Power and Rate Adaptation for MQAM/OFDM Systems under Fast Fading Channels

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Abstract—**In this paper, the effect of power and rate adaptation on the spectral efficiency of orthogonal frequency division multiplexing (OFDM) systems using M-ary quadrature amplitude modulation (MQAM) is investigated, in the presence of the fast fading channels, under power and instantaneous bit error rate (BER) constraints. A lower bound on the maximum spectral efficiency of adaptive OFDM/MQAM systems is obtained, together with a closed-form expression for the average spectral efficiency of adaptive OFDM systems. Theoretical and numerical results show that the adaptive MQAM/OFDM systems under fast fading channel have substantial gain in spectral efficiency over the non-adaptive counterparts.**

Keywords- Orthogonal Frequency Division Multiplexing (OFDM), Intercarrier Interference (ICI), Power and Rate Adaptation, Spectral Efficiency, High Mobility

I. INTRODUCTION

The orthogonal frequency-division multiplexing (OFDM) has been shown to be an effective technique to overcome inter-symbol interference (ISI) caused by frequency-selective fading with a simple transceiver structure. It has emerged as the leading transmission technique for a wide range of wireless communication standards [1]. However, the OFDM system under high mobility environment makes the system more sensitive to fast fading channels. The inter-carrier interference (ICI) caused by the time selectivity of wireless channel will degrade the spectral efficiency of system [2]. Using adaptive modulation with OFDM can enhance the spectral efficiency of system by adapting the data rate and transmit power of each subchannel according to the instantaneous channel state information at the transmitter [3].

Adaptive resource allocation in OFDM systems has been extensively studied in the literature, including [4]-[6]. Especially, many researchers considered the adaptive OFDM systems under carrier frequency offset (CFO). Cheon and Hong derived the average bit error rate of OFDM systems in the presence of CFO [7]. Rugini and Banelli presented the BER analysis of OFDM systems with CFO in Rician and Rayleigh fading channel [8]. Krishna Nehra and Mohammad shikh-Bahaei presented spectral efficiency of adaptive MQAM/OFDM systems with CFO over fading channels [9]. However, to the best of our knowledge, no previously published work studied the adaptive OFDM systems under very high mobility, say up to 500km/h.

It is the objective of this paper to investigate the effect of fast fading channel on the spectral efficiency of adaptive MQAM/OFDM systems under average power and instantaneous BER constraints. Especially, in order to ensure the instantaneous BER constraint under high mobility, a lower bound on the maximum spectral efficiency in adaptive OFDM/MQAM systems is obtained, and it is suggested to use the truncated integer rate adaptive OFDM in practical system for improving the average spectral efficiency. A closed-form expression for the average spectral efficiency of adaptive OFDM systems under fast fading channel is also derived.

The rest of this paper is arranged as follows: Part II introduces system model; Part III discusses non-adaptive MQAM/OFDM scheme under fast fading channels; Part IV presents adaptive MQAM/OFDM scheme under fast fading channels; Part V analyzes numerical results, followed by some concluding remarks.

II. SYSTEM MODEL

We consider an OFDM system with N subcarriers. The time-domain transmitted signal can be written as

$$s(n)=\frac{1}{\sqrt{N}}\sum_{k=0}^{N-1} d_k e^{j2\pi nk/N}, -L \le n \le N-1 \tag{1}$$

where L is the length of the guard interval and d_k stands for the frequency domain data symbol transmitted over the kth OFDM subchannel. We assume that all symbols have the same energy $E_s = E\{|d_k|^2\}$ per subcarrier, Then the received signal at the input of the discrete Fourier transform (DFT) takes the known form

$$y(n)=\sum_{l=0}^{L} h(n,l)s(n-l)+w(n) \tag{2}$$

where $h(n,l)$ is the channel impulse response of the l th tap at the time n. We assume Rayleigh fading channels, and Jakes' Doppler spectrum with maximum Doppler frequency $f_{max} = f_c v / c$; where f_c is the carrier frequency (Hz); v is the speed of mobile terminal (km/h); c is the speed of light. Assume that the maximum channel delay spread be less

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than or equal to the guard interval L; $w(n)$ denotes the additive white Gaussian noise with variance σ^2. The k th subcarrier output from the DFT can be expressed as [10]

$$Y_k = \frac{1}{\sqrt{N}}\sum_{n=0}^{N-1} y(n)e^{-j2\pi nk/N} = d_k H_k + I_k + W_k \quad (3)$$

where
$$H_k = (1/N)\sum_{n=0}^{N-1} H_k(n) \quad (4)$$

$$I_k = 1/N\sum_{m=0,m\neq k}^{N-1} d_m \sum_{n=0}^{N-1} H_m(n)\exp[j2\pi n(m-k)/N] \quad (5)$$

$H_k(n) = \sum_{l=0}^{L-1} h(n,l)\exp(-j2\pi lk/N)$ is the Fourier transform of the channel impluse response at time n. The second term in (3) represents ICI caused by the time-varying nature of the channel. $W_k = 1/\sqrt{N\sum_{n=0}^{N-1} w(n)}\exp(-j2\pi nk/N)$, and σ^2 is the variance of the W_k. From (5), the ICI power of the k th OFDM subcarrier can be obtained as [10]

$$P_{ICI}^k = E\left\{|I_k|^2\right\} = \sum_{m=0,m\neq k}^{N-1} E\left\{|d_m|^2\right\}\rho_{k,m} \quad (6)$$

Where $\rho_{k,m} = 1/N^2(N + 2\sum_{n=1}^{N-1}(N-n)J_0(2\pi f_{\max} T_{OFDM} n/N)$ $\times\cos(2\pi n(m-k)/N))$, $T_{OFDM} = 1/\Delta f = N/B$, (we assume the overhead due to the guard interval is ignored. The guard would reduce the spectral efficiency in practical OFDM systems), B is the total bandwidth (Hz). $f_{\max}T_{OFDM} = f_c vN/cB$ is the normalized Doppler frequency of system. $J_0(\cdot)$ denotes the zeroth-order Bessel function of the first kind.

Since the data on each subcarrier are uncorrelated, and $E\left\{|d_m|^2\right\} = E_s$. It follows from (6) easily that the ICI power, P_{ICI}^k, is independent of the subcarrier index k and has the following form[10,11]

$$P_{ICI} = E_s\left(1 - \frac{1}{N^2}\left(N + 2\sum_{n=1}^{N-1}(N-n)J_0(\frac{2\pi f_{\max}T_{OFDM}n}{N}\right)\right) \quad (7)$$

The normalized ICI power P_{N_ICI} is adopted, where $P_{N\_ICI} = P_{ICI}/E_s$. When f_c, N, B are constant, P_{ICI} increases with the speed v. In a time-invariant channel, the value of v is small or equal to zero, so P_{ICI} is small or zero. In this paper, we have two assumptions [9,12].

A1. Each subchannel is narrow enough so that it experiences frequency-flat fading.

A2. H_k has complex Gaussian distribution with zero mean and variance φ for all k at each OFDM interval [10].

where $\varphi = \left(N + 2\sum_{n=1}^{N-1}(N-n)J_0\left(\frac{2\pi f_{\max}T_{OFDM}n}{N}\right)\right)/N^2$. (8)

Assuming that the transmitted symbols are mutually uncorrelated, the instantaneous effective SINR for the kth subcarrier with fixed power allocation can be written as [12]

$$SINR_k = \frac{|H_k|^2\bar{\gamma}}{P_{N\_ICI}\bar{\gamma}+1} = \frac{\gamma[k]}{P_{N\_ICI}\bar{\gamma}+1} \quad (9)$$

where $|H_k|^2\bar{\gamma} = \gamma[k]$ is the instantaneous SNR for the k th subcarrier. $\bar{\gamma}$ is the average SNR when there is no ICI. The average effective SINR $\overline{SINR_k}$ is defined as

$$\overline{SINR_k} = \frac{E\left\{|H_k|^2\right\}\bar{\gamma}}{P_{N\_ICI}\bar{\gamma}+1} = \frac{\bar{\gamma}\varphi}{P_{N\_ICI}\bar{\gamma}+1}. \quad (10)$$

From (10), it follows that $\overline{SINR_k}$ decreases as the speed increases when $\bar{\gamma}$ is fixed. Fig.1 shows the average effective SINR as a fuction of $\bar{\gamma}$. As can be seen from Fig. 1, the received average SINR increases with the average transmitted SNR. When the velocity equals to 100km/h, the it changes almost linearly as function of the average SNR. However, when the velocity reaches 500km/h, the trend of the increase of the SINR is no longer linear due to the fact that the ICI increasing also with speed.

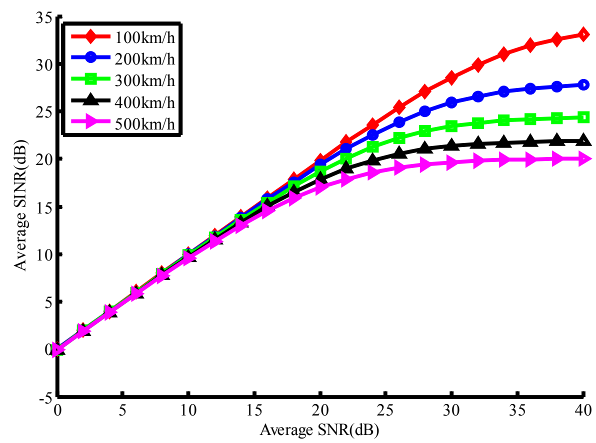

Fig. 1 Average SINR vs. Average SNR

III. NON-ADAPTIVE MQAM/OFDM SCHEME

Assume M-ary QAM (MQAM) symbols are transmitted over each subchannel of an OFDM system. Consequently, the number of bits/symbol sent over the k th subchannel is $\beta(\gamma[k]) = \log_2 M(\gamma[k])$. The instantaneous BER for the k th subcarrier is approximated by [13]

$$BER_{MQAM}(\gamma[k]) \approx \frac{2}{\beta(\gamma[k])}\left(1 - \frac{1}{\sqrt{2^{\beta(\gamma[k])}}}\right) erfc\left(\sqrt{1.5\frac{\gamma[k]}{(2^{\beta(\gamma[k])}-1)(P_{N\_ICI}\bar{\gamma}+1)}}\right) \quad (11)$$

Since (11) cannot be invertible easily, we consider a different BER approximation formula [13]

$$BER_{MQAM}(\gamma[k]) \approx 0.2\exp\left(\frac{-1.6\gamma[k]}{(2^{\beta(\gamma[k])}-1)(P_{N\_ICI}\bar{\gamma}+1)}\right) \quad (12)$$

For the case of a non-adaptive modulation, $\beta(\gamma[k]) = \beta$ is a constant for all k. The average BER can be defined as

$$Ave\_BER_{MQAM} \approx \int_0^{\infty} 0.2\exp\left(\frac{-1.6v\bar{\gamma}}{(2^{\beta}-1)(P_{N\_ICI}\bar{\gamma}+1)}\right)p_u(u)du \quad (13)$$

where $p_u(u) = \exp(-u)$, for $u \geq 0$, $u = |H_k|^2$.

Assuming P_{tar} is the target average BER, the maximum bit load given the average BER constraint is

$$\beta = \log_2[\frac{1.6\bar{\gamma}}{(0.2/P_{tar}-1)(P_{N\_ICI}\bar{\gamma}+1)}+1]\,. \tag{14}$$

Fig. 2 shows tightness of the simplified average BER approximation for MQAM, according to (12), with different bit rates for velocities 100km/h and 500km/h, respectively. It is evident that the simplified approximation nearly predicts the BER expression given by (11). It also shows that the BER performance degrades with the increase of vehicle speed when the bit rate is fixed. In order to guarantee the BER performance, the bit rate must be reduced under high mobility.

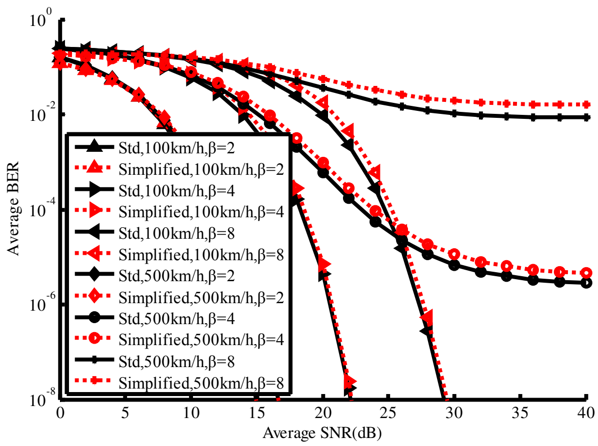

Fig. 2 Average BER vs. Average SNR

IV. ADAPTIVE MQAM/OFDM SCHEME

For adaptive OFDM, different power levels and modulation bit load are allocated to different subchannels. The instantaneous BER of each subchannel is

$$BER_{MQAM}(\gamma[k]) \approx 0.2\exp\left[\frac{-1.6\gamma[k]\frac{s(\gamma[k])}{\bar{S}}}{(2^{\beta(\gamma[k])}-1)(P^k_{N\_ICI}\bar{\gamma}+1)}\right] \tag{15}$$

where the transmit signal power $s(\gamma[k])$ and $\beta(\gamma[k])$ are adapted with $\gamma[k]$, subject to the average signal power $\bar{S}$, and the instantaneous BER constraints $BER_{MQAM}(\gamma[k]) = P_{tar}$. $P^k_{N\_ICI}$ is the normalized ICI power of the k th subcarrier. From (6) it follows that

$$P^k_{N\_ICI} = \sum_{m=0,m\neq k} \frac{s(\gamma[k])}{\bar{S}}\rho_{k,m} \tag{16}$$

Note that, it is very difficult to calculate the exact $P^k_{N\_ICI}$ when the signal powers transmitted over different subchannels are not the same. However, we can obtain an upper bound for it in terms of the largest transmitted normalized power $P\_\max = \max_m\{s(\gamma[m])/\bar{S}\}$, $\sum_{m=0}^{N-1} s(\gamma[m])/\bar{S} = 1$ of all the subcarriers easily. Consequently, employing the upper bound for the normalized ICI variance of the all subcarriers, determined by $P\_\max$, the upper bound of the instantaneous BER for each subchannel can be given as

$$BER_{MQAM}(\gamma[k]) \le 0.2\exp\left[\frac{-1.6\gamma[k]\frac{s(\gamma[k])}{\bar{S}}}{(2^{\beta(\gamma[k])}-1)(P\_\max P_{N\_ICI}\bar{\gamma}+1)}\right]. \tag{17}$$

According to (17), the maximum bit load size is obtained as

$$\beta(\gamma[k]) \le \log_2\left[1+\frac{(-1.6/\ln(P_{tar}/0.2))\gamma[k]\frac{s(\gamma[k])}{\bar{S}}}{(P\_\max P_{N\_ICI}\bar{\gamma}+1)}\right]. \tag{18}$$

The maximum bit load in (18) is a lower bound for each subchannel because of the largest ICI power. According to the assumption A2 for the channel model, it can be shown that the average capacity of an adaptive OFDM system does not depend on the system parameters or on the specific power delay profile of the WSSUS mobile channels [9].

To maximize the average capacity of an adaptive OFDM system, following constrained optimization problem is considered:

$$\max_{s(\gamma[k])} \int \beta(\gamma[k])p_{\gamma[k]}(\gamma[k])d\gamma[k] \tag{19a}$$

subject to

$$E_{\gamma[k]}\{s(\gamma[k])\} \le \bar{S} \qquad \forall k \in N \tag{19b}$$

$$s(\gamma[k]) \ge 0 \qquad \forall k \in N \tag{19c}$$

$$BER_{MQAM}(\gamma[k]) \le P_{tar} \qquad \forall k \in N \tag{19d}$$

where $E_x\{\}$ denotes expectation with respect to x. Then, the Lagrangian for the optimization problem is defined as

$$J\{s(\gamma[k])\} = \int \log_2\left[1+\frac{(-1.6/\ln(P_{tar}/0.2))\gamma[k]\frac{s(\gamma[k])}{\bar{S}}}{(P\_\max P_{N\_ICI}\bar{\gamma}+1)}\right]$$

$$\times p_{\gamma[k]}(\gamma[k])d\gamma[k] - \lambda(\int s(\gamma[k])p_{\gamma[k]}(\gamma[k])d\gamma[k] - \bar{S}) \tag{20}$$

where λ is the Lagrange multiplier. The optimal power adaptation must be nonnegative and satisfy

$$\frac{\partial J\{s(\gamma[k])\}}{\partial s(\gamma[k])} = 0, \qquad s(\gamma[k]) \ge 0, \qquad \beta(\gamma[k]) \ge 0\,. \tag{21}$$

Solving (21) yields the optimal power adaptation

$$\frac{s(\gamma[k])}{\bar{S}} = \frac{1}{\lambda\ln(2)\bar{S}} - \frac{P\_\max P_{N\_ICI}\bar{\gamma}+1}{(-1.6/\ln(P_{tar}/0.2))\gamma[k]}\,. \tag{22}$$

Note that the Lagrange multiplier λ can be determined from the average power constraint using numerical methods. The optimal rate adaptation can then be given as

$$\beta(\gamma[k]) = \log_2\left[\frac{(-1.6/\ln(P_{tar}/0.2))\gamma[k]}{(\lambda\ln(2)\bar{S})(P\_\max P_{N\_ICI}\bar{\gamma}+1)}\right] \text{ bps/Hz}\,. \tag{23}$$

In practice, however, only the integer value of the rate is acceptable. Therefore, the rate is truncated to the nearest integer value. The average capacity of the adaptive OFDM system is then follows as

$$Capacity_{\max} = \int_{\gamma 0}^{\infty} \log_2 \left[\frac{(-1.6/\ln(P_{tar}/0.2))\gamma[k]}{(\lambda \ln(2)\overline{S})(P\_\max P_{N\_ICI}\overline{\gamma}+1)} \right] , \times p_{\gamma[k]}(\gamma[k]) d\gamma[k] \quad (24)$$

where $\gamma_0 = \dfrac{\left(P\_\max P_{N\_ICI}\overline{\gamma}+1\right)\lambda \ln(2)\overline{S}}{-1.6/\ln\left(P_{tar}/0.2\right)}$ is the optimized threshold for $\gamma[k]$ below which the channel is not used. Note that, this threshold can be determined from (22) so as to $s(\gamma[k])/\overline{S} \geq 0$. To find the closed-form approximation for (24), we use the pdf of $p_{\gamma[k]}(\gamma[k])$ given by

$$p_{\gamma[k]}(\gamma[k]) = \frac{\exp(-\gamma[k]/\overline{\gamma[k]})}{\overline{\gamma[k]}} . \quad (25)$$

Here, $\overline{\gamma[k]} = \overline{\gamma} E\left\{|H_k|^2\right\}$ is the average received SNR and $E\left\{|H_k|^2\right\}$ is independent of the subcarrier index k, as can be seen from (8), Therefore, $\overline{\gamma[k]}$ can be substituted by $\varphi\overline{\gamma}$. As shown in the Appendix, (24) can be evaluated as

$$Capacity_{\max} = -\frac{1}{\ln(2)} Ei\left(-\frac{\gamma_0}{\varphi\overline{\gamma}}\right) \quad (26)$$

where $Ei(\cdot)$ denotes the exponential integral [14].

In order to evaluate $P\_\max$ in (20), we employ the instantaneous BER expression (15) for each subchannel k where the normalized ICI power for subchannel is computed. However, the resulting constraint optimization problem, stated by the Eqs. (19a) to (19b), needs the knowledge of the other subchannel powers, $s(\gamma[m])/\overline{S}$, $m = 0,1,\cdots N-1(m \neq k)$ which makes the solution computationally intractable. One feasible way to solve the problem is to assume that the normalized ICI power of the k th subchannel is determined by its own power. That is, $P_{N\_ICI}^{k} \approx s(\gamma[m])/\overline{S} \times P_{N\_ICI}$. However, the BER performance, in this case, cannot meet the constraint (19d) since the transmit powers of the adjacent subcarriers are larger than that of the k th subcarrier. On the other hand, when H_k is the best subchannel implies that $s(\gamma[k])/\overline{S}$ as well as P_{ICI}^{k}, determined by $s(\gamma[k])/\overline{S}$, take their maximum values resulting in the constraint (19d) be satisfied. Consequently, $P\_\max$ can be determined as $P\_\max = \lim_{\gamma[k]->\infty} s(\gamma[k])/\overline{S}$. We can obtain an upper bound from (22) as

$$P\_\max = \lim_{\gamma[k]->\infty} \left(\frac{s(\gamma[k])}{\overline{S}}\right) = \frac{1}{\lambda \ln(2)\overline{S}} \quad (27)$$

For the worst case, the ICI is determined by the largest power, when $\gamma[k] = \infty$ and a lower bound on the maximum spectral efficiency in adaptive OFDM/MQAM systems is obtained.

V. Numerical Results and Discussion

In this section, we examine the performance of the solution for the power and rate adaptation derived in the previous sections. In all simulations presented here, we assume N=1024, f_c=2.5 GHz, Δf = 15 KHz, v =100km/h and 500km/h. The BER requirement is 10^{-3}.

In Fig. 3, the adaptive power control scheme $s(\gamma[k])/\overline{S}$ is plotted as a function of the average SNR. The figure shows similar trends with respect to $\gamma[k]$ for different velocities. It also indicates that the larger speed yields larger cutoff and larger transmit power as $\gamma[k] \to \infty$. The larger cutoff at the larger velocities is due to fact that ICI power gets also larger. Higher transmit power at higher speeds as $\gamma[k] \to \infty$ is also due to the average power constraint.

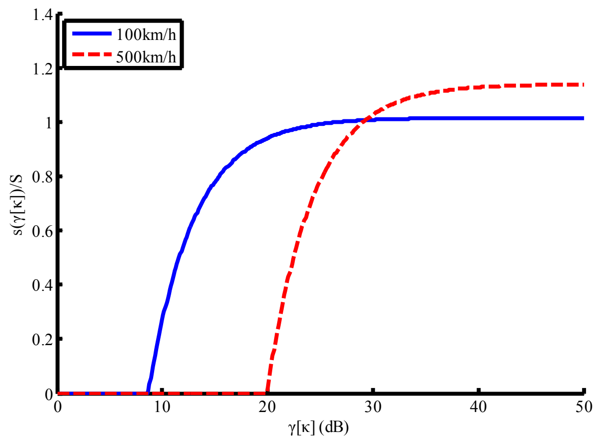

Fig. 3 $s(\gamma[k])/\overline{S}$ for MQAM ($\overline{BER} = 10^{-3}, \overline{\gamma[k]} = 35dB$)

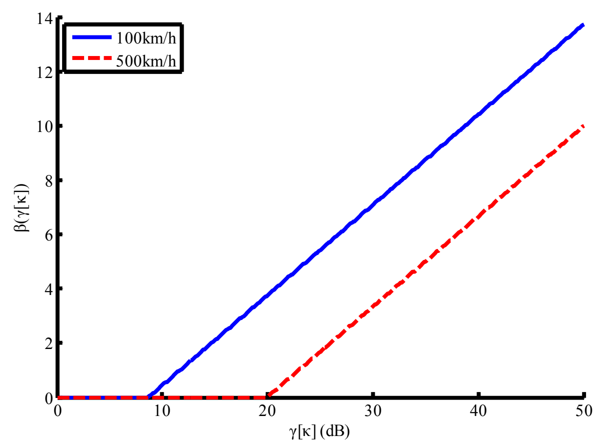

Fig. 4 $\beta(\gamma[k])$ for MQAM ($\overline{BER} = 10^{-3}, \overline{\gamma[k]} = 35dB$)

In Fig. 4, the bit rate adaptation $\beta(\gamma[k])$ is plotted as a function of the average SNR. We conclude from Fig.4 that it is possible to transmit more bits as $\gamma[k]$ increases and that the larger speed yields the larger cutoff. It also shows that the lower speed has the larger bit rate than higher speed counterpart when $\gamma[k]$ is fixed. As it can be seen from Fig.4, the higher speed case yields lower bit rate than the lower speed case even with larger transmit power because of the larger ICI variance at higher speeds.

Fig. 5 shows the average spectral efficiency of the adaptive OFDM systems as well as of the non-adaptive OFDM for different values of velocities. It also indicates that the higher speeds have lower average spectral efficiency, mainly due to the fact that it induces higher ICI. As it can be seen from Fig.5, the adaptive OFDM can achieve higher gains in spectral efficiency compared with non-adaptive OFDM under different velocities resulting in a floor in the average spectral efficiency. We also observed that the spectral efficiency of the system cannot be improved with the average SNR, increasing beyond a certain level. This is mainly due to the contribution of the average SNR to the ICI. The average spectral efficiencies of truncated integer rate adaptive OFDM are also given in Fig. 5. In spite of the fact that its spectral efficiency is close to the adaptive OFDM, we observe that there is still a certain gap, since the optimal parameters are obtained in the rate-domain.

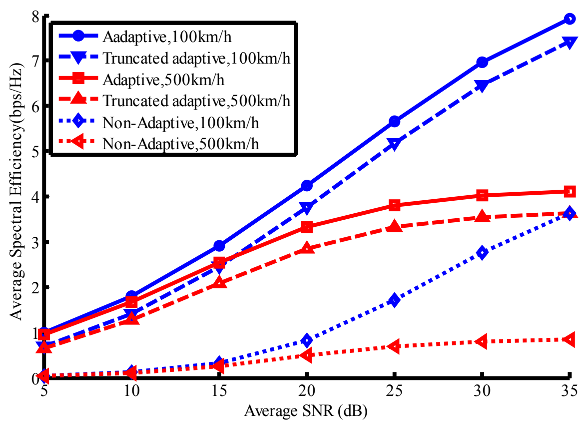

Fig. 5 Average spectral efficiency vs. Average SNR

VI. Conclusions

In this paper, a power and rate adaptation scheme has been studied to maximize average spectral efficiency of MQAM/OFDM systems ın the presence of the fast fading channels. Theoretical and numerical results have shown that adaptive OFDM systems under fast fading channels have considerable gain over non-adaptive counterparts. In fact, the proposed adaptive system under fast fading channels tends to have an average floor of spectral efficiency, depending on the ICI and the average SNR. Since very rapidly time varying channels lead to larger ICI, the average spectral efficiency will be seriously degraded under high mobility. Besides, the performance of the truncated integer rate adaptive OFDM was shown to be close to that of the continuous rate adaptive OFDM. Consequently, the truncated version can be applied in practical system for simplicity under high mobility scenarios.

Appendix A Derivation of (24)

$$Capacity_{\max} = \int_{\gamma 0}^{\infty} \log_2\left[\frac{(-1.6/\ln(P_{tar}/0.2))\gamma[k]}{(\lambda\ln(2)\bar{S})(P\_\max\cdot P_{N\_ICI}^{up}\,\bar{\gamma}+1)}\right] \times p_{\gamma[k]}(\gamma[k])d\gamma[k]$$

Assume

$\xi = (-1.6/\ln(P_{tar}/0.2))$, $\eta = (\lambda\ln(2)\bar{S})$, $\psi = (P\_\max\cdot P_{N\_ICI}\bar{\gamma}+1)$.

$$Capacity_{\max} = \int_{\gamma 0}^{\infty}\log_2\left[\frac{\xi\gamma[k]}{\eta\psi}\right]p_{\gamma[k]}(\gamma[k])d\gamma[k]$$
$$= \frac{1}{\varphi\bar{\gamma}}\int_{\gamma 0}^{\infty}\log_2\left[\frac{\xi\gamma[k]}{\eta\psi}\right]\cdot\exp(-\gamma[k]/\varphi\bar{\gamma})d\gamma[k]$$

For $t = \gamma[k]-\gamma_0$, we can express the above integral as follows

$$Capacity_{\max} = \frac{1}{\ln(2)\varphi\bar{\gamma}}\int_0^{\infty}\ln\left[\frac{\xi(t+\gamma_0)}{\eta\psi}\right]\exp(-(t+\gamma_0)/\varphi\bar{\gamma})dt$$

By means of the integral formula

$$\int_0^{\infty}\ln(\chi t+1)\exp(-ut) = -\frac{1}{u}\exp(\frac{u}{\chi})Ei(-\frac{u}{\chi})$$

we obtain the final result as follows

$$Capacity_{\max} = -\frac{1}{\ln(2)}Ei\left(-\frac{\gamma_0}{\varphi\bar{\gamma}}\right) \tag{28}$$

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