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Hybrid Data Transmission Technique for Multimedia Satellite Broadcasting

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SUMMARY A hybrid data transmission technique for multimedia satellite broadcasting is proposed. The main-channel data and sub-channel data are simultaneously transmitted using QPSK modulation and 2ASK modulation, respectively, but the latter modulation timing is offset by half the main-channel QPSK symbol length in time. The BER performance in a Gaussian channel, the transmission bandwidth, and the transmit power peak factor are theoretically analyzed for various impulse responses of the sub-channel transmit filter. It is found that the use of the sub-channel transmit filter having a sine impulse response minimizes the sub-channel BER while keeping the transmission bandwidth and the transmit power peak factor lower than those of CAPSK transmission.

key words: *satellite broadcasting, data transmission, multimedia communication*

1. Introduction

In multimedia satellite TV communications, simultaneous transmission of a main-channel data stream (existing TV programs) and an additional data stream with different data rate and quality from the main-channel is required. The present digital satellite CS TV broadcasting system uses quadrature phase shift keying (QPSK). One way to realize multimedia broadcasting is to employ higher level modulation [1], e.g., 8-level phase shift keying (8PSK), 16PSK, 16 quadrature amplitude modulation (QAM), or 16 amplitude phase shift keying (APSK) modulation [2]. With higher level modulation, there may be two problems. Existing digital satellite CS TV receivers, already spread over a nation, must be replaced with new receivers. However, this is not a practical solution from an economical point of view. Furthermore, the main-channel bit error rate (BER) performance may degrade, e.g., the required signal energy per bit-to-background noise power spectrum density ratio (E_b/N_0) for achieving BER=10^{-6} increases by 3.5 dB if 8PSK modulation is used instead of QPSK modulation. Another way to realize multimedia broadcasting is to time-multiplex the main-channel data and sub-channel data and transmit using QPSK modulation. In this case, however, existing digital satellite CS TV receivers must also be replaced by new receivers.

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In this paper, a new hybrid data transmission technique is proposed so that existing receivers can receive the main-channel data without any quality degradation, while new receivers can receive both main-channel and sub-channel data. The proposed hybrid data transmission technique transmits simultaneously the main-channel data and sub-channel data using QPSK modulation and 2-level amplitude shift keying (2ASK) modulation, respectively, but the latter modulation timing is offset by half the main-channel QPSK symbol length in time.

The remainder of this paper is organized as follows. In Sect. 2, the proposed hybrid data transmission technique is described. Section 3 theoretically analyzes the main-channel and sub-channel BER performances in a Gaussian channel. The choice of the sub-channel transmit filter is important. The BER performance in a Gaussian channel, the transmission bandwidth, and the transmit power peak factor are theoretically analyzed for various impulse responses of the sub-channel transmit filter. The maximum achievable sub-channel bit rate is discussed for keeping the main-channel transmission quality at BER=10^{-6}. Section 4 draws some conclusions.

2. Hybrid Data Transmission

In the proposed hybrid data transmission, the main-channel data and sub-channel data are simultaneously transmitted using QPSK modulation and 2ASK modulation, respectively. The sub-channel data transmission using 2ASK is described and then, the signal waveform design is presented.

2.1 2ASK Modulation for Sub-Channel Data Transmission

Since 2ASK modulation can minimize the inter-channel interference (ICI) while applying a simple binary coherent detection, it is chosen as the sub-channel data transmission. In order to minimize ICI from the sub-channel to the main-channel, the sub-channel modulation timing is offset by $T/2$, where T is the QPSK symbol length of the main-channel. The decision timing for the main-channel n-th QPSK symbol is nT while that for the sub-channel is $(n+1/2)T$. The impulse response of the main-channel transmit filter is designed so as to

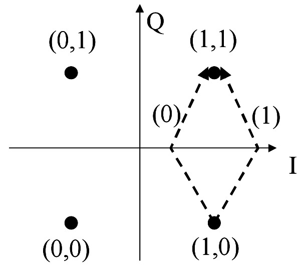


Fig. 1 An example of signal trajectory.

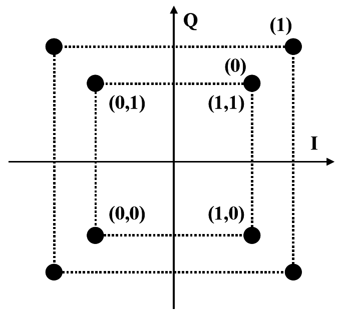


Fig. 2 8CAPSK signal constellation.

provide constant amplitude at $(n+1/2)T$ when the main-channel QPSK symbol transits to adjacent symbol in the QPSK signal space. The sub-channel data is transmitted only when the main-channel QPSK symbol transits to adjacent symbol in the QPSK signal space.

An example of signal trajectory of the proposed hybrid data transmission is illustrated in Fig. 1. The sub-channel binary data, "1" or "0," is transmitted only when the main channel QPSK symbol transits from $(1-j1)/\sqrt{2}$ to $(1+j1)/\sqrt{2}$. In this example, the in-phase (I) component is modulated using coherent 2ASK and the decision timing for the sub-channel is $(n+1/2)T$. It is necessary to allocate larger power to the main-channel in order to minimize the main-channel performance degradation in terms of the required E_b/N_0 for achieving a certain BER. This means that the sub-channel transmission condition is much worse than the main-channel; hence an M-times repetition transmission is applied to the sub-channel. At the receiver, the received M symbols are summed up coherently and binary decision is performed. Therefore, the average bit rate of the sub-channel is one $4M$-th of the main-channel bit rate.

Another modulation candidate for the multimedia broadcasting is the 8-level coherent amplitude and phase shift keying (8CAPSK) or the 8-level differential APSK (8DAPSK) [3]. The main-channel data and the sub-channel data are simultaneously transmitted using QPSK modulation and 2ASK modulation, respectively. 8CAPSK signal constellation is illustrated in Fig. 2. Since 8CAPSK modulation provides a performance superior to 8DAPSK modulation, we consider the former for comparison with our proposed hybrid data transmission system. Performance comparison is presented in Sect. 3.

2.2 Signal Waveform Design

The total average transmit power is given by $P_{total} = P_{main} + P_{sub}/2$, where P_{main} and P_{sub} are respectively the average power per symbol of the main-channel and that of the sub-channel. The transmit signal can be represented as

$$s_T(t) = s_{T\_main}(t) + s_{T\_sub}(t), \tag{1}$$

where $s_{T\_main}(t)$ and $s_{T\_sub}(t)$ are the main-channel signal waveform and sub-channel signal waveform, respectively, and are represented as

$$\begin{cases} s_{T\_main}(t) = \sqrt{(1-\alpha)P_{total}} \displaystyle\sum_{n=-\infty}^{\infty} s_{main}(n) \\ \quad \cdot h_{T\_main}(t-nT) \\ s_{T\_sub}(t) = \sqrt{2\alpha P_{total}} \displaystyle\sum_{m=-\infty}^{\infty} s_{sub}(m) \\ \quad \cdot h_{T\_sub}(t-mT) \end{cases}, \tag{2}$$

with $s_{main}(n)$ and $s_{sub}(m)$ being the main-channel n-th QPSK symbol and the sub-channel m-th 2ASK symbol, respectively, and $|s_{main}(n)| = |s_{sub}(n)| = 1$. In Eq. (2), $h_{T\_main}(t)$ and $h_{T\_sub}(t)$ are the transmit filter impulse responses of the main-channel and the sub-channel, respectively. The parameter α represents the power ratio of the sub-channel to the total average power and is defined as

$$\alpha = \frac{P_{Sub}/2}{P_{total}} = \frac{P_{Sub}/2}{P_{main} + P_{sub}/2}. \tag{3}$$

For allowing a simple binary decision on the sub-channel 2ASK modulated signal, $h_{T\_main}(t)$ is chosen so that the amplitude of the in-phase (I) component or the quadrature (Q) component of the main-channel remains constant when the main-channel QPSK symbol transits to adjacent symbol in the QPSK signal space. The following triangle impulse response is used for $h_{T\_main}(t)$:

$$h_{T\_main}(t) = \begin{cases} \sqrt{3/2}(1-|t/T|), & |t| \le T \\ 0, & \text{otherwise} \end{cases} \tag{4}$$

On the other hand, four types of impulse response shape are considered for the sub-channel transmit filter. They are listed in Table 1.

In the following, the optimum impulse response of the sub-channel transmit filter is found firstly in order to minimize the sub-channel BER while keeping the main-channel BER at BER=10^{-6}, secondly to minimize the signal bandwidth, thirdly to maximize the sub-channel bit rate, and finally to minimize the transmit power peak factor.

Table 1 Impulse responses of $h_{T\_sub}(t)$.

Triangle	Sine
$\begin{cases}\sqrt{3}(1-\lvert 2t/T-1\rvert), & 0\le t\le T\\ 0, & \text{otherwise}\end{cases}$	$\begin{cases}\sqrt{2}\sin(\pi t/T), & 0\le t\le T\\ 0, & \text{otherwise}\end{cases}$
Trapezoid	**Rectangle**
$\begin{cases}\frac{kt}{T}\sqrt{\frac{3k}{3k-4}}, & 0\le t\le T/k\\ \sqrt{\frac{3k}{3k-4}}, & T/k\le t\le (k-1)T/k\\ \frac{k(T-t)}{T}\sqrt{\frac{3k}{3k-4}}, & (k-1)T/k\le t\le T\\ 0, & \text{otherwise}\end{cases}$	$\begin{cases}1, & 0\le t\le T\\ 0, & \text{otherwise}\end{cases}$

3. Theoretical Analysis

In this section, the main-channel and sub-channel BER performances in a Gaussian channel are theoretically evaluated. Firstly, the optimum power allocation between the main-channel and sub-channel is discussed. Next, the maximum achievable sub-channel bit rate is found for keeping the main-channel BER at BER=10^{-6}. Finally, the transmission bandwidth and the required transmit peak power are computed and compared with those of 8CAPSK modulation.

3.1 Optimization of α

As the value of α increases, less transmit power is allocated to the main-channel and hence, the main-channel BER may increase. Due to receive filtering, inter-channel interference (ICI) and inter-symbol interference (ISI) are produced [3, pp.530–553]. The impact of the transmit power allocation is discussed taking into account ICI and ISI. Neglecting the background noise, we find the maximum allowable value of α to keep the main-channel BER below the prescribed value, i.e., BER=10^{-8}. The total peak interference power I_{total} is the sum of average ISI power (denoted by $I_{main\to main}$) and peak ICI power (denoted by $I_{sub\to main}$) and is given by

$$\begin{aligned} I_{total} &= I_{main\to main} + I_{sub\to main} \\ &= (1-\alpha)P_{total}\left\{h^2_{m\to m}(T) + h^2_{m\to m}(-T)\right\}, \\ &\quad + 2\alpha P_{total}\left\{h^2_{s\to m}(T) + h^2_{s\to m}(-T)\right\} \end{aligned} \quad (5)$$

where $h_{m\to m}(t)$ and $h_{s\to m}(t)$ are ISI of the main-channel and ICI from the sub-channel to the main-channel, respectively, and are computed from

$$\begin{cases} h_{m\to m}(t) = \int_{-\infty}^{\infty} h_{T\_main}(t-\tau)h_{R\_main}(\tau)d\tau \\ h_{s\to m}(t) = \int_{-\infty}^{\infty} h_{T\_sub}(t-\tau)h_{R\_main}(\tau)d\tau \end{cases}, \quad (6)$$

with $h_{R\_main}(\tau)$ and $h_{R\_sub}(\tau)$ being the receive filter impulse responses of the main-channel and sub-channel, respectively.

Applying a Gaussian approximation to the interference, it is found that the main-channel signal-to-interference power ratio (SIR) must be above 15 dB to achieve the BER=10^{-8}. However, if the main-channel receive filter is matched to $h_{T\_main}(\tau)$ of Eq. (4), the relative ISI power, defined as I_{total}/P_{total}, becomes -6 dB and the resultant BER owing to ISI is larger than 10^{-6}. Therefore, we use a Gaussian filter in order to reduce ISI at the cost of increasing noise bandwidth [3, pp.530–553]. However, note that a matched filter matched to $h_{T\_sub}(\tau)$ is used in the sub-channel receiver. Remember that the relative interference power is given by $I_{total}/\{(1-\alpha)P_{total}h^2_{m\to m}(0)\}$. The maximum allowable value of α (denoted by α_{max1}) to achieve SIR=15 dB is given by

$$\alpha_{max1} = 1 - \frac{2\{h^2_{s\to m}(T) + h^2_{s\to m}(-T)\}}{\left[\begin{array}{l} 10^{-1.5}h^2_{m\to m}(0) \\ \quad -\left\{h^2_{m\to m}(T) + h^2_{m\to m}(-T)\right\} \\ \quad\quad +2\left\{h^2_{s\to m}(T) + h^2_{s\to m}(-T)\right\} \end{array}\right]}. \quad (7)$$

On the other hand, the maximum allowable value of α (denoted by α_{max2}) to achieve BER=10^{-6} is given by

$$\alpha_{max2} = 1 - 10^{x/10}BT. \quad (8)$$

where x is the allowable main-channel E_b/N_0 degradation in dB at BER=10^{-6} and B is the equivalent noise bandwidth of the main-channel Gaussian filter. Therefore, the allowable value of α is given by

$$\alpha = \min\{\alpha_{max1}, \alpha_{max2}\}. \quad (9)$$

3.2 Optimum Set of α and BT Product

Transmission bandwidth, maximum sub-channel bit rate, and transmit power peak factor are computed to find the allowable value of α and BT product for keeping the main-channel BER at BER=10^{-6}. Then, the sub-channel transmit filter impulse response is found that minimizes the sub-channel BER while keeping the main-channel BER at BER=10^{-6}.

The SNR at the decision instant for the main-channel is $(1-\alpha)P_{total}h^2_{m\to m}(0)/BN_0$. The main-channel BER is given by [3, pp.234–254]

$$P_{b\_main} = \frac{1}{2}erfc\left(\sqrt{\left(\frac{E_b}{N_0}\right)\frac{1-\alpha}{BT}}h_{m\to m}(0)\right). \quad (10)$$

Binary decision is performed at $t=(m+0.5)T$ on the sub-channel. The ICI $I_{main\to sub}$ from the main-channel to the sub-channel is given by

$$I_{main\to sub} = \pm\sqrt{(1-\alpha)P_{total}}h_{m\to s}(0) + j0$$

Table 2 Allowable α and BT product.

E_b/N_0 degradation at BER=10^{-6}	Impulse response of sub-channel transmit filter			
	Triangle	Sine	Trapezoid	Rectangle
1dB	α=9.5x10^{-3} BT=1.247	α=9.3x10^{-3} BT=1.247	α=6.5x10^{-3} BT=1.250	α=4.2x10^{-3} BT=1.254
1.5dB	α=4.0x10^{-2} BT=1.315	α=3.1x10^{-2} BT=1.335	α=2.1x10^{-2} BT=1.363	α=1.3x10^{-2} BT=1.383
2dB	α=6.9x10^{-2} BT=1.356	α=5.5x10^{-2} BT=1.369	α=3.5x10^{-2} BT=1.383	α=2.1x10^{-2} BT=1.394

$$\text{or} \ \pm j\sqrt{(1-\alpha)P_{total}}h_{m\to s}(0) \tag{11}$$

depending on the main channel symbol transition, where

$$h_{m\to s}(0) = \int_{-\infty}^{\infty} h_{T\_main}(-\tau)h_{R\_sub}(\tau)d\tau. \tag{12}$$

Assuming error-free main-channel decision, the average BER of sub-channel is given by

$$P_{b\_sub} = \frac{1}{2} erfc\left(\sqrt{2\alpha M\left(\frac{E_b}{N_0}\right)_{sub}} h_{s\to s}(T/2)\right). \tag{13}$$

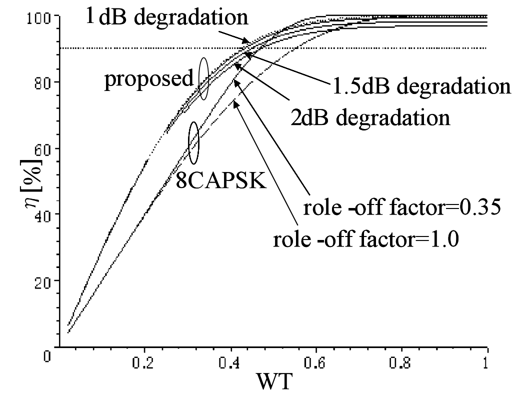
where $(E_b/N_0)_{sub}$ is the sub-channel signal energy per bit-to-background noise power spectrum density ratio. It should be noted that if the main-channel decision is in error, the sub-channel decision becomes erroneous. Therefore, the resultant BER of the sub-channel can be given by

$$\tilde{P}_{b\_sub} = P_{b\_main} + (1 - P_{b\_main})P_{b\_sub}. \tag{14}$$

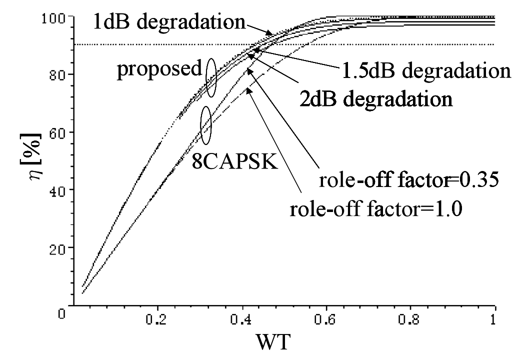
Using Eqs. (7), (8), and (9), the allowable value of α_{max1} to achieve SIR=15 dB is obtained and then, α_{max2} for various values of BT product of the main-channel Gaussian receive filter. The main-channel BER performance is computed using Eq. (10) to find the optimum set of the maximum α and the minimum BT product for the given E_b/N_0 degradation at BER=10^{-6}. The results are presented in Table 2 for various impulse responses of the sub-channel transmit filter. As the value of α increases, the sub-channel BER performance improves because more power is allocated to the sub-channel. Larger α is allowed if smaller BT product is used. It can be found from Table 2 that the triangle and sine impulse responses allow largest α while achieving the smallest BT. Therefore, in the following, only the triangle and sine impulse responses are considered.

3.3 Transmission Bandwidth Consideration

The triangle and sine impulse responses are considered as the sub-channel transmit filter. The transmission bandwidth of the hybrid data transmission is computed when the main-channel E_b/N_0 degradation at BER=10^{-6} is 1, 1.5, and 2 dB.



(a) Triangle impulse response



(b) Sine impulse response

Fig. 3 Pass-band power ratio.

The power spectrum density (PSD) of the hybrid data transmission system is the sum of the PSDs of main-channel and sub-channel modulated signals. The pass-band power ratio η is defined for the given bandwidth W as [4]

$$\eta = \frac{\int_{-W/2}^{W/2} PSD(f - f_c)df}{\int_{-\infty}^{\infty} PSD(f - f_c)df}, \tag{15}$$

from which the value of η is computed, where f_c is the carrier frequency. The result is plotted in Fig. 3 as a function of WT for the main-channel E_b/N_0 degradations at BER=10^{-6} of 1, 1.5, and 2 dB. For comparison, the pass-band power ratio of 8CAPSK modulation system using square root raised cosine filter is also plotted in Fig. 3. The filter roll-off factor of 0.35 (used in the existing CS TV broadcasting) and 1.0 are assumed. As larger E_b/N_0 degradation is allowed for the main-channel, the bandwidth of the hybrid data transmission system becomes wider. It can be seen that the 90% transmission bandwidth for the sine impulse response is almost the same for triangle impulse response and is narrower than that of 8CAPSK modulation system using roll-off factor of 0.35 ($W_{90\%} = 0.47/T$).

Table 3 Maximum bit rate of sub-channel.

E_b/N_0 degradation at BER=10^{-6}	Impulse response of sub-channel transmit filter		8CAPSK
	Triangle	Sine	
1 dB	R/28 bps (M=7)	R/28 bps (M=7)	R/6 bps (M=3)
1.5dB	R/8 bps (M=2)	R/12 bps (M=3)	R/4 bps (M=2)
2 dB	R/4 bps (M=1)	R/8 bps (M=2)	R/4 bps (M=2)

3.4 Maximum Sub-Channel Bit Rate

Assuming $P_{b\_main} = 10^{-6}$, the minimum required repetition number M of the sub-channel data transmission is obtained for achieving BER=10^{-2} using Eq. (14). The sub-channel bit rate becomes $R/(4M)$, where R is the main-channel bit rate, and is presented in Table 3 for the triangle and sine impulse responses of the sub-channel transmit filter (the receive filter is matched to the transmit filter). It is found that the triangle impulse response maximizes the sub-channel bit rate, however, the achievable maximum bit rate is lower than or equal to that of 8CAPSK modulation system. The BER expressions for 8CAPSK modulation system are shown in Appendix. It is seen from Table 3 that when 1 dB E_b/N_0 degradation is allowed for the main-channel transmission, the maximum sub-channel bit rate can be one 28-th of the main-channel bit rate for both the triangle and sine impulse responses. If E_b/N_0 degradation of 1.5 dB is allowed, the sub-channel bit rate increases to one 8th and one twelfth of the main-channel bit rate for the triangle and sine impulse responses, respectively. If the allowable E_b/N_0 degradation is 2 dB, the sub-channel bit becomes the same as and half that of 8CAPSK modulation system for the triangle and sine responses, respectively.

3.5 Transmit Power Peak Factor

The transmit power peak factor is an important design parameter for the satellite power system and transponder. In this section, the transmit power peak factor of the hybrid data transmission system is evaluated and compared with that of 8CAPSK.

It is assumed that the main-channel QPSK symbol transits from (1,0) at $t = nT$ to (1,1) at $t = (n+1)T$, and the sub-channel data is transmitted (see Fig. 1). When the value of the sub-channel power-to-total power ratio α is zero, the transmit signal peak appears at $t = nT$. However, as the value of α increases beyond a certain value, the transmit signal peak appears at $t = (n+0.5)T$, which is the center timing of the sub-channel symbol. The transmitted main-channel signal becomes from Eqs. (2) and (4)

$$s_{T\_main}(t) = \begin{cases} \frac{1-j}{2}\sqrt{3(1-\alpha)P_{total}} & \text{at } t = nT \\ \frac{1}{2}\sqrt{3(1-\alpha)P_{total}} & \text{at } t = (n+0.5)T \end{cases}. \quad (16)$$

The sub-channel signal transmitted at $t = (n+0.5)T$ is

$$s_{T\_sub}(t = (n+0.5)T) = \begin{cases} \sqrt{6\alpha P_{total}} & \text{for the triangle impulse response} \\ 2\sqrt{\alpha P_{total}} & \text{for the sine impulse response} \end{cases}, \quad (17)$$

while

$$s_{T\_sub}(t = nT) = 0. \quad (18)$$

Therefore, the transmit power peak factor is given by

$$|s_T|_{peak}/\sqrt{P_{total}} = \begin{cases} \max\{\sqrt{3(1-\alpha)/2}, \sqrt{3(1-\alpha)}/2 + \sqrt{6\alpha}\} & \text{for traiangle impulse response} \\ \max\{\sqrt{3(1-\alpha)/2}, \sqrt{3(1-\alpha)}/2 + 2\sqrt{\alpha}\} & \text{for sine impulse response} \end{cases}. \quad (19)$$

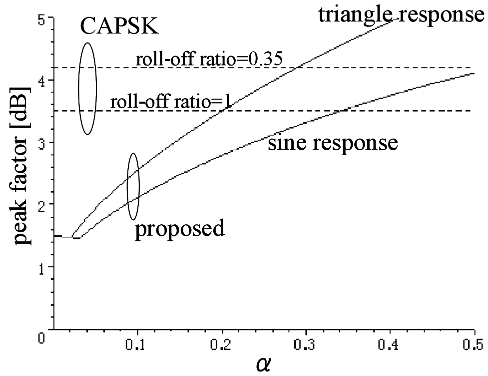


Fig. 4 Peak factor.

The computed peak factor is plotted as a function of α in Fig. 4. It can be found that the sine impulse response provides smaller peak factor than the triangle impulse response. The peak factor of 8CAPSK signal transmission for the square root raised cosine filter is equal to that of QPSK [3, p.146] and is plotted in Fig. 4 for comparison. It is seen that the peak factor of the proposed hybrid transmission system using triangle impulse response can be lower than that of CAPSK signal transmission using the roll-off factor of 1 if α is less than 0.2.

4. Conclusion

A new hybrid data transmission technique was proposed for multimedia satellite broadcasting. The main-channel data and sub-channel data are simultaneously transmitted using QPSK modulation and 2ASK modulation, respectively, but the latter modulation timing is offset by half the main-channel QPSK symbol length to minimize the ICI from the sub-channel to the main-channel. By examining the ISI and ICI, we theoretically analyzed the BER performance in a Gaussian channel, the transmission bandwidth, and the transmit power peak factor. From the theoretical analysis presented in this paper, we can draw the following conclusions:

(a) The sine and triangle impulse responses of the sub-channel transmit filter minimize the sub-channel BER while keeping the main-channel BER at BER=10^{-6} and require almost the same 90% transmission bandwidth. However, since the sine impulse response provides smaller peak factor, the sine impulse response is considered to be the optimum.
(b) The maximum sub-channel bit rate can be one 28-th of the main-channel bit rate for both the triangle and sine impulse responses if 1 dB E_b/N_0 degradation at BER=10^{-6} is allowed for the main-channel transmission. If E_b/N_0 degradation of 2 dB is allowed, the sub-channel bit rate becomes the same as and half that of 8CAPSK transmission system for triangle impulse response and sine impulse response, respectively.
(c) Both the triangle and sine impulse responses can lower the peak factor than that of 8CAPSK signal transmission system.

As a summary, the proposed hybrid transmission using sine impulse response can minimize the sub-channel BER while keeping the signal bandwidth and transmit power peak factor lower than those of 8CAPSK transmission system. In this paper, only a Gaussian channel was considered. The performance analysis in a fading channel is left for a future study.

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Appendix

The two amplitude levels of 8CAPSK are given by $r_L = \sqrt{2/(\beta^2+1)}$ and $r_H = \sqrt{2\beta/(\beta^2+1)}$, where $\beta = r_H/r_L > 1$ and $(r_L^2 + r_H^2)/2 = 1$ [2]. The BER expressions for the main-channel and the sub-channel in a Gaussian channel are given by

$$\begin{cases} P_{b\_main\_CAPSK} \\ \quad = \dfrac{1}{4}\left\{ erfc\left(\sqrt{\left(\frac{E_b}{N_0}\right)} r_H\right) + erfc\left(\sqrt{\left(\frac{E_b}{N_0}\right)} r_L\right)\right\} \\ P_{b\_sub\_CAPSK} \\ \quad = \dfrac{1}{2} erfc\left(M\frac{(r_H - r_L)}{\sqrt{2}}\sqrt{\left(\frac{E_b}{N_0}\right)_{sub}}\right) \end{cases}, \quad (A\cdot 1)$$

where (E_b/N_0) and $(E_b/N_0)_{sub}$ are the signal energy per bit-to-background noise power spectrum density ratio of the main-channel and sub-channel, respectively.

Masatoshi Hamada received his B.A. degree in liberal arts from the University of the Air, Japan, in 1993, and M.S. degree in electrical engineering from Tohoku University, Sendai, Japan, in 2001. Since 1992, he is a registered consulting engineer approved by the Ministry of Science and Technology in Japan. He joined Japan Broadcasting Corporation in 1982, and conducted research and development related to digital communications system and broadcasting satellite system. His research interests are in digital wireless transmission techniques and their applications to multimedia wireless communications systems. He was a co-recipient of APCC paper award in 2001.

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