CONCATENATED SPACE-TIME BLOCK CODED AND TURBO CODED SYMBOL-BY-SYMBOL ADAPTIVE OFDM AND MULTI-CARRIER CDMA SYSTEMS

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ABSTRACT

Symbol-by-symbol adaptive Orthogonal Frequency Division Multiplex (OFDM) modems counteract the near instantaneous channel quality variations and hence attain an increased throughput in comparison to their fixed-mode counterparts. By contrast, various diversity techniques, such as Rake receivers and space-time coding, mitigate the channel quality variations in their effort to obtain a reduced BER. This paper investigates a combined system constituted by a constant-power adaptive modem employing space-time coded diversity techniques in the context of both OFDM and MC-CDMA. The combined system is configured to produce a constant uncoded BER and exhibits virtually error free performance, when a turbo convolutional code is concatenated with a space-time block code. It was found that the advantage of the adaptive modem erodes, as the overall diversity-order increases.

1. INTRODUCTION

The next generation wireless communication systems are expected to deliver more Internet traffic, than conventional voice traffic. As Internet Protocol (IP)-based telephone services become popular and their voice quality is improved, even voice traffic may become merged with the Internet traffic. Apart from peer-to-peer multimedia services, most Internet traffic exhibits an asymmetric nature, requiring a higher throughput in the down-link. Orthogonal Frequency Division Multiplex (OFDM) based multi-carrier systems [1] approach the theoretically highest possible 2Bd/Hz Shannonian bandwidth efficiency. Hence, they are considered attractive for down-link wireless Internet services in future fourth generation (4G) systems as well as in high-speed Wireless Local Area Networks (WLAN). However, OFDM in its basic form cannot fully benefit from the multi-path diversity potential of wideband channels.

Multi-Carrier Code Division Multiple Access (MC-CDMA) [2] is an OFDM-based frequency domain spreading technique, which exploits frequency domain diversity and constitutes an attractive multiple access scheme for employment in synchronous environments. It was reported that the synchronisation requirement of MC-CDMA is within 10% of the frame length [3]. Thus, an MC-CDMA system having the appropriate modem parameters can be used as a multiple access scheme in the down link of fixed or slowly moving terminals, where near-synchronous operation is feasible. Since MC-CDMA facilitates diversity reception similarly to a Rake receiver, the performance of single-user MC-CDMA is characterised by that of an ideal Rake receiver. In a multi-user scenario joint-detection assisted MC-CDMA employing the MMSE-BDFE [4] receiver approaches the single-user performance.

When channel coding is employed in conjunction with frequency domain interleaving, OFDM substantially benefits from the frequency domain diversity. However, OFDM may not be capable of exploiting the diversity potential of the channel to the same extent as MC-CDMA. Hence, it is interesting to compare the coded BERs of OFDM and MMSE-BDFE aided MC-CDMA in conjunction with concatenated turbo codes and space-time block codes over wideband Rayleigh channels.

Various combinations of Space-Time (ST) codes and channel codes can be used over wideband channels [5]. An attractive option is to use a half-rate turbo convolutional code concatenated to a space-time block code using two transmit antennas and to expand the signal constellation to a higher order modulation mode in order to match the throughput of the system using no channel coding. Another approach to maintaining a high effective throughput is to use a high-rate turbo BCH code in conjunction with a ST trellis code or ST block code and a lower order modulation mode, than in case of the half-rate FEC scheme. It was reported in [5] that the former approach gives a lower BER, than the latter. Hence, we will employ a half-rate turbo convolutional code in our comparative study.

Adaptive modulation [6, 7] attempts to provide the highest possible throughput given the current channel quality, while maintaining the required data transmission integrity. We employed constant-power Adaptive Quadrature Amplitude Modulation (AQAM) [1]. Again, wideband fading exhibits two-dimensional channel quality variation, namely both time domain variation and frequency domain variation, and OFDM lends itself to exploiting these two-dimensional channel quality variations [8, 9]. In other words, time domain adaptivity and frequency domain adaptivity can be simultaneously exploited in OFDM. By contrast, while providing frequency domain diversity with the aid of averaging the channel qualities of several sub-carriers, MC-CDMA is less amenable to frequency domain adaptation, than to time domain adaptation.

The aim of this contribution is to compare the performances of the combined adaptive OFDM and MC-CDMA modems. Although adaptive coded multi-carrier modulation systems have been extensively studied [9, 10, 11], the effect of diversity has not been considered.

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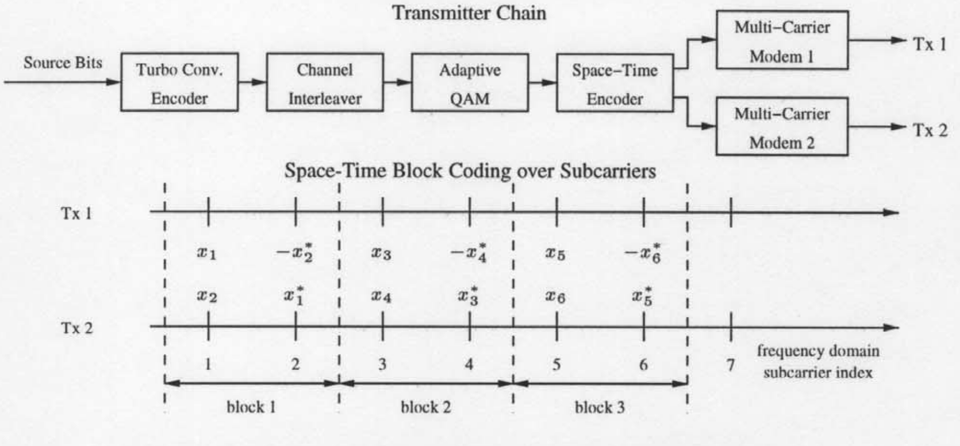


Figure 1: Transmitter structure and space-time block encoding scheme

2. SYSTEM MODEL AND SWITCHING LEVELS

Figure 1 portrays the stylised transmitter structure of our system. The source bits are channel coded by a half-rate turbo convolutional encoder [12] using a constraint length of $K = 3$ as well as an interleaver size of $L = 3072$ bits and interleaved by a random block interleaver. Then, the AQAM block selects a modulation mode from the set of no transmission, BPSK, QPSK, 16-QAM and 64-QAM depending on the instantaneous channel quality perceived by the receiver, according to the predetermined SNR-dependent switching thresholds. It is assumed that the perfectly estimated channel quality experienced by receiver A is fed back to transmitter B superimposed on the next burst transmitted to receiver B. The modulation mode switching levels of our AQAM scheme determine the average BER as well as the average throughput. A set of optimum switching thresholds was derived in [13] for transmission over flat Rayleigh fading channels. However, AQAM modems employing these switching thresholds inevitably exhibit a variable average BER across the SNR range, despite aiming for a given target BER, namely B_t. In order to achieve a constant target BER, while maintaining the maximum possible throughput, a new set of SNR-dependent switching thresholds was devised for the transmission over wideband channels [14]. Figure 2 illustrates the switching levels optimised for both adaptive OFDM and adaptive MC-CDMA for the target BER of $B_t = 10^{-3}$. The optimum switching levels decrease, as the average channel SNR increases and hence higher-throughput modulation modes can be invoked more frequently. Figure 2 also shows the 'avalanche' SNR, beyond which adaptive mode switching is abandoned in favour of the fixed highest-order modulation mode, namely 64-QAM, since the BER of 64-QAM satisfies the target BER requirement.

The modulated symbol is now space-time encoded. As seen at the bottom of Figure 1, Alamouti's space-time block code [15] is applied across the frequency domain. A pair of the adjacent sub-carriers belonging to the same space-time encoding block is assumed to have the same channel quality. We employed a Wireless Asynchronous Transfer Mode (W-ATM) channel model [1, pp.474] transmitting at a carrier frequency of 60GHz, at a sampling rate of 225MHz and employing 512 sub-carriers. Specifically, we used a 3-path fading channel model, where the average SNR of each path is given by $\bar{\gamma}_1 = 0.79192\bar{\gamma}$, $\bar{\gamma}_2 = 0.12424\bar{\gamma}$ and $\bar{\gamma}_3 = 0.08384\bar{\gamma}$. Each channel associated with a different antenna is assumed to exhibit independent fading.

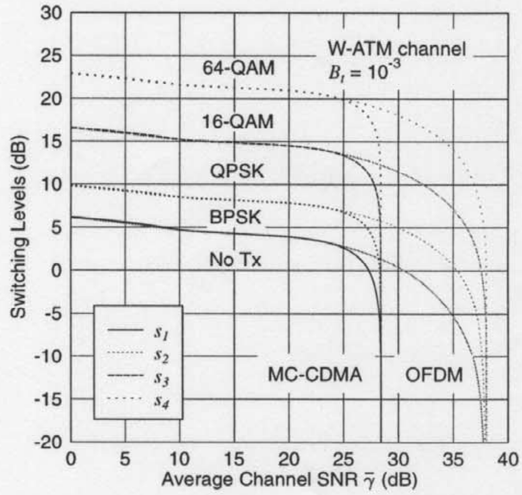
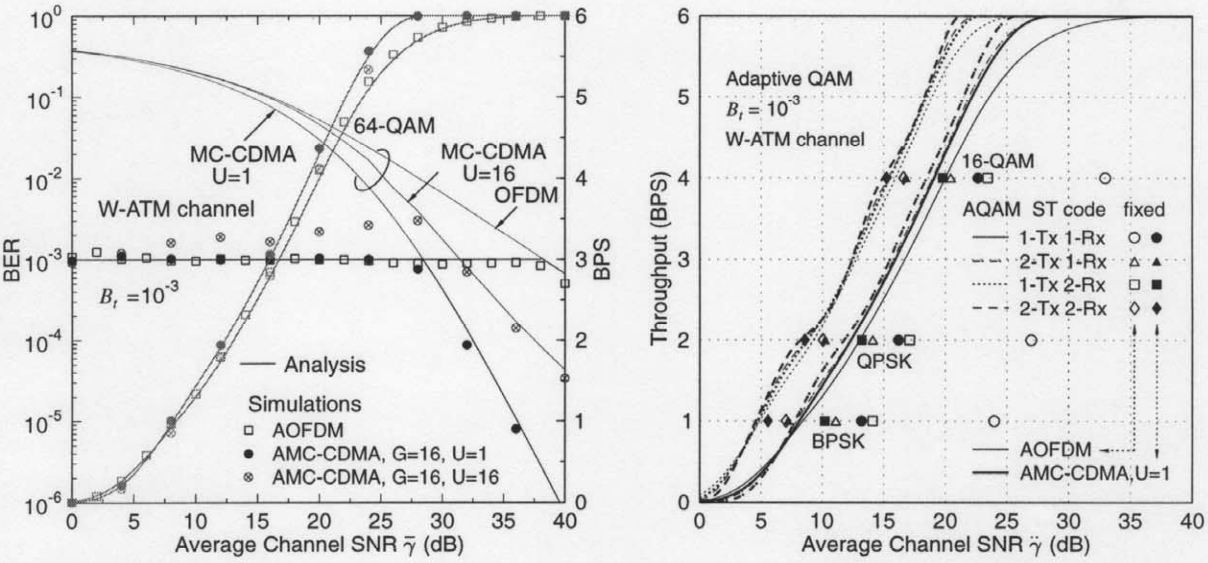


Figure 2: The optimum switching levels devised for the target BER of $B_t = 10^{-3}$, when using 1 Tx antenna and 1 Rx antenna. The W-ATM channel model [1, pp.474] is assumed for MC-CDMA. The switching levels for OFDM were obtained for narrow-band Rayleigh channels, which can be used for any multi-path profile, since OFDM renders the dispersive channel non-dispersive.

3. UNCODED ADAPTIVE SYSTEM

The simulation results for our uncoded adaptive modems are presented in Figure 3. Since we employed the optimum switching levels, both our adaptive OFDM (AOFDM) and the adaptive single-user MC-CDMA (AMC-CDMA) modems maintain the constant target BER of 10^{-3} up to the 'avalanche' SNR value, and then follow the BER curve of the 64-QAM mode. However, 'full-user' AMC-CDMA supporting $U = 16$ users with the aid of a spreading factor of $G = 16$ and employing the MMSE-BDFE Joint Detection (JD) receiver [4] exhibits a slightly higher average BER, than the target of $B_t = 10^{-3}$ due to the residual Multi-User Interference (MUI) of the imperfect joint detector. Since we derived the optimum switching levels based on a single-user system, the levels are no longer optimum, when residual MUI is present. The average throughputs expressed in terms of Bits Per Symbol (BPS) steadily increase and reach the throughput of 64-QAM, namely 6



(a) BER and Throughput, No ST coding

(b) Throughput with ST coding

Figure 3: Performance of uncoded five-mode AOFDM and AMC-CDMA. The target BER is $B_t = 10^{-3}$ transmitting over the W-ATM channel [1, pp.474]. (a) The constant average BER is maintained for AOFDM and single user AMC-CDMA, while 'full-user' AMC-CDMA exhibits a slightly higher average BER due to the residual MUI. (b) The SNR gain of adaptive modems decreases as ST coding increases the diversity order. The BPS curves appear in pairs, corresponding to AOFDM and AMC-CDMA - indicated by the thin and thick lines, respectively - for each of the four different ST code configurations. The markers represent the SNRs required by the fixed-mode OFDM and MC-CDMA schemes for maintaining the target BER of 10^{-3} in conjunction with the four ST-coded schemes.

BPS. The throughput degradation of 'full' user MC-CDMA was within a fraction of one dB. Observe in Figure 3(a) that the analytical and simulation results are in good agreement, which we denoted by the lines and distinct symbols, respectively.

The effects of ST coding on the average BPS throughput are displayed in Figure 3(b). Specifically, the thick lines represent the average BPS throughput of our AMC-CDMA scheme, while the thin lines represent those of our AOFDM modem. The four pairs of hollow and filled markers associated with four ST-coded scenarios represent the BPS throughput versus SNR values associated with fixed-mode OFDM and fixed-mode MMSE-BDFE JD assisted MC-CDMA. Specifically, the right most markers correspond to the 1-Tx / 1-Rx, the second to the 2-Tx / 1-Rx, the third to the 1-Tx / 2-Rx and the left most to the 2-Tx / 2-Rx scenarios. First of all, we can observe that the BPS throughput curves of OFDM and single-user MC-CDMA are close to each other, namely within 1 dB for most of the SNR range. This is surprising, considering that the fixed-mode MMSE-BDFE JD assisted MC-CDMA scheme was reported to exhibit around 10dB SNR gain at a BER of 10^{-3} and 30dB gain at a BER of 10^{-6} over OFDM [16]. This is confirmed in Figure 3(b) by observing that the SNR difference between the ∘ and • markers is around 10dB, regardless whether the 4, 2 or 1 BPS scenario is concerned.

Let us now compare the SNR gains of the adaptive modems over the fixed modems. The SNR difference between the BPS curve of AOFDM and the fixed-mode OFDM represented by the symbol ∘ at the same throughput is around 15dB. The corresponding SNR difference between the adaptive and fixed-mode 4, 2 or 1 BPS MC-CDMA modem is around 5dB. More explicitly, since in the context of the W-ATM channel model [1, pp.474] fixed-mode MC-CDMA appears to exhibit a 10dB SNR gain over fixed-mode OFDM, the additional 5dB SNR gain of AMC-CDMA over its fixed-mode counterpart results in a total SNR gain of 15dB over fixed-mode OFDM. Hence ultimately the performance of AOFDM and AMC-CDMA becomes similar.

Let us now examine the effect of ST block coding. The SNR gain of the fixed-mode scheme due to the introduction of a 2-Tx / 1-Rx ST block code is represented as the SNR difference between the two right most markers. These gains are nearly 10dB for fixed-mode OFDM, while they are only 3dB for fixed-mode MC-CDMA modems. However, the corresponding gains are less than 1dB for both adaptive modems. Since the transmitter power is halved due to using two Tx antennas in the ST codec, a 3dB channel SNR penalty was already applied to the curves in Figure 3(b). The introduction of the second receive antenna instead of the second transmit antenna eliminates this 3dB penalty. Finally, the 2-Tx / 2-Rx system gives around 3-4dB SNR gain in the context of fixed-mode OFDM and a 2-3dB SNR gain for MC-CDMA, in both cases over the 1-Tx / 2-Rx system. By contrast, the gain of the 2-Tx / 2-Rx scheme over the 1-Tx / 2-Rx based adaptive modems was, again, less than 1dB in Figure 3(b). More importantly, for the 2-Tx / 2-Rx scenario the advantage of employing adaptive modulation vanishes, since the fixed-mode MC-CDMA modem performs as well as the AMC-CDMA modem in this scenario. Moreover, the fixed-mode MC-CDMA modem still outperforms the fixed-mode OFDM modem by about 2dB. We conclude that since the diversity-order increases with the introduction of ST block codes, the channel quality variation becomes sufficiently low for the performance advantage of adaptive modems to vanish. This is achieved at the price of a higher complexity due to employing two transmitters and two receivers.

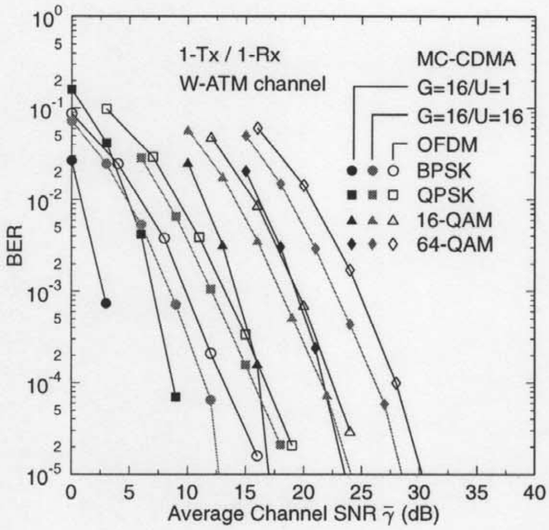


Figure 4: Performance of turbo convolutional coded fixed-mode OFDM and MC-CDMA over the W-ATM channel of [1, pp.474]. JD MC-CDMA still outperforms OFDM. However, the SNR gain of JD MC-CDMA over OFDM is reduced to 1-2dB at a BER of 10^{-4}.

4. TURBO-CODED FIXED MODEM

When channel coding is employed in the fixed-mode multi-carrier systems, it is expected that OFDM benefits more substantially from the frequency domain diversity than MC-CDMA, which benefited more than OFDM without channel coding. The simulation results depicted in Figure 4 show that the various turbo-coded fixed-mode MC-CDMA systems consistently outperform OFDM. However, the SNR differences between the turbo-coded BER curves of OFDM and MC-CDMA are reduced considerably.

5. TURBO CODED ADAPTIVE SYSTEM

The performance of the concatenated ST block coded and turbo convolutional coded adaptive modems is depicted in Figure 5 . We applied the optimum set of switching levels designed for the uncoded BER of 3×10^{-2}. This uncoded target BER was obtained from the relations of the uncoded and the turbo coded BPSK modems employing the same coding parameters over AWGN channels, with the ultimate objective of obtaining a coded BER below 10^{-7} for our adaptive modems. However, our simulation results yielded zero bit errors when transmitting 10^9 bits, except for some SNRs, when employing only a single antenna.

Figure 5(a) shows the BER of our turbo coded adaptive modems, when a single antenna is used. We observe in the figure that the BER reaches its highest value around the 'avalanche' SNR point, where the adaptive modulation scheme consistently activates 64-QAM. The system is most vulnerable around this point. In order to interpret this phenomenon, let us briefly consider the associated interleaving aspects. For practical reasons we have used a fixed interleaver length of $L = 3072$ bits. When the instantaneous channel quality was high, the $L = 3072$ bits were spanning a shorter time-duration during their passage over the fading channel. Hence the channel errors appeared more bursty, than in the lower-throughput AQAM modes, which transmitted the $L = 3072$ bits over a longer duration, hence dispersing the error bursts over a longer duration of time. The associated more random dispersion of erroneous bits enhances the coding power of the turbo code. On the other hand, in the SNR region beyond the 'avalanche' SNR point the system exhibited a lower uncoded BER, reducing the coded BER even further. This observation suggests that further research ought to determine the set of switching thresholds for a coded adaptive system.

We can also observe that the turbo coded BER of AOFDM is higher than that of AMC-CDMA in the SNR rage of 10-20dB, even though the uncoded BER is the same. This appears to be the effect of the limited exploitation of frequency domain diversity in coded OFDM, compared to MC-CDMA, which leads to a more bursty uncoded error distribution, hence degrading the turbo coded performance. The fact that ST block coding aided multiple antenna systems show virtually error free performance corroborates our argument.

Figure 5(b) compares the throughputs of the coded adaptive modems and the uncoded adaptive modems exhibiting a comparable average BER. The SNR gains due to channel coding were in the range of 0dB to 8dB depending on the SNR region and the employed scenarios. Each bundle of throughput curves corresponds to the scenarios of 1-Tx/1-Rx OFDM, 1-Tx/1-Rx MC-CDMA, 2-Tx/1-Rx OFDM, 2-Tx/1-Rx MC-CDMA, 1-Tx/2-Rx OFDM, 1-Tx/2-Rx MC-CDMA, 2-Tx/2-Rx OFDM and 2-Tx/2-Rx MC-CDMA starting from the far right curve for the throughput values higher than 0.5 BPS. The SNR difference between the throughput curves of the ST and turbo coded AOFDM and those of the corresponding AMC-CDMA schemes was reduced compared to the uncoded performance curves of Figure 3(b). The SNR gain owing to ST block coding in the context of AOFDM and AMC-CDMA was limited to about 1dB due to the halved transmitter power. Therefore, again, ST block coding appears to be less effective for adaptive modems.

6. CONCLUSION

The performance of ST block coded constant-power adaptive multi-carrier modems employing optimum SNR-dependent modem mode switching levels were investigated. The adaptive modems maintained the constant target BER, whilst maximising the average throughput. As expected, it was found that ST block coding reduces the relative performance advantage of adaptive modulation, since it increases the diversity order and eventually reduces the channel quality variations. When turbo convolutional coding was concatenated to the ST block codes, near-error-free transmission was achieved at the expense of the halving the average throughput. Compared to the uncoded system, the turbo coded system was capable of achieving higher throughput in the low SNR region at the cost of higher complexity. The study of the relationship between the uncoded BER and the corresponding coded BER showed that adaptive modems obtain higher coding gains, than that of fixed modems. This was due to the fact that the adaptive modem avoids burst errors even in deep channel fades by reducing the number of bits per modulated symbol eventually to zero.

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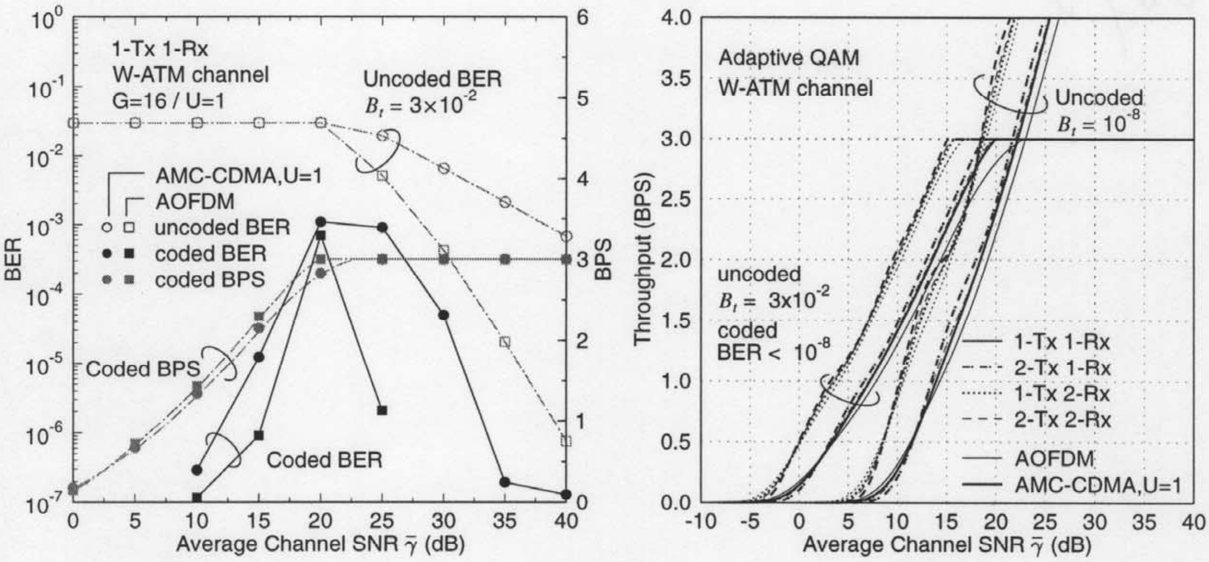

(a) BER (b) Throughput

Figure 5: Performance of the concatenated ST block coded and turbo convolutional coded adaptive OFDM and MC-CDMA systems over W-ATM channel of [1, pp.474]. The uncoded target BER is 3×10^{-2}. The coded BER was less than 10^{-8} for most of the SNR range, resulting in virtually error free transmission. (a) The coded BER becomes higher near the 'avalanche' SNR point, when a single antenna was used. (b) The coded adaptive modems have SNR gains up to 7dB compared to their uncoded counterparts achieving a comparable average BER.

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