OFDM/TDM Using FDE for Broadband Wireless Communication Systems

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論文内容要旨

1. Introduction

Orthogonal frequency division multiplexing (OFDM) has been attracting much attention for high-data rate transmission over a wireless channel [1]. However, OFDM has a problem with high peak-to-average power ratio (PAPR), which causes overall system performance degradation [1]. Furthermore, OFDM cannot obtain frequency diversity gain in a frequency-selective fading channel. Our work steams from these two problems.

2. OFDM/TDM using FDE

For improving the transmission performance and overcoming the PAPR problem of OFDM, an OFDM/TDM [2] using FDE [3] was presented. Our work is an extension and modification of the work presented in [2], where the objective is to increase the transmission data rate for the given bandwidth. Our objective, however, is to reduce the number of subcarriers, while keeping the data rate the same as conventional OFDM.

The signaling interval (called OFDM/TDM frame) of conventional OFDM with N_c subcarriers is divided into K slots as shown in Fig. 2. A sequence of data-modulated symbols $\{d_g(i); i=0\sim N_c-1\}$ is divided into blocks with $N_m=N_c/K$ symbols each. The k-th block symbol sequence in the gth frame is denoted by $\{d_g^k(i); i=0\sim N_m-1\}$, where $d_g^k(i)=d_g(kN_m+i)$ for $k=0\sim K-1$ with $E[|d_g(i)|^2]=1$. $E[\cdot]$ is the ensemble average operation. The g-th frame OFDM/TDM signal can be expressed using the equivalent lowpass representation as

$$s_g(t)=\sqrt{\frac{2P}{N_m}}\sum_{i=0}^{N_m-1} d_g^{\lfloor t/N_m \rfloor}(i)\exp\left(j2\pi t\frac{i}{N_m}\right) \qquad (1)$$

for $t=0\sim N_c-1$, where $\lfloor x \rfloor$ and P represent the largest integer smaller than or equal to x and the average signal power, respectively. After insertion of an N_m-sample GI, the OFDM/TDM signal is transmitted over a frequency-selective fading channel.

The received g-th OFDM/TDM frame is decomposed into N_c frequency components as

$$R_g(n)=S_g(n)H_g(n)+N_g(n), \qquad (2)$$

where $S_g(n)$, $H_g(n)$ and $N_g(n)$, respectively, denote the Fourier transforms of the g-th frame OFDM/TDM transmit signal, the channel impulse response and the additive white Gaussian noise (AWGN). One-tap MMSE-FDE is applied to $R_g(n)$ as [4]

$$\hat{R}_g(n)=w_g(n)R_g(n), \qquad (3)$$

where $w(n)$ denotes the MMSE equalization weight, which is given as [5]

$$w_g(n)=H_g^*(n)\Big/\left(\left|H_g(n)\right|^2+2\sigma_g^2\right), \qquad (4)$$

where $2\sigma_g^2$ and $(\cdot)^*$ denote the noise variance and the complex conjugate operation, respectively.

The time-domain OFDM/TDM signal is recovered by applying N_c-point IFFT to $\{\hat{R}_g(n); n=0\sim N_c-1\}$, and then, the demodulation of OFDM signal with N_m subcarriers is done by N_m-point FFT to obtain the decision variable as

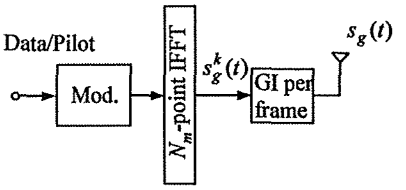
$$\begin{aligned}\hat{d}^k(i)=&\sqrt{\frac{2P}{N_m}}d^k(i)\left(\frac{1}{N_c}\sum_{n=0}^{N_c-1}\hat{H}(n)\right)+\frac{1}{N_c}\sum_{n=0}^{N_c-1}\hat{N}(n)\Psi(n)\\&+\frac{1}{N_c}\sum_{n=0}^{N_c-1}S(n)\left[\hat{H}(n)-\frac{1}{N_c}\sum_{m=0}^{N_c-1}\hat{H}(m)\right]\Psi(n)\end{aligned} \quad ,(5)$$

where the first term is the desired signal component, the second term is the noise and the third term is ISI component. Hence, the conditional signal-to-interference plus noise power ratio (SINR) is given by

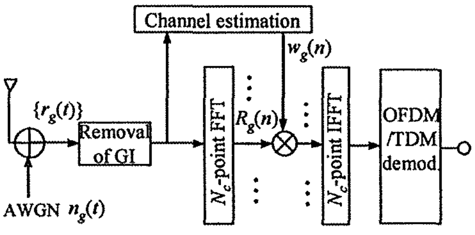
$$\gamma\left(\frac{P}{\sigma^2},H\right)=\frac{2\left(\frac{P}{\sigma^2}\right)\left|\frac{1}{N_c}\sum_{n=0}^{N_c-1}\hat{H}(n)\right|^2}{\frac{1}{K}\sum_{n=0}^{N_c-1}\left\{\begin{array}{l}|w(n)|^2+\left(\frac{P}{\sigma^2}\right)\\ \times\left|\hat{H}(n)-\left(\frac{1}{N_c}\sum_{m=0}^{N_c-1}\hat{H}(m)\right)\right|^2\end{array}\right\}|\Psi(n)|^2} \qquad (6)$$

with $|\Psi(n)|^2 = \left|\sin\left(\pi N_m \frac{n}{N_c}\right) \Big/ N_m \sin\left(\pi \frac{n}{N_c}\right)\right|^2 \leq 1$. The theoretical average BER can be numerically evaluated by averaging Eq. (6) over $\{H(n); n=0\sim N_c-1\}$ as [6]

$$P_b\left(\frac{E_s}{N_0}\right) = \int\cdot\cdot\int \frac{1}{2} erfc\left[\sqrt{\frac{1}{4}\gamma}\right] p(\{H(n)\}) \prod_n dH(n). \quad (7)$$



(a) Transmitter



(b) Receiver

Fig. 1. OFDM/TDM transmitter/receiver structure.

The average BER performance of the OFDM/TDM using MMSE-FDE is illustrated in Fig. 2 as a function of the average signal energy per bit-to-AWGN power spectrum density ratio E_b/N_0 (=0.5(E_s/N_0)×(1+N_g/N_c)) with a uniform power delay profile (α=0 dB). It is seen from Fig. 2 that as K increases, the MMSE-FDE consistently improves the BER performance. This is because, as K increases, the transmitted symbol energy is distributed over a K times wider bandwidth and MMSE-FDE is used to reduce ISI and exploit the channel frequency-selectivity through the frequency diversity effect.

3. Pilot-assisted Channel Estimation

MMSE-FDE requires accurate channel estimation (CE) [7] and thus, a pilot-assisted CE suitable for OFDM/TDM using MMSE-FDE is presented.

For pilot-assisted CE, the pilot frame is transmitted followed by N_d OFDM/TDM data frames. First, by reverse modulation, the instantaneous channel gain estimate at the nth frequency is obtained as $\tilde{H}(n) = R(n)/P(n)$ for n=0~N_c-1, where $P(n)$ is the nth frequency component of the time-domain pilot sequence $p(t)$. After reverse modulation, N_c-point IFFT is applied to $\{\tilde{H}(n); n=0\sim N_c-1\}$ to obtain the instantaneous channel impulse response $\{\tilde{h}(t); t=0\sim N_c-1\}$. Assuming that the actual channel impulse response is present only within the GI, the estimated channel impulse response beyond the GI (i.e., $n=N_g\sim N_c-1$) is replaced with zeros to reduce the noise and then, N_c-point FFT is applied to $\{h_e(t); t=0\sim N_c-1\}$ to obtain the improved channel gain estimates $\{H_e(n); n=0\sim N_c-1\}$.

The noise component at the nth frequency can be estimated by removing the received pilot component $H_e(n)P(n)$ from $R(n)$ as $N_e(n)=R(n)-H_e(n)P(n)$ for n=0~N_c-1. The noise power estimate can be obtained by averaging power of estimated noise components. The channel gain estimate and noise power estimate to be used for FDE are denoted by $H_e(n)$ and σ_e^2, respectively (i.e., $H(n)$ and σ^2 in Eq. (4) are replaced by $H_e(n)$ and σ_e^2, respectively). The average BER performance of OFDM/TDM with pilot-assisted CE with and without delay-time domain windowing is plotted in Fig. 3, as a function of the E_b/N_0. It can be seen from the figure that when delay-time domain windowing is used, the signal-to-noise ration (SNR) of the channel estimates is improved by a factor of N_c/N_g, leading to an improved BER performance.

4. Frequency-domain STTD for OFDM/TDM

Recently, STTD [8] has been gaining much attention since its use at a base station alleviates the complexity problem of mobile receivers. In this chapter, joint frequency-domain STTD and antenna diversity reception based on MMSE criterion for OFDM/TDM transmission is presented.

At the transmitter (see Fig. 4), N_c-point FFT is applied to decompose each OFDM/TDM signal frame given by Eq. (1) into N_c frequency components given by $\{S_{e(\text{or } o)}(n)\}$. The Alamouti's STTD encoding rule [7] is directly applied to each frequency component and then, N_c-point IFFT is applied to obtain the STTD encoded OFDM/TDM signal frames. In the even OFDM/TDM frame interval (q=2u), the STTD encoded OFDM/TDM signals, to be transmitted from the first and second antennas, are $s_e(t)$ and $s_o(t)$, respectively, for t=0~N_c-1. In the odd OFDM/TDM frame interval (q=2u+1), the STTD encoded signals, to be transmitted from the first and second antennas, are given as

$$\begin{cases} \text{Antenna 0}: \dfrac{1}{N_c}\displaystyle\sum_{n=0}^{N_c-1}\{-S_e^*(n)\}\exp\left[j2\pi t\frac{n}{N_c}\right] \\ \text{Antenna 1}: \dfrac{1}{N_c}\displaystyle\sum_{n=0}^{N_c-1}\{S_o^*(n)\}\exp\left[j2\pi t\frac{n}{N_c}\right] \end{cases} \text{for } t=N_c\sim 2N_c-1.$$

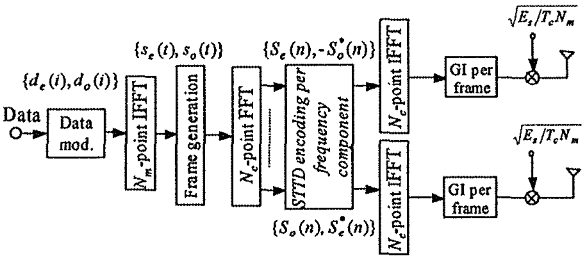


Figure 4. STTD encoding for OFDM/TDM.

After removal of GI, the even and odd OFDM/TDM frame signals, are decomposed by N_c-point FFT into N_c frequency components $\{R_{e(\text{or } o),m_r}(n); n=0\sim N_c-1\}$. The joint STTD decoding and antenna diversity reception is carried out on each frequency component as

$$\begin{cases} \hat{R}_e(n) = \displaystyle\sum_{m_r=0}^{N_r-1}\left\{w_{0,m_r}^*(n)R_{e,m_r}(n) + w_{1,m_r}(n)R_{o,m_r}^*(n)\right\} \\ \hat{R}_o(n) = \displaystyle\sum_{m_r=0}^{N_r-1}\left\{w_{1,m_r}^*(n)R_{e,m_r}(n) - w_{0,m_r}(n)R_{o,m_r}^*(n)\right\} \end{cases}, \quad (8)$$

where $w_{0(\text{or } 1),m_r}(n)$ is the MMSE weight given by

$$w_{0(1),m_r}(n) = H_{0(1),m_r}(n) \Bigg/ \left(\sum_{m_t=0}^{1}\sum_{m_r=0}^{N_r-1}\left|H_{m_t,m_r}(n)\right|^2 + 2\sigma^2\right), \quad (9)$$

where $H_{m_t,m_r}(n)$ and $2\sigma^2$ denote the channel gain between the m_t-th transmit antenna and the m_r-th receive antenna and the variance of the sum of noise and residual interference, respectively. The time-domain OFDM/TDM signal is recovered by applying N_c-point IFFT to $\{\hat{R}_{e(\text{or } o)}(n)\}$ and then, the demodulation is done by N_m-point FFT to obtain the decision variables in the even (or odd) block as

$$\hat{d}_e^k(i)=\frac{1}{N_c}\sum_{m=0}^{N_c-1}\sum_{j=0}^{N_r-1}\sum_{l=0}^{1}\hat{H}_{l,j}(m)S_e(n)\Psi(n)$$
$$+\sum_{n=0}^{N_c-1}S_e(n)\sum_{m_r=0}^{N_r-1}\left[\sum_{m_t=0}^{1}\hat{H}_{m_t,m_r}(n)-\sum_{m=0}^{N_c-1}\sum_{j=0}^{N_r-1}\sum_{l=0}^{1}\hat{H}_{l,j}(m)\right]\Psi(n)\,.\qquad(10)$$
$$+\sum_{n=0}^{N_c-1}\sum_{m_r=0}^{N_r-1}\left[\hat{N}_{m_r}(n)+\hat{N}_{m_r}(n)\right]\Psi(n)$$

Then, the conditional SINR is given by

$$\gamma\left(\frac{P}{\sigma^2},H_{m_t,m_r}\right)$$
$$=\frac{\dfrac{P}{\sigma^2}\left|\dfrac{1}{N_c}\displaystyle\sum_{m=0}^{N_c-1}\sum_{j=0}^{N_r-1}\sum_{l=0}^{1}\hat{H}_{l,j}(m)\right|^2}{\dfrac{1}{K}\displaystyle\sum_{n=0}^{N_c-1}\sum_{m_r=0}^{N_r-1}\left[\begin{array}{l}\dfrac{1}{2}\dfrac{P}{\sigma^2}\left|\begin{array}{l}\displaystyle\sum_{m_t=0}^{1}\hat{H}_{m_t,m_r}(n)-\\ \dfrac{1}{N_c}\displaystyle\sum_{m=0}^{N_c-1}\sum_{j=0}^{N_r-1}\sum_{l=0}^{1}\hat{H}_{l,j}(m)\end{array}\right|^2\\ +\displaystyle\sum_{m_t=0}^{1}\left|w_{m_t,m_r}(n)\right|^2\end{array}\right]\left|\Psi(n)\right|^2}\,.\qquad(11)$$

The theoretical average BER is numerically evaluated by averaging Eq. (7) over $\{H_{m_t,m_r}(n);\,n=0\sim N_c-1\}$.

Figure 5 shows the average BER performance of OFDM/TDM with STTD for $N_r=1$ as a function of the E_b/N_0 for the normalized Doppler frequency $f_DT_s=1.4\times10^{-4}$. As K increases from 1 to 16, the required E_b/N_0 can be reduced to 23 dB due to frequency-diversity gain (a frequency diversity gain of 11.3 dB). When $K=16$, the use of proposed frequency-domain STTD encoding further reduces the required E_b/N_0 by about 8.2 dB due to spatial diversity gain.

5. Further PAPR Reduction for OFDM/TDM

To further reduce the PAPR of OFDM amplitude clipping can be applied. A trade-off between the PAPR reduction and the BER performance is present; the PAPR is reduced as the level of clipping reduces, but the BER degrades due to signal distortion.

The OFDM/TDM transmit signal is passed through the amplitude clipping and filtering block [9]

$$\hat{s}^k(t)=\begin{cases}s^k(t), & \left|s^k(t)\right|\le\beta\\ \beta\dfrac{s^k(t)}{\left|s^k(t)\right|}, & \text{otherwise}\end{cases}\qquad(12)$$

for $t=0\sim N-1$, where β denotes the amplitude of the clipping level. As a result of this operation, the maximum peak power is suppressed to the clipping level.

Using the Bussgang theorem [10], a nonlinear output can be separated as a sum of a useful attenuated input replica and an uncorrelated clipping noise as $\bar{s}(t)=\alpha s(t)+\tilde{s}(t)$, where α and $\tilde{s}(t)$, respectively, denote the attenuation constant and clipping noise. The attenuation constant α, for lower β, can be well approximated as [11]

$$\alpha=1-\exp\left\{-\beta^2\right\}+\frac{\sqrt{\pi}}{2}erfc\{\beta\}\,.\qquad(13)$$

After removing the GI, the received signal is decomposed into N_c frequency components as

$$R_g(n)=\alpha S_g(n)H_g(n)+\tilde{S}_g(n)H_g(n)+N_g(n)\qquad(14)$$

where $\tilde{S}_g(n)$ is the Fourier transform of clipping noise. One-tap FDE is applied to $R_g(n)$ to obtain $\hat{R}_g(n)=w(n)R_g(n)$, where $w(n)$ is given as

$$w(n)=\alpha H_g^*(n)\Big/\left(\left|H_g(n)\right|^2\left\{1-e^{-\beta^2}\right\}+2\sigma^2\right).\qquad(15)$$

In Eq. (13), α is assumed to be known at the receiver. OFDM/TDM demodulator output in this case is given as

$$\hat{d}^k(i)=\sqrt{\frac{2P}{N_m}}\frac{\alpha}{N_c}\sum_{m=0}^{N_c-1}\hat{H}(m)d^k(i)+\mu_{ISI}+\mu_{clip}+\mu_{AWGN}\qquad(16)$$

and hence, the conditional SINR is given by

$$\gamma\left(\frac{P}{\sigma^2},\beta,\{H(n)\}\right)$$
$$=\frac{\dfrac{P}{\sigma^2}\alpha^2\left|\dfrac{1}{N_c}\displaystyle\sum_{n=0}^{N_c-1}\hat{H}(n)\right|^2}{\dfrac{P}{K\sigma^2}\displaystyle\sum_{n=0}^{N_c-1}\left\{\begin{array}{l}\alpha^2\left|\hat{H}(n)-\dfrac{1}{N_c}\displaystyle\sum_{m=0}^{N_c-1}\hat{H}(m)\right|^2+\left|w(n)\right|^2\\ +\left[1-\exp\left\{-\beta^2\right\}-\alpha\right]\left|\hat{H}(n)\right|^2\end{array}\right\}\left|\Psi(n)\right|^2}\,.\qquad(17)$$

The theoretical average BER is numerically evaluated by averaging Eq. (7) over $\{H(n);\,n=0\sim N_c-1\}$.

The theoretical and computer simulated average BER performance for OFDM/TDM with $K=16$ is plotted in Fig. 6 as a function of the E_b/N_0, for amplitude clipping level β=0, 2, 5 and ∞ dB (β=∞ corresponds to no clipping). It is seen that, for β>4 dB, the BER performance of OFDM/TDM is almost not affected by amplitude clipping. The BER degradation, when β=5 dB at average $E_b/N_0=17$ dB, is small as 10^{-4} in comparison to β=∞.

6. HARQ Throughput Performance of OFDM/TDM

Broadband wireless packet technology is one of the core technologies for the next generation of mobile communications systems. Hybrid automatic repeat request (HARQ) with rate compatible punctured turbo (RCPT) codes is one promising technique [12].

OFDM/TDM transmitter and receiver structures are illustrated in Fig. 7. In this chapter, we use turbo encoder as presented in the previous chapter.

Three HARQ schemes are considered, represented by *S-Px* (Systematic-Puncture period $P=x$). $\{p_k^{(1)}\}$ and $\{p_k^{(2)}\}$ are punctured with $P=x$ and x different sequences of length $2N/x$ are obtained, where N is the CRC encoded sequence length. In all the schemes the first transmission consists of transmitting only the systematic bit sequence $\{u_k\}$ of length N. The number of bits transmitted in the second transmission onwards differs depending on the puncturing period.

The impact of OFDM/TDM parameter K on throughput with puncturing period $P=2$, 4 and 8 as a parameter is shown in Fig. 8. The figure shows that in low $E_b/N_0=12$ dB region change of K only slightly affects throughput of the OFDM/TDM for puncturing period $P=2$, 4 and 8. However, for higher E_b/N_0 (=18 and 30 dB) region the change of K impacts throughput such that as K increases the throughput also increases for P=2, 4 and 8.

7. Conclusions

In this work, OFDM/TDM signal transmission using FDE over a frequency-selective fading channel is presented to improve the BER performance while reducing the PAPR of the conventional OFDM. The numerical evaluation of the average BER performance shows that OFDM/TDM using MMSE-FDE provides a lower BER than conventional OFDM due to the frequency diversity gain.

Since MMSE-FDE requires accurate channel estimates a pilot-assisted CE suitable for OFDM/TDM using MMSE-FDE was presented. It was shown that the OFDM/TDM with presented pilot-assisted CE provides a lower BER and a very good tracking ability against fast fading in comparison with the conventional OFDM.

To further improve the performance, a joint frequency-domain STTD and antenna diversity reception based on MMSE criterion for OFDM/TDM signal transmission is presented. The numerical evaluation of the frequency-domain STTD-encoded BER performance of OFDM/TDM in a frequency-selective Rayleigh fading channel shows the improved BER performance in comparison with conventional OFDM.

For further PAPR reduction it was shown that amplitude clipped OFDM/TDM can be used to reduce the required E_b/N_0 or the amplitude clipping level for the given BER in comparison with conventional OFDM with slight increase in PSD.

Finally, to improve the HARQ throughput performance of conventional OFDM, the use of OFDM/TDM using MMSE-FDE with HARQ is presented. The maximum throughput of HARQ OFDM/TDM using MMSE-FDE is achieved when minimum amount of redundancy bits is transmitted with a higher throughput in comparison with the conventional OFDM.

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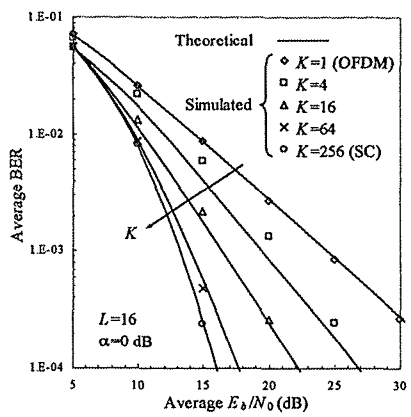

Figure 2. BER performance

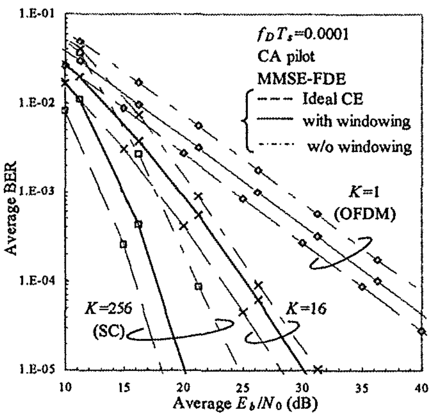

Figure 3. Impact of CE.

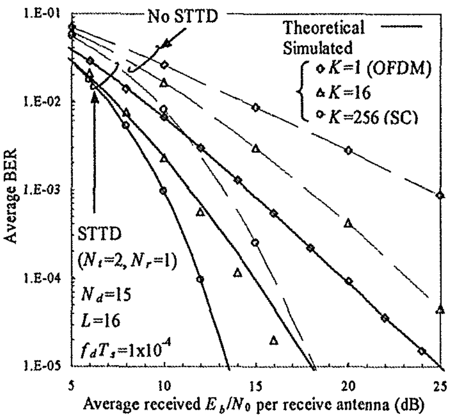

Figure 5. Effect of Frequency-domain STTD.

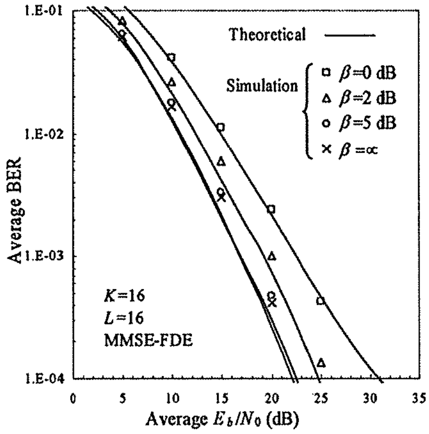

Figure 6. Impact of clipping

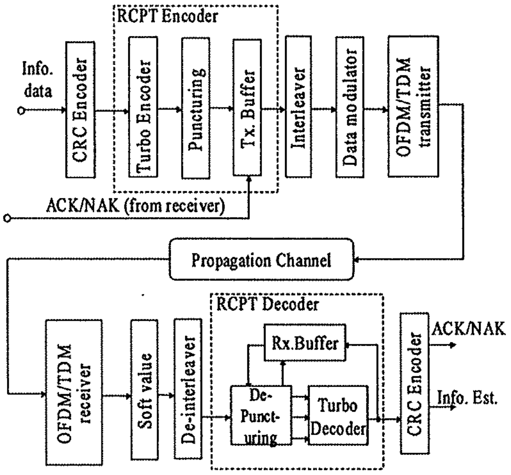

Figure 7. OFDM/TDM transmission system model.

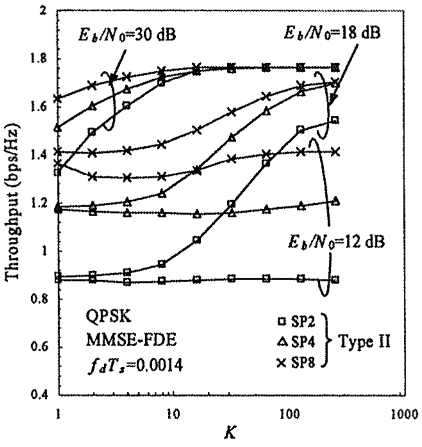

Figure 8. Throughput for different K.

論文審査結果の要旨

次世代無線通信システムでは周波数利用効率の優れたディジタル無線伝送技術が必要とされている。最近注目されている直交周波数分割多重（OFDM）伝送は，変調波のピーク対平均電力比（PAPR）が高く，広いダイナミックレンジを有する線形送信電力増幅器が必要になるという欠点がある。本論文は，時分割多重（TDM）とOFDMを組み合わせてPAPR低減するOFDM/TDM伝送に関する一連の研究成果をまとめたものであり，全編７章からなる。

第１章は緒論である。

第２章では，周波数領域等化（FDE）を用いるOFDM/TDMを提案し，OFDMよりも低いPAPRを達成しながら優れたビット誤り率（BER）特性を実現できることを，BER解析により明らかにしている。この優れたBER特性は最小平均自乗誤差FDE（MMSE-FDE）による周波数ダイバーシチ効果によるものである。OFDM/TDMはOFDMとシングルキャリア伝送の利点を合わせ持つ伝送技術であり，次世代システムにおける無線伝送技術としての可能性を有している。

第３章では，FDEを用いるOFDM/TDMに適したチャネル推定技術を提案している。FDEを行うためには，サブキャリア間隔をTDMスロット数で割った値の周波数間隔でチャネル利得を推定する必要がある。端末が高速移動している場合にはチャネル利得がスロット毎に変動する高速フェージングが発生する。提案技術は，既知パイロットを利用するチャネル推定に時間領域フィルタと周波数領域補間フィルタを組み合わせることで，FDEに必要な周波数間隔でのチャネル利得推定と高速フェージングへの高い追従能力を有している。

第３章では，FDEを用いるOFDM/TDMへの時空間符号化送信ダイバーシチ（STTD）の適用法について述べている。OFDM信号と同じブロックサイズの高速フーリエ変換（FFT）により送信OFDM/TDM信号を直交周波数分解した後に各周波数成分をSTTD符号化し，逆FFTにより時間領域信号に戻して送信する方法を提案している。これを基地局送信に用いれば，受信端末の演算量を増やすことなく空間ダイバーシチ効果が得られる。これは，OFDM/TDMの伝送特性向上を可能にする実用上優れた成果である。

第５章では，OFDM/TDMのPAPRをさらに低減する選択マッピング（SLM）を提案している。SLMではPAPRを最小とする位相系列を周波数領域信号に乗じて送信する。提案SLMでは，OFDM/TDMの特徴を生かし周波数領域と時間領域を入れ替えてPAPRを最小とする位相系列を探索することで，系列探索のための演算量の増加を抑えている。これは実用システムへのOFDM/TDMの適用を可能とする優れた成果である。

第６章は，符号化と自動再送要求（ARQ）を組み合わせたハイブリッドARQへのOFDM/TDMの適用効果を明らかにしている。無符号化時に周波数ダイバーシチ効果が得られるOFDM/TDMはOFDMより高いスループットを実現できることを計算機シミュレーションにより明らかにしている。これは，パケット伝送が中心となる次世代システムの実現に向けた極めて重要な成果である。

第７章は結論である。

以上要するに本論文は，次世代無線通信システムの実現に向けてPAPRを低減した周波数利用効率に優れた無線伝送技術を提案し，その有効性を明らかにしたものであり，無線通信工学の発展に寄与するところが少なくない。

よって，本論文は博士（工学）の学位論文として合格と認める。