Performance of Multi-carrier $M$-ary QAM for High Rate Transmission in Wireless Communications

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Abstract: High bit rate data transmission is required for video, high quality audio, and mobile ISDN services in wireless communications. In this paper, the performance of multi-carrier $M$-ary QAM for high rate transmission is evaluated in wireless communications. The effects of delay spread and co-channel interference is taken into account. It is shown that multi-carrier $M$-ary QAM with fading compensation techniques and diversity receptions achieves reliable communications for high bit rate data transmission in wireless communications.

I. INTRODUCTION

The current services in wireless communications are low bit rate transmission such as voice signals. In future wireless communications systems, high bit rate data transmission is required for video, high quality audio, and mobile ISDN services. Due to the spectral deficiency in wireless communications, modulation schemes with high spectral efficiency are required.

In wireless communications channels, the received signal is heavily distorted when the transmission rate is high due to frequency selective fading. Multi-carrier transmission can offer immunity against frequency selective fading [1][2]. The immunity increases as the number of carriers increases. However, too many carriers result in the high hardware complexity [3].

Quadrature amplitude modulation (QAM) is a spectral efficient modulation. The application of QAM in fading channels requires very precise fading compensation schemes. There are two types of fading compensation techniques: pilot tone aided scheme [4], and pilot symbol aided scheme [5]. The pilot symbol aided scheme is a practical technique to compensate for fading without requiring complex hardware. The low order Gaussian interpolations are used for practical fading compensation applications [6].

Convolutional codes are used for error performance improvement in wireless communications. The error performance is further improved by using channel state information in decoding algorithm [7]. Diversity techniques are also used for performance improvement in wireless communications. Among combining techniques, maximal ratio combining yields maximal possible improvement that diversity systems can obtain over fading channels [8].

In this paper, multi-carrier $M$-ary QAM with convolutional coding is considered for high rate transmission in wireless communications. Wireless communications channels are modeled as a frequency selective Rayleigh fading channel with co-channel interference and additive white Gaussian noise. Pilot symbol aided fading compensation scheme is used with second order Gaussian interpolation. Maximal ratio combining is used for diversity receptions.

In Section II, system model is given. Simulation results are given in Section III and conclusion is drawn in Section IV.

II. SYSTEM MODEL

The system block diagram is given in Fig. 1. Convolutional code with rate 1/2 and constraint length 9 is used. Coded bit sequences are divided into $C$ parts and each of which is modulated with corresponding subcarrier. $M$-ary quadrature amplitude modulation (QAM) is used for each subcarrier. A Gray code is used to map the encoder output to the $M$-ary QAM symbol.

Nonoverlapping frequency division multiplexing is used. Pilot symbol is inserted for fading compensation per $N$ symbols in each subchannel. Assume that each subchannel suffers from equivalent amount of fading. Consider only one subchannel from now on. The subchannel model is given in Fig. 2 which is a frequency selective Rayleigh fading channel with co-channel...
interference and additive white Gaussian noise (AWGN). The transmitted signal in a subchannel is given by

\[ s(t) = R(t) \cos \omega t - Q(t) \sin \omega t = \text{Re}(R(t) + jQ(t))e^{j\theta}, \]

where \( R(t) \) and \( Q(t) \) are the bandlimited in-phase and quadrature baseband signals respectively and \( \omega \) is the carrier frequency. The complex envelope of the signal is given by

\[ R(t) + jQ(t) = \sum_{k=-\infty}^{\infty} a_k e^{j(\theta_k + kT)}, \]

where \( a_k \) and \( \theta_k \) is the envelope and the phase of \( k \)th QAM channel symbol respectively and \( T \) is the symbol interval in each subchannel. The impulse response of the raised cosine filter with roll-off factor \( \beta \) is given by [9]

\[ p(t) = \sin(\pi(\frac{t}{T}) \times \cos(\frac{\beta t}{T})) \times \frac{1 - 4\beta^2 t^2}{T^2}. \]

The signal \( s(t) \) is randomly modulated by a Rayleigh envelope \( R_s(t) \) and uniform phase \( \phi(t) \). A delayed signal \( s(t-\tau) \) is randomly modulated by a Rayleigh envelope \( R_s(t) \) and uniform phase \( \phi(t) \). The co-channel signal is given by

\[ C(t) = I_C(t) \cos \omega t - Q_C(t) \sin \omega t = \text{Re}(I_C(t) + jQ_C(t))e^{j\phi}, \]

where the complex envelope is given by

\[ I_C(t) + jQ_C(t) = \sum_{k=-\infty}^{\infty} a_k e^{j(\phi_k + kT)}e^{j(\theta_k + kT)} \]

and \( \phi_k \) is the envelope and the phase of \( k \)th QAM channel symbol of the co-channel respectively and \( \phi \) and \( \tau_c \) is the random phase offset and delay of the co-channel. The co-channel signal is also randomly modulated by a Rayleigh envelope \( R_x(t) \) and uniform phase \( \phi_x(t) \). Assume that the processes \( X(k,t) = R_s(t) \cos \phi_x(t) \) and \( Y(k,t) = R_s(t) \sin \phi_x(t), \) \( i = 1, 2, 3 \) are statistically mutually independent. The raised-cosine filters are used in the transmitter and brick-wall filters with bandwidth equal to \( (1+\beta)/T \) are used in the receiver [10]. The complex envelope of the received signals is given by

\[ U(t) + jV(t) = (R(t) + jQ(t))R_s(t) e^{j\phi(t)} \]
\[ + (R(t-\tau) + jQ(t-\tau))e^{j\phi(t)}e^{j\phi(t)} \]
\[ + (I_C(t) + jQ_C(t)R_s(t) e^{j\phi(t)} \]
\[ + X_1(t) + jY_1(t). \]

where \( X_1(t) \) and \( Y_1(t) \) are the real and imaginary part of the complex envelope of the bandlimited Gaussian noise respectively.

The fading process for all symbols is estimated from pilot symbol with second order Gaussian interpolation. After fading compensation with maximal ratio combiner, demodulation is performed. Decoder collects hard decision bits and estimated fading envelope of each QAM symbol from demodulator. The estimated fading envelope of each symbol is used as path metric weighting factor in Viterbi algorithm for corresponding channel bits [11].

### III. SIMULATION RESULTS

The multi-carrier \( M \)-ary QAM system shown in Fig. 1 is simulated on computer and the bit error rate (BER) performance is obtained. Consider the transmission rate of 1 Mbps. Code rate \( r = 1/2 \) and constraint length \( K = 9 \) convolutional code is used of which minimum free distance is 12. Pilot symbol is inserted every 7 symbols. Consider the number of subcarriers \( C \leq 8 \) symbols only. Doppler frequency is assumed to be 30 Hz.

The BER of 16-ary QAM and 64-ary QAM is shown in Fig. 3 as a function of signal to co-channel interference ratio (SIR) with symbol diversity order \( L = 1, 2, 4 \). Consider the case average \( E_s/N_0 \) is 10 dB. When SIR is larger than 18 dB, the effect of co-channel interference is negligible since the BER depends on average \( E_s/N_0 \) in this range.

The BER of 16-ary QAM is shown in Fig. 4 as a function of delay time \( \tau \) and the main-path to delayed-path power ratio (CDR) with symbol diversity order \( L = 1, 2, 4 \). Consider the case that average \( E_s/N_0 \) is 10 dB and there is no co-channel interference. The BER increases as \( \tau \) increases. The effect of \( \tau \) for BER increases as CDR decreases but the effect of \( \tau \) for BER does not change as \( L \) increases.

Consider the case that delay time \( \tau \) is 1 \( \mu \)sec. The BER of 16-ary QAM with \( C \) carriers is shown in Fig. 5 with \( L = 1, 2 \) when CDR is 0 dB and SIR is 20 dB. With \( C \geq 4 \) and \( L = 2 \), 16-ary QAM does not suffer from error floor at BER \( 10^{-8} \). The BER is affected more by \( L \) than by \( C \). It is necessary to use diversity receptions.

The BER of 64-ary QAM with \( C \) carriers is shown in Fig. 6 with \( L = 1, 2 \) when CDR is 0 dB and SIR is 20 dB. With \( C \geq 4 \) and \( L = 2 \), 64-ary QAM do not suffer from error floor at BER \( 10^{-8} \). The BER is affected more by \( L \) than by \( C \). It is shown in Figs. 5 and 6 that
16-ary QAM has 8 dB performance advantage over 64-ary QAM at BER $10^{-8}$.

Consider the case that delay time $\tau$ is 5 nsec. The BER of 16-ary QAM with $C$ carriers is shown in Fig. 7 with $L = 1$, 2 when CDR is 0 dB and SIR is 20 dB. With $C = 8$ and $L = 2$, 16-ary QAM suffers from error floor at BER $10^{-4}$. The BER is affected more by $C$ than by $L$. With less than 8 subcarriers, 16-ary QAM suffers from error floor for all cases, therefore it requires more than 8 subcarriers.

The BER of 64-ary QAM with $C$ carriers is shown in Fig. 8 with $L = 1$, 2 when CDR is 0 dB and SIR is 20 dB. With $C = 8$ and $L = 2$, 64-ary QAM suffers from error floor at BER $10^{-4}$. With less than 8 subcarriers, 64-ary QAM suffers from error floor for all cases, therefore it requires more than 8 subcarriers like 16-ary QAM.

IV. CONCLUSION

In this paper, multi-carrier $M$-ary quadrature amplitude modulation (QAM) with convolutional code is considered for high rate transmission in wireless communications. Wireless communications channels are modeled as a frequency selective Rayleigh fading channel with co-channel interference and additive white Gaussian noise. When signal to interference ratio is larger than 18 dB, the effect of co-channel interference is negligible since the bit error rate (BER) depends on average $E_b/N_o$ in this range. The BER increases as delay time increases. The effect of delay time for the BER increases as CDR decreases but the effect of delay time for BER does not change as the symbol diversity order increases.

When delay time is 1 nsec, with more than 4 subcarriers and symbol diversity order 2, both 16-ary QAM and 64-ary QAM do not suffer from error floor at BER $10^{-8}$. The BER is affected more by the symbol diversity order than by the number of subcarriers. It is necessary to use diversity reception. 16-ary QAM has 8 dB performance advantage over 64-ary QAM at BER $10^{-8}$. The coded multi-carrier 16-ary and 64-ary QAM can achieve very low BER with fading compensation technique and diversity reception.

When delay time is 5 nsec, with 8 subcarriers and symbol diversity order 2, both 16-ary QAM and 64-ary QAM suffer from error floor at BER $10^{-6}$ and $10^{-4}$ respectively. The BER is affected more by the number of subcarriers than the symbol diversity order. Both 16-ary QAM and 64-ary QAM require more than 8 subcarriers.

REFERENCES

Fig. 1. System block diagram.

Fig. 2. Subchannel model.

Fig. 3. BER of $M$-ary QAM as a function of SIR. Average $E_b/N_0 = 10$ dB.

Fig. 4. BER of 16-ary QAM as a function of $\tau$ and CDR. Average $E_b/N_0 = 10$ dB, SIR = $\infty$. 
Fig. 5. BER of 16-ary QAM with C carriers when $\tau = 1 \mu s$, CDR = 0 dB, and SIR = 20 dB.

Fig. 6. BER of 64-ary QAM with C carriers when $\tau = 1 \mu s$, CDR = 0 dB, and SIR = 20 dB.

Fig. 7. BER of 16-ary QAM with C carriers when $\tau = 5 \mu s$, CDR = 0 dB, and SIR = 20 dB.

Fig. 8. BER of 64-ary QAM with C carriers when $\tau = 5 \mu s$, CDR = 0 dB, and SIR = 20 dB.