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Performance Evaluation of Wavelet Packet Modulation over Mobile Satellite Channel

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Abstract: The performance of WPM over the mobile satellite channel is presented and analyzed. The theory analysis and the simulation results show that the orthogonality of WPM can help the system be robust to the multipath effect and the extend period of WPM symbols can decrease the frequency selective fading of the system. The simulation result demonstrates that the performance of mobile satellite communication system using WPM is dependent on the support length of the wavelets, therefore a ratio decreasing algorithm is proposed in this study to improve the performance by weakening the support length effect. The simulation result shows that the better performance can be achieved by using proposed method.

Key words: WPM, satellite channel, Lutz model, multipath, ratio decreasing algorithm

INTRODUCTION

Satellite mobile communication has gained enormous attentions in the wake of third-generation (3G) and fourth-generation (4G) wireless communications systems and their challenges. Researchers at present are focusing their attentions on the satellite domain by considering it as an integrate part of the so-called information superhighway (Liang and Nai-tong, 2002).

Satellite mobile systems are developed to provide connectivity between remote terrestrial networks, direct network access, Internet services using fixed or mobile terminals, high data-rate transmissions and interactive multimedia applications. New generations of broadband satellite mobile communication systems are currently being developed to support multimedia and Internet-based applications. For example, the Spaceway system provides downlink transmission rates of up to 100 Mbit $\sec^{-1}$ and a total capacity of up to 4.4 Gbit $\sec^{-1}$ (Ibnkahla *et al*., 2004). Most of these researches and development scenarios have considered the nongeostationary satellite network for providing satellite based mobile multimedia services because of its low propagation delay and low path loss.

However, the mobile satellite channels are complicated. The relative movement between the satellite and the receiver causes the radio propagation channel to have a random and time-varying behavior. The transmitted signals undergo shadow, multipath fading, Doppler shift in addition to AWGN which degrade transmission performance severely.

The Wavelet Transform (WT) is a technique for time-frequency domain analysis, simultaneous transmission of data at multiple rates by using different scales can be done by WPM (Jamin and Petri , 2005), therefore, when the tone and impulse interference is received in Time Division Multiplex (TDM) or Orthogonal Frequency Division Multiplexing (OFDM), all symbols are degraded, while WPM keeps many symbols away from the interference by composing an appropriate packet structure (Eiji and Huan-Bang, 2002). The WPM also decreases the ISI without Cyclic Prefix (CP) which is needed by the OFDM under the frequency-selective fading channel. Recently, WPM has been proposed as one of multicarrier transmission methods applied to the satellite mobile communication systems (Sakakibara *et al*., 2005). A lot of researches on the characteristics of the WPM have been done but little attentions given to the performance of the satellite mobile communication systems using WPM.

In this study, the performance of the satellite mobile communication system using WPM is presented and the performance of WPM over the satellite mobile channels is discussed.

PHYSICAL CHANNEL MODEL

To analyze the performance of WPM over the satellite mobile channels, the physical channel model and characteristics will be presented. In this study the Lutz's model (Mehrnia and Hashemi, 1999) is considered as the channel model.

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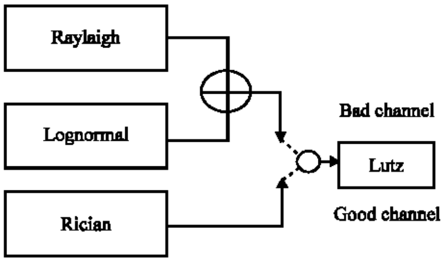

Fig. 1: Luzt's model

The Lutz's model is the total shadowing model suitable for all satellite mobile communication channels, which provides the best fit distribution in all environments. In the model, the channel is classified as good or bad; the Lutz's model is described as Fig. 1.

The good channel is characterized by a clear Line-Or-Sight (LOS) component and strong received signal, resulting in Rice distribution. In the bad channel, intervening obstacles block the LOS path and information is received through multipath components with average power which is lognormally distributed. The overall probability distribution function is:

$$f_{Lutz}(r) = Af_{Rice}(r)+(1-A)f_{Suzuki}(r) \tag{1}$$

where, A and (1-A) are probabilities of having the good and the bad channels, respectively.

As described above, when in bad channel, there is no LOS and the received signal suffered shadowed multipath fading. The multipath fading involved flat fading and frequency-selective fading. The frequency selective fading which caused by time spreading (the longest time delay is longer than the symbol period) degrades the performance severely. Therefore some method needs to be used to solve the problem.

The Doppler shift is not considered here, as in the satellite communication system the Doppler shift can be predicted by the orbit parameters and be equalized according to the prediction result.

WPM SATELLITE COMMUNICATION SYSTEM

Wavelet packet modulation: Recently, WPM has been proposed as one of multicarrier transmission methods used in the mobile satellite communication systems. Wavelet packets are a class of generalized. Wavelet transform with basis functions localizing well in both time and frequency domains. They are constructed using Quadrature Mirror Filter (QMF) pairs h(n) and g(n), satisfying the following conditions (Lindsey, 1997).

$$\sum_{n=-\infty}^{n=+\infty} h(n) = \sqrt{2} \tag{2}$$

$$\sum_{n=-\infty}^{n=+\infty} h(n)h(n-2k) = 2\delta(k) \tag{3}$$

$$g(n) = (-1)^n h(L-n-1) \tag{4}$$

where, usually h(n) and g(n) are low-and high-pass filters, respectively and L is the span of the filters. The h(n) and g(n) are respectively used to define the sequence of basis functions $\varphi_n(t)$, called wavelet packets, can be described as follow:

$$\begin{cases} \varphi_{2n}(t) = \sum\limits_{k\in Z} h(k)\varphi_n(2t-k) \\ \varphi_{2n+1}(t) = \sum\limits_{k\in Z} g(k)\varphi_n(2t-k) \end{cases} \tag{5}$$

Wavelet packets have the following orthogonally properties:

$$\begin{cases} \langle \varphi_n(t-j), \varphi_n(t-k) \rangle = \delta(j-k) \\ \langle \varphi_{2n}(t-j), \varphi_{2n+1}(t-k) \rangle = 0 \end{cases} \tag{6}$$

where, $\langle Q_n(t-j), Q_n(t-k) \rangle$ is the inner product of functions and $\delta(j-k)$ denotes the delta function. Based on h(n) and g(n) and the corresponding reversed filters h(-n) and g(-n) four operators (H^{-1}, G^{-1}, H, G) are defined that can be used to construct a wavelet packet tree. H and G are the downsampling convolution operators and H^{-1} and G^{-1} are upsampling deconvolution. The four operators acting on the sequence of samples x(n) are defined as follow:

$$\begin{cases} H\{x\}(2n) = \sum\limits_{k\in Z} x(k)h(k-2n) \\ G\{x\}(2n) = \sum\limits_{k\in Z} x(k)g(k-2n) \end{cases} \tag{7}$$

$$\begin{cases} H^{-1}\{x\}(n) = \sum\limits_{k\in Z} x(k)h(n-2k) \\ G^{-1}\{x\}(n) = \sum\limits_{k\in Z} x(k)g(n-2k) \end{cases} \tag{8}$$

Figure 2 shows the construction of these operators. Operators H and G can be used to decompose (analyze) any discrete function x(n) in the space $l^2(z)$ into two orthogonal subspaces. Each decomposition (H or G) step results in two coefficient vectors each half the length of the input vector keeping the total length of data unchanged. This operation can be iterated by cascading the operators for multiple numbers of steps. In this iterative decomposition procedure, the output coefficient

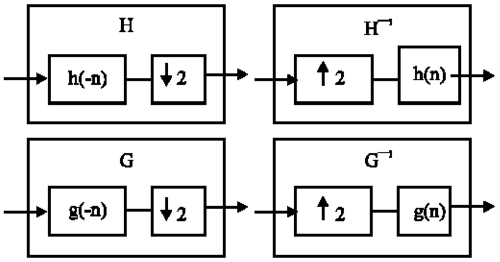

Fig. 2: Analysis and synthesis filters using H, G, H^{-1}, G^{-1} operators

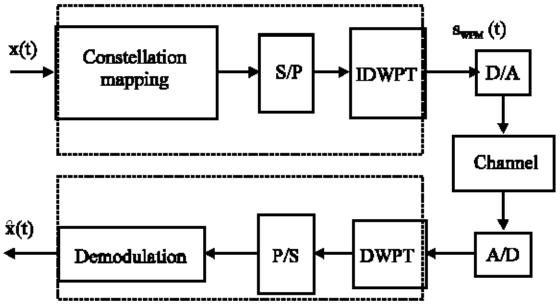

Fig. 3: Wavelet packet modulation functional block diagram

vectors have size reduced at each step by 2 so that eventually these output vectors become scalars. This decomposition process using H and G is called Discrete Wavelet Packet Transform (DWPT). The decomposition is a reversible process and the Inverse Discrete Wavelet Packet Transform (IDWPT) can be used to reconstruct the original input vector from the coefficients vectors. The IDWPT is a series of upsampling filtering processes defined by the operators H^{-1} and G^{-1}.

A function block diagram of the WPM system is shown in Fig. 3. Similar to the OFDM system, at the transmitter an IDWPT block is used to complete the modulation, while at the receiver a DWPT block is used to complete the demodulation.

The WPM signal can be described as follow:

$$s_{WPM}(t) = \sum_{i=-\infty}^{\infty} \sum_{(l,n)\in\rho} x_l^n(i)\sqrt{2^l}\varphi_n\left(2^l t - i\right) \quad (9)$$

where, t denotes the time index, *i* denotes the transmission time interval $[iT_S; (i+1)T_S]$ (T_S is the transmitted symbol duration) and (|, n)єr is the way to discretize the subspace with $1 \le l \le j$ being the rank of subband and n being the subspace number. The multicarriers number $M = 2^J$.

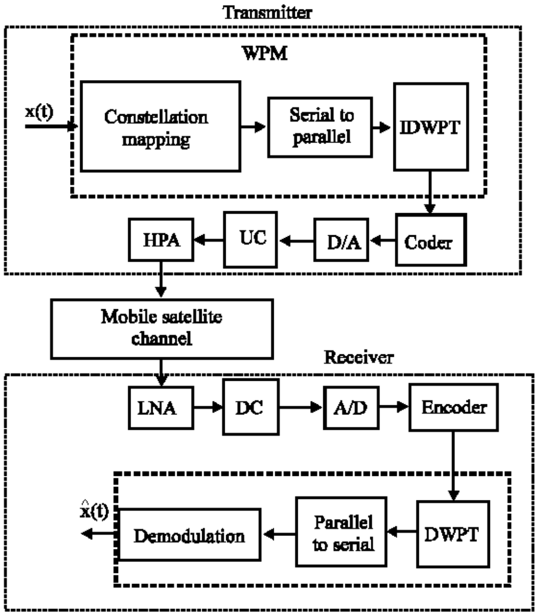

Fig. 4: Functional block diagram of satellite communication system based on WPM

Satellite communication system using WPM: The structure of WPM brings benefits a lot when apply it to the satellite mobile communication systems. For example, the WPM signals have the expanded symbol period without CP which can decrease the effect of the frequency-selective fading. Moreover, the flexibility is the major advantage of WPM, i.e., simultaneous transmission of the data at multiple rates by adjusting scales makes it eminently suitable for future generation of satellite mobile communication system.

The basic elements for a satellite communication system applying WPM are given in Fig. 4. For clarity, the redundant units are not shown. In the transmitter, the WPM signal is modulated onto a carrier wave at an intermediate frequency after being coded and upconverted to the required microwave carrier frequency by upconverted (UC) block. After amplification by High Power Amplifier (HPA), the signal will be transmitted in channel. In the receiver branch the incoming signal is amplified in a Low-Noise Amplifier (LNA) and downconverted to intermediate frequency. After demodulation, the original signal is recovered.

PERFORMANCE ANALYSIS OF SATELLITE COMMUNICATION SYSTEM USING WPM

As the WPM is a new kind of multicarrier modulation method, a lot of earlier researches are mainly focusing on the characteristics of the ground WPM system, but little attentions are given to the satellite systems using WPM. In this part, basing on the WPM satellite mobile communication system established above, the performance of WPM over mobile satellite channel is discussed.

The relative movement between the satellite and the receiver causes the radio propagation channel to have a random and time-varying behavior. Shadowing, multipath fading, Doppler shift and AWGN are four major factors which affect the performance of the satellite mobile communication systems. The Doppler shift can be predicted by the satellite parameters such as orbit and velocity and the equalizing can be made according to the predict result. Therefore, the performance of mobile satellite communication system using WPM over multipath fading and AWGN environment is analyzed.

Performance in multipath environment: In WPM, the transmission bandwidth is divided in parallel. Therefore, the symbol duration is increased and the intersymbol interference (ISI) caused by time-dispersive fading (frequency selective fading) environment can be mitigated (Sakakibara *et al*., 2005). Therefore, multipath fading but frequency-selective fading is considered here.

For the satellite communication system using WPM, data are modulated via the IDWPT operation and demodulated via DWPT. The overlapped nature of wavelet filters requires g symbol periods to decode one data vector. Therefore, the signal used to decode one data can be described as:

$$S_{WPM}(t)=\sum_{(n,l)\in\rho}x_l^n\varphi_{n,l}(t)+\sum_{m=1}^{g-1}\sum_{(n,l)\in\rho}x_{l,m}^n\varphi_{n,l}(t-mT) \tag{10}$$

To match for the data in subchannel j, the transmitted waveform is matched with carrier j:

$$\begin{aligned}&\left\langle s_{WPM}(t),\varphi_{j,l}(t)\right\rangle\\&=\sum_{(n,l)\in\rho}x_l^n\left\langle\varphi_{n,l},\varphi_{j,l}(t)\right\rangle+\sum_{m=1}^{g-1}\sum_{(n,l)\in\rho}x_{l,m}^n\left\langle\varphi_{n,l}(t-mT),\varphi_{j,l}(t)\right\rangle\end{aligned} \tag{11}$$

Where:

$$\begin{cases}\left\langle\varphi_{j,l}(t),\varphi_{j,l}(t)\right\rangle=R_{j,j}^l(0)=1\\\left\langle\varphi_{k,l}(t-aT),\varphi_{j,l}(t-bT)\right\rangle=R_{k,j}^l(aT-bT)=0\end{cases} \tag{12}$$

Eq. 11 can be described as:

$$\begin{aligned}&\left\langle s_{WPM}(t),\varphi_{j,l}(t)\right\rangle\\&=x_l^jR_{j,j}^l(0)+\sum_{(n\neq j,l)\in\rho}x_l^nR_{n,j}^l(0)+\sum_{m=1}^{g-1}\sum_{(n,l)\in\rho}x_{l,m}^nR_{n,j}^l(mT)\\&=x_l^jR_{j,j}^l(0)\end{aligned} \tag{13}$$

The received signal affect by multipath fading can be given as follow:

$$\begin{aligned}&S'_{WPM}(t)=s_{WPM}(t)+a_1s_{WPM}(t-\tau_1)+\cdots+a_Ns_{WPM}(t-\tau_N)\\&=\left(\sum_{(n,l)\in\rho}x_l^n\varphi_{n,l}(t)+\sum_{m=1}^{g-1}\sum_{(n,l)\in\rho}x_{l,m}^n\varphi_{n,l}(t-mT)\right)+\cdots+\\&\left(a_N\sum_{(n,l)\in\rho}x_l^n\varphi_{n,l}(t-\tau_N)+a_N\sum_{m=1}^{g-1}\sum_{(n,l)\in\rho}x_{l,m}^n\varphi_{n,l}(t-mT-\tau_N)\right)\end{aligned} \tag{14}$$

where, a_i is the amplitude value of the ith path. Here only one symbol period is considered. When matching the data on carrier j, the equation can be described as:

$$\begin{aligned}&\left\langle s'_{WPM}(t),\varphi_{j,l}(t)\right\rangle\\&=\left(\begin{aligned}&\sum_{(n,l)\in\rho}x_l^n\left\langle\varphi_{n,l}(t),\varphi_{j,l}(t)\right\rangle+\\&\sum_{m=1}^{g-1}\sum_{(n,l)\in\rho}x_{l,m}^n\left\langle\varphi_{n,l}(t-mT),\varphi_{j,l}(t)\right\rangle\end{aligned}\right)+\cdots\\&+\left(\begin{aligned}&a_N\sum_{(n,l)\in\rho}x_l^n\left\langle\varphi_{n,l}(t-\tau_N),\varphi_{j,l}(t)\right\rangle+\\&a_N\sum_{m=1}^{g-1}\sum_{(n,l)\in\rho}x_{l,m}^n\left\langle\varphi_{n,l}(t-mT-\tau_N),\varphi_{j,l}(t)\right\rangle\end{aligned}\right)\end{aligned} \tag{15}$$

According to Eq. 12 and Eq. 13, 15 can be given as:

$$\begin{aligned}&\left\langle S'_{WPM}(t),\varphi_{j,l}(t)\right\rangle\\&=\left(\begin{aligned}&X_l^jR_{n,j}^l(0)+\sum_{(n\neq j,l)\in\rho}x_l^nR_{n,j}^l(0)+\\&\sum_{m=1}^{g-1}\sum_{(n,l)\in\rho}x_{l,m}^nR_{n,j}^l(mT)\end{aligned}\right)+\cdots\\&+\left(\begin{aligned}&a_Nx_l^jR_{j,j}^l(\tau_N)+a_N\sum_{(n\neq j,l)\in\rho}x_l^nR_{n,j}^l(\tau_N)+\\&a_1\sum_{m=1}^{g-1}\sum_{(n,l)\in\rho}x_{l,m}^nR_{n,j}^l(mT+\tau_N)\end{aligned}\right)\\&=x_l^jR_{j,j}^l(0)\end{aligned} \tag{16}$$

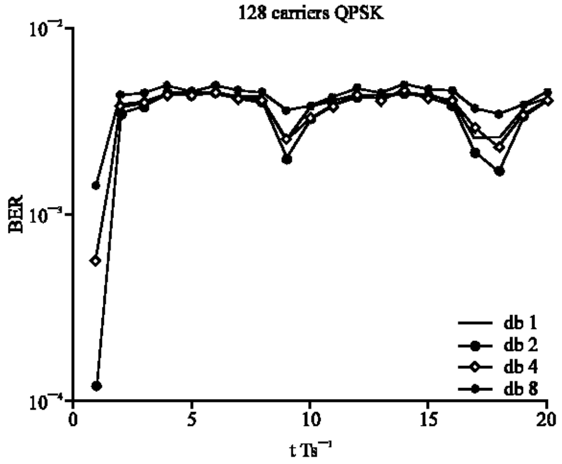

Fig. 5: BER performance in multipath environment

The result of Eq. 16 is equal to Eq. 13, which demonstrate that the WPM is robust to the effect of the multipath fading (flat fading). But the loss of orthogonality between the subcarriers would immediately introduce more ISI and ICI.

As the WPM with longer symbol period can be immune from the frequency-selective fading, therefore, in the simulation, only the flat fading is considered and a simple case of 2-path channel model is used. The first path has unit power and the second path power is 3 dB lower. The relative delay of the second path $\tau = NT_s$ is a simulation parameter with SNR = 20 dB. The Bit Error Ratio (BER) versus the second path delay τ curves of WPM (db1), WPM (db2), WPM (db4) and WPM (db8) schemes with QPSK modulated subcarriers is shown in Fig. 5. The results show that, a good performance can be obtained in the presence of multipath fading by using WPM, all curves are quite similar and thus the increase of the wavelet order has little impact on the performance.

System performance in an AWGN environment: The construction of a wavelet packet basis is entirely defined by the wavelet scaling filter; hence its selection is critical. Here, the performance of mobile satellite communication system using WPM with different wavelet packet bases in an AWGN environment is discussed.

The transmitted WPM signal at the receiver polluted by AWGN can be described as follow:

$$s'_{WPM}(t) = s_{WPM}(t) + n(t) \qquad (17)$$

where, n(t) denotes a zero-mean white Gaussian noise with power $N_0/2$. The demodulation of the received signal can be achieved by Wavelet Packet Transform (WPT) which can be described as Fig. 6.

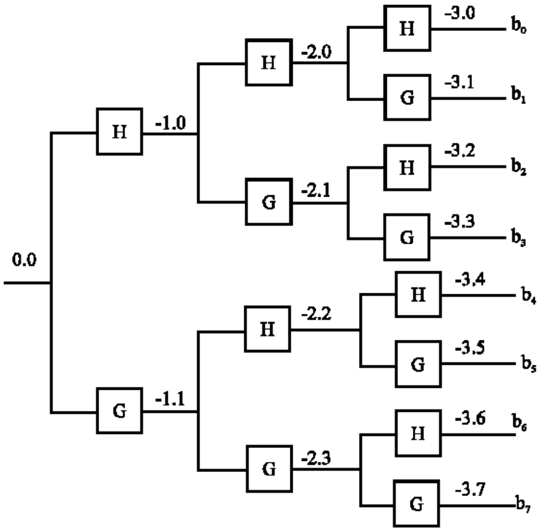

Fig. 6: Wavelet packet tree

Table 1: Summary of wavelet family characteristic

Full name	Abbreviated name	Vanishing order	Length L0
Haar	Haar	1	2
Daubechie	dbN	N	2N
Symlets	SymN	N	2N
Coiflet	CoifN	N	6N

The performance analysis of satellite communication system using WPM is based on widely used wavelets such as Haar, dbN, symN and coifN. While, there are numerous alternative wavelet families can be used as well, those wavelets leading to fast transforms through the tree algorithm are more attractive.

WPM needs no CP and in an AWGN channel, the lowest probability of erroneous symbol decision is achieved if the waveforms are mutually orthogonal, the orthogonality of wavelet packet has been described in Eq. 13, however, the support length of the wavelets causes the redundancy when composing and decomposing the wavelet packet tree. This redundancy will increase the BER. For example Daubechies N = 4 wavelet and Daubechies N = 8 wavelet, both are orthogonal, compactly supported wavelets. The N = 4 wavelet has 4 vanishing moments and a support length of 7; N = 8 wavelet has 8 vanishing moments and a support length of 15 (Mallat, 1999). Therefore, the redundancy brought by db 4 wavelet is equal to 6M (M denotes the number of subcarriers) and redundancy brought by db 8 wavelet is equal to 14M. The longer the support length, the more redundancy which leads to the increasing of the BER it brings to the system.

Table 1 shown the characteristics of the wavelets and families mentioned above.

The performance comparison between the satellite communication system using OFDM and WPM is

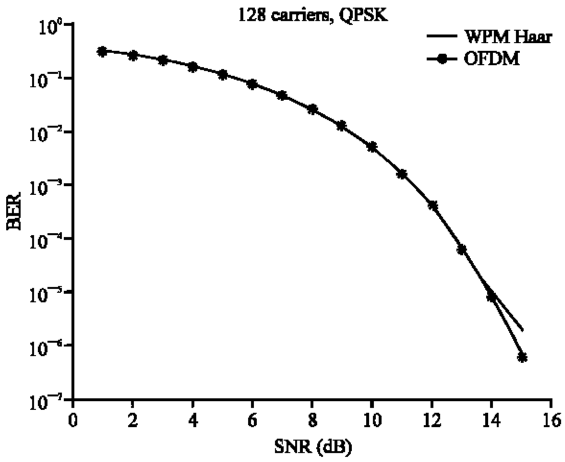

Fig. 7: The comparison between OFDM and WPM

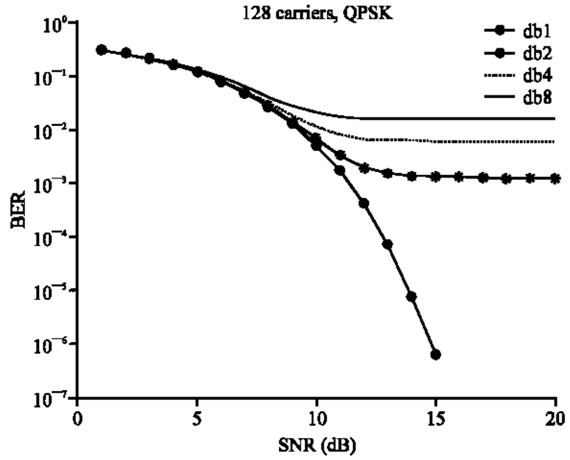

Fig. 9: BER performance of dbN

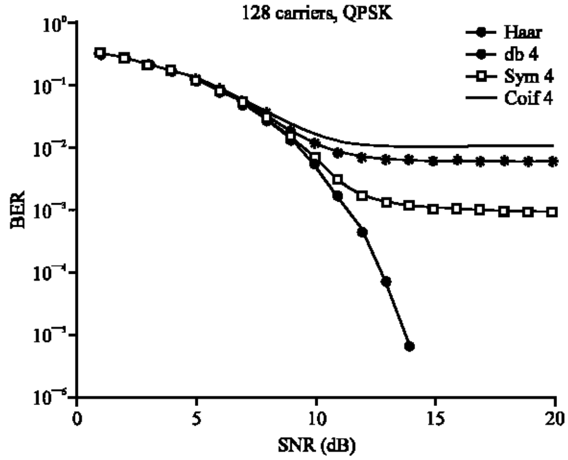

Fig. 8: BER performance of different wavelets

Table 2: Simulation parameters

Modulation Scheme	QPSK
Subbands No.	128
Wavelet basis	Haar, db 4, sym 4, coif 4

presented in Fig. 7. When using Haar (db 1 and sym1) wavelet in WPM, the performance of the two methods are nearly the same.

The performance of mobile satellite communication system using WPM with different wavelets and support lengths is simulated and the results are presented in Fig. 7 and 8. The simulation in Fig. 7 shows the BER performance of WPM with different wavelets, the detailed simulation parameters are shown in Table 2.

Figure 8 depicts the BER performance of satellite communication system using WPM with different wavelets. The simulation results show that when SNR<7dB, the BER of different wavelets are nearly the same. This is because when SNR<7dB, the AWGN is a major factor which affect the BER performance and the effect of redundancy caused by the support length can be ignored; However, when SNR>7dB the BER of Haar wavelet is obviously better than the other wavelets and BER values still decrease with the increasing of SNR, but for db 4, sym 4 and coif 4, the curves are nearly flat. This is because when SNR>7dB, the BER performance is mainly decided by the redundancy caused by the support length and the effect of AWGN can be ignored. As the support length of Haar wavelet is the shortest one which gives the least redundancy when composing and decomposing the wavelet packet tree and the BER of Haar wavelet brought by the redundancy is equal to zero. For the other three wavelets, db 4 and sym 4 have the same support length but shorter than coif 4, therefore their performance are better than coif 4. SymN wavelet has a good symmetry which helps it get better performance than dbN wavelet.

Simulation of BER performance based on dbN wavelet with different support length is shown in Fig. 9. As analyzed above, the support length of wavelet play an important part in WPM satellite communication system. Longer support length brings more redundancy which increases the BER, but as a coin has two sides, suitable length can help to achieve good performance such as to get better frequency domain localization.

THE IMPROVED METHOD

As analyzed above, the performance of WPM has been found dependent on the support length of the wavelet basis. Hence, a ratio decreasing method is proposed here to weaken the effect of the support length and improve the performance of WPM system.

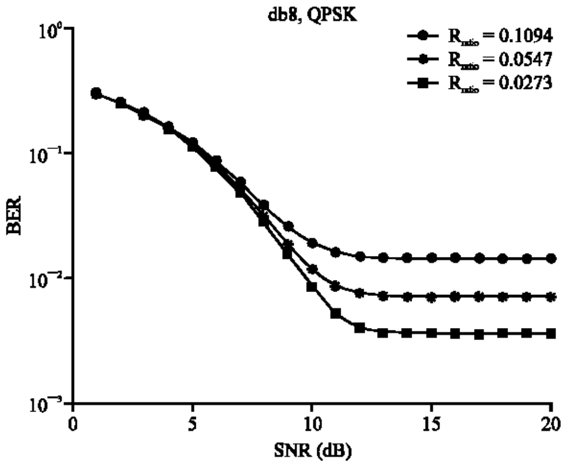

Fig. 10: BER performance of different R_{ratio}

Table 3: Simulation parameters

Modulation scheme	QPSK
Wavelet Basis	db 8
Subbands No.	1024 512 256
Ratio	0.1094 0.0547 0.0273

The ratio of the ratio decreasing method denotes the ratio between the redundancy caused by the support length of the wavelet basis and the transmission bandwidth; the ratio can be given as:

$$R_{ratio} = \frac{(2N-2)M}{\sum_{i=1}^{M} R_i} = \frac{(2N-2)M}{B} \tag{18}$$

where, N denotes the vanishing order and M denotes the number of carriers. $R_i = 1/T_i$ denotes the transmission rate of the ith subband and B denotes the total bandwidth. The lowest probability of erroneous symbol decision is achieved if the R_{ratio} is smallest. It is clear that increase B or decrease M both can reduce R_{ratio}.

BER performance under the different R_{ratio} is shown in Fig. 10. The detailed simulation parameters are given in Table 3. The experimental results demonstrate that performance improvement is significant depending on the R_{ratio} when it decreases from 0.1094 to 0.0273 by decreasing M from 1024 to 256 but keeping bandwidth B unchanged. However, one of salient features of WPM is its expanded symbol period T_i which can decrease the effect of the multipath channel distortion when $T_i > \tau_{max}$. If M is too small, T_i will be shorter than the maximum value of the multipath delay τ.

For practical application of WPM in satellite communication system, a tradeoff should be made among the subcarriers number, total bandwidth and the support length. In the severe frequency-selective fading environment, one way to reduce R_{ratio} is to increase B, however, if the bandwidth is limited, wavelet with shorter support length should be chosen. In some conditions, the longer support length is needed with the limitative bandwidth such as in interference environment (Gautier and Lienard, 2007), in this condition, the number of subcarriers should not be enormous.

From the analysis above, it can be concluded that WPM method with longer wavelet support length and enormous multicarriers is more suitable for wideband communication systems such as wideband satellite communication system.

CONCLUSION

In this study the performance of WPM over the mobile satellite channels is discussed. The analysis and simulation results show that the WPM can help the system be robust to the multipath effect and be immune from frequency selective fading. BER performance of the satellite communication system using WPM is dependent on the support length of the wavelet basis. A ratio decreasing method is proposed to weaken the effect caused by support length. Analysis and simulation results demonstrate that the improvement of the proposed method is significant.

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