Space-Time IQ-interleaved TCM and TTCM for AWGN and Rayleigh Fading Channels

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Abstract

Space-Time Block Coded Inphase-Quadrature phase (IQ)-interleaved Trellis Coded Modulation (TCM) and Turbo TCM (TTCM) schemes are proposed, which are capable of quadrupling the diversity order of conventional symbol-interleaved TCM and TTCM. The increased diversity order of the proposed schemes provides significant coding gains, when communicating over non-dispersive Rayleigh fading channels without compromising the coding gain achievable over Gaussian channels.

Introduction: Trellis Coded Modulation (TCM) [1, 2] was originally designed for transmission over Additive White Gaussian Noise (AWGN) channels, where it is capable of achieving coding gain without bandwidth expansion. Turbo TCM (TTCM) [2, 3] is a more recent bandwidth efficient transmission scheme, which has a structure similar to that of the family of binary turbo codes, distinguishing itself by employing TCM schemes as component codes. Both the TCM and TTCM schemes employed set partitioning based signal labelling, in order to increase the minimum Euclidean distance between the encoded information bits. Symbol interleavers were utilised both for the turbo interleaver and for the channel interleaver, for the sake of achieving time diversity when communicating over Rayleigh fading channels.

It was shown in [4] that the maximisation of the minimum Hamming distance measured in terms of the number of different symbols between any two transmitted symbol sequences is the key design criterion for TCM schemes contrived for flat Rayleigh fading channels, in particular when communicating at high Signal-to-Noise Ratios (SNR). In an effort to increase the achievable time diversity, a multidimensional TCM scheme utilising one symbol interleaver and two encoders was proposed in [5], where the individual encoders specify the Inphase (I) and Quadrature phase (Q) components of the complex transmitted signal, respectively. Another TCM scheme using constellation rotation was proposed in [6], which utilised two separate channel interleavers for interleaving the I and Q components of the complex transmitted signals, but assumed the absence of I/Q *cross-coupling*, when communicating over complex fading channels.

ST-IQ TCM/TTCM: In order to improve the performance of the existing state-of-the-art systems, in this contribution we proposed the novel system seen in Figure 1 which consists of **Space-Time Block Codes (STBC) [7] and an IQ-interleaved TCM/TTCM scheme using no constellation rotation.** We consider two transmitters and one receiver for the Space-Time (ST) scheme and two independent IQ interleavers for the TCM/TTCM arrangement, as shown in the block diagram of Figure 1. We denote the IQ-interleaved modulated signal by $\tilde{s} = \tilde{s}_I + j\tilde{s}_Q$, which is transmitted over the flat Rayleigh fading channel having a complex fading coefficient of $h = \alpha e^{j\theta}$ with the aid of two STBC transmitters. During the first symbol period the signals $x_1 = \tilde{s}_1$ and $x_2 = \tilde{s}_2$ are transmitted, while during the second symbol period, the signals $-x_2^*$ and x_1^* are emitted from the transmit antennas 1 and 2, respectively. We assume that the fading envelope and phase are constant across the two time slots. The signal is also contaminated by the zero-mean AWGN n exhibiting a variance of $\sigma^2 = N_0/2$, where N_0 is the single-sided noise power spectral density. It can be shown that the two signals received during the two consecutive symbol periods can be represented in matrix form as $\mathbf{r} = \mathbf{A} \cdot \mathbf{x} + \mathbf{n}$: $\begin{pmatrix} r_1 \\ r_2^* \end{pmatrix} = \begin{pmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} n_1 \\ n_2^* \end{pmatrix}$, where $\mathbf{A}$ is termed the system matrix. Note that the I (or Q) component of the received signal r_i, namely $r_{i,I}$ (or $r_{i,Q}$) where $i \in \{1, 2\}$, is dependent on both the I and Q components of x_1 and x_2, namely on $x_{1,I}$, $x_{1,Q}$, $x_{2,I}$ and $x_{2,Q}$, due to the cross-coupling effect imposed by the complex channel. It is however desirable to decouple them, so that we can compute the I (or Q) branch metrics m_I (or m_Q) in Figure 1 for a particular x_i independently, as a function of only $x_{1,I}$ and $x_{2,I}$ (or $x_{1,Q}$ and $x_{2,Q}$). Observe that the decoupling operation has been carried out during the STBC decoding, where the received vector $\mathbf{r}$ is multiplied with the conjugate transpose of $\mathbf{A}$, namely with $\mathbf{A}^{\mathbf{H}}$, yielding $\hat{\mathbf{x}} = \mathbf{A}^{\mathbf{H}} \cdot \mathbf{r}$: $\begin{pmatrix} \hat{x}_1 \\ \hat{x}_2 \end{pmatrix} = \left(\alpha_1^2 + \alpha_2^2\right) \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} \hat{n}_1 \\ \hat{n}_2 \end{pmatrix}$, where $\hat{n}_1$ and $\hat{n}_2$ contain the resultant noise. More specifically, the signal $\hat{x}_1 = (\alpha_1^2 + \alpha_2^2)x_1 + \hat{n}_1$ is the decoupled version of r_1, where $\hat{x}_{1,I}$ (or $\hat{x}_{1,Q}$) is independent of $x_{1,Q}$ and $x_{2,Q}$ (or $x_{1,I}$ and $x_{2,I}$). Hence, it can be readily shown that the associated IQ branch metrics of the STBC coded signal x_1 can be derived from $\hat{x}_1 = \hat{x}_{1,I} + j\hat{x}_{1,Q}$ as: $\tilde{\mathrm{m}}_I(x_{1,I}|\hat{x}_{1,I}, D_I) = -\frac{\left(\hat{x}_{1,I} - D_I x_{1,I}\right)^2}{2\sigma^2 D_I}$ and $\tilde{\mathrm{m}}_Q(x_{1,Q}|\hat{x}_{1,Q}, D_Q) = -\frac{\left(\hat{x}_{1,Q} - D_Q x_{1,Q}\right)^2}{2\sigma^2 D_Q}$, where we have $D_I = D_Q = D = \left(\alpha_1^2 + \alpha_2^2\right)$. The branch metric for x_2 is computed similarly. The effect of the associated second order transmit diversity can be observed in the context of the term $(\alpha_1^2 + \alpha_2^2)$. Note that $\tilde{\mathrm{m}}_I$ and $\tilde{\mathrm{m}}_Q$ share the same D

value for the same transmitted signal of $x(=\tilde{s})$, but after the IQ deinterleaver of Figure 1 m_I and m_Q will be associated with a different D value. The branch metric of the TCM/TTCM-coded signal s is computed from $\mathrm{m}(s) = \mathrm{m}_I(x_I = s_I) + \mathrm{m}_Q(x_Q = s_Q)$. Since there are two independent IQ coordinates for a complex TCM/TTCM symbol, and since they are independently interleaved, m_I and m_Q provide independent diversity for a particular symbol. More explicitly, since we have $D_I \neq D_Q$, the IQ-interleaved TCM/TTCM scheme is expected to double the achievable diversity order compared to its symbol-interleaved counterpart. For a single-transmitter scheme, the corresponding IQ branch metric $\tilde{\mathrm{m}}_I$ and $\tilde{\mathrm{m}}_Q$ can be computed from that of the STBC scheme using $D = \alpha^2$ and $\mathbf{A} = h$.

Simulation results: We evaluated the performance of the proposed schemes using 16-level Quadrature Amplitude Modulation (16QAM) in the context of both the non-iterative 64-state TCM scheme [1] and that of the iterative 8-state TTCM arrangement using four decoding iterations [3]. The rationale of using 64 and 8 states respectively was that the TCM and TTCM schemes considered here exhibit a similar decoding complexity expressed in terms of the total number of trellis states, since there are two 8-state TTCM decoders, which are invoked in four iterations, yielding a total of $2 \cdot 8 \cdot 4 = 64$ TTCM trellis states. The effective throughput was 3 Bits Per Symbol (BPS) in both cases.

In Figure 2, we show the Bit Error Ratio (BER) versus signal to noise ratio per bit, namely E_b/N_0, performance of 16QAM based ST-IQ TCM, IQ TCM, ST TCM, conventional TCM as well as that of uncoded 8-level Phase-Shift-Keying (8PSK), for transmission over uncorrelated flat Rayleigh fading channels. Again all of the **TCM schemes** had an effective throughput of 3 BPS. Although it is not explicitly shown due to lack of space, we found that all the TCM schemes exhibit a similar performance to each other in AWGN channels. By contrast, when communicating over uncorrelated flat Rayleigh fading channels, the BER curve of IQ TCM merged with that of ST TCM in the high-SNR region of Figure 2, since they both exhibit twice the diversity potential compared to conventional TCM. As seen in Figure 2 with the advent of ST-IQ TCM, a further 6dB gain can be obtained at a BER of 10^{-5} compared to the IQ TCM and ST TCM schemes.

By contrast, in Figure 3 we show the BER versus E_b/N_0 performance of the 16QAM based **TTCM schemes**, namely that of ST-IQ TTCM, IQ TTCM, ST TTCM, conventional TTCM as well as that of uncoded 8PSK, for transmission over uncorrelated flat Rayleigh fading channels. Again, a similar performance trend is observed to that of the TCM schemes of Figure 2, although the achievable diversity/coding gain of TTCM is smaller than that of TCM due to the fact that TTCM has achieved part of its attainable diversity gain with the aid of its iterative turbo decoding. Nonetheless, at a BER of 10^{-5}, the performance of ST-IQ TTCM is about 5.1dB better than that of the conventional TTCM scheme.

Conclusions: In this contribution we proposed the novel ST-IQ and IQ TCM/TTCM schemes for transmissions over both AWGN and flat Rayleigh fading channels. Both the ST-IQ TCM and ST-IQ TTCM schemes are capable of providing significant diversity gains over their conventional counterparts. Specifically, in case of uncorrelated flat Rayleigh fading channel, coding gains of 26.1dB and 28.2dB were achieved over uncoded 8PSK at a BER of 10^{-4}, respectively. For systems requiring the reduced complexity of a single-transmitter scheme, IQ TCM/TTCM is still capable of doubling the achievable diversity potential of TCM/TTCM with the aid of a single transmit antenna.

References

[1] G. Ungerböck, "Channel coding with multilevel/phase signals," *IEEE Transactions on Information Theory*, vol. 28, pp. 55–67, January 1982.

[2] L. Hanzo, T. H. Liew and B. L. Yeap, *Turbo Coding, Turbo Equalisation and Space Time Coding for Transmission over Wireless channels.* New York, USA: John Willy IEEE Press, 2002.

[3] P. Robertson, T. Wörz, "Bandwidth-efficient turbo trellis-coded modulation using punctured component codes," *IEEE Journal on Selected Areas in Communications*, vol. 16, pp. 206–218, February 1998.

[4] D. Divsalar and M. K. Simon, "The design of trellis coded MPSK for fading channel: Performance criteria," *IEEE Transactions on Communications*, vol. 36, pp. 1004–1012, September 1988.

[5] S. Al-Semari and T. Fuja, "I-Q TCM: Reliable communication over the Rayleigh fading channel close to the cuttoff rate," *IEEE Transactions on Information Theory*, vol. 43, pp. 250–262, January 1997.

[6] B. D. Jelicic and S. Roy, "Design of trellis coded QAM for flat fading and AWGN channels," *IEEE Transactions on Vehicular Technology*, vol. 44, pp. 192–201, February 1994.

[7] S. M. Alamouti, "A simple transmitter diversity scheme for wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 16, pp. 1451–1458, October 1998.

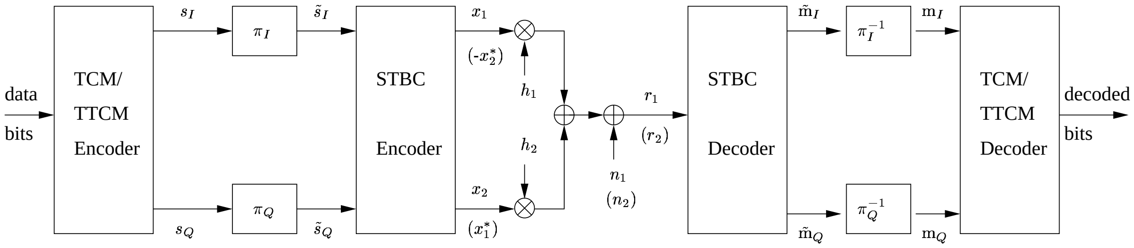

Figure 1: Block diagram of the ST-based IQ-interleaved system. The notations π and π^{-1} denote the interleaver and deinterleaver, while (.) denotes the STBC signals during the second symbol period.

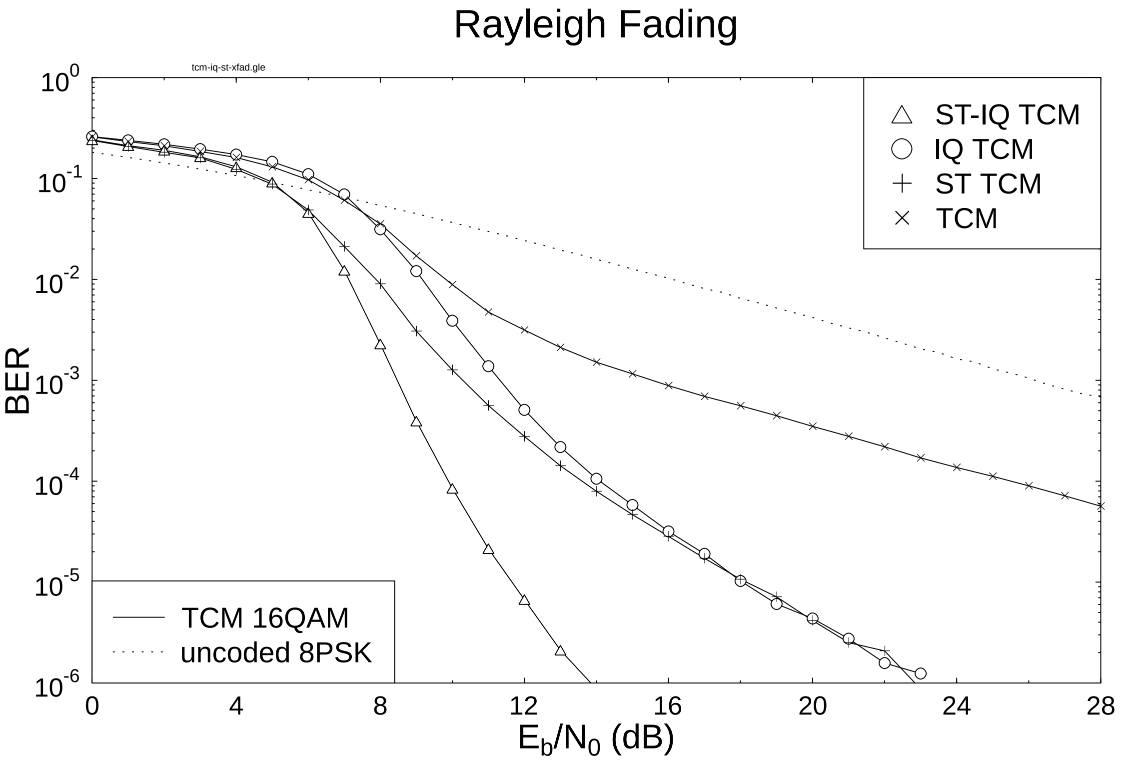

Figure 2: BER versus E_b/N_0 performance of 16QAM based ST-IQ TCM, IQ TCM, ST TCM, conventional TCM and uncoded 8PSK. All of these **TCM** schemes have an effective throughput of 3 BPS.

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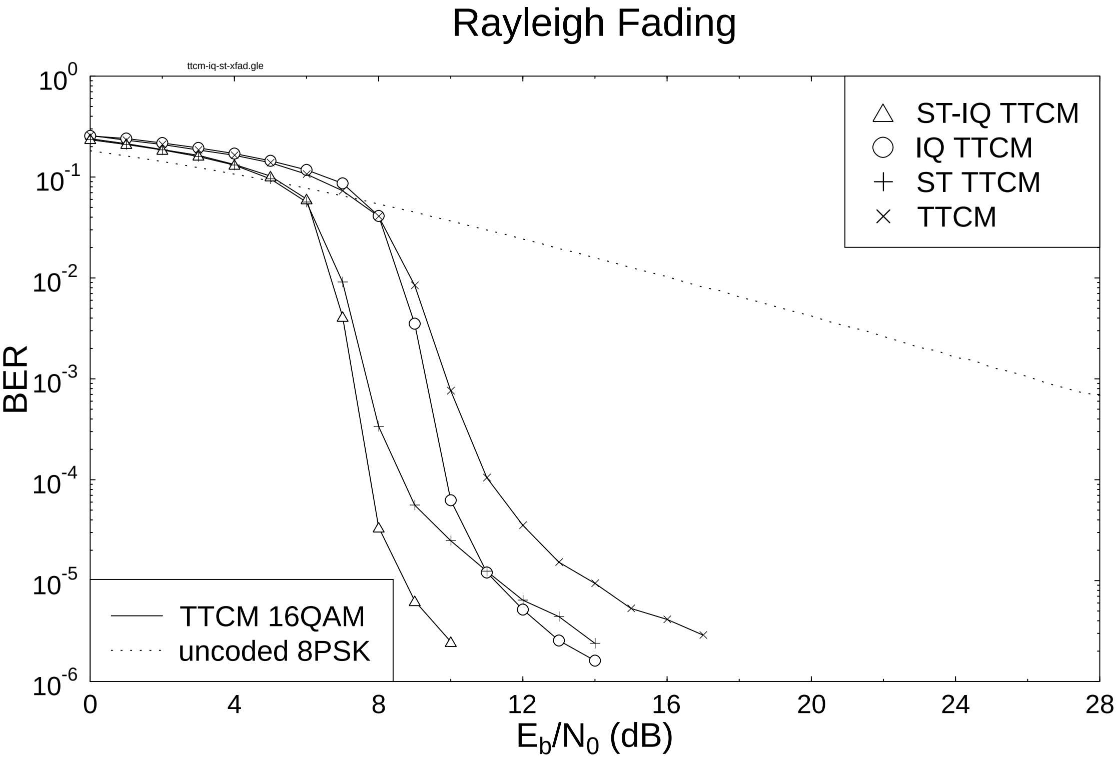

Figure 3: BER versus E_b/N_0 performance of 16QAM based ST-IQ TTCM, IQ TTCM, ST TTCM, conventional TTCM and uncoded 8PSK. All of these **TTCM** schemes have an effective throughput of 3 BPS.