INTERFERENCE CANCELLATION FOR ADAPTIVE MULTI-MODE TERMINALS

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ABSTRACT

Adaptive modulation can achieve channel capacity gains by adapting the number of bits per transmission symbol on a burst-by-burst basis, in harmony with channel quality fluctuations. This is demonstrated in Figures 6 and 7 for target bit error rates of 1 and 0.01 %, respectively, in comparison to conventional fixed modems. However, the achievable gains depend strongly on the prevalant interference levels and hence interference cancellation is invoked on the basis of adjusting the demodulation decision boundaries after estimating the interfering channel's magnitude and phase. Using the modem-mode switching levels of Table 2 and with the aid of interference cancellation, target BERs of 1 and 0.01 % can be maintained over slow-fading channels for a wide range of channel Signal-to-noise ratios (SNR) and Signal-to-interference ratios (SIR), as seen in Figures 4 and 5, respectively.

1. BACKGROUND

Various aspects of adaptive multi-level modems were documented for example in References [1]-[7]. Their underlying principle is that the number of bits per modulation symbol is varied on a burst-by-burst basis in order to adapt to time-variant channel conditions. We employed 0-6 bits per modulation symbol at a constant signalling rate. In Reference [5] we documented the Bit Error Rate (BER) and Bits per Symbol (BPS) performance of such schemes, while using the set of optimised switching levels shown in Table 1. There are two specific set of switching levels l_1-l_4 in the Table, optimised for a speech and a data transmission system with target BERs of 1 and 0.01 %, respectively [5]. The interference resistance of these schemes was characterised in Reference [7] and here we set out to improve their performance employing interference cancellation.

Wales [10] recognised that if the inter-symbol interference came from a single interferer, then the joint equalisation and co-channel interference cancellation could be improved by acquiring information about the phase and amplitude of the co-channel interference propagation channel. He proposed obtaining information about the co-channel interference propagation channel by exploiting the orthogonality of the different training sequences. Berangi et al [11] showed up to a factor of 30 improvement in BER for narrow-band constant amplitude modulation schemes through Rayleigh fading channels.

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Switching levels(dB)	l_1	l_2	l_3	l_4
Mean-Speech (1%)	3.31	6.48	11.61	17.64
Mean-BER Data (0.01%)	7.98	10.42	16.76	26.33

Table 1: Switching levels for speech and computer data systems through a Rayleigh channel, shown in instantaneous channel SNR (dB) to achieve Mean BERs of 1×10^{-2} and 1×10^{-4}, respectively

In this contribution we focused our attention on designing an adaptive modem, maintaining target BERs of 1 and 0.01 %, respectively, under interfered conditions, which we refer to as the speech and data transmission schemes [5]. Our experiments were conducted within the framework of the Advanced Time Division Multiple Access (ATDMA)[9] scheme, using Time Division Duplexing (TDD), which lends itself to estimating the transmission channel's quality on the basis of the received signal quality, upon relying on the channel's reciprocity. In our co-channel interference investigations the signal was transmitted through a 10 ms^{-1} vehicular speed Rayleigh channel and the interference was faded through an independent 1 ms^{-1} channel.

2. INTERFERENCE CANCELLATION

2.1. Principle of Interference Cancellation

The interference canceller's operation is essentially based on the ideas outlined by Wales in Reference [10] and its concept is highlighted for the situation, where a BPSK signal experiences Co-channel Interference (CCI) from a single BPSK interferer. The principle is readily extended for other scenarios. Consider the transmission of binary bits, at a rate of T^{-1}, where $b_s(nT)$ is the n^{th} bit. This may be modulated as a stream of BPSK symbols. As a simplification, it will be assumed that the interference is phase non-coherent and time synchronous with the signal. Therefore, the transmitted symbols may be represented in the baseband by their value at the perfect sample position, namely by:

$$X_s(nT) = \begin{cases} +1 + j0 & \text{if } b_s(nT) = 0 \\ -1 + j0 & \text{if } b_s(nT) = 1, \end{cases} \quad (1)$$

assuming that the clock recovery will be perfect at the receiver. A single BPSK interferer's transmission may be represented by:

$$X_i(nT) = \begin{cases} +1 + j0 & \text{if } b_i(nT) = 0 \\ -1 + j0 & \text{if } b_i(nT) = 1. \end{cases} \quad (2)$$

The channel distortion introduced to $X_s(nT)$ and $X_i(nT)$ are respectively given by the complex variables $R_s(nT)$ and $R_i(nT)$. Therefore, the received signal is given by

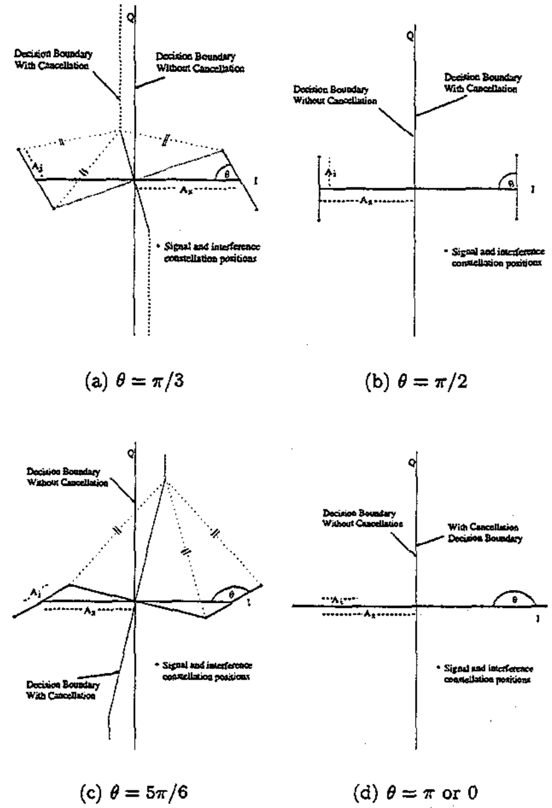
$$Y(nT) = R_s(nT) \cdot X_s(nT) + R_i(nT) \cdot X_i(nT) + N(t) \quad (3)$$

where $N(t)$ is the complex Gaussian noise.

Restricting our investigations to narrow-band channels, and initially assuming perfect knowledge of the complex channel gains $R_s(nT)$ and $R_i(nT)$, the receiver can determine, which of the two legitimate signal symbols $X_s(nT)$ and interfering symbols $X_i(nT)$ are most likely to have been transmitted on the basis of the received signal $Y(nT)$. This is simply achieved by determining the possible values of $R_s(nT) \cdot X_s(nT) + R_i(nT) \cdot X_i(nT)$, and finding the value with the minimum Euclidean distance from $Y(nT)$. In the case of a BPSK signal and BPSK interference $R_s(nT) \cdot X_s(nT) + R_i(nT) \cdot X_i(nT)$ has four possible values, assuming fixed values of $X_s(nT)$ and $X_i(nT)$. Without loss of generality we assume $R_s(nT) = 1 + j0$ for all n. Figure 1 shows the four possible received points for arbitrary and equi-probable phase values of $\theta = \pi/3, \pi/2, 5\pi/6$ or π where, θ is the phase of $R_i(nT)$. This Figure will be discussed in more detail during our forthcoming discourse.

It is assumed that the interfering signal can have any relative phase with respect to the desired signal. The effective angle between the two constellations in the base-band is given by θ, where all values of θ are equally likely. The amplitude of the signal is given by A_s and the amplitude of the interferer is given by A_i. The effect of corrupting the BPSK signal with a BPSK interferer generates an interfered received signal constellation, constituted by four phasors, as shown in Figure 1. The Figure includes the conventional decision boundaries for BPSK, as would be used in the absence of interference. Given the knowledge of the channel magnitude and phase as well as the type of the interfering phasor constellation, the cancellation of interference can be carried out by modifying the decision boundaries appropriately, in order to improve the BER performance. Specifically, we capitalise on this knowledge by adjusting the decision boundaries, such that they remain equidistant from the interfered constellation points. This results in a relatively simple geometric scenario in Figure 1 for BPSK, where the equal distances are clearly marked, but becomes less intuitive for higher-order modulation schemes. Hence the derivations of the decision boundaries for higher-order constellations is omitted due to lack of space.

In order to clarify the above geometric constraint further, when using interference cancellation, the decision boundary is constituted by a locus of points equi-distant from two out



(a) $\theta = \pi/3$ (b) $\theta = \pi/2$

(c) $\theta = 5\pi/6$ (d) $\theta = \pi$ or 0

Figure 1: Constellation diagrams of BPSK signal, with a phase non-coherent BPSK co-channel interferer at 8dB SIR, before the addition of AWGN for various θ values showing the decision boundary with and without interference cancellation

of the four constellation points of the combined BPSK signal plus superimposed BPSK interferer. These two interfered phasor points must not be associated with the same useful phasor, consequently they are always chosen such that both of the possible useful phasor points are represented. To elaborate further, the equi-distant criterion must be met with respect to those two specific phasor points, which are at the minimum possible Euclidean distance from eachother, given the set of four phasors. In Figures 1(b) and 1(d) the decision boundaries with cancellation are the same as those without. However, in Figure 1(a) and 1(c) the decision boundaries are constituted by three linear sections. The break-point between the adjacent boundary sections is, where three constellation points are equi-distant from the decision boundary, as suggested by the marked distances. From the geometry of the Figure it can be shown that the coordinates for the two decision boundary break points are given by: $(A_s - A_i\cos(\theta), (A_s - A_i\cos(\theta)) \cdot A_i\cos(\theta))$ and $(A_s + A_i\cos(\theta), (A_i\cos(\theta) - A_s) \cdot A_i\cos(\theta))$. The decision boundary for a BPSK signal with a BPSK interferer will be a linear function passing through these two points and vertical outside this range. However, the shape of the decision

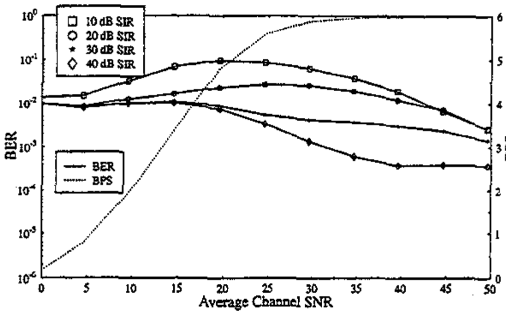


Figure 2: Down-link BER over a slow Rayleigh fading channel with various SIR levels at the MS and no interference at the BS, the original optimised adaptive speech switching levels and interference cancellation with perfect estimation and mid-amble estimation of the signal and interference channels, respectively, where $\alpha = 0.35$

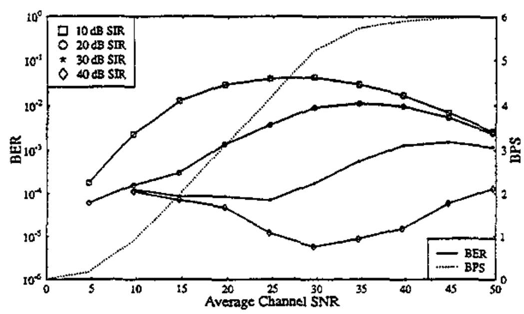


Figure 3: Down-link BER over a slow Rayleigh fading channel with various SIR levels at the MS and no interference at the BS, the original optimised adaptive computer data switching levels and interference cancellation with perfect estimation and mid-amble estimation of the signal and interference channels, respectively, where $\alpha = 0.35$

boundary will always depend on the actual value of θ.

2.2. Interference Cancellation in Adaptive Modems

In this Section we consider the performance of interference cancellation in conjunction with adaptive modulation. These experiments are based upon the system environment highlighted in Section 1, however, it is additionally assumed that there is an equal probability of a 'No Transmission', BPSK, QPSK, Square 16 or 64 QAM symbol interfering with the data transmission and that the modulation schemes used in both the signal and interfering channels are known at the receiver. The transmission of this control information was discussed in Reference [6] by the authors, where a non-uniform five-phasor PSK constellation was introduced for their signalling.

Figures 2 and 3 show the BER and BPS performance of the optimised mean BER, speech and computer data scheme with switching levels given in Table 1, ie with switching levels ignoring the effects of interference, over slow Rayleigh fading channels with various levels of CCI from a single interferer, when interference cancellation is employed. These benchmarker curves were generated with perfect estimation of the wanted channel and exploitation of the ATDMA mid-amble [9] to estimate the interfering channel. However, for certain combinations of the SNR and SIR values involved both the speech and data schemes fail to achieve the BER target.

	Speech				Computer Data			
SIR (dB)	l_1	l_2	l_3	l_4	l_1	l_2	l_3	l_4
10	4	10	27	35	Unused			
20	3	6	12	30	14	30	38	60
30	3	6	12	18	8	11	17	60
40	3	6	12	18	8	11	17	25

Table 2: Manually determined switching levels, in dB, for adaptive schemes over Rayleigh fading channels experiencing co-channel interference and employing interference cancellation, where the performance is shown in Figures 4 and 5

As seen in the captions, the down-link results shown in Figures 2 and 3 are based upon estimating the expected down-link channel quality on the basis of an interference-free up-link. In other words, the up-link transmission is used as a measure of the channel quality, in order to estimate the conditions for the next down-link transmission and to decide, which modulation scheme should be employed - in the absence of interference. Although this is an unlikely scenario in a cellular environment, here this assumption is used to generate a set of benchmarker curves. Furthermore, when interference cancellation is employed, this situation is much more realistic, since both the signal and interferer channels are estimated by separate orthogonal mid-ambles [10], minimising the effects of interference upon the channel estimation. In order to achieve the target BERs of 1×10^{-2} and 1×10^{-4} in the presence of interference, simply using the switching levels from Table 1 and employing interference cancellation is clearly insufficient.

In order to obtain the optimum switching levels of Table 1 for Rayleigh fading channels under various channel conditions in the absence of interference, in our previous work Powell's optimisation has been used [5]. This has been possible, because a numerical solution to the Bit Error Rate (BER) and Bit per Symbol (BPS) performance of adaptive modulation was derived for these cases and therefore iterative optimisation has been feasible. However, a full numerical solution for adaptive modulation, with an independent co-channel interferer and cancellation, sofar has not been found. Therefore, the switching levels giving cognizance to the effects of interference are derived by an iterative manual technique.

The interference cancellation was simulated with the perfect magnitude and phase estimations of the wanted signal channel and mid-amble based results for the interfering channel. The proposed switching levels are given in Table 2 and the associated performance curves are shown in Figures 4 and 5. Observe in the Figures that with the aid of interference cancellation adaptive modulation may be used for both speech and data transmission with an average BER below 1×10^{-2} and 1×10^{-4} over a Rayleigh fading channel for average channel SNRs from 0 to 50 dB, if the required

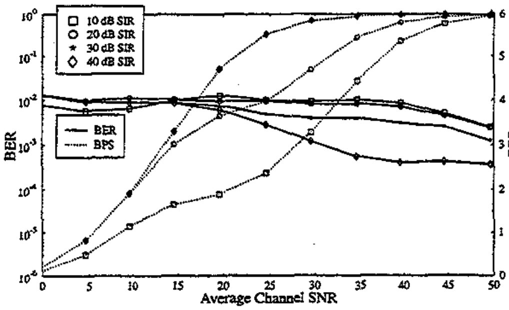


Figure 4: Down-link BER over a slow Rayleigh fading channel with various SIR levels at the MS and no interference at the BS, the manually adjusted for interference cancellation adaptive speech switching levels and interference cancellation with perfect estimation and mid-amble estimation of the signal and interference channels, respectively, where $\alpha = 0.35$

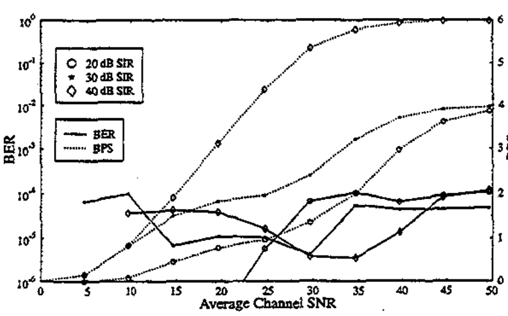


Figure 5: Down-link BER over a slow Rayleigh fading channel with various SIR levels at the MS and no interference at the BS, the manually adjusted for interference cancellation adaptive computer data switching levels and interference cancellation with perfect estimation and mid-amble estimation of the signal and interference channels, respectively, where $\alpha = 0.35$

SIR conditions are met under the worst-case scenario of a single interfering adaptive modem. Before concluding, let us now consider the achieved channel capacity of our adaptive modem in the next Section.

3. CHANNEL CAPACITY

The above discussion has focused upon the BER and BPS performance of various modems, but it is also of considerable interest to compare the relative channel capacities of the fixed and adaptive schemes by also considering the effects of interference and interference cancellation. This type of comparison is not as pertinent, as the radio capacity or area spectral efficiency [2] technique, although it dispenses with the need for a micro-cellular design propagation system. Figures 6 and 7 show the capacity that may be achieved for a given E_b/N_0, using fixed and adaptive modulation schemes with target BERs of 1×10^{-2} and

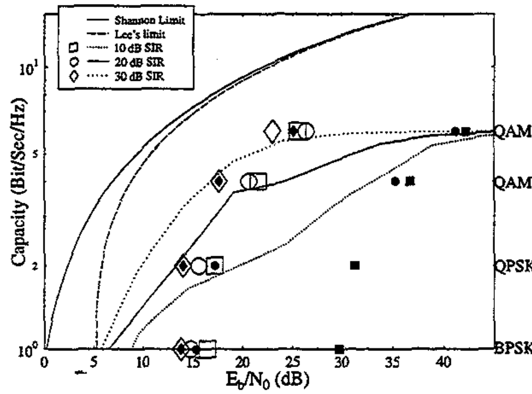


Figure 6: Capacity limit and upper-bound performance of fixed and adaptive modulation schemes in Rayleigh fading channels for specific BER of 1×10^{-2}. Signalling and pilot over-heads were neglected, assuming perfect filtering and single-sided bandwidth with $\alpha = 0$. A single Rayleigh fading co-channel interferer at 10, 20 and 30 dB SIR was used for adaptive schemes, shown with lines, and 10, 20 and 30 dB SIRs were employed for the fixed schemes shown with markers. Interference cancellation was invoked, where **'large hollow' markers represent BPSK interference and 'small bold' markers correspond to Square 64 QAM interference.**

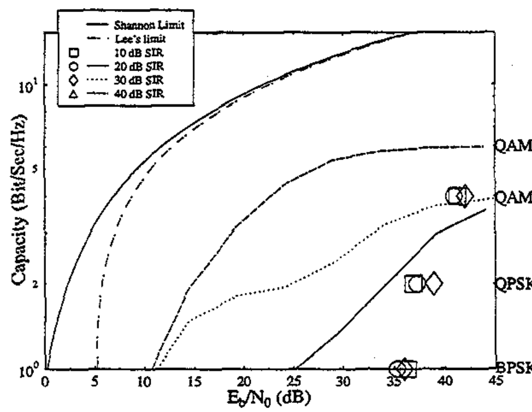


Figure 7: Capacity limit and upper-bound performance of fixed and adaptive modulation schemes in Rayleigh fading channels for specific BER of 1×10^{-4}. Signalling and pilot over-heads were neglected, assuming perfect filtering and single-sided bandwidth with $\alpha = 0$. A single Rayleigh fading co-channel interferer at 10, 20 and 30 dB SIR was used for adaptive schemes, shown with lines, and 10, 20 and 30 dB SIRs were employed for the fixed schemes shown with markers. Interference cancellation was invoked, where **'large hollow' markers represent BPSK interference.** There are no 'small bold' markers in this Figure to represent Square 64 QAM interference, since these values fell outside the plotted range.

1×10^{-4}, over a slow Rayleigh fading channel, assuming a single interferer at various SIRs and the use of interference cancellation. The fixed modem schemes' BER vesus SNR and SIR performance curves were not included here due to lack of space. The roll-off factor, α, is set to zero for normalisation purposes, and the 'small bold' markers represent the performance of fixed schemes, when the interfering signal is square 64 QAM, while the 'large hollow' markers represent the performance for fixed schemes, when the interfering symbol is BPSK. The adaptive results are derived from Figures 4 and 5. Considering Figure 6, it can be seen that the adaptive performance at 10 dB SIR is closer to Shannon's or Lee's [8] channel capacity limit than the fixed 1, 2 and 4 BPS schemes with the same level of interference, when they are corrupted by square 64 QAM and interference cancellation is invoked. This is also the case, when comparing the adaptive scheme with the fixed 1 BPS scheme and a single BPSK interferer.

The other fixed schemes out-perform the adaptive modem at 10 dB SIR. At 30 dB SIR, however, only the 6 BPS fixed scheme can outperform the adaptive scheme, irrespective of the type of interferer. Considering Figure 7, which shows the adaptive data system's performance at 1×10^{-4} BER, it can be seen that the 10 dB SIR adaptive scheme is not represented, and neither are the fixed schemes with 64 QAM interferers. This is, because the maximum average channel SNRs of Figures 4 and 5 are insufficient to determine the E_b/N_0, at which a BER of 1×10^{-4} is achieved. In some cases the required E_b/N_0 could be very high, nonetheless, Figure 7 shows that at 30 dB SIR and above the adaptive scheme is generally more efficient than the fixed schemes with any interferer and at 20 dB it is more efficient than the fixed schemes with square 64 QAM interferes.

Figures 6 and 7 give a summary of the channel capacity performance of the fixed and adaptive schemes, with interference and interference cancellation. However, it is important to note that they neglect the exact BERs encountered other than stating that a specific average target has been achieved. It is important to note, lastly that the higher-BER speech system exhibited a substantially higher channel capacity than the lower-rate data system, which is a consequence of allowing a more frequent employment of the higher-order constellations and tolearting the associated higher BER.

4. CONCLUSION

The performance of burst-by-burst adaptive modems has been studied in conjunction with interference cancellation over interfered slow Rayleigh-fading channels. We found that adaptive modulation is best suited to benign, low-interference indoor environments. This is because TDD is the most appropriate scheme to estimate the channel conditions, and un-equalised indoors TDD requires sufficiently low propagation delays. Adaptive modulation is also most suitable for low indoors pedestrian velocities. In such an indoors environment, co-channel interference would be mitigated by walls and ceilings in the building. However, there is scope for interference to be produced on a short term basis, when a combination of doors are opened, internal partitions are moved inside the building or a vehicle passes the building, reflecting some potentially interfering signal back into the property. Such examples of interference are likely to result in single interferes, a scenario which is amenable to interference cancellation. The results shown in Figures 6 and 7 demonstrate that adaptive modulation can achieve significant capacity gains compared with fixed modulation schemes in such situations. The benefits of adaptive modulation are greater than shown in Figures 6 and 7 because the instantaneous BER of the adaptive scheme is often significantly lower than the target.

5. ACKNOWLEDGEMENT

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