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A. Shafi and M. Bettayeb (*Electrical Engineering Department, King Fahd University of Petroleum and Minerals, KFUPM, Dhahran 31261, Saudi Arabia*)

A. Zerguine (*Physics Department, King Fahd University of Petroleum, and Minerals, KFUPM, Dhahran 31261, Saudi Arabia*)

E-mail: {ahmar, azzedine, maamarab}@kfupm.edu.sa

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Performance comparison of space-time coding techniques

D. Bevan and R. Tanner

Simulation results for the comparative performance of a number of space-time coding (STC) schemes in a multiple-input-multiple-output (MIMO) channel are presented, and compared with a single-antenna benchmark and two-antenna space-time transit diversity (STTD) scheme. Both the space-time trellis coding (STTC) and BLAST approaches offer high spectral efficiencies, but STTC outperforms BLAST in terms of its power efficiency.

Introduction: Space-time coding (STC), as a technique for exploitating the multiple-input-multiple-output (MIMO) radio channel, is currently generating considerable interest in the mobile communications literature [1 – 3]. Such coding schemes promise enhanced performance in terms of power efficiency (i.e. good error performance at low SNR) and spectral (bandwidth) efficiency due to the exploitation of the inherent parallelism and diversity within the MIMO channel. Space-time encoders basically operate by taking an input stream of information bits, and from these generates vector outputs of simultaneous transmissions at a number of transmit antennas. These vector transmissions are called space-time symbols (STSs). In this Letter we present simulation results for the comparative performance of a number of STC schemes in an MIMO channel, and discuss reasons for the performance trends that we identify.

Simulation description: We briefly describe here the simulation setup and assumptions in general terms before giving more details of the candidate STC algorithms. The simulations are carried out for a simplified system at the symbol-level, whereby frames of STS are transmitted with constant power over a quasi-static flat Rayleigh fading MIMO channel. Thus the complex (Gaussian) random fading coefficient between each transmitter antenna and each receiver antenna is constant over a frame, and independent of every other fading coefficient for the same frame and for other frames. The notation N_T:N_R is used to denote the numbers of antennas at each end of the link. Each frame carries 400 information bits (800 in the case of uncoded BLAST), where an information bit is defined as a data bit at the input of the space-time enoder (to which tail bits are added if necessary, to return the encoder to a known state). The performance is quantified in terms of the required E_s/N_0 and E_b/N_0 at each receiver antenna for a mean frame error rate (FER) of 10%. E_S is the mean energy (squared value) of the received STS at each receiver antenna, and E_b is the mean energy per information bit at each receiver antenna (i.e. E_S divided by the spectral efficiency). The 10% value of FER was chosen to be a suitable threshold since this had been found to be approximately the level at which the power efficiency of the code is maximised if an ARQ protocol is employed in a packet-data link.

Candidate space-time codes: In this Section we provide a brief description of the various candidate STC schemes, the performances of which have been simulated with the results presented below. The scheme labelled benchmark is a 1/2 rate $k = 9$ maximum free distance binary convolutional encoder [4], with output bits mapped to QPSK symbols. In a static 1:1 channel it achieves 10% FER for an E_b/N_0 of 2.2dB and 1% BER for an E_b/N_0 of 1.7dB. STTD is a concatenation of the benchmark encoder with the space-time transmit diversity block code [5]. The STTC-32 code ([1] Fig. 6) has 32 states and two information bits per STS. MC-STTC-256 is a novel space-time trellis coding scheme achieved through a concatenation of the benchmark encoder, a QPSK modulation mapper, and a demultiplexer to the different transmit antennas. It thus has $2^{k-1} = 256$ states in the trellis, and a spectral efficiency equal to the number of transmit antennas employed. A Viterbi-based maximum likelihood sequence estimation (MLSE) receiver structure was used for all of the coding schemes described here.

A number of layered space-time schemes were also simulated (labelled 'BLAST'), based on the structure discussed in [2, 3]. The variants of BLAST shown in Table 1 use a genie-aided subtraction of the transmission from the stronger transmit antenna when detecting the transmission from the weaker antenna. That is, the signal seen at the receiver antennas from the stronger transmit antenna (for a given frame) was perfectly subtracted prior to detection of the signal from the weaker antenna. The uncoded BLAST case uses no error correction code (it is raw QPSK), hence it achieved a high spectral efficiency of 4bit/s/Hz for a 2:2 MIMO configuration. Separate frames of data (each carrying 400 information bits) were simultaneously transmitted from each of the two transmit antennas. The stronger of the two frames was detected first, by spatially nulling out (zero forcing) the weaker transmission, before detecting the bits. A genie-aided subtraction process was then applied to perfectly subtract this signal at the receiver, before maximum-ratio combination (MRC) [4] beamforming to the weaker transmission (i.e. avoiding the requirement to null the stronger, since it has already been subtracted). Finally we carried out detection of the noisy QPSK data at the output of this beamformer, which is our noisy received signal from the weaker transmit antenna.

Table 1: Simulated performance of STC algorithms

STC-Algorithm (N_T : N_R)	E_b/N_0 for 10% FER	Spectral efficiency	E_S/N_0 (SNR) for 10% FER
Benchmark	dB	(bit/s/Hz)	dB
1:1	11.0	1.0	11.0
2:1	4.5	1.0	4.5
1:4	–0.5	1.0	–0.5
STTD			
2:1	7.2	1.0	7.2
2:2	2.2	1.0	2.2
STTC-32			
2:1	11.0	2.0	14.0
2:2	4.6	2.0	7.6
MC-STTC-256			
2:1	9.6	2.0	12.6
2:2	3.5	2.0	6.5
4:1	12.0	4.0	18.0
4:2	4.0	4.0	10.0
4:4	–1.5	4.0	4.5
Uncoded BLAST 2:2	12.0	4.0	18.0
Coded BLAST 2:2	7.1	2.0	10.1

The coded-BLAST case used two separate benchmark encoders, one for each antenna, followed by a symbol mapper to QPSK prior to transmission. The receiver processing was carried out similarly to that applied to the uncoded BLAST case in that beamformer nulling was applied to isolate the signal from the stronger transmit antenna (along with a transfer of soft metrics from the beamformer preprocessor to the respective decoder) followed by genie-aided subtraction and MRC to generate soft metrics pertaining to the second antenna transmission.

Simulation results: The results of the simulations are shown in Table 1 showing the tradeoff of E_b/N_0 performance (power efficiency) against spectral efficiency. It should be noted that the benchmark 1:4 number has been extrapolated from results at a lower FER.

Examining the results of Table 1 it can be seen that the benchmark has poor performance in the 1:1 case, with a required E_b/N_0 of 11.0dB. This was 8.8dB higher than the static channel performance, and was due to the high fade margin required due to the lack of diversity. This performance could be improved either by increasing the number of receiver antennas (yielding both SNR gain and diversity gain) or by increasing the number of transmit antennas and using STTD, or both. In the latter case, for STTD 2:2, this resulted in a required E_b/N_0 of only 2.2dB.

The spectral efficiency could be doubled to 2bit/s/Hz using the STTC-32 code, but at the cost of a 2.4dB degradation in the mean E_b/N_0. If the number of code states was increased to 256 using the MC-STTC-256, such that the number of states is now equal to that in the benchmark case, we improved our 2:2 performance to an E_b/N_0 of 3.5dB. For the MC-STTC-256 case, if receiver was extended to have four antennas at each end of the link, we could further improve both our power efficiency, achieving an E_b/N_0 of −1.5dB, and our spectral efficiency, achieving 4bit/s/Hz. So even using this (potentially) suboptimal code, it can be seen that when we change from an STTD 2:1 scheme to MC-STTC-256 4:4 we obtain an 8.7dB E_b/N_0 reduction for a four times increase in spectral efficiency.

The uncoded BLAST scheme shown in Table 1 performed poorly in terms of E_b/N_0, but had a high spectral efficiency due to the absence of redundancy, and the use of parallel transmission paths. However, it can be seen that by the application of coding the E_b/N_0 performance of BLAST was improved by 4.9dB. This was achieved at the expense of a reduction in spectral efficiency. The notional order of diversity is somewhere between 1 and 2, since the order of diversity is 1 for the detection of the stronger signal, and 2 for detection of the weaker signal. Therefore it would be expected that the performance of the coded BLAST would lie somewhere between that of the baseline 1:1 and 1:2 cases (11.0 and 4.5dB E_b/N_0, respectively), and hence the simulation result of 7.1dB seems intuitively reasonable. It should be noted that this result relies on the subtraction performance approaching that of a magic genie. Preliminary simulation investigations for non-genie-aided BLAST indicate that in practice the performance of coded BLAST 2:2 is in fact some 2–3dB worse than this, owing to the effect of error propagation down the layers. This would suggest that the transmission from the stronger transmit antenna (for any given frame) is (despite its higher transmit power) actually more vulnerable (and therefore has a higher frame error probability) than the transmission from the weaker, due to the 'noise amplification' in the receiver antenna nulling process.

In summary, based on the above reasoning, even coded BLAST would not be expected to reach the performance of baseline 1:2, although it should be remembered that it is achieving twice the spectral efficiency. Finally, it is suggested that further performance gains could possibly be achieved by adding more complexity to the BLAST transmitter and receiver processing, for example by (i) time-switching the coded data frames across the two transmit antennas, as proposed by Foschini [2], and/or (ii) reiterating the decoding process by subtracting the transmission of the weaker transmit antenna away from the received signal, and reattempting detection of the transmission from the stronger transmit antenna (step and repeat until detection convergence).

Conclusions: Of the space-time coding approaches simulated, the STTC techniques offer the best tradeoff of performance against complexity (when considered purely in terms of number of encoder/decoder states) for the applications of interest. A simply derived yet novel STTC has been presented (namely the MC-STTC-256), based on the 1/2-rate convolution encoder, which offers promising performance. It is reasonable to expect that generator polynomials with even better performance in this quasi-static fading channel can be found.

The layered (BLAST) codes, as described in this Letter, offered poorer performance. This was largely due to the loss of diversity, which arose due to the antenna nulling process, and error-propagation effects due to imperfect subtraction. It is believed that coded BLAST schemes will always prove to be inferior in performance to STTC due to this diversity loss, and because of the fact that the decoders are inefficient, since they do not 'share' information in order to carry out joint estimation of the separate transmitted layers.

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D. Bevan and R. Tanner (*Nortel Networks, Harlow Laboratories, London Road, Harlow, CM17 9NA, United Kingdom*)
E-mail: ddnb@nortelnetworks.co.uk

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Prime-factor algorithms for generalised discrete Hartley transform

Guoan Bi and Chao Lu

A prime factor fast algorithm for the type-II generalised discrete Hartley transform is presented. In addition to reducing the number of arithmetic operations and achieving a regular computational structure, a simple index mapping method is proposed to minimise the overall implementation complexity.

Introduction: The generalised discrete Hartley transform (GDHT) has been used in various digital signal processing applications [1 – 3]. It has been shown that the GDHT and the discrete wavelet transform (DWT) have the same definition [4] if differences in scaling constants are ignored. By using the DWT definition, Wang derived fast algorithms [2] to reduce computational complexity. Fast algorithms were also reported for one- and two-dimensional generalised DHTs [5, 6]. However, the derivation of these algorithms was tedious and optimisation of the required computational complexity and structures was difficult. Prime-factor decomposition has been widely used for the discrete Fourier transform (DFT), DHT and discrete cosine transform (DCT) to reduce the number of arithmetic operations. However, the computational structure is generally complex and an index mapping process is required, which adds a substantial overhead in terms of computational and implementation complexity. Based on prime-factor decomposition, we present a derivation of a fast algorithm for the type-II GDHT which can naturally minimise such a computational overhead.