The potential and limitations of adaptive modulation over slow Rayleigh fading channels

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Abstract

The upper-bound performance of adaptive modulation in Rayleigh channels is given and the results of optimisation of the switching levels are presented. The resulting performance is compared with fixed modulation schemes in a narrow-band Rayleigh fading channel. The switching levels are re-optimised for co-channel interference environments and comparison with fixed modulation schemes is conducted again.

1 Introduction

Mobile radio channels exhibit fluctuations in received signal power and phase. Pilot Symbol Assisted Modulation (PSAM) [1] can mitigate the effect of the phase distortion introduced by the channel. It can achieve a Signal to Noise Ratio (SNR) vs Bit Error Rate (BER) performance to within 2dB of what may be achieved using perfect channel compensation. However, pilot-based compensation for the received power fluctuations results in amplification of the corrupting noise at the receiver, as well as amplification of the signal. Clearly, PSAM can do nothing to combat the fluctuating short term SNR that is experienced in a fading channel.

There are two distinct approaches towards combating short term fluctuations of the SNR, such as that experienced in a fading channel. One approach is to use statistical coding techniques with interleaving, the other is to employ some deterministic technique for example adaptive modulation [2]. Coding and interleaving are employed in current (second generation) digital mobile radio systems e.g. [3]. To enable third generation digital mobile radio systems to support multimedia services, we are proposing adaptive modulation for a particular mode of operation for Universal Mobile Telephone System (UMTS). Adaptive modulation level schemes exploit the fluctuating nature of the received signal level without increasing the co-channel interference power. This is most conveniently achieved in a Time Division Duplex (TDD) system, especially in an indoors environment where propagation delays are small and mobile velocities are typically low. The signal power of a TDD frame, received at one end of the TDD link, is used to estimate the level of fading that will be experienced in the reverse link time slot. The number of modulation levels is then selected for the reverse link on the basis of this estimate and the level of Bit Error Rate (BER) which is acceptable to the overall system. In such an environment a low normalised Doppler frequency would be expected and clearly the performance would degrade as the correlation between channel conditions of the up and down links is reduced. Under such circumstances the system would switch to using coding and interleaving in preference to adaptive modulation. Figure 1 illustrates the performance of a single mode adaptive and single mode coding with interleaving scheme as a function of normalised Doppler frequency [4]. It is proposed that an intelligent system could determine which of the two single modes of operation would be most favourable for given channel conditions and switch between them resulting in a Dual Mode system. The Dual Mode performance is also shown in Figure 1. However, in this paper the performance of the Dual Mode hand-set is considered when the normalised Doppler frequency is such that only the adaptive modulation mode is activated.

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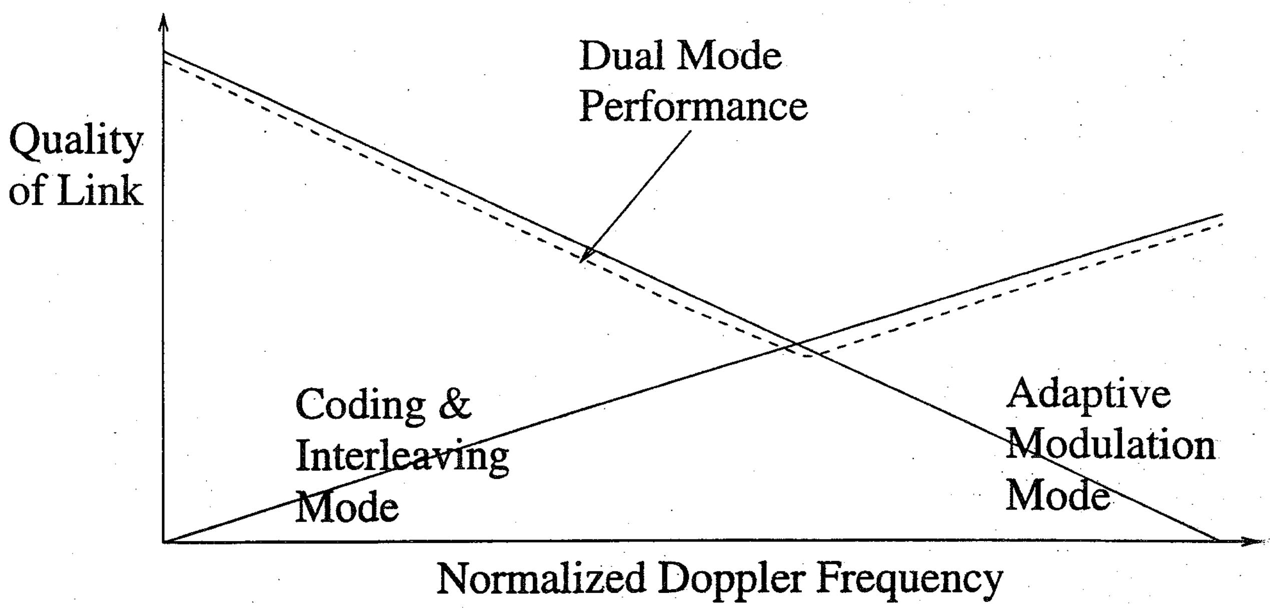

Figure 1: Stylised performance characteristics of, single mode adaptive modulation system, single mode coding with interleaving system and a dual mode adaptive modulation and coding with interleaving system, relative to normalised Doppler frequency.

2 Performance

The received signal level, s, is compared with a set of N switching levels, l_n, and an appropriate Modulation Scheme (MS) is selected accordingly. Following Kamio et al [5] the MS that is used is selected as follows;

$$\mathrm{MS} = \begin{cases} \text{No Transmission} & \text{if} \quad l_1 > s \\ \text{BPSK} & \text{if} \quad l_1 \leq s < l_2 \\ \text{QPSK} & \text{if} \quad l_2 \leq s < l_3 \\ \text{Square 16 Point QAM} & \text{if} \quad l_3 \leq s < l_4 \\ \text{Square 64 Point QAM} & \text{if} \quad s \geq l_4 \end{cases} \tag{1}$$

where the values of l_n will be discussed later.

The values of l_1, l_2, l_3 and l_4 define the performance of an adaptive modulation scheme in a set of given channel conditions. The upper bound performance of an adaptive modulation scheme was derived in [6]. The BER performance of coherent modulation schemes with 1, 2, 4 and 6 Bits Per Symbol (BPS) assuming perfect clock and carrier recovery in a Gaussian channel are known [2]. The corresponding expressions are given below:

$$P_b(\gamma) = Q\left(\sqrt{2\gamma}\right), \tag{2}$$

$$P_q(\gamma) = Q\left(\sqrt{\gamma}\right), \tag{3}$$

$$P_{16}(\gamma) = \frac{1}{4}\left[Q\left(\sqrt{\frac{\gamma}{5}}\right) + \left(3Q\sqrt{\frac{\gamma}{5}}\right)\right] + \frac{1}{2}Q\left(\sqrt{\frac{\gamma}{5}}\right), \tag{4}$$

$$\begin{aligned} P_{64}(\gamma) &= \frac{1}{12}\left[Q\left(\sqrt{\frac{\gamma}{21}}\right) + Q\left(3\cdot\sqrt{\frac{\gamma}{21}}\right) + Q\left(5\cdot\sqrt{\frac{\gamma}{21}}\right) + Q\left(7\cdot\sqrt{\frac{\gamma}{21}}\right)\right] \\ &+ \frac{1}{6}Q\left(\sqrt{\frac{\gamma}{21}}\right) + \frac{1}{6}Q\left(3\cdot\sqrt{\frac{\gamma}{21}}\right) + \frac{1}{12}Q\left(5\cdot\sqrt{\frac{\gamma}{21}}\right) + \frac{1}{12}Q\left(7\cdot\sqrt{\frac{\gamma}{21}}\right) \\ &+ \frac{1}{3}Q\left(\sqrt{\frac{\gamma}{21}}\right) + \frac{1}{4}Q\left(3\cdot\sqrt{\frac{\gamma}{21}}\right) - \frac{1}{4}Q\left(5\cdot\sqrt{\frac{\gamma}{21}}\right) - \frac{1}{6}Q\left(7\cdot\sqrt{\frac{\gamma}{21}}\right) \\ &+ \frac{1}{6}Q\left(9\cdot\sqrt{\frac{\gamma}{21}}\right) + \frac{1}{12}Q\left(11\cdot\sqrt{\frac{\gamma}{21}}\right) - \frac{1}{12}Q\left(13\cdot\sqrt{\frac{\gamma}{21}}\right), \end{aligned} \tag{5}$$

where γ is the SNR, $Q(x) = \frac{1}{\sqrt{2\pi}}\int_x^\infty e^{-x^2/2}dx$, and $P_b(\gamma)$, $P_q(\gamma)$, $P_{16}(\gamma)$ and $P_{64}(\gamma)$ are the mean BERs of BPSK, QPSK, square 16 point square QAM, and square 64 point QAM, respectively. The PDF of the

	l_1	l_2	l_3	l_4
Speech (dB)	3.31	6.48	11.61	17.64
Computer Data (dB)	7.98	10.42	16.76	26.33

Table 1: Optimised switching levels for speech and computer data systems through a Rayleigh channel, shown in SNR dB

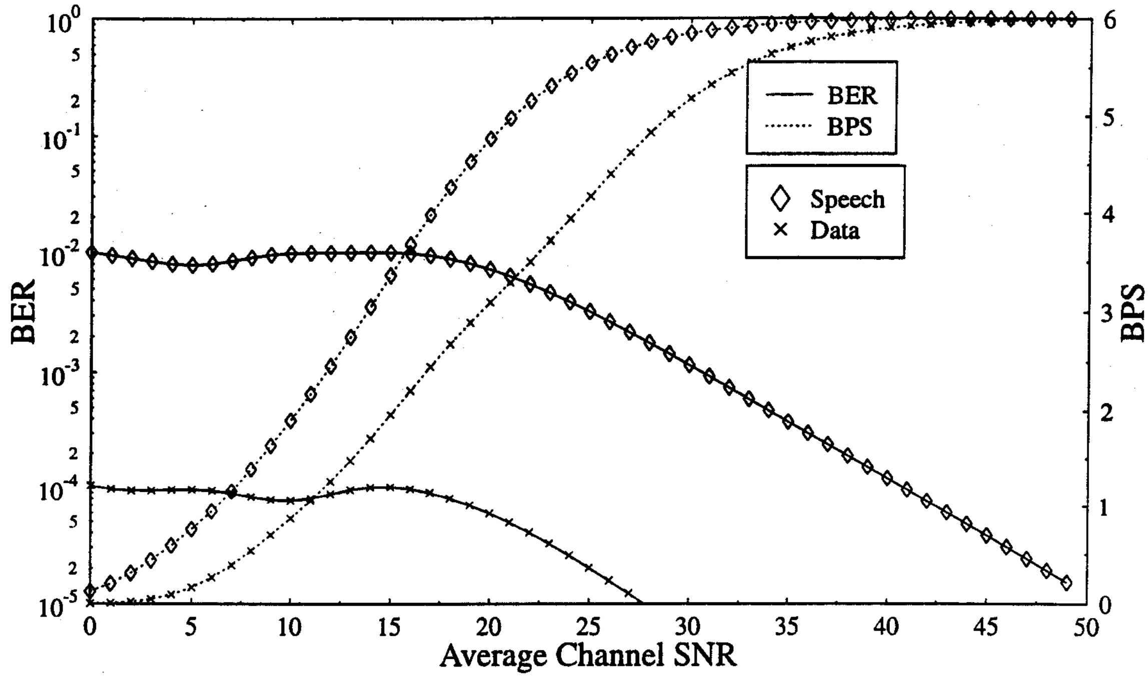

Figure 2: Upper bound BER and BPS performance of adaptive QAM in Rayleigh Channel optimised separately for Speech and Data transfer.

fluctuations of the instantaneous received amplitude, s, in a Rayleigh channel are given by:

$$F(s,S) = \frac{2s^{\frac{1}{2}}}{S} \cdot e^{-s/S}, \tag{6}$$

and, therefore, the narrow-band upper bound BER performance of an adaptive modulation scheme similar to that described in [5] may be computed from:

$$P_a(S/N) = B^{-1} \begin{bmatrix} 1\int_{l_1}^{l_2} P_b(s/N)\cdot F(s,S) & ds \\ +2\int_{l_2}^{l_3} P_q(s/N)\cdot F(s,S) & ds \\ +4\int_{l_3}^{l_4} P_{16}(s/N)\cdot F(s,S) & ds \\ +6\int_{l_4}^{\infty} P_{64}(s/N)\cdot F(s,S) & ds \end{bmatrix} \tag{7}$$

where B is the mean number of BPS and is given by:

$$\begin{aligned} B &= 1\cdot\int_{l_1}^{l_2} F(s,S)\,ds + 2\cdot\int_{l_2}^{l_3} F(s,S)\,ds \\ &+ 4\cdot\int_{l_3}^{l_4} F(s,S)\,ds + 6\cdot\int_{l_4}^{\infty} F(s,S)\,ds \end{aligned} \tag{8}$$

The switching levels in Equation 7 may be optimised [7] for target BER. Table 1 shows the optimised switching levels for two schemes referred to as Speech and Computer Data with respective BERs of 1×10^{-2} and 1×10^{-4}, respectively. The BER and BPS performance of the two schemes through a Rayleigh channel are shown in Figure 2.

Figure 3 shows the capacity limit [8] for signaling over a noisy band-limited channel with arbitrary BER. It also shows the performance of fixed BPSK, QPSK, and square 16 and 64 point QAM when signaled through a Rayleigh channel and assuming an acceptable BER of 1×10^{-2} and 1×10^{-4}. Finally, the diagram shows the performance of the optimised adaptive schemes with the same acceptable BERs.

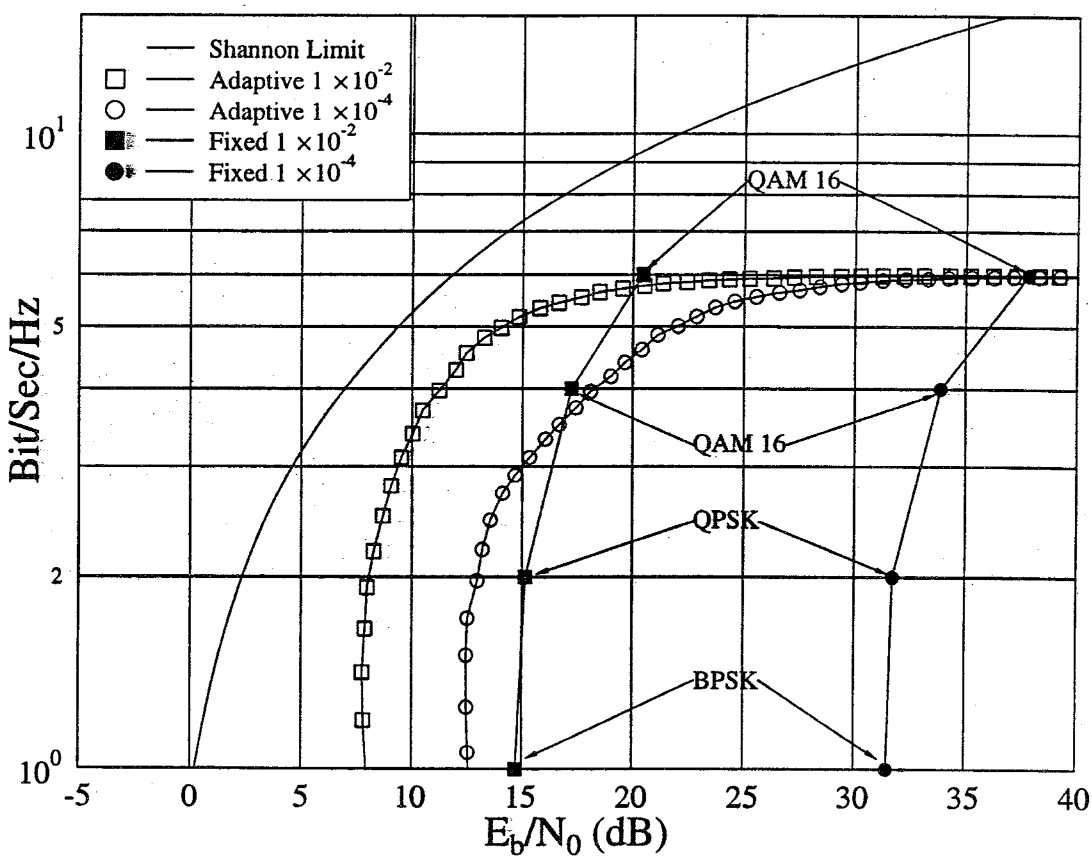

Figure 3: Capacity limit and performance of fixed and adaptive modulation schemes in Rayleigh fading channels with arbitrary BERs of 1×10^{-2} and 1×10^{-4}.

Table 2 can be derived from Figure 3. This highlights how fixed modulation schemes, in fading channel wastes capacity in order to achieve a required average BER. This is particularly true when low BERs are required. However, it also shows how up to in the case of BERs of 1×10^{-2} and 1×10^{-4} 7 and 18 dB respectively of the wasted symbol energy can be saved by employing adaptive modulation.

3 Control

The model presented has given an upper bound on the performance of adaptive modulation in a fading channel. It is assumed that the receiver is aware of what modulation scheme was employed by the transmitter. It is proposed that control information is passed with every data frame to identify the modulation scheme that has been employed. This control information can be considered redundant in the sense it carries no data and, therefore, erodes some of the benefits outlined above.

Further, should the control information be corrupted the whole frame would be incorrectly decoded. To

	Fixed	Fixed	Adaptive	Adaptive
BPS	1×10^{-2}	1×10^{-4}	1×10^{-2}	1×10^{-4}
1	14	31	7	13
2	13	29	5	12
4	10	25	4	11
6	9	25	15	25

Table 2: Difference in performance, measured in E_b/N_0, between the capacity limit and both fixed and adaptive schemes in a Raleigh fading channel at BERs of 1×10^{-2} and 1×10^{-4}.

	SIR(dB)	l_1	l_2	l_3	l_4
Computer Data (dB)	10	*	*	*	*
Computer Data (dB)	20	42.98	80.54	*	*
Computer Data (dB)	30	22.36	43.03	120.02	*
Speech (dB)	10	37.20	*	*	*
Speech (dB)	20	6.56	10.40	18.52	*
Speech (dB)	30	4.32	7.84	13.93	18.94

Table 3: Optimised switching levels for speech and computer data down-link through a Rayleigh channel, shown in SNR dB, with various down-link SIRs and 10 dB up-link SIR

overcome this multiple control symbols may be transmitted. Torrance [9] proposed uneven protection control symbols to try and reduce the redundant information while reducing erroneous decoding of the control information.

4 Variable Throughput

Figure 2 shows that the average BPS is a function of average channel SNR. However, the actual BPS fluctuates as a function of the normalised Doppler frequency as well as the average channel SNR [10]. Therefore, the throughput across the channel varies which can present problems when latency is a design critical issue.

One alternative to consider variable rate coding strategies [11] which would vary on the basis of the short term channel condition. Alternatively by combining may users, statistical multiplexing [12] could be employed.

5 Interference

Interference corrupts a received symbol in an adaptive scheme, in much the same way as it would with fixed modulation. However, the interference also has an adverse effect the channel estimation because the interference at the up and down links is independent. Therefore, the performance of the speech and computer data schemes proposed above will be degraded by interference.

To overcome this deterioration two methods are proposed. The first, which is considered in more detail here, involves re-optimising the switching levels depending upon the long term SIR and the other is interference cancelation [13]. Re-optimisation is performed by setting the same target BERs as for the interference-less scenario an is conducted for the down-link BER, although it is equivalent for the up-link. The BER was evaluated by simulation assuming a single Rayleigh fading interferer and a up-link SIR of 10dBs. The optimisation was performed as in [7] for three mean SIRs of 10dB, 20dB and 30dB and the resulting switching level are shown in Table 3 where a '*' represents an unobtainable switching level.

The performance of the re-optimised schemes are plotted in Figure 4. Considering initially a comparison between the adaptive and fixed speech schemes, it can be seen that adaptive modulation nearly always offers improvements over fixed schemes for 20 and 30 dB SIR. However, at 10 dB SIR the fixed schemes can not achieve the desired BER with infinite E_n/N_0 while the adaptive scheme can achieve 0.5 bits/second/Hz at 40 dB E_n/N_0. The fixed computer data schemes can not achieve the target BER in the presence of 30 dB interference, however, the adaptive scheme achieves can reach the target BER at both 30 and 20 dB SIR.

Wales [13] proposes using interference cancellation within GSM. However, adaptive modulation is be employed when Doppler frequencies are low. This is likely to correspond to an indoors environment where dispersion is unlikely to be a problem. Therefore, a multi-mode system could employ its equaliser hardware to the problem of interference cancelation.

6 Conclusion

It has been shown that adaptive modulation, under ideal circumstances, can offer large margins of improvement over fixed modulation schemes in Rayleigh fading channels. However, some of that benefit is reduced because of the need for control symbols and the resulting variable transmission rates. The performance of adaptive modulation has been considered in a co-channel interference environment, the system parameters re-optimised and again large potential benefits have been identified.

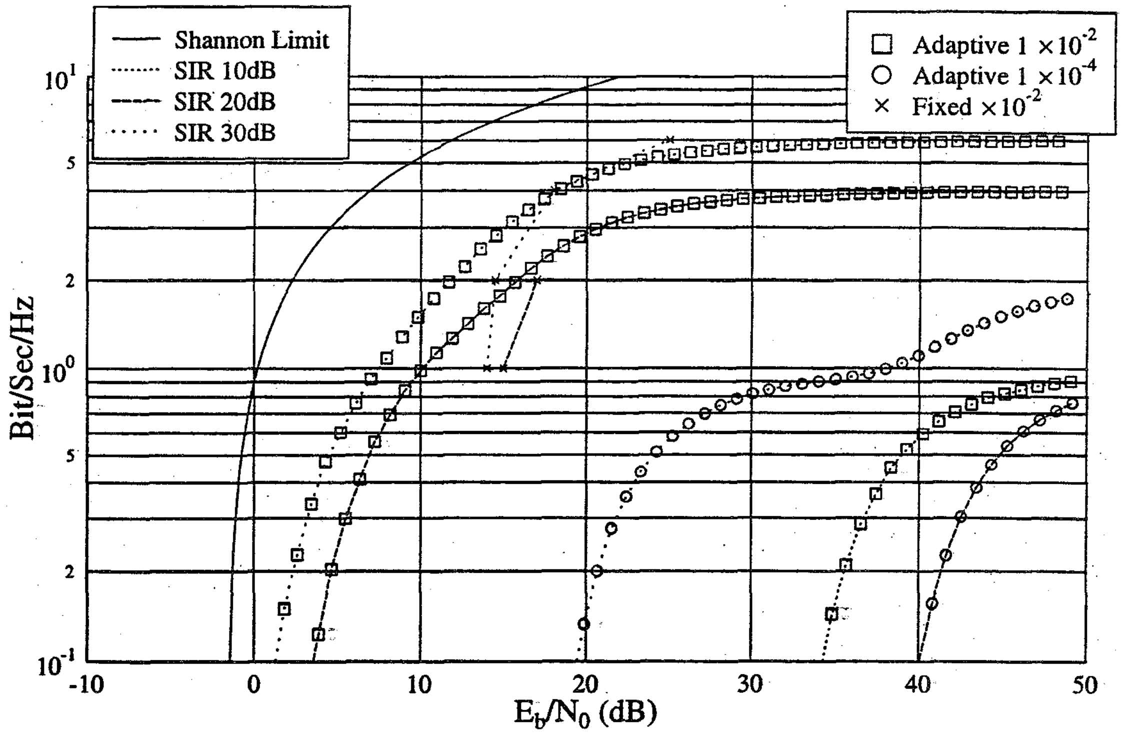

Figure 4: Upper bound BER and BPS performance of adaptive QAM in Rayleigh Channel with single Rayleigh interferer optimised separately for Speech and Data transfer.

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