INTERFERENCE RESILIENCE OF BURST-BY-BURST ADAPTIVE MODEMS

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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. In this treatise their interference resilience is quantified and the modem mode switching levels are determined under interfered conditions. The associated performance curves are portrayed in Figures 6, 7 and 8 for target bit error rates of 1 and 0.01 %, respectively. The corresponding modem mode switching levels are summarised in Tables 2, 2 and 4, respectively.

1. INTRODUCTION

Burst-by-burst adaptive multi-level modulation was first suggested by Steele and Webb [1] using differentially encoded, non-coherently detected modems. In recent years further investigations have been carried out using pilot-assisted rectangular constellations [2]-[9], invoking a more robust Transmission Scheme (TS) on a burts-by-burst basis, when the channel is of low quality and vice-versa, while maintaining a certain target bit error rate (BER) performance. The most appropriate TS is dependent upon the time-variant instantaneous Signal-to-noise Ratio (SNR) and Signal-to-interference Ratio (SIR). The TS can be chosen according to the following regime [6]:

$$\mathrm{TS} = \begin{cases} \text{No Transmission (Notx)} & \text{if} \quad l_1 > s^2/N \\ \text{BPSK} & \text{if} \quad l_1 \leq s^2/N < l_2 \\ \text{QPSK} & \text{if} \quad l_2 \leq s^2/N < l_3 \\ \text{Square 16 Point QAM} & \text{if} \quad l_3 \leq s^2/N < l_4 \\ \text{Square 64 Point QAM} & \text{if} \quad s^2/N \geq l_4, \end{cases} \tag{1}$$

where s is the instantaneous signal level, N is the average noise power, and l_1, l_2, l_3 and l_4, are the BER-dependent optimised switching levels. Time Division Duplex (TDD) was proposed, in order to exploit the reciprocity of the channel under high SIR-conditions, which allowed us to estimate the prevalent SNR on a burst-by-burst basis [6]. The reciprocity of the up- and down-link channel conditions in the TDD frame is best approximated, if the corresponding TDD slots are adjacent.

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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 Reference [6] a combined BER- and BPS-based optimisation cost-function was defined and minimised, in order to find the required TS switching levels for maintaining average target BERs of 1×10^{-2} and 1×10^{-4}, irrespective of the instantaneous channel SNR. We referred to the former scheme as the speech TS, while to the latter as the adaptive data TS. The optimised TS switching levels l_1, l_2, l_3 and l_4 are summarised in Table 1 [6]. The average BPS performance B of our adaptive modem was derived for a Rayleigh fading channel in Reference [5], which can be written as:

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

where $F(s, S)$ is the PDF of the Rayleigh channel, S is the average power and the integrals characterise the received signal level domains, where the 1, 2, 4 and 6 bits/symb TSs of Equation 1 are used. In Reference [9] the latency performance of these schemes was quantified and frequency hopping was proposed to mitigate its latency and buffer requirements.

In this contribution we focused our attention on the optimum choice of adaptive modem switching levels required to maintain target BERs of 1 and 0.01 %, respectively, under interfered conditions. Our experiments were conducted within the framework of the Advanced Time Division Multiple Access (ATDMA)[10] scheme. 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. Let us now commence our detailed investigation of the associated interference aspects.

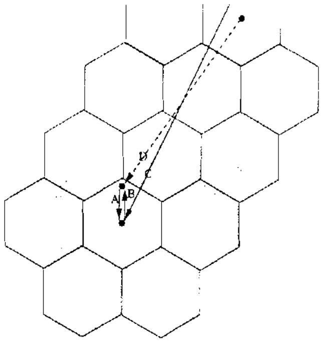

Figure 1: The path A is equivalent to B, however, the interference D combined with the signal B and the interference A combined with the signal C reduce this equivalence.

2. THE EFFECTS OF MULTI-USER INTERFERENCE ON ADAPTIVE MODULATION SCHEMES

2.1. Impact of interference upon channel estimate

The effect of Cochannel Interference (CCI) upon an adaptive modulation scheme is potentially more detrimental than for a fixed modulation scheme. The reason for this is that the interference at the base-station (BS) and mobile-station (MS) is uncorrelated. Therefore, the interference corrupts not only the received symbols, but also adversely affects the TDD-based estimation of the channel quality. These problems are initially considered separately.

The lack of correlation between the up- and down-link interference is illustrated in Figure 1. Here, it can be seen that although the channel characteristics of path A (MS to BS) will approximate those of path B (BS to MS), the interference from paths C (interfering MS to BS) and D (interfering BS to MS) could be very different. This is because the average signal strength received from the interfering BS and interfering MS may vary considerably. Furthermore, even if transmission along each path resulted in the same received average signal strength, both paths will be fading independently. It is assumed that for a given SIR value the statistical characteristics of the interference upon the up-link signal are the same as those on the down-link. This permits the analysis of only the down-link BER without loss of generality.

Hence we conducted a set of experiments, which considered the down-link BER over a Rayleigh fading channel with ∞dB SIR at the mobile-station. The channel was assumed to fade slowly and the estimates of the channel gain made at the base-station were performed in the presence of a single independent Rayleigh fading interferer. Our investigations were carried out at SIRs of 0, 10, 20, 30, and ∞dB for both the speech optimised switching levels and the computer data optimised switching levels.

The results are shown in Figures 2 and 3. There are two types of curves in the Figures, namely the bit error rate (BER) and the bits per symbol (BPS) curves, which are scaled on the left and right vertical axes, respectively. Let us initially consider the interference-free curves associated

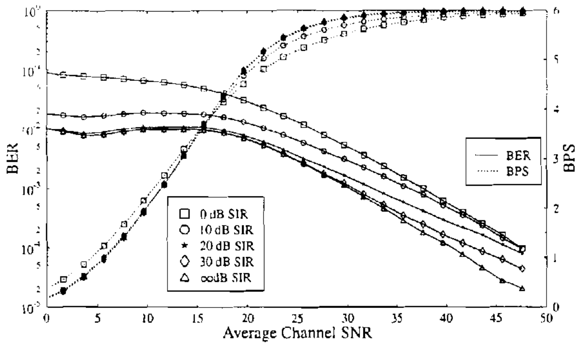

Figure 2: Down-link BER over a slow Rayleigh fading channel with ∞dB SIR at the MS and independent Rayleigh fading interference at the BS with SIRs of 0, 10, 20, 30, and ∞dB with adaptive speech system mean BER switching levels. The interference at the BS affect only the channel-quality estimates.

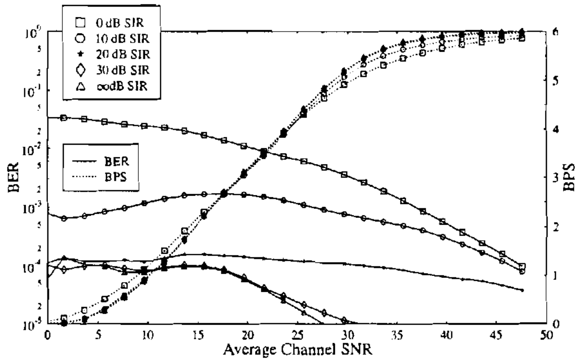

Figure 3: Down-link BER over a slow Rayleigh fading channel with ∞dB SIR at the MS and independent Rayleigh fading interference at the BS with SIRs of 0, 10, 20, 30, and ∞dB with adaptive computer-data system mean BER switching levels. The interference at the BS affect only the channel-quality estimates.

with an SIR of ∞. As mentioned in the Introduction, we contrived a 1 % BER adaptive speech system and a higher-integrity 0.01 % BER data system. The adaptive modulation scheme switching levels were optimised by Powell's optimisation technique for maintaining these target BERs over fading channels [6]. As the average channel SNR improved, the adaptive modem was able to employ higher-order constellations and this improved the average BPS modem performance. For high average SNRs, however, the BPS performance saturated at 6 bits/symbol and the BER curves decayed below the target BERs, since for reasons of moderate complexity the adaptive scheme was unable to opt for more than 6 bits/symbol constellations.

There are a number of interesting further conclusions to be drawn from these Figures, however, for reasons of space economy these are left for the reader to explore. Here we simply state that the adaptive modulation's down-link performance is degraded, even in the absence of interference at the mobile, by interference at the base-station, because the up-link interference results in the channel estimation being corrupted and a sub-optimum modulation scheme being employed. In terms of the design of the adaptive speech and data modulation schemes with BERs of 1×10^{-2} and 1×10^{-4} it may be concluded that the average up-link SIR must be 10 and 20 dB, or above, for the respective systems, in order to maintain the required target BERs. Furthermore, it transpires from the detailed analysis of the results of Figures 2 and 3 that the adaptive switching levels optimised for non-interfered channels have to be reconsidered in order to account for the effects of interference and improve the overall system's robustness, which is the subject of the next Subsection.

2.2. Re-optimisation of Adaptive Switching Levels

As in the previous Section, only the performance of the down-link was considered. However, it is assumed that the performance of the up-link would be identical, provided that the assumptions made about down-link interference applied to the up-link and vice versa. The effect of only down-link interference, ie interference at the MS only, is shown in Figures 4 and 5 for the speech and computer data systems, respectively. That is, in contrast to our previous experiments, where the up-link interference corrupted the channel quality estimates, in these experiments the effect of the interference upon the channel estimate is neglected. For both the speech and computer data systems we found that the throughput was unaffected by the interference inflicted at the MS, since the channel-quality estimates are unaffected. This was anticipated, since the decision upon which modulation scheme should be employed is made at the base-station, which is unaffected by the interference experienced by the mobile-station.

However, the BER was increased considerably for both the speech and computer data systems, as the SIR reduced, since the MS's effective experienced channel quality was reduced. In all cases except the speech system at 30 and 40 dB SIR, the introduction of co-channel interference at the MS resulted in an increased BER, as the average channel SNR increased. The explanation for this is that at higher average channel SNRs the receiver is led to believe that a high channel quality prevails and hence the probability of a higher order modulation scheme being employed increases, as was the case in the absence of interference. However, these high-order modulation schemes are more susceptible to interference as well as to noise. Therefore, bearing in mind that the switching levels were optimised in the absence of interference, it is clear that the BER is increased.

A logical approach to overcoming the interference would be to back-off the switching levels at which the higher order modulation schemes should be employed. Such a technique would require an outer loop to identify the level of average interference and select a different set of switching levels accordingly. This could be achieved by considering the average received signal strength and comparing it with some information about the quality of the reception. This quality measure could be obtained from either channel coding overload rate or soft-decision information about the distance between received symbols and the ideal modulation constellation points. In this treatise we opted for employing different switching levels, when the average interference varied by 10 dB, noting that the estimation of the prevalant SIR was left for future study.

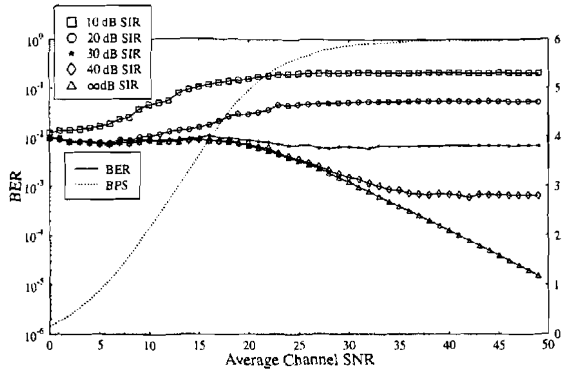

Figure 4: Down-link BER over a slow Rayleigh fading channel with 10, 20, 30, 40 and ∞dB SIR at the MS and no interference at the BS with the adaptive speech system mean BER switching levels, $\alpha = 0.35$ and no interference cancellation.

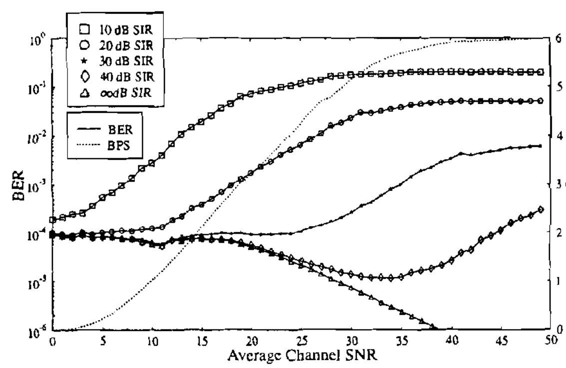

Figure 5: Down-link BER over a slow Rayleigh fading channel with 10, 20, 30, 40 and ∞dB SIR at the MS and no interference at the BS with adaptive computer data system mean BER switching levels, $\alpha = 0.35$ and no interference cancellation.

In order to obtain the modified TS switching levels in the presence of interference, the optimisation algorithm described in Reference [6] was employed again. Specifically, the BER and BPS performances were evaluated for average channel SNRs in the range of 0 dB to 50 dB in 1dB intervals, using the optimisation cost function defined as:

$$\text{Total Cost} = \sum_{i=0}^{50} \text{BER Cost}(i) + \text{BPS Cost}(i) \qquad (3)$$

where

$$\text{BER Cost}(i) = \begin{cases} 10log_{10}\left(\frac{\text{BER}_m(i)}{\text{BER}_d(i)}\right) & \text{if BER}_m(i) > \text{BER}_d(i) \\ 0 & \text{otherwise} \end{cases} \qquad (4)$$

Scheme	l_1	l_2	l_3	l_4
10 dB SIR	4.06	9.37	14.05	18.38
20 dB SIR	3.02	7.07	11.59	44.38
30 dB SIR	2.98	6.48	11.60	17.64
40 dB SIR	2.33	6.55	11.33	17.36

Table 2: Re-optimised switching levels for speech system through a Rayleigh channel with independent Rayleigh interference at different average SIRs; switching levels shown in dB SNR.

$$\text{BPS Cost}(i) = \begin{cases} \text{BPS}_d(i) - \text{BPS}_m(i) & \text{if } \text{BPS}_d(i) > \text{BPS}_m(i) \\ 0 & \text{otherwise} \end{cases} \tag{5}$$

and $\text{BER}_m(i)$, $\text{BER}_d(i)$, $\text{BPS}_m(i)$ and $\text{BPS}_d(i)$ are respectively the measured and desired BER and BPS at an average channel SNR of i. It can be seen from Equations 3, 4 and 5 that the cost function can only be positive and increases, when either the BER or the BPS performance become inferior to their desired performance at an average channel SNR of i. Equation 4 utilises the logarithm function to increase the significance of small BERs. A weighting factor of 10 is employed in order to bias the optimisation towards achieving the desired BER performance in preference to the BPS performance. Under interfered conditions the cost function of Equation 5 was slightly modified to:

$$\text{BPS Cost}(i) = \begin{cases} 5 \cdot (\text{BPS}_d(i) - \text{BPS}_m(i)) & \text{if } \text{BPS}_d(i) > \text{BPS}_m(i) \\ 0 & \text{otherwise.} \end{cases} \tag{6}$$

This increased the weighting towards achieving the desired BPS performance at the cost of the desired BER performance. It was necessary to invoke this modification, since otherwise due to the presence of high interference levels the optimisation total cost given by Equation 3 was minimised, when the no-transmit mode was employed for all signal levels.

Re-optimised switching levels were derived for both the speech and computer data systems, where the desired performances were the same as before, that is, a speech system with average BER and BPS performance targets of 1×10^{-2} and 4.5 bits/symbol, respectively, and a computer data system with average BER and BPS performance figures of 1×10^{-4} and 3 bits/symbol, respectively. For the speech system the switching levels were re-optimised for 10, 20, 30 and 40 dBs SIR and for the computer data system they were optimised for 20, 30 and 40 dBs SIR. No switching levels were derived for the computer data system at 10 dB down-link SIR, because the reverse link channel estimation has already been shown unacceptable in Figure 3 at this level of interference, when the desired BER is 1×10^{-4}. The initial switching levels that were used to start the re-optimisation algorithm were the switching levels derived in the original optimisation, at ∞ dB SIR. These were the levels that are shown in Table 1.

The re-optimised switching levels for the speech and computer data systems are shown in Tables 2 and 3, respectively. The BER and BPS performance of both schemes with the re-optimised switching levels are shown in Figures 6 and 7, where the original optimised schemes' performance at ∞ dB are also included for comparison.

The re-optimised switching levels for the speech system are generally similar to the switching levels that were obtained with the original optimisation at ∞ dB SIR. The exceptions are the switching levels obtained with the re-optimisation at 10 dB SIR, where all levels are generally 1-3 dB SNR higher than the original corresponding optimal levels, and l_4 for the re-optimisation at 20 dB SIR, which is approximately 27 dB higher than the original optimal level. This value of l_4 appears inconsistent compared with the l_4 values at other SIRs. However, at 10 dB SIR $l_4 > 18.38$ would have had produced a greater increase in total cost, in terms of the cost increase associated with reducing the throughput, compared with the cost reduction registered from reducing the BER. This is because the Square 64 and 16 QAM BER performance is similarly bad at 10 dB SIR and consequently reducing l_4 will result in Square 16 QAM being employed rather than Square 64 QAM. Therefore it can be observed, compared with the 20 dB SIR case, that the 10 dB SIR case benefits less from the reduction of the BER cost associated with reducing l_4, but it is penalised equally in terms of the increases in BPS cost associated with the same reduction of l_4. At 30 dB SIR there is no need to reduce l_4, because the target BER is achieved.

The effect of the significant changes in switching levels, and the more subtle changes can be identified in the performance curves. Inspection of the BPS performance curves shown in Figure 6 reveals that the throughput for the re-optimised speech schemes at 20, 30 and 40 dB SIR closely coincided with the originally optimised scheme between 0 and 12.5 dB average channel SNR. Above 12.5 dB average channel SNR the 20 dB SIR re-optimised throughput is lower than observed with the other schemes. This is the effect of the large value of l_4 in the 20 dB re-optimised scheme. Furthermore, the throughput of the 10 dB SIR re-optimised scheme is below the originally optimised scheme's throughput and again, this is an expected consequence of the increased value of the switching levels for the re-optimised scheme at 10 dB SIR.

Considering the BER performance curves in Figure 6 it may be observed that only the 30, 40 and ∞ dB SIR re-optimised switching levels result in the target BER being achieved for all average channel SNRs, at the respective interference levels. The 10 and 20 dB SIR re-optimised switching levels fail to achieve the target BER over the entire average channel SNR range. However, the same observation may be made about the originally ISI-free optimised switching levels and their BER performance which was shown in Figure 4. It is not surprising that the 30 and 40 dB SIR re-optimised switching levels result in similar BER performance to the original optimised switching levels with 30 and 40 dB SIR, because the switching levels are so similar. Furthermore, the re-optimisation at these interference levels was unlikely to result in the switching levels being altered significantly, since the original switching levels already met the BER performance criteria. Re-optimising the switching levels for 10 and 20 dB SIR resulted in significant changes in the switching levels, when compared with the original optimised levels. This change in switching levels reflects in

Scheme	l_1	l_2	l_3	l_4
20 dB SIR	30.13	40.37	42.92	72.99
30 dB SIR	7.93	11.22	32.14	102.81
40 dB SIR	7.88	10.42	17.44	53.41

Table 3: Re-optimised switching levels for computer data system through a Rayleigh channel with independent Rayleigh interference at different average SIRs; switching levels shown in dB SNR.

the change in BER performance that can be observed by comparing Figures 4 and 6. This comparison reveals that the re-optimisation improved the BER performance at 10 dB SIR below an average channel SNR of 15 dB and at 20 dB SIR from 10 - 50 dB average channel SNRs. In the latter case the effect was approximately a factor five BER reduction.

The re-optimised switching levels for the computer data system at 20, 30 and 40 dB SIR differ considerably more from the original ∞ dB SIR levels, than the speech switching levels at 20, 30 and 40 dB SIR do from their original ∞ dB SIR optimised switching levels. This is because the originally optimised switching levels for the computer data system, when the SIR was 40 dB or less, resulted in a lower BER performance than that desired. Therefore, re-optimisation resulted in the switching levels being modified. Employing the original computer data system switching levels, that were optimised for ∞ dB SIR, in interfered channels revealed that SIRs greater than 40 dB would be required to achieve the desired BER for average channel SNRs from 0 to 50 dB. The re-optimised switching levels result in the desired BER being achieved for 20[1] and 40 dB SIR. Moreover, re-optimisation at a specific SIR results in the performance of the re-optimised switching levels at 30 dB SIR approaching the desired BER performance.

The penalty of employing re-optimised switching levels, is as expected, a reduction in throughput. In the case of the BPS performance of the switching levels re-optimised for 20 dB SIR there is no throughput for average channel SNRs below 17 dB and, therefore, the BER performance below this level is uninteresting and the corresponding BER curve was omitted. The average throughput performance of the re-optimised switching levels at 20 dB SIR is approximately equivalent to BPSK at 40 dB average channel SNR. The BER at this average SNR is less than 1×10^{-6}. In closing we note that we evaluted the fixed BPSK BER performance at the same average channel SNR, which was found to be 2.3×10^{-3}. Following the above experiments we intuitively felt that further exploration of the switching-threshold dependent trade-offs is beneficial and we report on these endeavours in the next Section.

2.2.1. *Intuitive Threshold Adjustment*

The re-optimised switching levels for the speech system in the presence of CCI are considered again. Since the target BER performance of 1 % was not achieved for the 10 and 20

[1]The 20 dB SIR re-optimised switching levels result in an extremely low BER with maximum value of 5.78×10^{-10} at 50 dB average channel SNR and the corresponding curve is therefore not plotted in Figure 7

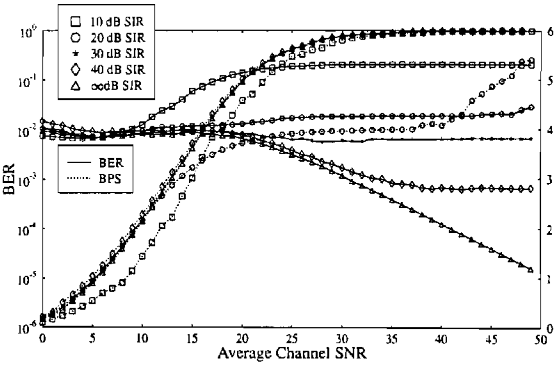

Figure 6: Down-link BER over a slow Rayleigh fading channel with 10, 20, 30, 40 and ∞dB SIR at the MS and no interference at the BS and **adaptive modulation with switching levels re-optimised for each SIR.** The desired performance was BER 1×10^{-2} and 4.5 BPS, $\alpha = 0.35$ and no interference cancellation.

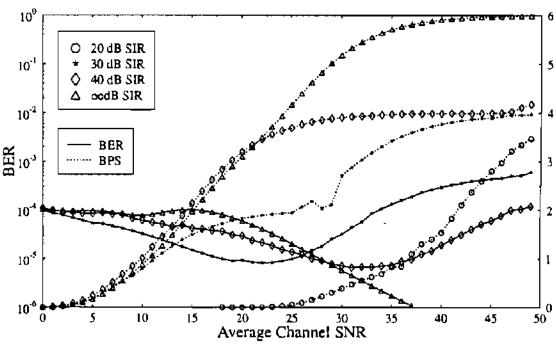

Figure 7: Down-link BER over a slow Rayleigh fading channel with 20, 30, 40 and ∞dB SIR at the MS and no interference at the BS and **adaptive modulation with switching levels re-optimised for each SIR.** The desired performance was BER 1×10^{-4} and 3 BPS, $\alpha = 0.35$ and no interference cancellation.

dB down-link SIR, there is some doubt over the suitability of the optimisation algorithm or the definition of the cost function. Therefore, in an attempt to achieve the desired BER performance the re-optimised switching levels at 10 dB SIR were manually adjusted. Figure 8 portrays the performance of the adaptive modem employing the manually adjusted switching levels and Table 4 shows a summary of the manually selected levels.

The set of switching levels, 'Manual 1', are the values from the re-optimisation that were given in Table 2 at 10 dB SIR and are included for comparison. The set of 'Manual 2' values reduces the employment of Square 64 QAM by invoking it only at very high SNRs. Logically, this also reduces the average throughput for average channel SNRs higher than approximately 12 dB. Square 64 QAM is the most corruption sensitive modulation scheme and reducing its employment reduced the average BER. However, the performance at 10 dB SIR is still worse than the target BER, of 1%, across the range of average channel SNRs. The 'Manual 3' set of switching levels reduces the throughput

Scheme	$l_1(dB)$	l_2 (dB)	l_3 (dB)	l_4 (dB)
Manual 1	4.06	9.37	14.05	18.38
Manual 2	4.06	9.37	14.05	45.00
Manual 3	4.06	9.37	25.00	45.00
Manual 4	4.06	1000	1000	1000

Table 4: Manually selected switching levels expressed in SNR dB for performance curves in Figure 8.

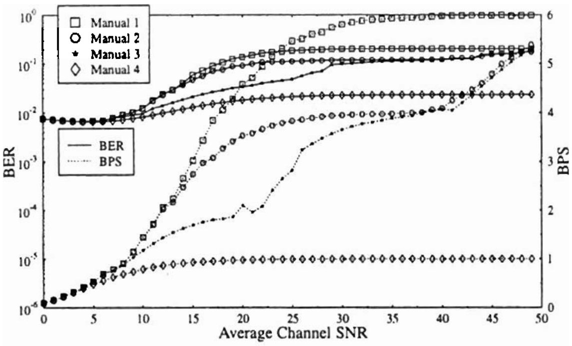

Figure 8: Down-link BER over a slow Rayleigh fading channel with ∞dB SIR at the base-station and 10dB SIR independent Rayleigh fading interference at the mobile-station using manually selected switching levels shown in Table 4 and $\alpha = 0.35$.

further by reducing the employment of Square 16 QAM. This again reduces the throughput, but does improve the BER mainly in the range of average channel SNRs from 10 to 30 dB. However, the target BER performance is not achieved, especially at higher average channel SNRs.

In an extreme attempt to achieve the target BER at high average channel SNRs the switching levels 'Manual 4' were evaluated. These essentially eliminated the employment of QPSK, and Square 16 and 64 QAM. The resulting performance at high average channel SNRs is unsurprising. The average BPS performance converges to the fixed BPSK performance, that is one BPS, and, although not shown due to lack of space, the BER performance converges with the fixed BPSK residual BER performance of 2.5×10^{-2} at 10 dB SIR. Therefore, in order to reduce the BER below the BPSK residual, l_1 must be increased. This is undesirable, because at low average channel SNR the target BER is obtained with l_1 at its current value. Therefore, increasing l_1 extends the range of 'No transmission' and hence will result in excessively low BER and a state of permanent 'No transmission' at low average channel SNRs. This is similar to what was experienced, when l_1 became large in the 20 dB SIR re-optimisation for the computer data target system.

It can be concluded that switching threshold re-optimisation, as described above, may be employed to reduce the margin between the desired BER and that achieved in the presence of interference. However, as a mechanism to improve the system's performance in our future work interference cancellation will be invoked.

3. SUMMARY AND CONCLUSION

In this treatise our discussions were centred around the optimum choice of adaptive modem switching levels required to maintain target BERs of 1 and 0.01 %, respectively, under interfered conditions. The associated performance curves were portrayed in Figures 6, 7 and 8. The corresponding switching levels were summarised in Tables 2, 3 and 4, respectively. In conclusion, the effects of interference result in BER and BPS performance degradation, hence our future work will be targeted at improving the system performance employing interference cancellation.

4. ACKNOWLEDGEMENT

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