Iteratively Detected Generalised MC DS-CDMA Using Layered Steered Space-Time Spreading

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***Abstract*— We present a novel tri-functional Multiple-Input Multiple-Output (MIMO) scheme that intrinsically amalgamates Space-Time Spreading (STS), the Vertical Bell Labs Layered Space-Time (V-BLAST) scheme and beamforming with generalised MultiCarrier Direct Sequence Code Division Multiple Access (MC DS-CDMA). Further system performance improvements can be attained by employing channel coding, where the source bits are serial-to-parallel converted to two layers, each constituted by a serial concatenation of an outer code amalgamated with a unity-rate code for the sake of improving the convergence behaviour of the proposed system. Additionally, the convergence behaviour of the iteratively detected scheme is evaluated with the aid of Extrinsic Information Transfer (EXIT) charts. We also propose a novel Logarithmic Likelihood Ratio (LLR) postprocessing technique for improving the iteratively detected system's performance. Explicitly, after I=10 decoding iterations and employing an interleaver depth of D_{int}=160,000 bits, the proposed system supporting K=4 users attains a BER below 10^{-5} for E_b/N_0 values in excess of -2.8 dB.**

I. Introduction

The information-theoretic aspects of Multiple-Input Multiple Output (MIMO) systems were considered by several authors [1, 2], where it was demonstrated that MIMO systems exhibit capacity gains in comparison to the employment of a single antenna at both the transmitter and receiver. Space-Time Spreading (STS) [3] was proposed as an extension of Space-Time Block Coding (STBC) [4, 5] for the downlink of Wideband Code Division Multiple Access (WCDMA) [6]. STS is capable of providing a spatial diversity gain, which results in an improved BER performance. On the other hand, the Vertical Bell Labs Layered Space-Time (V-BLAST) scheme was proposed in [7] for providing a multiplexing gain, i.e. for providing an increase of a specific user's effective bandwidth efficiency without the need for any increase in the transmitted power or in the system's bandwidth. Furthermore, a MIMO scheme that combines the benefits of V-BLAST and STBC was proposed in [8], which was referred to as a Double Space-Time Transmit Diversity (D-STTD). Hence, D-STTD benefits from the diversity gain of the STBC and the multiplexing gain of the V-BLAST arrangement.

On the other hand, beamforming [9] constitutes an effective technique of reducing the multiple-access interference, where the antenna gain is increased in the direction of the desired user, whilst reducing the gain towards the interfering users. Several attempts have been made to design hybrid MIMO schemes combining STBCs with beamforming [10].

The turbo principle [11] was considered in [12] for iterative soft demapping in the context of multilevel modulation schemes combined with channel decoding. Moreover, in [13] it was shown that a recursive inner code is needed in order to avoid the formation of a Bit-Error Ratio (BER) floor. Furthermore, Extrinsic Information Transfer (EXIT) charts [14] have been proposed for studying the convergence behaviour of iterative decoding by describing the flow of extrinsic information through the soft-in soft-out constituent decoders.

In this paper we propose a tri-functional MIMO scheme that intrinsically amalgamates STS, V-BLAST and beamforming with generalised MC DS-CDMA [15]. The proposed system is referred to as Layered Steered Space-Time Spreading (LSSTS) aided generalised MC DS-CDMA. The system is characterised by the spatial diversity gain of the STS, the multiplexing gain of the V-BLAST, the frequency diversity gain of the generalised MC DS-CDMA as well as the achievable beamforming gain. In the generalised MC DS-CDMA scheme considered in this contribution, the subcarrier frequencies are arranged in a way, which guarantees that the same STS signal is spread to and hence transmitted by the specific V number of subcarriers having the maximum possible frequency separation, so that they experience independent fading and achieve the maximum attainable frequency diversity. We also propose an iterative detection aided LSSTS scheme and use EXIT charts [14] to analyse the convergence behaviour of the proposed iterative detection aided scheme. Finally, we propose a novel Logarithmic Likelihood Ratio (LLR) postprocessing technique for improving the iteratively detected systems' performance. Explicitly, after I=10 decoding iterations and employing an interleaver depth of $D_{int} = 160,000$ bits, the proposed system supporting K=4 users attains a BER below 10^{-5} at E_b/N_0 of -2.8 dB.

The rest of the paper is organised as follows. In Section II we present the encoding and decoding algorithms of the novel LSSTS aided generalised MC DS-CDMA scheme. Iterative detection of the proposed system is discussed in Section III, where we propose the LLR postprocessing technique and discuss the attainable performance results. Finally, we present our conclusions in Section IV.

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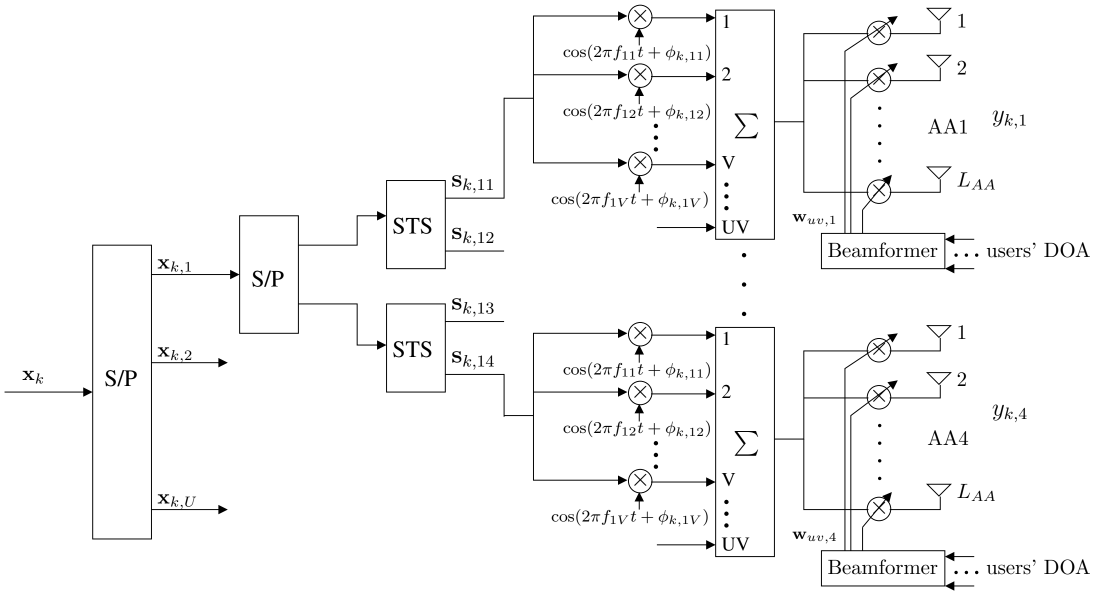

Fig. 1. The k_{th} user's LSSTS aided Generalised MC DS-CDMA transmitter model.

II. Layered Steered Space-Time Spreading Aided Generalised MC DS-CDMA

The block diagram of the proposed downlink LSSTS scheme is shown in Figure 1, where the system employs N_t=4 transmit Antenna Arrays (AA) for communication with a receiver equipped with N_r=2 antennas. The transmit AAs are spaced sufficiently far apart in order to experience independent fading, while the L_{AA} number of elements of each of the AAs are spaced at a distance of half the wavelength for the sake of achieving beamforming. The system employs STS and hence can support K users that can be differentiated by their user-specific spreading code $\bar{\mathbf{c}}_k$, where $k \in [1, K]$.

A. Transmitter Model

The transmitter schematic of the kth user is shown in Figure 1, where the generalised MC DS-CDMA scheme of [15] using UV number of subcarriers is employed. In the transmitter of Figure 1, a block of UN_t data symbols $\mathbf{x}_k$ is Serial-to-Parallel (S/P) converted to U parallel sub-blocks $\{\mathbf{x}_{k,1}, \mathbf{x}_{k,2}, \cdots, \mathbf{x}_{k,U}\}$. Afterwards, each set of N_t symbols is S/P converted to 2 groups, where each group is encoded using the 2-antenna-aided STS procedure of [3], where the transmitted signal is spread to two transmit antennas with the aid of the orthogonal spreading codes of $\{\bar{\mathbf{c}}_{k,1}, \bar{\mathbf{c}}_{k,2}\}$, k=1, 2, ..., K. The spreading codes $\bar{\mathbf{c}}_{k,1}$ and $\bar{\mathbf{c}}_{k,2}$ are generated from the same user-specific spreading code $\bar{\mathbf{c}}_k$ as in [3].

The $4U$ outputs of the $2U$ number of STS blocks modulate a group of subcarrier frequencies $\{f_{u,1}, f_{u,2}, ..., f_{u,V}\}$. The UV number of subcarrier signals are superimposed on each other in order to form the complex modulated signal. Finally, according to the kth user's channel information, the $4UV$ number of signals of the kth user are weighted by the transmit weight vector $\mathbf{w}_{uv,n}^{(k)}$ determined for his/her uvth subcarrier, which is generated for the nth AA. The k_{th} user's signal transmitted from the ith transmit antenna, i=1, 2, 3, 4, can be written as follows:

$$\mathbf{y}_{k,i}(t) = \mathbf{y}_{k,i}(\tau + aN_tT_s) \quad (1)$$
$$= \sum_{u=1}^{U}\sum_{v=1}^{V}\sqrt{\frac{2P_k}{8VL_{AA}}}\mathbf{w}_{uv,i}^{k} \cdot \mathbf{s}_{k,ui}\cos(2\pi f_{uv}\tau + \phi_{k,uv}),$$

where T_s is the symbol duration, a=0, 1, . . ., $0 \leq \tau < N_tT_s$, P_k/V represents the transmitted power of each subcarrier, the factor L_{AA} in the denominator is due to beamforming. The factor 8 in the denominator suggests that the two STS layers using 2 transmit antennas each and 2 orthogonal spreading codes distributes its power proportionally in space and time.

The spectral efficiency of the proposed system can be formulated as follows. Assuming that the system employs a modulation scheme transmitting B bits-per-symbol, the resultant spectral efficiency of the LSSTS aided Generalised MC DS-CDMA scheme is given by $2UB$ bits-per-channel-use.

B. Receiver Model

The Channel Impulse Response (CIR) vector $h_{uv,nm}(t)$ spanning the nth transmit antenna array, $n \in [1, N_t]$, and the mth receive antenna, $m \in [1, N_r]$, while employing the uvth subcarrier and based on the assumption that the array elements are separated by half a wavelength can be expressed as:

$$\mathbf{h}_{uv,nm}^{k}(t) \;=\; \alpha_{uv,nm}^{k}(t) \cdot \mathbf{d}_{nm}^{k} \quad (2)$$

where $\alpha_{nm}(t)$ is a Rayleigh faded envelope, $\mathbf{d}_{nm}^{k} = [1, \exp(j[\pi\sin(\psi_{nm})]), \ldots, \exp(j[(L_{AA}-1)\pi\sin(\psi_{nm})])]^T$ and ψ_{nm} is the nmth link's Direction Of Arrival (DOA). As for the AA specific DOA, we consider a scenario where the distance between the transmitter and the receiver is significantly higher than that between the AAs and thus we can assume that the signals arrive at the different AAs in parallel, i.e. the DOA at the different AAs is the same.

Assuming that the K users' data expressed in the form of Equation (1) are transmitted synchronously over a dispersive Rayleigh fading channel characterised by the CIR of

Equation (2), the complex-valued received signal of user 1 impinging on the mth receive antenna can be expressed as

$$\begin{aligned}\mathbf{z}_m^1 &= \sum_{k=1}^{K}\sum_{u=1}^{U}\sum_{v=1}^{V}\sum_{n=1}^{N_t}\mathbf{h}_{uv,nm}\cdot\mathbf{y}_{k,uvn}+\mathbf{n}_m \quad (3)\\ &= \sqrt{\frac{2P_k}{8VL_{AA}}}\sum_{k=1}^{K}\sum_{u=1}^{U}\sum_{v=1}^{V}\sum_{n=1}^{N_t}\mathbf{a}_{uv,nm}\\ &\quad \cdot\mathbf{w}_{uv,n}^1\cdot\mathbf{s}_{k,un}\cos(2\pi f_{uv}\tau+\phi_{k,uv})+\mathbf{n}_m,\end{aligned}$$

where $\mathbf{w}_{uv,nm}^k$ is generated by the Maximum Ratio Combining (MRC)-aided beamformer [9], which exploits the knowledge of the DOA. Let $\mathbf{w}_{uv,nm}^1$=$\mathbf{d}_{nm}^{1\dagger}$, then the k=1st user's received signal matrix $\mathbf{r}$ including the received and despread data over the two receive antennas and the UV subcarriers after STS despreading, can be written as[1]:

$$\mathbf{r}=\mathbf{H}\cdot\mathbf{X}+\mathbf{N}, \quad (4)$$

where $\mathbf{H}$ and $\mathbf{X}$ can be arranged in a matrix form as in [16] and $\mathbf{N}$ represents the noise matrix. Detection is carried out in two steps, first interference cancellation is performed according to [8, 16], followed by the STS decoding procedure of [3].

Finally, after combining the k=1st user's identical replicas of the same signal transmitted by spreading over V number of subcarriers, the decision variables corresponding to the symbols transmitted in the uth sub-block can be expressed as $\widetilde{x}_{1,u}=\sum_{v=1}^{V}\widetilde{x}_{1,uv}$. The decoded signal can be expressed as

$$\widetilde{x}=\sqrt{\frac{2P_1L_{AA}}{8V}}\sum_{v=1}^{V}\left(|\widetilde{\alpha}_{uv,1}|^2+|\widetilde{\alpha}_{uv,2}|^2\right)x+\eta. \quad (5)$$

Therefore, according to Equation (5) the decoded signal has a diversity order of $2V$, while assuming that the subcarrier frequencies are arranged in a way, which guarantees that the same STS signal is spread to and hence transmitted by the specific V number of subcarriers having the maximum possible frequency separation.

Figure 2 shows the BER performance of the proposed LSSTS aided generalised MC DS-CDMA system employing BPSK modulation as well as a TD spreading factor of N_e=32 and supporting K=32 users. In Figure 2 we show the benefits of employing the different components in the LSSTS scheme. Observe in Figure 2 that when V=1 and L_{AA}=1, the LSSTS BER performance is identical to that of the STS scheme of [3], while attaining a bandwidth efficiency that is twice that of the STS scheme of [3]. On the other hand, as shown in Figure 2, when the number of elements L_{AA} per AA increases, the attainable BER performance improves. Furthermore, we increase the number of subcarriers V in order to increase the diversity order of the system, as shown in Figure 2 for $V>1$.

[1]In the following analysis we remove the subscript uv for simplicity of notation.

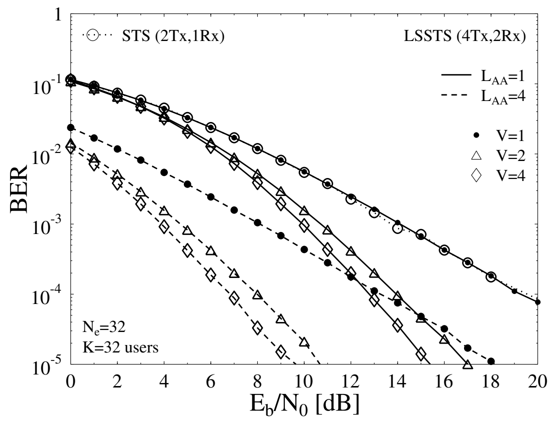

Fig. 2. BER performance of the LSSTS system in Figure 1 employing N_t=4 AAs and N_r=2 antennas in conjunction with a varying number of L_{AA} elements per AA as well as a varying number of subcarriers V, while employing K=32 users and a spreading factor N_e=32. The per-user throughput is 2 bits-per-channel-use.

III. Iterative detection of coded LSSTS scheme

In this section an iteratively detected coded LSSTS scheme is proposed in order to attain further performance improvements, where two parallel layers each constituted by a serially concatenated Recursive Systematic Convolutional (RSC) code and a Unity Rate Code (URC) are implemented in the transmitter and then iterative detection of the RSC and URC decoders is invoked in both layers of the receiver. In the structure of Figure 3 the transmitted source bits $\mathbf{u}_1$ are first S/P converted to two parallel substreams $\mathbf{u}_{11}$ and $\mathbf{u}_{12}$. Each substream is encoded by the outer $1/2$-rate RSC code's Encoder. The outer channel encoded bits $\mathbf{c}_1$ and $\mathbf{c}_2$ of the two parallel bit streams are then interleaved by a random bit interleaver, where the interleaved bits in each stream are then encoded by a corresponding URC encoder. The URC encoded bits in each stream are then interleaved by random bit interleavers to be finally Gray mapped to QPSK symbols and transmitted using steered STS. Note that the RSC encoders I and II are identical, the URC encoders III and IV are identical as well as the QPSK modulators I and II are identical.

As shown in Figures 3, the received and decoded complex-valued symbol streams $\tilde{\mathbf{x}}_1$ and $\tilde{\mathbf{x}}_2$ are fed into the QPSK demappers I and II. The output of the demappers represents the LLR metric $L_{M,I}(\mathbf{b}_1)$ and $L_{M,II}(\mathbf{b}_2)$ passed from the QPSK demappers to the URC decoders in the two layers of the decoder of Figure 3. As seen in Figure 3, the URC decoder in each layer processes the information forwarded by the demapper in conjunction with the *a priori* information passed from the outer RSC decoder in order to generate the extrinsic LLR values $L_{III,e}(\mathbf{u}_2)$ and $L_{IV,e}(\mathbf{u}_3)$, which are deinterleaved by a soft-bit deinterleaver, as seen in Figure 3. Next, the soft bits $L_{I,a}(\mathbf{c}_1)$ and $L_{II,a}(\mathbf{c}_2)$ are passed to the RSC decoders of Figure 3 in order to compute the extrinsic LLR values $L_{I,e}(\mathbf{c}_1)$ and $L_{II,e}(\mathbf{c}_2)$ for all the channel-coded bits $\mathbf{c}_1$ and $\mathbf{c}_2$. Each layer then applies iterative detection exchanging extrinsic information between the corresponding RSC and URC decoders, as shown in Figure 3. The output $L_{I,p}(\mathbf{u}_{11})$ and $L_{II,p}(\mathbf{u}_{12})$ of the RSC decoders is then P/S

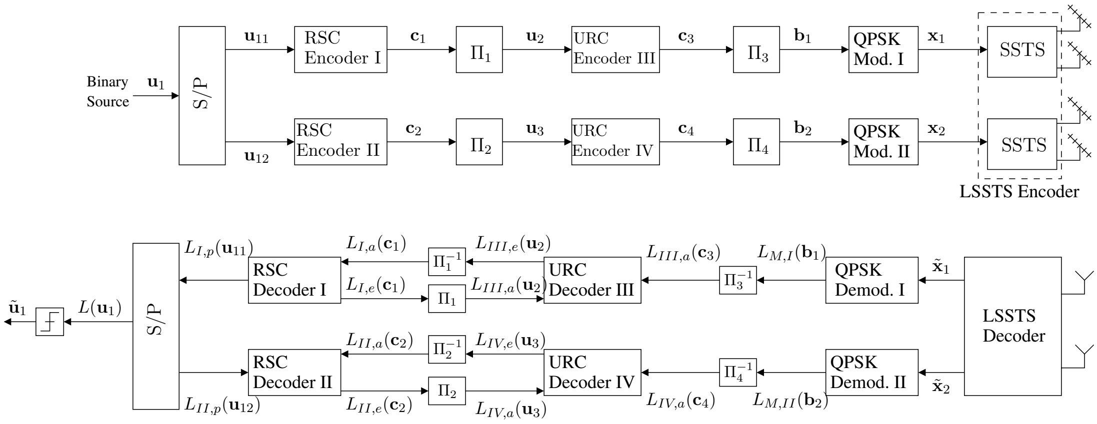

Fig. 3. Block diagram of the proposed downlink iteratively detected system employing RSC encoder in series with a URC encoder and transmitting through a QPSK aided LSSTS.

converted to produce a single stream $L(\mathbf{u}_1)$, which is passed to the hard-decision decoder of Figure 3.

A. EXIT Charts and LLR Postprocessing

The EXIT chart of one layer of the iteratively detected LSSTS scheme of Figure 3 is shown in Figure 4. The outer code employed is a $1/2$-rate memory-2 RSC code, denoted as RSC(2,1,3), in conjunction with an octal generator polynomial of (G_r, G)=$(7,5)_8$, where G_r is the feedback polynomial and G is the feedforward polynomial. On the other hand, the inner code is a simple URC scheme, described by the pair of octal generator polynomials (G_r, G)=$(3,2)_8$. The EXIT curves in Figure 4 are plotted for the URC and RSC decoders of one layer in Figure 3, since the two layers have identical performance due to the fact that the interference cancellation employed by the LSSTS decoder eliminates completely the interference of one STS layer on the other. Furthermore, the EXIT chart of Figure 4 was generated for the system employing N_t=4 transmit AAs and N_r=2 antennas, while using L_{AA}=4 elements per AA and V=4 subcarriers.

As shown in Figure 4, the URC decoder has several EXIT curves for the same E_b/N_0 value. The dark line marked by the legend "no LLR limits" in Figure 4 corresponds to the URC decoder, which has a recursive encoder and therefore as discussed in [17] it is expected that the EXIT curve of the URC decoder will reach the $(1.0, 1.0)$ point. However, the URC decoder EXIT curve in Figure 4 does not reach the $(1.0, 1.0)$ point. We attempted to limit the maximum and minimum of the LLR values $L_{M,I}(\mathbf{b}_1)$ and $L_{M,II}(\mathbf{b}_2)$ for the sake of avoiding the problem of numerical overflow in the computer's memory. This solution allowed the EXIT curve of the URC decoder to reach the $(1.0, 1.0)$ point, as shown in Figure 4 by the dotted line associated with the legend "LLR limit=10". On the other hand, for the sake of testing the accuracy of the URC EXIT curve, while imposing a limit on the LLR values, we generated artificial Gaussian distributed and uncorrelated LLRs $L_{M,I}(\mathbf{b}_1)$ and $L_{M.II}(\mathbf{b}_2)$, where the resultant EXIT curve is shown in Figure 4 by the dotted line having the legend "artificial LLR generation". The artificial LLRs are generated assuming that the transmitted bits are known at the receiver for testing purposes. As depicted in Figure 4, there is a difference

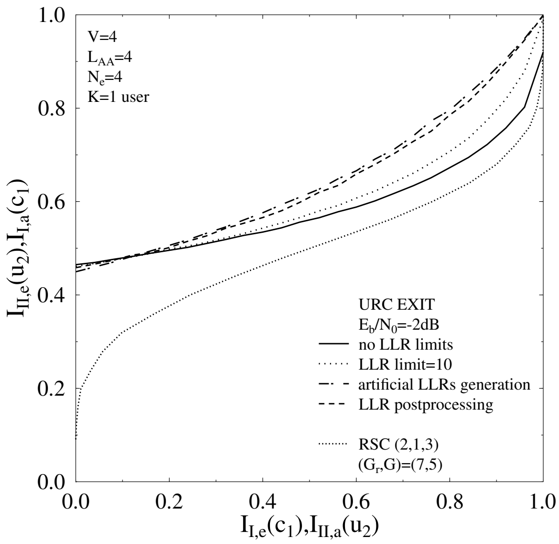

Fig. 4. EXIT chart of a RSC-coded and URC-precoded proposed iteratively detected system of Figure 3 employing GM aided QPSK in conjunction with N_t=4, N_r=2, V=4, L_{AA}=4, K=1 user and $E_b/N_0 = -2.0$ dB. The inner and outer EXIT curves were generated for one layer of the system in Figure 3.

between the EXIT curves generated while limiting the LLRs and where the artificial LLRs were generated. Therefore, the problem in the resulting EXIT curves is not the computer memory's overflow.

The QPSK demappers of Figure 3 compute their LLR outputs based on the assumption that their input data stream, which is output from the LSSTS decoder, is Gaussian distributed. However, the output of the LSSTS decoder is not Gaussian distributed. Therefore, the reason for the EXIT curve behaviour in Figure 4 is the probability distribution of the input data to the QPSK demappers. A simple solution is to find the probability distribution of the LSSTS decoder's output and use it for the computation of the LLRs in the QPSK demappers. However, it is not straightforward to find a mathematical formula to model the PDF of $\tilde{\mathbf{x}}$. On the other hand, it is possible to compute the LLRs based on the histogram of the received and decoded data $\tilde{\mathbf{x}}$. However, computing the histogram for every received frame is a complex and time-consuming process.

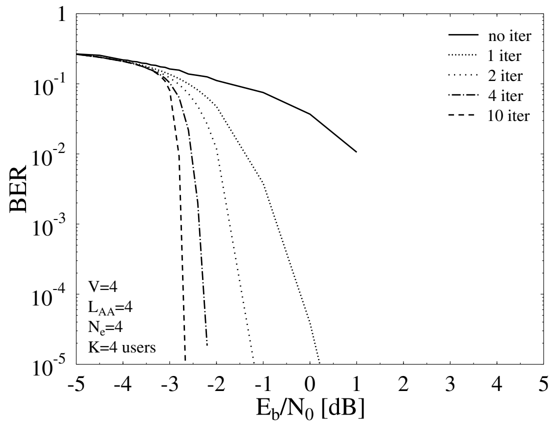

Fig. 5. Performance comparison of the GM-based RSC-coded and URC precoded system of Figure 3 in conjunction with V=4 subcarriers, L_{AA}=4 elements per AA, N_e=4 and K=4 users, when using an interleaver depth of D_{int}=160,000 bits for a variable number of iterations.

An empirical transformation of the $L_M(\mathbf{b})^2$ LLR values has been found for the sake of correcting the relationship between the LLR values and their corresponding probabilities, so that the LLR values satisfy the consistency condition of [18]. The transformation is applied to the LLR values at the output of the QPSK demappers and hence it is referred to as LLR postprocessing. The resultant empirical transformation can be expressed as:

$$\text{LLR}_{out} = \frac{L_M(\mathbf{b})}{1.25\,(\log_2(V)+1) - 0.75\lceil \frac{K}{N_e} - 1\rceil}, \quad (6)$$

where N_e is the spreading factor of the user-specific spreading code $\bar{\mathbf{c}}_k$ and LLR_{out} represents the LLR passed from the QPSK demappers I and II to the deinterleavers Π_3 and Π_4 of Figure 3, respectively. Figure 4 also shows the EXIT curve of the inner URC decoder after the LLR postprocessing technique was employed. As shown in Figure 4, the EXIT curve of the system where the LLR postprocessing is employed is similar to that where the artificial LLRs were considered.

B. Results and Discussions

Figure 5 compares the BER performance of the proposed iteratively detected system supporting K=4 users in conjunction with Gray Mapping (GM) aided QPSK for different number of iterations, when employing an interleaver depth of D_{int}=160,000 bits. The result in Figure 5 corresponds to the system associated with N_t=4 transmit AAs, N_r=2 receive antennas, V=4 subcarriers, L_{AA}=4 elements per AA and N_e=4. Additionally, perfect channel knowledge is assumed at both the receiver as well as at the transmit beamformer. Figure 5 demonstrates that the system approaches a BER below 10^{-5} at E_b/N_0=−2.8 dB after I=10 iterations.

IV. Conclusion

In this paper, we proposed a novel tri-functional downlink MIMO scheme that intrinsically amalgamates STS, V-BLAST and beamforming combined with generalised MC DS-CDMA. Additionally, in order to improve the achievable performance of the proposed system, we presented the iterative detection aided structure of Figure 3 and proposed an LLR postprocessing technique for improving the attainable system performance. Explicitly, after I=10 decoding iterations and employing an interleaver depth of $D_{int} = 160,000$ bits, the proposed system attained a BER below 10^{-5} at E_b/N_0 in excess of -2.8 dB.

[2] In the notation $L_M(\mathbf{b})$ we remove the postscripts I and II denoting the number of the decoder for the simplicity of notation.

References

[1] E. Telatar, "Capacity of multi-antenna Gaussian channels," *European Transactions on Telecommunications*, vol. 10, pp. 585–595, November/December 1999.

[2] G.J. Foschini and M.J. Gans, "On limits of wireless communications in a fading environment when using multiple antennas," *Kluwer Academic Publishers, Wireless Personal Communications*, pp. 311–335, 1998.

[3] B. Hochwald, T.L. Marzetta and C.B. Papadias, "A transmitter diversity scheme for wideband CDMA systems based on space-time spreading," *IEEE Journal on Selected Areas in Communications*, vol. 19, no. 1, pp. 48–60, 2001.

[4] S.M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 8, pp. 1451–1458, 1998.

[5] V. Tarokh, H. Jafarkhani and A.R. Calderbank, "Space-time block codes from orthogonal designs," *IEEE Transactions on Information Theory*, vol. 45, no. 5, pp. 1456–1467, 1999.

[6] L. Hanzo, L.-L. Yang, E.-L. Kuan and K. Yen, *Single and multi-carrier DS-CDMA: Multi-user detection, space-time spreading, synchronisation, networking and standards*. Chichester, England: John Wiley and Sons Ltd and IEEE Press, 2003.

[7] P.W. Wolniansky, G.J. Foschini, G.D. Golden and R.A. Valenzuela, "V-BLAST: an architecture for realizing very high data rates over the rich-scattering wireless channel," in *International Symposium on Signals, Systems and Electronics*, (Pisa), pp. 295–300, September 1998.

[8] E.N. Onggosanusi, A.G. Dabak and T.A. Schmidl, "High rate space-time block coded scheme: performance and improvement in correlated fading channels," in *IEEE Wireless Communications and Networking Conference*, vol. 1, pp. 194–199, March 2002.

[9] J. Blogh and L. Hanzo, *Third-generation systems and intelligent wireless networking: smart antennas and adaptive modulation*. John Wiley & Sons - IEEE Press, 2002.

[10] G. Jongren, M. Skoglund and B. Ottersten, "Combining beamforming and orthogonal space-time block coding," *IEEE Transactions on Information Theory*, vol. 48, pp. 611–627, March 2002.

[11] C. Berrou, A. Glavieux and P. Thitimajshima, "Near Shannon limit error-correcting coding and decoding: Turbo-codes. 1," in *IEEE International Conference on Communications*, vol. 2, (Geneva), pp. 1064–1070, May 1993.

[12] S. ten Brink, J. Speidel and R.-H. Yan, "Iterative demapping and decoding for multilevel modulation," in *IEEE Global Telecommunications Conference (GLOBCOM)*, vol. 1, (Sydney,NSW), pp. 579–584, 1998.

[13] S. Benedetto, D. Divsalar, G. Montorsi and F. Pollara, "Serial concatenation of interleaved codes: performance analysis, design and iterative decoding," *IEEE Transactions on Information Theory*, vol. 44, pp. 909–926, May 1998.

[14] S. ten Brink, "Designing iterative decoding schemes with the extrinsic information transfer chart," *AEÜ International Journal of Electronics and Communications*, vol. 54, pp. 389–398, November 2000.

[15] L.-L. Yang and L. Hanzo, "Performance of generalized multicarrier DS-CDMA over Nakagami-m fading channels," *IEEE Transactions on Communications*, vol. 50, pp. 956–966, June 2002.

[16] A.F. Naguib, N. Seshadri and A.R. Calderbank, "Increasing data rate over wireless channels," *IEEE Signal Processing Magazine*, vol. 17, pp. 76–92, May 2000.

[17] M. El-Hajjar, O. Alamri, S. X. Ng and L. Hanzo, "Turbo detection of precoded sphere packing modulation using four transmit antennas for differential space-time spreading," *IEEE Transactions on Wireless Communications*, vol. 7, pp. 943–952, March 2008.

[18] J. Hagenauer, "The EXIT chart - Introduction to extrinsic information transfer in iterative processing," in *European Signal Processing Conference*, (Vienna, Austria), pp. 1541–1548, September 2004.