmission of satellite power is proposed.

For improvement of the transmission characteristics, it is suggested to use clipping of the OFDM signals. By clipping, the PAPR of the OFDM signals can be limited so that unwanted expansion of the FM signals outside the bandwidth is reduced and the FM gain can be increased. If the clipping of the OFDM signals is deeper, the PAPR can be made smaller, but the BER characteristics are degraded. On the other hand, the FM modulation index can be increased in effect by the clipping, so that the FM gain can be increased. In this paper, optimization of clipping is carried out considering this trade-off.

As a modulation scheme for the OFDM signals in the digital terrestrial broadcasting, 64QAM format is used. For performance comparison, QPSK is also studied.

From these investigations, it is found that there are two significant advantages, namely, an FM gain in the satellite transmission system using the OFDM/FM with appropriate clipping, and the use of the satellite power at its saturation point. Due to these advantages, the proposed system is highly useful, since more than 10 dB of improvement in the characteristics can be obtained in comparison with direct satellite transmission of the OFDM signals.

In the proposed method, only one channel of the television signals is transmitted for each satellite transmission. Hence, the method is inefficient from the viewpoint of bandwidth use of the satellite. As described above, the number of transmitted channels can be increased by making the receiving ground station larger and using the PSK-FDM scheme in place of the OFDM scheme as the modulation format in the repeater section. In such cases, however, the size of the receiving station becomes larger and its complexity is increased. Since retransmitting stations are typically installed on remote islands and in remote areas, it is desirable that the stations be small in size and maintenance-free. In this paper, a simple system is proposed by limiting the system almost entirely to repeater functions.

In the above, the transmission system and its characteristics are discussed for the case in which digital television signals are transmitted through a repeater to a remote location by means of a satellite. With regard to the relay transmission and retransmission of the television signals, several aspects of service and operation need to be considered in addition to the technical issues discussed here.

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