Improving ADSL Performance with Selective QAM Mapping and Hybrid ARQ

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Abstract:- Asymmetric Digital Subscriber Line (ADSL) is a high-rate transmission standard used for broadband access. Error performance and bandwidth efficiency are the two main concerns in ADSL transmission, hence prompting the need for appropriate techniques to provide improved error protection and noise robustness in ADSL systems. This paper proposes an enhanced ADSL transmission model which incorporates Trellis Coded Modulation (TCM), selective or prioritised QAM constellation mapping and Hybrid Automatic Repeat reQuest HARQ with diversity combining. Simulation results demonstrate that the proposed scheme provides a significant gain of over 3 dB in Eb/No over a conventional ADSL system which does not use HARQ. It also achieves a 30 percent gain in throughput over a conventional ADSL which uses HARQ without diversity combining.

Keywords: ADSL, Selective QAM, TCM, HARQ, Diversity Combining.

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1. Introduction

ADSL is a major platform for delivering broadband services through high speed transmission over existing twisted-pair local loops [1]. The asymmetric nature of ADSL allows a higher bandwidth for downstream transmission making better utilisation of the channel [2]. Previous and ongoing research in the field of broadband access, in particular ADSL, have been driven by the growing need for higher data rates and the limitations of the current copper network infrastructure [3]. The main challenges addressed by these research emanate from the impairments associated with the wider bandwidth used by DSL systems.

In the last decade, key techniques namely DMT and efficient error control coding schemes such as Reed-Solomon (RS) codes have greatly improved ADSL transmission. With the usual DMT scheme, the frequency bands for upstream and downstream transmission in ADSL are further split into smaller frequency channels of 4.3125 kHz, each of them exploited to optimize the transmission quality by transmitting a greater number of bits to the sub-channels having better signal-to-noise ratios [4].

Several research papers have attempted to address the basic issue of noise mitigation in ADSL systems through an array of techniques including Forward Error Correction (FEC), interleaving, and novel discrete bit loading schemes for DMT-based systems [3], [5], [6]. Trellis-coded modulation schemes which make use of two-dimensional constellations have demonstrated improved error performance without requiring more bandwidth or sacrificing the data rate [7], [8], [9]. Multi-dimensional TCM was then introduced, bringing further improvement in terms of coding gain over the usual two-dimensional schemes [10]. The limits imposed by Impulse Noise (IN) on ADSL transmission in terms of rate and delay triggered research on ways to counter the corruption of data by IN in DSL systems resulting in the combined use of interleaving and RS coding that is currently deployed in ADSL [4]. Error and Erasure Decoding (EED) schemes have also been proposed as a method for interleaving delay reduction in DSL systems [5]. The possible application of ARQ in future ADSL standards for improved impulsive noise robustness was suggested in [11]. Various other researchers have investigated the use of Unequal Error Protection (UEP) as a technique for the construction of bandwidth efficient modulation codes systematically for example [12] and [13]. In [14], the authors studied the implications of Hierarchical QAM (HQAM) on the bit error rate over flat Rayleigh fading environments taking into account the effect of imperfect channel estimation. The results obtained with the selective or prioritised QAM constellation indicated a better error performance of the bits placed in high priority positions. In [15], two schemes with prioritised QAM constellation mapping were implemented in a Turbo coded QAM system to exploit the UEP potential of the QAM constellation and provide better protection to the systematic bits of the Long Term Evolution (LTE) Turbo encoder. Analysis of the results showed improved performance for BERs above 10-1 with prioritised 16-QAM while the use of prioritised 64-QAM produced enhanced performance for all BERs. In [16], prioritised 64-QAM mapping of the bits from an LTE Turbo encoder was carried out and the implementation of this scheme yielded a 2 dB gain in Signal to Noise Ratio (SNR) performance compared to the system without prioritised 64-QAM mapping. Finally in [17], a technical review of ADSL data transmission was provided and the authors analysed the effects of Near End Cross Talk (NEXT), Far End Cross Talk (FEXT) and Additive White Gaussian Noise (AWGN) on the performance of an ADSL system.

This paper proposes an ADSL system which integrates techniques such as TCM, HARQ with diversity combining and selective QAM constellation mapping. Firstly, TCM is applied to the last four channels of the DMT modulator where each of the sub-channels present are modulated with 16-QAM. Prioritised constellation mapping provides greater protection to the systematic bits output by the TCM encoder when they are placed on the 16-QAM constellation. The second technique employed is Type 1 HARQ which is a combination of Forward Error Correction (FEC) and ARQ-error control. Error-detection is performed by the cyclic redundancy check (CRC), and FEC information is provided by Reed Solomon codes. Transmission is performed frame-wise so if an error is detected in a frame at the receiver, the erroneously received frame is resent by the transmitter until it is correctly decoded, or when the maximum number of retransmissions is reached. The final technique used is diversity combining whereby the wrongly received frames are not discarded but stored in a buffer and later combined with the frame from the next retransmission before being demodulated. Simulations showed that the proposed system provides significant gains in the BER performance compared to a conventional ADSL system.

The organization of this paper is as follows. Section 2 describes the proposed ADSL system model. Section 3 presents the simulation results and analysis. Section 4 concludes the paper.

2. SYSTEM MODEL

The complete ADSL transmission system for the proposed scheme with TCM, prioritised 16-QAM constellation mapping, HARQ and diversity combining is shown in Figure 1. This system is an extended version of the one given in [17]. The complete conventional ADSL system and that with TCM and adaptive bit loading has been well explained in [17]. For the schemes implemented in this paper, modifications have been made in the form of a feedback path from the ADSL receiver to the ADSL transmitter in order to incorporate HARQ. Additionally, changes to the DMT modulator and demodulator block include the prioritised or selective 16-QAM constellation mapping for the last 64 sub-channels which undergo TCM encoding.

Each frame generated consists of 1552 bits which are split into two 776 bit-streams, where the first stream is processed by the first path, i.e. the fast buffer, and the second stream is processed by the second path, i.e. the interleaved buffer [17]. After concatenation, a frame of 1680 bits is obtained which is input to the DMT modulator block. This frame is first split into 16 channels which are each further split into 16 sub-channels according to a bit loading table, yielding a total of 256 sub-channels. This emulates dividing the transmission spectrum of the twisted-pair copper phone line into 256 sub-channels. Conventional QAM is performed on the first 192 sub-channels according to the number of bits allocated to each of them.

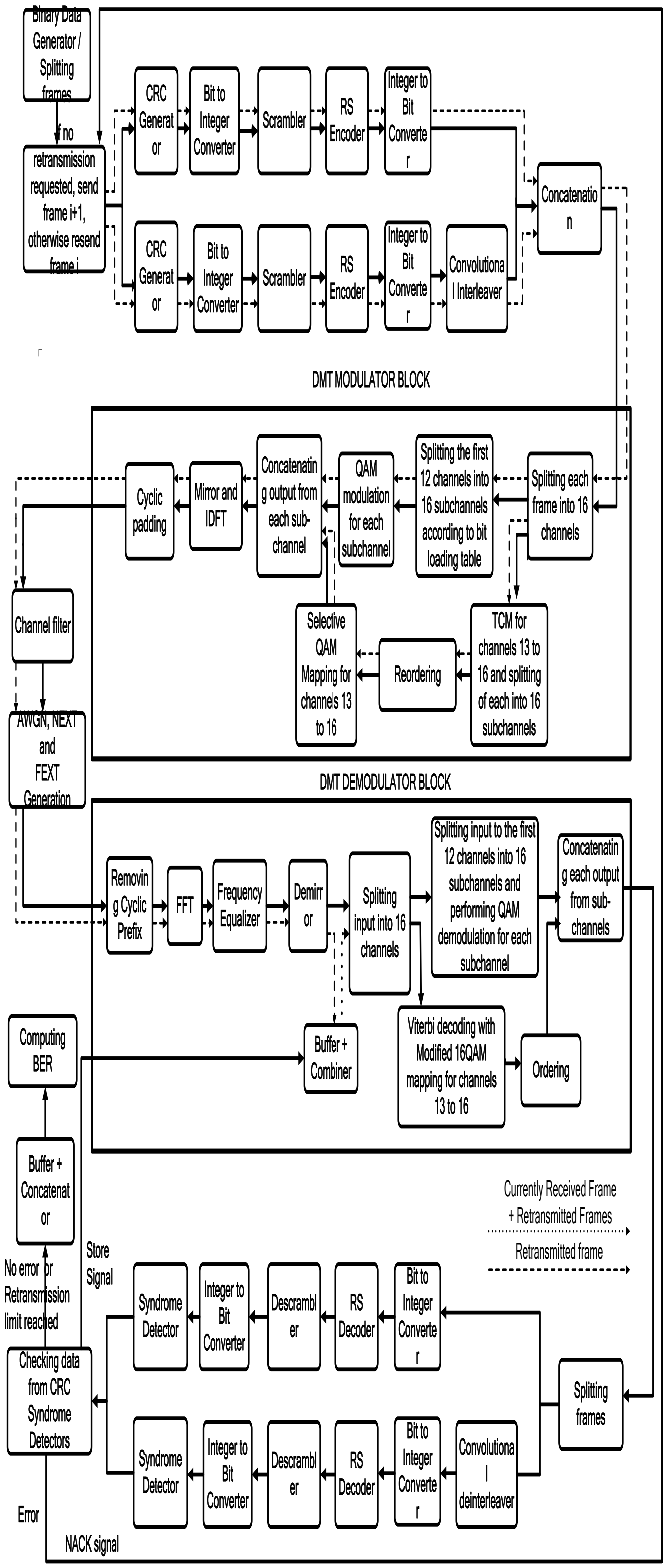

Figure 1: Complete system with TCM, adaptive loading, prioritised 16-QAM and HARQ.

The last 64 sub-channels are each allocated 3 bits which are then fed to the Wei's trellis encoder shown in Figure 2.

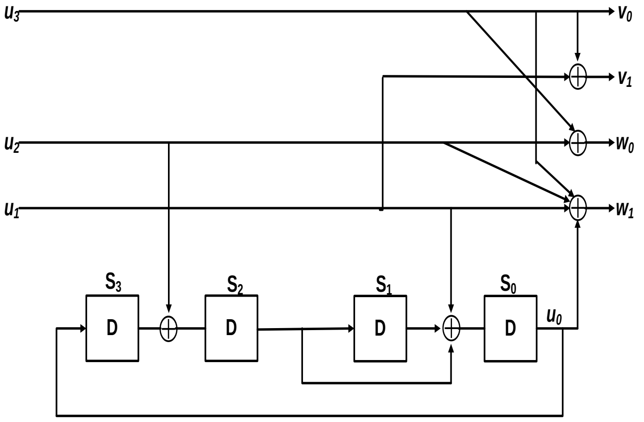

Figure 2: Finite state machine for Wei's encoder [9].

Four bits v0, v1, w0 and w1 are output from the encoder. In order to perform prioritized or selective constellation mapping, such that the systematic bit, v0, from the encoder is placed at one of the most strongly protected points on the 16-QAM constellation, bit reordering is performed on each group of four bits v0, v1, w0 and w1 before modulation. Each bit position in the 4 bit symbol for 16QAM has a different BER and consequently has a different level of protection during transmission in an AWGN environment [16]. From Figure 3, it can be observed that Bit 1 and Bit 3 in every symbol have the same value in each quadrant of the prioritised / selective constellation [16]. Hence, these two bits have the highest protection against noise at low channel qualities while the remaining two bits (Bits 2 and 4) exhibit the same error protection levels [16].

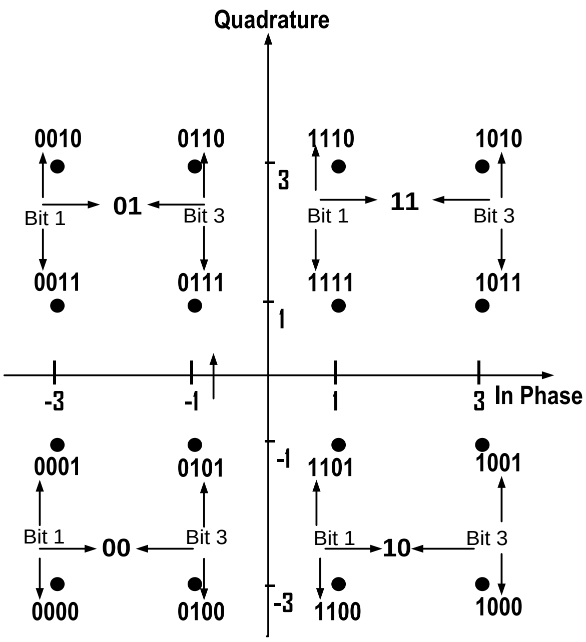

Figure 3: Prioritised 16-QAM constellation.

After bit reordering, v_1 occupies the first position and v_0 the third position of every four bits that are mapped on one symbol of the 16-QAM constellation. This allows systematic bit v_0 to benefit from better protection against noise and increases the probability of correctly decoding it at the receiver. After modulation, each group of four bits v_0, v_1, w_0 and w_1 will be mapped onto a complex symbol represented as $x_t^I + jx_t^Q$ where x_t^I is the in-phase component and x_t^Q the quadrature component transmitted at time t. Since there are 16 states and three inputs (u_1,u_2 and u_3) in the TCM encoder and there are 16 x 2^3 = 128 possible branches in the corresponding TCM decoder. The complex symbol along any branch l is denoted as $x_t^I(l) + jx_t^Q(l)$ where l can take values 1,2,…128 depending on the input and state from which the complex symbol was generated.

At the demodulator side, output from the De-mirror block consists of 256 rows of complex values which are split into 256 sub-channels. The number of bits in each sub-channel then determines the QAM constellation to be used for demodulating the complex values obtained for that particular sub-channel. Demodulation is carried out for the first 192 sub-channels using conventional QAM constellation while TCM decoding is performed for the last 64 sub-channels which achieves joint demodulation and decoding. TCM decoding used the Viterbi algorithm [18,19] which essentially minimizes the conditional probability density function that the signal r is received given that x was transmitted which can be expressed as $f(r|x)$ as follows:

$$f(r/x) = f(r_1/x_1)\times f(r_2/x_2)\times\ldots\times f(r_T/x_T) = \prod_{t=1}^{T}\prod_{i=1}^{n}\frac{1}{\sigma\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{r_{ti}-x_{ti}}{\sigma}\right)^2\right] \quad (1)$$

where,

T is the total number of symbols that can be processed in one instance of Viterbi decoding,

t is the time instant at which a symbol is received,

i is the ith component of the symbol received at time t,

n is the total number of components in the symbol,

σ is the standard deviation of the noise variance

The function $f(r|x)$ is also called the likelihood function. With TCM, n = 2 because the symbol will have only an in-phase and a quadrature component. Hence the likelihood function can be expressed as:

$$f(r/x) = \prod_{t=1}^{T}\frac{1}{\sigma\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{r_t^I - x_t^I(l)}{\sigma}\right)^2\right] x \frac{1}{\sigma\sqrt{2\pi}}\exp\left[-\frac{1}{2}\left(\frac{r_t^Q - x_t^Q(l)}{\sigma}\right)^2\right] \quad (2)$$

Where,

r_t^I and r_t^Q are the received in-phase and quadrature components at time t, $x_t^I(l)$ and $x_t^Q(l)$ are the transmitted in-phase and quadrature components at time t corresponding to branch l.

$f(r|x)$ can also be expressed as a log likelihood function which is given as follows:

$$\log f(r/x) = \sum_{t=1}^{T}\frac{1}{\sigma\sqrt{2\pi}} - \frac{1}{2}\left[\left(\frac{r_t^I - x_t^I(l)}{\sigma}\right)^2 + \left(\frac{r_t^Q - x_t^Q(l)}{\sigma}\right)^2\right] \quad (3)$$

A Viterbi decoder [18, 19] is a maximum log likelihood decoder whose aim is to maximise the log likelihood function log $f(r|x)$. This can be achieved by minimizing the term

$\sum_{t=1}^{T}\left[\left(\frac{r_t^I - x_t^I(l)}{\sigma}\right)^2 + \left(\frac{r_t^Q - x_t^Q(l)}{\sigma}\right)^2\right]$ for all values of l in equation (3).

After TCM decoding, the decoded bits are ordered back into their original positions before concatenating each output from the sub-channels as shown in Figure 3.

The CRC syndrome detectors in the ADSL receiver calculates the checksum or parity check of the received bits in the codeword and compares it to the received checksum [20]. This block has two outputs where the first output is the message word with the checksum removed and the second is the error flag which indicates whether the message word is received in error or not. An error flag of zero denotes a correctly received word, and if non-zero, an erroneous word is detected. The error flag is obtained by summing the values in all of the state registers of the CRC syndrome detector. In the event that the output from the CRC detectors is non-zero, a NACK signal is sent to the transmitted indicating that the frame received contains errors and should be resent by the transmitter. Simultaneously, a store signal is sent to the Buffer and Combiner found in the Demodulator block so as to store the currently received frame which will be combined with the incoming retransmitted frame. The Combiner performs the averaging with the symbols of all current and retransmitted received frames and the resulting output is then sent for demodulation or TCM decoding accordingly [21]. The combining process can be described as per the following equations:

$$r_t^I(c) = \frac{1}{N}\sum_{k=1}^{N} r_t^I(k) \tag{4}$$

$$r_t^Q(c) = \frac{1}{N}\sum_{k=1}^{N} r_t^Q(k) \tag{5}$$

Where,

$r_t^I(c)$ is the combined in-phase signal obtained by averaging all the stored versions of the in-phase component from the first to the *N*th transmission.

$r_t^Q(c)$ is the combined quadrature signal obtained by averaging all the stored versions of the quadrature component from the first to the *N*th transmission.

This process is repeated until no error is detected in the received frame or the limit of five retransmissions for that particular frame has been reached.

Alternatively, if the CRC matrix contains only zeros, it means the frame received is error-free and it is therefore sent to the Buffer and Concatenator block of the receiver. No NACK signal is sent and as a result, the transmitter will transmit the next frame. The throughput, which is the rate of successful message delivery, is calculated as follows for the HARQ schemes implemented:

$$\text{Throughput, } \eta = \frac{F_T}{F_T + F_{RT}} \tag{6}$$

where,

F_T is the total number of frames transmitted, and

F_{RT} is the total number of retransmitted frames.

3. SIMULATION RESULTS AND ANALYSIS

The following six ADSL schemes are implemented and their performances are analysed and compared:

Scheme1: An ADSL system with prioritised 16-QAM constellation mapping, HARQ including diversity combining and TCM with adaptive bit loading.

Scheme2: It employs prioritised 16-QAM constellation mapping, TCM with adaptive bit loading and HARQ but does not include diversity combining.

Scheme3: A scheme which uses prioritised 16-QAM constellation mapping and TCM with adaptive bit loading only.

Scheme4: This scheme involves only TCM and adaptive bit loading. Prioritised 16-QAM mapping is not performed and as such, the bit re-ordering performed at the output of the trellis encoder shown in Figure 2 is omitted.

Scheme5: Conventional ADSL system with adaptive bit loading.

Scheme6: This scheme is a conventional ADSL system with adaptive bit loading which also incorporates a feedback path for implementation of HARQ.

Each scheme has been simulated with 1000 frames, i.e., 1,552,000 bits transmitted on a modelled-twisted pair channel in the presence of AWGN, NEXT and FEXT. For the schemes with HARQ, a retransmission limit of 5 is applied. The number of NEXT disturbers is set to 8 while the number of FEXT disturbers is kept at 49 which is the maximum number of disturbers that can be contained in a multi-pair cable. The energy per bit to noise power spectral density ratio (E_b/N_0), is varied from 17 to 22 dB. This Eb/No range has been chosen because it covers the whole range of BER values from 10^{-1} to 10^{-6} which is the most significant range for assessing the performance of a communication system. For Eb/No values below 17dB, the BER of some of the schemes investigated would fall well above 10^{-1} and at such high BERs useful communication is not possible. Hence the performance has not been investigated for Eb/No values below 17dB. The graphs of BER against for each scheme are plotted for different number of users in the system, specifically for 8 users, 4 users and 12 users. Graphs of throughput against E_b/N_0 for schemes 1, 2 and 6 are also plotted.

Figure 4 shows the graph of BER against E_b/N_0 for the case of 4 users. It is clearly observed that Scheme 6 outperforms all the other schemes by a large margin with about 3.5 dB of gain over conventional ADSL for the whole range of E_b/N_0 used for the simulations. It can also be seen that here Scheme 3 performs slightly better than Scheme 4 even at higher values of E_b/N_0. Without diversity combining, Scheme 2 achieves noticeably better performance than schemes 3, 4 and 5, however, the noteworthy gain of 1.2 dB of Scheme 1 over Scheme 2 suggests that diversity combining has a greater positive effect on the BER performance of the HARQ schemes with fewer number of users.

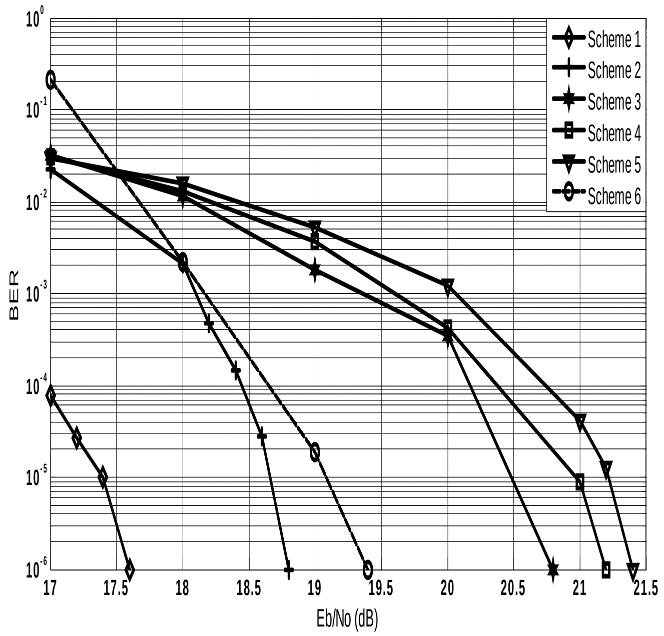

Figure 4: Comparison of BER performance with 4 users.

Figure 5 shows the graph of BER against E_b/N_0 for the case of 8 users. It is observed that Scheme 1, that is, the ADSL system with prioritised 16-QAM constellation mapping, HARQ with diversity combining and TCM with adaptive bit loading provides the best performance with a noticeable gain of over 3 dB for BER > 10^{-5} over conventional ADSL (Scheme 5). At E_b/N_0 of 17 dB, Scheme 1 also provides a gain of about 1.5 dB over Scheme 2, which does not include diversity combining. The prioritised 16-QAM constellation mapping in Scheme 3 realises the same BER performance as Scheme 4, which uses only TCM with adaptive bit loading, for E_b/N_0 17 to 20 dB but an average gain of about 0.8 dB is obtained for BER <10^{-4}. This suggests that while TCM in ADSL improves BER performance, the combined use of prioritised QAM constellation mapping and TCM provides an enhanced performance at higher values of E_b/N_0. Moreover, Scheme 1 and Scheme 2 both outperform Scheme 6, which is a conventional ADSL system with HARQ only with Scheme 1 providing an average gain of about 1 dB over Scheme 6 for BER > 10^{-5}.

Figure 6 shows the graph of BER against E_b/N_0 for the case of 12 users. Schemes 1 and 2, which make use of HARQ maintain their substantial gain over conventional ADSL and TCM schemes. Scheme 1 achieves over 4 dB of gain for E_b/N_0=17 dB and an average gain of 3 dB gain for E_b/N_0 18 dB onwards over Scheme 5, that is, conventional ADSL. However, it can be observed that Scheme 6, which is conventional ADSL with HARQ, matches the performance of Scheme 2 for BER > 10^{-4} indicating a loss in performance at lower E_b/N_0 for Scheme 2 when HARQ without diversity combining is employed. Scheme 3, which uses prioritised constellation mapping and TCM only, provides a slight gain over Scheme 4 for 10^{-5} < BER < 10^{-3}, around 0.5 dB at E_b/N_0=20.4 dB.

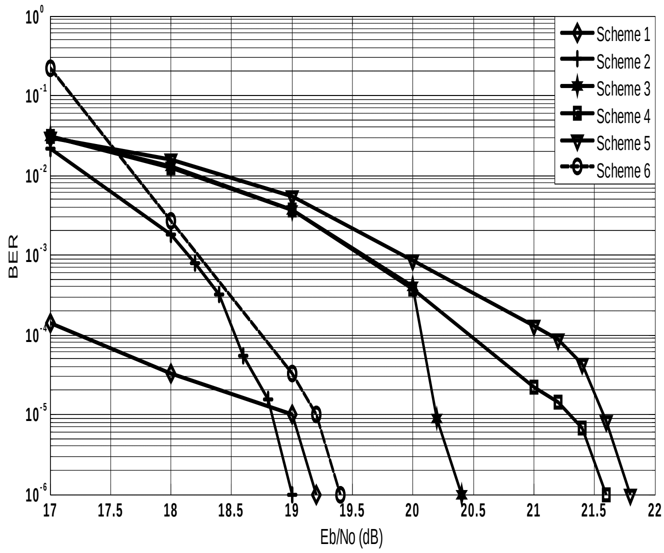

Figure 5: Comparison of BER performance with 8 users.

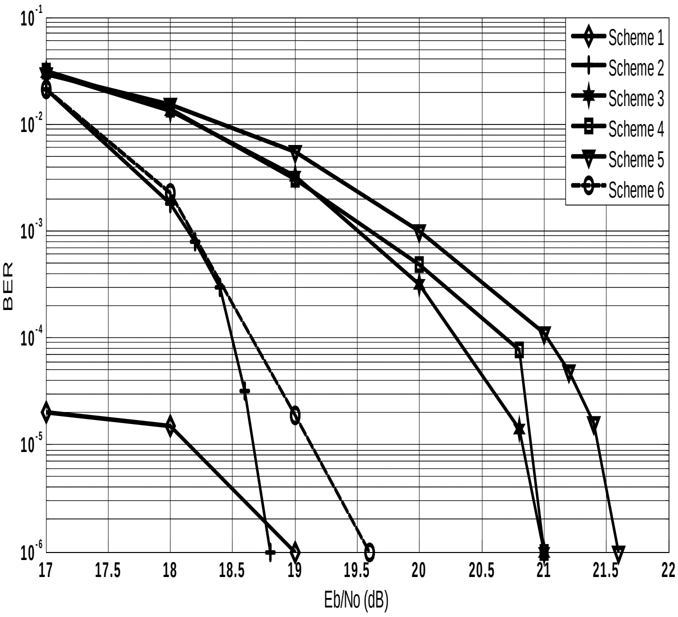

Figure 6: Comparison of BER performance with 12 users.

Figure 7 shows the graph of throughput against E_b/N_0 for the HARQ schemes for the system with 4 users. It can be observed that Scheme 1, which makes use of diversity combining, outperforms the conventional ADSL system with HARQ (Scheme 6) and the ADSL system with prioritised 16-QAM constellation mapping and HARQ (Scheme 2) by achieving a 30 percent throughput gain over both schemes at E_b/N_0= 17 dB. At E_b/N_0= 17.5, Scheme 1 provides 21 percent of gain in throughput over Scheme 6 and a 15 percent gain in throughput over Scheme 1.

Figure 8 shows the graph of throughput against E_b/N_0 for the schemes employing HARQ, that is, Scheme 1, 2 and 6 for the 8 user case. It can be observed that Scheme 1 achieves better throughput performance as compared to conventional ADSL with HARQ (Scheme 6) and considerably outperforms Scheme 2 as well, for values of E_b/N_0 ranging from 17 to 19 dB. Scheme

2 which uses prioritised 16-QAM mapping and HARQ provides better performance over Scheme 6 with an average gain in throughput of 5 percent in the range E_b/N_0=17.5 dB to E_b/N_0=19.5 dB. However, Scheme 1 which uses diversity combining achieves 30 percent more throughput at E_b/N_0=17 dB than Scheme 2. This implies that diversity combining can successfully increase the throughput at lower E_b/N_0. However, considering the fact that prioritisation is only applied to the 4 last channels of the system with TCM, it can be assumed that a higher gain in throughput performance of Schemes 1 and 2 compared to the system not employing prioritised 16-QAM mapping is achievable if TCM encoding of different rates is extended to more sub-channels and prioritisation is applied for the higher QAM constellations used in the system.

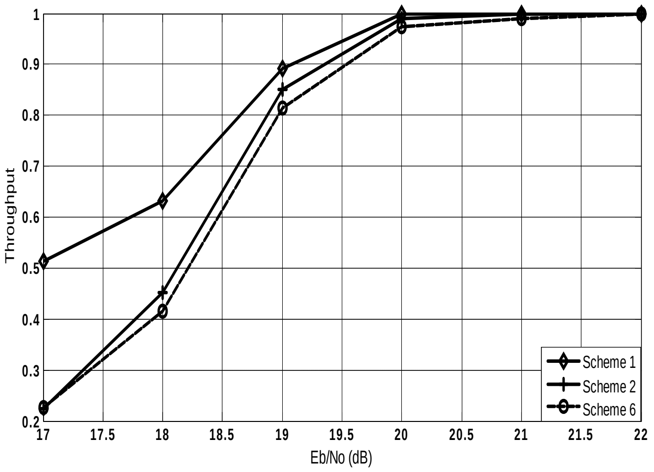

Figure 7: Comparison of throughput performance with 4 users.

Figure 9 shows the graph of throughput against Eb/N0 for Schemes 1, 2 and 6 for the system having 12 users. It is observed that the graphs follow the same trend as in Figure 6 and 7 suggesting that the throughput performance of the different Schemes is not much affected by the number of users.

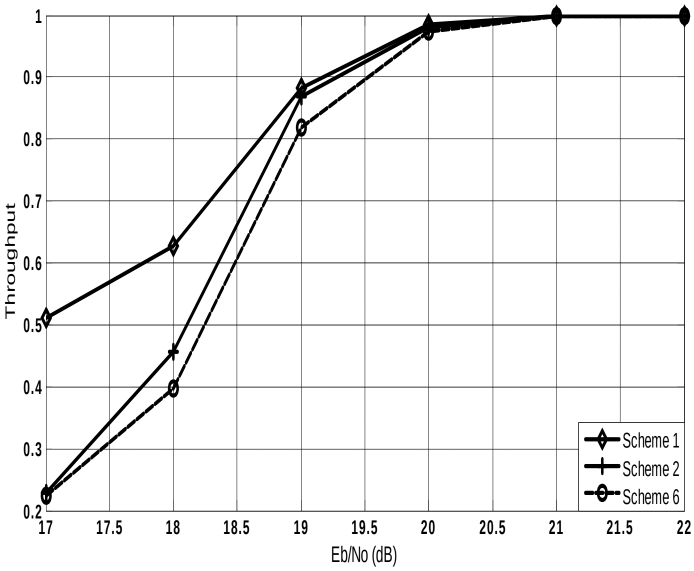

Figure 8: Comparison of throughput performance with 8 users.

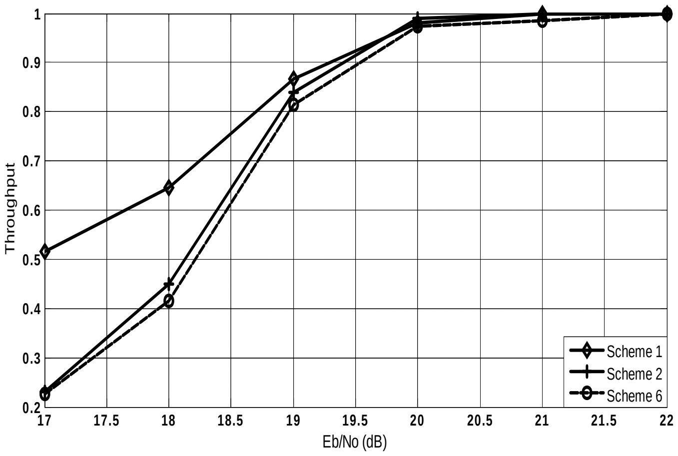

Figure 9:Comparison of throughput performance with 12users.

4. CONCLUSION

In this paper, a novel scheme for an ADSL system which employs the combined techniques of selective QAM constellation mapping, TCM with adaptive bit loading and HARQ with diversity combining is presented. The BER and throughput performance of this scheme are analysed and compared to five other schemes. Re-ordering of the bits output from the trellis encoder is performed to map the systematic bit on one of the most strongly protected points of the prioritised 16-QAM constellation. A feedback path from the ADSL receiver to the transmitter is also included to implement HARQ where a request for retransmission is made to the transmitter based on the output of the CRC syndrome detectors for each frame. Additionally, diversity combining of the retransmitted frames is performed. The proposed scheme provides a significant gain in BER performance of 3.5 dB and above for the different number of users investigated over a conventional ADSL scheme for BER > 10^{-5}. Without diversity combining, the scheme still outperforms all other schemes, nevertheless, it tends to match the performance of the scheme implementing conventional ADSL with HARQ for E_b/N_0 values lower than 18 dB. The main benefit of the proposed scheme is that it outperforms a conventional ADSL system which employs HARQ by around 2 dB in E_b/N_0 and 30 percent in throughput. Overall, the results obtained provide evidence to the potential of HARQ to improve reliability of ADSL transmission and to achieve better throughput and BER performance with the added techniques of diversity combining and prioritised constellation mapping.

5. ACKNOWLEDGMENTS

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