TCM, TTCM, BICM and BICM-ID Assisted Joint Detection Based CDMA

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Abstract—**In this contribution we studied the performance of Trellis Coded Modulation (TCM), Turbo Trellis Coded Modulation (TTCM), Bit-Interleaved Coded Modulation (BICM) and Iterative Decoding assisted BICM (BICM-ID) schemes applied in a Code-Division Multiple Access (CDMA) system in the context of 8-level Phase Shift Keying (8PSK) and 16-level Quadrature Amplitude Modulation (16QAM) for transmissions over dispersive Rayleigh fading channels. A Minimum Mean Square Error based Decision Feedback Equalizer (JD-MMSE-DFE) was utilised for multiuser detection and for mitigating the effects of both intersymbol interference as well as that of the multiuser access interference in the system. It was found that TCM is the best scheme when using a short interleaver, while TTCM is best scheme when using long interleaver, compared to the other investigated schemes at the same decoding complexity.**

I. Introduction

Coded Modulation (CM) is a bandwidth efficient scheme that combines the functions of coding and modulation. The basic approach in CM is that instead of sending a symbol formed by m information bits, for example two information bits in Quadrature Phase Shift Keying (QPSK), we introduce a parity bit, while maintaining the same effective throughput of 2 bits/symbol by doubling the number of constellation points in the original constellation to eight, i.e. by extending it to 8PSK. As a consequence, the redundant bit can be absorbed by the expansion of the signal constellation, instead of accepting a 50% increase in the signalling rate, i.e. bandwidth. A positive coding gain is achieved, when the detrimental effect of decreasing the Euclidean distance of the neighbouring phasors is outweighted by the coding gain of the convolutional coding incorporated.

Trellis Coded Modulation (TCM) [1] was proposed originally for Gaussian channels, but it was further developed for applications in mobile communications [2, 3]. Turbo Trellis Coded Modulation (TTCM) [4] is a more recent joint coding and modulation scheme that has a structure similar to that of the family of power efficient binary turbo codes [5], but employs TCM schemes as component codes. In high-order constellation modes the TTCM scheme has a better spectral efficiency, than binary turbo codes in the context of Orthogonal Frequency Division Multiplex (OFDM) transmissions over dispersive Rayleigh fading channels [6]. TCM and TTCM invoked (SP) based signal labeling, in order to achieve a higher Euclidean distance between the unprotected bits of the constellation. Random symbol interleavers were utilised for TCM and TTCM, since these schemes operate on the basis of symbols, rather than bits.

Another coded modulation scheme distinguishing itself by utilising bit-based interleaving in conjunction with Gray signal constellation labeling is referred to as Bit-Interleaved Coded Modulation (BICM) [7]. More explicitly, BICM combines conventional convolutional codes with several independent bit interleavers, in order to increase the achievable diversity order for transmission over fading channels to the binary Hamming distance of a code [7]. The number of parallel bit-interleavers equals the number of coded bits in a symbol for the BICM scheme proposed in [7]. The performance of BICM is better than that of TCM when communicating over uncorrelated or perfectly interleaved narrowband Rayleigh fading channels, but worse than that of TCM in Gaussian channels due to the reduced Euclidean distance of the bit-interleaved scheme [7, 8]. Recently iterative joint decoding and demodulation assisted BICM (BICM-ID) was proposed in an effort to further increase the achievable performance [8–10], which uses SP based signal labeling. The approach of BICM-ID is to increase the Euclidean distance of BICM and hence to exploit the full advantage of bit interleaving with the aid of soft-decision feedback based iterative decoding [10].

The Joint Detection (JD) [11] receivers are derivatives of the well-known single-user equalizers, which were originally designed for equalizing signals that have been distorted by Inter-Symbol Interference (ISI) due to multipath channels. The Minimum Mean Square Error Decision Feedback Equalizer (MMSE-DFE) based JD (JD-MMSE-DFE) scheme constitutes a powerful approach to mitigating the effects of multi-user interference (MUI) and ISI [12], while at the same time improving the system's performance by benefiting from the multipath diversity of the channels.

The rest of this treatise is organised as follows. Our system overview is presented in Section II and the JD-MMSE-DFE is discussed in Section II-A, while CM schemes are discussed in Section II-B. Our simulation results are discussed in Section III and finally our conclusions are offered in Section IV.

II. System Overview

The block diagram of the CM-assisted Joint Detection based CDMA (CM-JD-CDMA) system is shown in Figure 1. There are K users in the system, where each user is

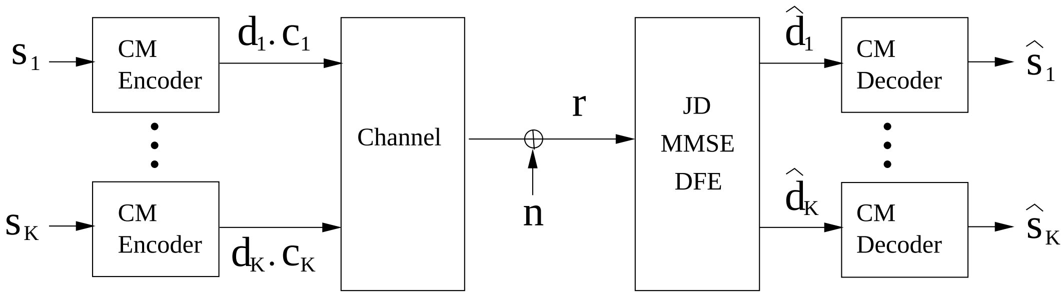

Fig. 1. Block diagram of the concatenated CM and JD-MMSE-DFE scheme.

assigned a spreading code. At first, the 2^m-ary information symbol S_k of user k, is encoded by the CM encoder to an 2^{m+1}-ary signal, d_k, by adding a parity bit to the original information symbol of m information bits. Then, d_k is spread by the spreading code c_k of user k before transmission through the channel. In this uplink scenario each user transmits his/her signal through different channels using a single transmit antenna per user. At the Base Station (BS), we consider one receive antenna for all users. The JD-MMSE-DFE subsystem of the BS's receiver jointly detects all users' signals. The estimate of the signal $\hat{d}_k$ of user k, is then fed from JD-MMSE-DFE to the CM decoder for generating the decoded output $\hat{S}_k$.

A. The JD-MMSE-DFE Subsystem

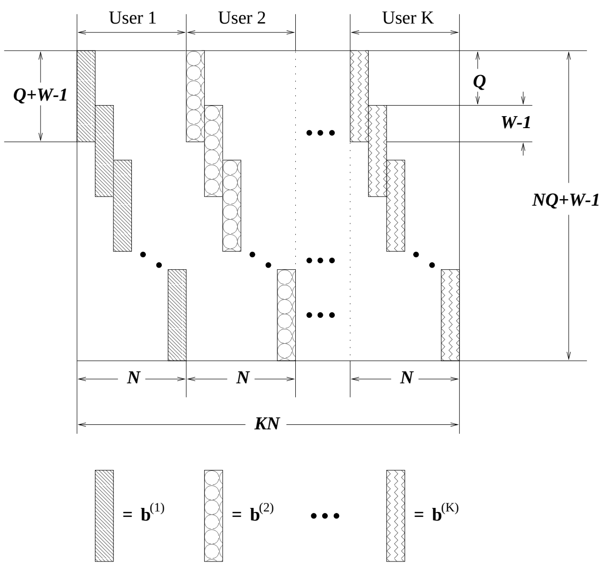

Fig. 2. Example of the system matrix $\mathbf{A}$ for a K-user CDMA system, where $\mathbf{b^{(1)}}$, $\mathbf{b^{(2)}}$ and $\mathbf{b^{K}}$ are column vectors representing the combined impulse responses of user 1, 2 and K respectively in Equation 2. The notations are as follows : N denotes the number of coded symbols transmitted by each transmitter, Q represents the number of chips in each spreading sequence and W indicates the length of the wideband channel impulse response (CIR).

Before highligting the structure of the JD-MMSE-DFE subsystem, let us consider the structure of the system matrix $\mathbf{A}$ for the K-user CDMA system in Figure 2. A synchronous system was considered here for simplicity. However, an asynchronous system matrix can also be constructed with the knowledge of the users' delays, provided that the value of the delay can be exactly determined. The combined impulse response $\mathbf{b_n^{(k)}}$ of user k, constituted by the convolution of the spreading sequence $\mathbf{c^{(k)}}$ and the channel impulse response (CIR) $\mathbf{h_n^{(k)}}$ formulated as:

$$\begin{aligned}
\mathbf{b_n^{(k)}} &= (b_n^{(k)}(1), b_n^{(k)}(2), \ldots, \\
&\qquad b_n^{(k)}(l), \ldots, b_n^{(k)}(Q+W-1))^T \qquad (1)\\
&= \mathbf{c^{(k)}} * \mathbf{h_n^{(k)}}, \qquad (2)\\
&\quad \text{for } k = 1 \ldots K; \quad n = 1, \ldots N,
\end{aligned}$$

where K represents the total number of users, N denotes the number of coded symbols transmitted by each transmitter, Q represents the number of chips in each spreading sequence and W indicates the length of the wideband CIR. The system matrix of user k, $\mathbf{A^{(k)}}$ is represented by:

$$[\mathbf{A^{(k)}}]_{\mathbf{in}} = \begin{cases} b_n^{(k)}(l) & \text{for } i = (n-1)Q + l; \\ & \quad n = 1, \ldots, N; \\ & \quad l = 1, \ldots, Q+W-1; \\ 0 & \text{otherwise.} \end{cases} \qquad (3)$$

The overall system matrix can be constructed by appending the matrix $\mathbf{A^{(k)}}$ of each of the K users column-wise:

$$\mathbf{A} = (\mathbf{A^{(1)}}, \mathbf{A^{(2)}}, \ldots, \mathbf{A^{(k)}}, \ldots, \mathbf{A^{(K)}}). \qquad (4)$$

Therefore, the discretised received composite signal can be represented in matrix form as:

$$\begin{aligned}
\mathbf{y} &= \mathbf{Ad} + \mathbf{n}, \qquad (5)\\
\mathbf{y} &= (y_1, y_2, \ldots, y_{NQ+W-1})^T,
\end{aligned}$$

where $\mathbf{n} = (\mathbf{n_1}, \mathbf{n_2}, \ldots, \mathbf{n_{NQ+W-1}})^{\mathbf{T}}$, is the noise sequence having a variance of σ^2. The covariance matrix of the noise is given by:

$$\mathbf{R_n} = E[\mathbf{n}.\mathbf{n^H}] = \sigma^{\mathbf{2}}\mathbf{I_{(NQ+W-1)}}, \qquad (6)$$

where $\mathbf{I}_{(NQ+W-1)}$ is the identity matrix having the dimension of $[NQ+W-1] \times [NQ+W-1]$. The composite signal vector $\mathbf{y}$ has $(NQ+W-1)$ elements for a transmission burst of length N symbols.

The basic concept of joint detection is centred around processing the received composite signal vector, $\mathbf{y}$, in order to determine the transmitted data vector, $\mathbf{d}$ of the user. The operations required for obtaining the JD-MMSE-DFE data estimates can be summarised as follows. First we construct the system matrix **A** in Equation 4. Then we obtain the output of the Whitening Matched Filter (WMF) [13]:

$$\hat{\mathbf{d}}_{\mathbf{WMF}} = \mathbf{A^H R_n^{-1} y}, \quad (7)$$

where $\mathbf{A^H}$ is the conjugate transpose of $\mathbf{A}$ and $\mathbf{R_n^{-1}}$ is the inverse of the noise covariance matrix $\mathbf{R_n}$. Next, Cholesky decomposition [14] of the matrix $(\mathbf{A}^H\mathbf{R}_n^{-1}\mathbf{A}+\mathbf{R}_d^{-1})$ is performed:

$$\mathbf{A^H R_n^{-1} A} + \mathbf{R_d^{-1}} = (\mathbf{DU})^{\mathbf{H}}\mathbf{DU}, \quad (8)$$

where $\mathbf{R_d^{-1}}$ is the inverse of the signal's covariance matrix $\mathbf{R_d}$, $\mathbf{D}$ is a diagonal matrix having real-valued elements and $\mathbf{U}$ is an upper triangular matrix, where all the elements on the main diagonal have the value of one. Consequently, the feed-forward filter output is obtained by solving the equation [11]:

$$\begin{aligned}\hat{\mathbf{y}} &= (\mathbf{D})^{-1}((\mathbf{DU})^{\mathbf{H}})^{-1}\ \mathbf{A^H R_n^{-1} y} \\ &= (\mathbf{D})^{-1}((\mathbf{DU})^{\mathbf{H}})^{-1}\ \hat{\mathbf{d}}_{\mathbf{WMF}}. \quad (9)\end{aligned}$$

Finally the feedback operation is invoked for producing the final estimate of the coded symbol, yielding [11]:

$$\hat{d}_i(\text{MMSE-BDFE}) = \hat{y}_i - \sum_{j=i+1}^{J=KN} [\mathbf{U}]_{\mathbf{ij}}\hat{\mathbf{t}}_{\mathbf{j}}, \quad (10)$$

where $\hat{t}_j$ is the hard decision value of the feedback estimate $\hat{d}_j$.

B. The Coded Modulation Subsystem

Due to the lack of space, here we specify only the generator polynomials of the CM schemes used in this section. For a detailed description of the various CM schemes the interested readers are referred to the literature. Specifically, [1–3] are recommended for TCM, TTCM is discussed in [4], BICM is considered in [7,8] and BICM-ID in [8–10]

TABLE I

SUMMARY OF THE TCM AND TTCM CONSTITUENT CODES PROPOSED BY UNGERBÖCK [1] AS WELL AS ROBERTSON AND WÖRZ [4], WHERE $\tilde{m}$ REFERS TO THE NUMBER OF CODED INFORMATION BITS. THE GENERATOR POLYNOMIAL, H^i, IS PRESENTED IN OCTAL FORMAT. THE '*' SYMBOL REFERS TO UNGERBÖCK'S CODE.

Code Rate	State	$\tilde{m}$	H^0	H^1	H^2	H^3
2/3 (8PSK)	8	2	11	02	04	–
	64 *	2	103	30	66	–
3/4 (16QAM)	8	3	11	02	04	10
	64 *	3	101	16	64	–

Table I shows the generator polynomials of the TCM and TTCM codes, which are presented in octal format. These are Recursive Systematic Convolutional (RSC) codes and the encoder attaches only one parity bit to the information bits. Hence, the code rate of the 2^{m+1}-ary signal is $R = \frac{m}{m+1}$.

TABLE II

SUMMARY OF THE CONVOLUTIONAL CODES EMPLOYED IN THE BICM ENCODER. THESE CODES WERE OBTAINED FROM PAGE 331 OF [15]. THE CODE GENERATOR POLYNOMIAL, g^i, IS PRESENTED IN OCTAL FORMAT.

Code Rate	State	g^0	g^1	g^2	g^3
2/3 (8PSK)	8	4	2	6	–
		1	4	7	–
	64	15	6	15	–
		6	15	17	–
3/4 (16QAM)	8	4	4	4	4
		0	6	2	4
		0	2	5	5
	64	6	1	0	7
		3	4	1	6
		2	3	7	4

Table II shows the BICM and BICM-ID codes' generator polynomials in octal format. These are non-systematic convolutional codes, which also produce one parity bit only. Hence, the code rates of these codes are similar to those of the TCM and TTCM codes, seen in Table I.

Soft decision trellis decoding utilizing the non-binary Log-Maximum A Posteriori (Log-MAP) algorithm [16] was invoked for decoding. The Log-MAP algorithm is a numerically stable version of the MAP algorithm operating in the log-domain, in order to reduce its complexity and to mitigate the numerical problems associated with the MAP algorithm [17]. The complexity of the coded modulation schemes is compared in terms of the number of decoding states and the number of decoding iterations. For a TCM or BICM code of memory M, the corresponding complexity is proportional to the number of decoding states $S = 2^M$. Since TTCM schemes invoke two component TCM codes, a TTCM code employing t iterations and using an S-state component code exhibits a complexity proportional to $2{\cdot}t{\cdot}S$ or $t \cdot 2^{M+1}$. As for BICM-ID schemes, only one decoder is used, but the demodulator is invoked in each decoding iteration. However, the complexity of the demodulator is assumed to be insignificant compared to that of the CM decoder. Hence, a BICM-ID code invoking t iterations using an S-state code exhibits a complexity proportional to $t.S$ or $t \cdot 2^M$. The codes shown in Tables I and II exhibit similar complexity, where TTCM utilises four decoding iterations, while BICM-ID utilises eight decoding iterations.

III. SIMULATION RESULTS AND DISCUSSIONS

Let us now investigate the performance of the proposed schemes using the simulation parameters shown in Table III, where 16-chip random spreading codes were utilised by each user. The transmission frame structure used is the FMA1 spread speech/data burst of the FRAMES proposal [18], which is shown in Figure 3. The channel model used is the COST 207 [19] seven path Bad Urban channel shown in Figure 4. Each path is faded according to independent Rayleigh fading statistics, as described by the parameters of Table III. We assumed that the receiver perfectly knows

TABLE III

SIMULATION PARAMETERS OF THE CM-JD-CDMA SYSTEM.

Parameter	Value
Doppler frequency	80 Hz
Spreading ratio, Q	16
Chip rate	2.167 MBaud
Frame burst structure	FRAMES Mode 1 Spread burst 1 [18] in Figure 3
Number of QAM symbols per JD block, N	28
Modulation mode	QPSK, 8PSK, 16QAM

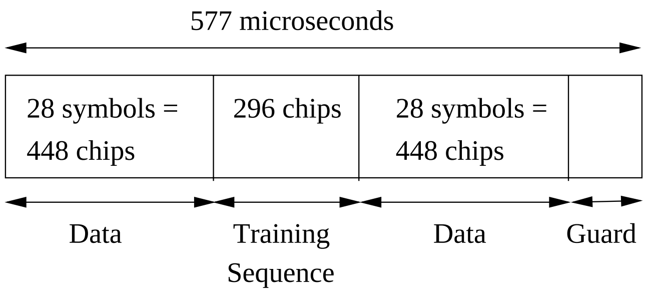

Fig. 3. Transmission burst structure of the FMA1 spread speech/data burst of the FRAMES proposal [18].

the CIRs although in reality this has to be estimated with the aid of the training sequence of the transmission frame shown in Figure 3. The fading envelope was kept constant for the duration of the transmission burst of 577 μs and it was faded before the next transmission burst.

In our performance evaluations, the uncoded QPSK system was compared to the CM assisted 8PSK system when aiming for an effective throughput of 2 information Bits Per Symbol (BPS). Similarly, the uncoded 8PSK system was compared to the CM assisted 16QAM system for a throughput of 3 BPS. Channel interleavers of length 112 symbols or 1120 symbols were utilised, which correspond to 2 transmission burst duration of 1.154 ms or 20 transmission burst durations of 11.54 ms, respectively.

Figure 5 shows the Bit Error Ratio (BER) versus Signal to Noise Ratio (SNR) performance of CM-JD-CDMA schemes for transmissions over the COST 207 [19] seven path Bad Urban channel shown in Figure 4 using the transmission burst structure of the FMA1 spread speech/data burst of the FRAMES proposal [18] shown in Figure 3, when utilising the simulation parameters of Table III and maintaining a throughput of **2 BPS**. Considering the performance of the TCM-JD-CDMA scheme using 8PSK modulation, the performance difference between the two- and four-user scenario is marginal indicated by the hollow and filled triangles in Figure 5 due to employing the powerful JD-MMSE-DFE scheme. Comparing the single-user uncoded-QPSK scheme represented by the cross, with the four-user CM-8PSK schemes utilising an interleaver length of 112 symbols at BER=10^{-4}, performance gains can be observed for all CM-8PSK schemes over the uncoded-QPSK scheme, except for the BICM-ID-8PSK scheme. It can be also observed in Figure 5 that the TCM-8PSK scheme constitutes the best candidate, showing an SNR gain of 1 dB at BER=10^{-4}. Due to the short interleaver length used, the TTCM and BICM-ID iterative decoding schemes were unable to perform efficiently. By contrast, the interleaver length does not dramatically affect the performance of the non-iterative TCM and BICM schemes [8]. Comparing the two-user TCM-8PSK scheme with the two-user TTCM-8PSK and BICM-ID-8PSK schemes utilising an interleaver length of 1120 symbols at BER=10^{-4}, TTCM-8PSK and BICM-ID-8PSK show a 1.8 dB and 1.2 dB SNR gain over TCM-8PSK, respectively. For a throughput of 2BPS, TTCM-8PSK utilising an interleaver length of 1120 symbols is the best candidate, exibiting an SNR gain of 2.9 dB over the uncoded-QPSK scheme at BER=10^{-4}.

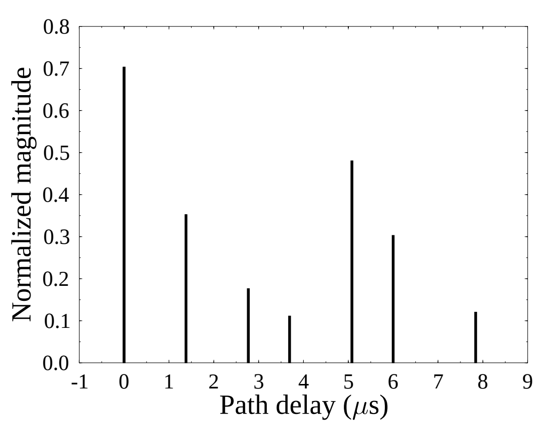

Fig. 4. Normalized channel impulse response of the COST 207 [19] **seven path Bad Urban channel.**

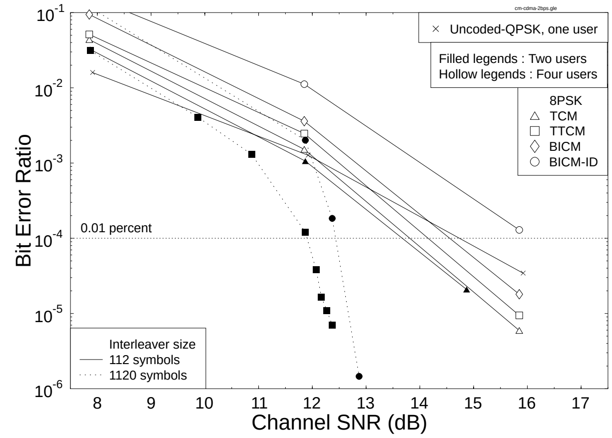

Fig. 5. Bit Error Ratio (BER) versus Signal to Noise Ratio (SNR) performance of the various CM-JD-CDMA schemes for transmissions over the COST 207 [19] seven path Bad Urban channel of Figure 4 using the transmission burst structure of the FMA1 spread speech/data burst of the FRAMES proposal [18] shown in Figure 3 utilising the simulation parameters of Table III for a throughput of **2 BPS**.

Figure 6 shows the BER versus SNR performance of CM-JD-CDMA schemes for transmissions over the COST 207 [19] seven path Bad Urban channel shown in Figure 4 using the transmission burst structure of the FMA1 spread

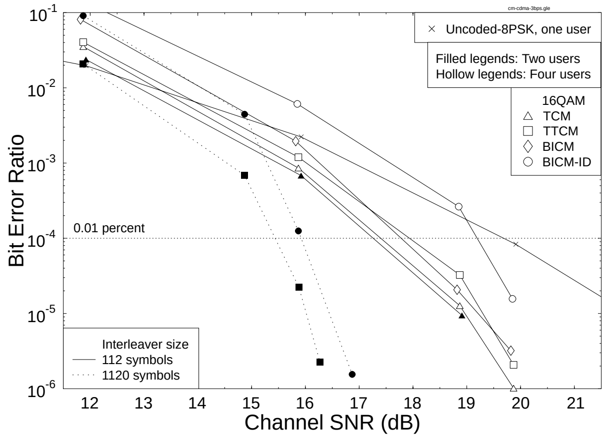

Fig. 6. BER versus SNR performance of the various CM-JD-CDMA schemes for transmissions over the COST 207 [19] seven path Bad Urban channel of Figure 4 using the transmission burst structure of the FMA1 spread speech/data burst of the FRAMES proposal [18] shown in Figure 3 utilising the simulation parameters of Table III for a throughput of **3 BPS**.

speech/data burst of the FRAMES proposal [18] shown in Figure 3 utilising the simulation parameters of Table III. In this the effective throughput is **3 BPS**. Comparing the performance of the TCM-JD-CDMA scheme using 16QAM, the performance difference between the scheme supporting two- and four-user is again marginal due to invoking the powerful JD-MMSE-DFE scheme. Comparing the single-user uncoded-8PSK scheme with the four-user CM-16QAM schemes utilising an interleaver length of 112 symbols at BER=10^{-4}, performance gains can be observed for all CM-16QAM schemes over the uncoded-8PSK scheme. The TCM-16QAM scheme constitutes the best candidate, showing an SNR gain of 2.3 dB. Comparing the two-user TCM-16QAM scheme with the two-user TTCM-16QAM and BICM-ID-16QAM schemes utilising an interleaver length of 1120 symbols at BER=10^{-4}, TTCM-16QAM and BICM-ID-16QAM show 1.8 dB and 1.3 dB SNR gains over TCM-16QAM, respectively. For the effective throughput of 3BPS, TTCM-16QAM utilising an interleaver length of 1120 symbols is the best candidate showing an SNR gain of 4.2 dB over the uncoded 8PSK scheme at BER=10^{-4}.

IV. Conclusion

In this contribution, TCM, TTCM, BICM and BICM-ID assisted JD-MMSE-DFE based CDMA schemes were proposed and evaluated in performance terms over the COST 207 [19] seven path Bad Urban channel. For systems using a short interleaver length of 112 symbols, TCM was found to be the best candidate when providing a throughput of 2 and 3 BPS. However, for systems that can afford a longer delay due to utilising a long interleaver length, TTCM was found to be the best candidate for providing a throughput of 2 and 3 BPS.

V. Acknowledgements

The financial support of the European Union under the auspices of the TRUST project and the EPSRC, Swindon UK is gratefully acknowledged.

References

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

[2] 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.

[3] D. Divsalar and M. K. Simon, "The design of trellis coded MPSK for fading channel: Set partitioning for optimum code design," *IEEE Transactions on Communications*, vol. 36, pp. 1013–1021, September 1988.

[4] 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.

[5] C. Berrou, A. Glavieux and P. Thitimajshima, "Near Shannon Limit Error-Correcting Coding and Decoding : Turbo Codes," in *Proceedings, IEEE International Confrence on Communications*, pp. 1064–1070, 1993.

[6] C. S. Lee, S. X. Ng, L. Piazzo and L. Hanzo, "TCM, TTCM, BICM and Iterative BICM Assisted OFDM-Based Digital Video Broadcasting to Mobile Receivers," *IEEE Vehicular Technology Conference*, p. 113, May 2001.

[7] E. Zehavi, "8-PSK trellis codes for a Rayleigh fading channel," *IEEE Transactions on Communications*, vol. 40, pp. 873–883, May 1992.

[8] S. X. Ng, T. H. Liew, L-L. Yang and L. Hanzo, "Comparative Study of TCM, TTCM, BICM and BICM-ID schemes," *IEEE Vehicular Technology Conference*, p. 265, May 2001.

[9] X. Li, J. A. Ritcey, "Trellis-Coded Modulation with Bit Interleaving and Iterative Decoding," *IEEE Journal on Selected Areas in Communications*, vol. 17, pp. 715–724, April 1999.

[10] X. Li, J. A. Ritcey, "Bit-interleaved coded modulation with iterative decoding using soft feedback," *IEE Electronics Letters*, vol. 34, pp. 942–943, May 1998.

[11] P. Jung and J. Blanz, "Joint detection with coherent receiver antenna diversity in CDMA mobile radio systems," *IEEE Transactions on Vehicular Technology*, vol. 44, pp. 76–88, Feb. 1995.

[12] E. L. Kuan, C. H. Wong and L. Hanzo, "Comparative study of joint-detection and interference cancellation based burst-by-burst adaptive CDMA scheme," *IEEE Vehicular Technology Conference*, pp. 653–657, September 1999.

[13] E. A. Lee and D. G. Messerschmitt, *Digital Communication*. Kluwer Academic Publishers, 1988.

[14] W. H. Press, S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery, *Numerical Recipes in C: The Art of Scientific Computing*. Cambridge University Press, 1993.

[15] S. Lin and D. J. Costello, Jr, *Error Control Coding: Fundamentals and Applications*. Inc. Englewood Cliffs, New Jersey 07632: Prentice-Hall, 1983.

[16] P. Robertson, E. Villebrum and P. Hoeher, "A Comparison of Optimal and Sub-Optimal MAP Decoding Algorithms Operating in Log Domain," in *Proceedings of the International Conference on Communications*, pp. 1009–1013, June 1995.

[17] L. R. Bahl, J. Cocke, F. Jelinek and J. Raviv, "Optimal Decoding of Linear Codes for Minimizing Symbol Error Rate," *IEEE Transactions on Information Theory*, vol. 20, pp. 284–287, March 1974.

[18] T. Ojanperä, A. Klein, and P.-O. Anderson, "FRAMES multiple access for UMTS," *IEE Colloquium (Digest)*, pp. 7/1–7/8, May 1997.

[19] M. Failli, "Digital land mobile radio communications COST 207," tech. rep., European Commission, Luxembourg, 1989.