Iteratively Detected Irregular Variable Length Coding and Sphere-Packing Modulation-Aided Differential Space-Time Spreading

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***Abstract*— In this paper we consider serially concatenated and iteratively decoded Irregular Variable Length Coding (IrVLC) combined with precoded Differential Space-Time Spreading (DSTS) aided multidimensional Sphere Packing (SP) modulation designed for near-capacity joint source and channel coding. The IrVLC scheme comprises a number of component Variable Length Coding (VLC) codebooks having different coding rates for the sake of encoding particular fractions of the input source symbol stream. The relative length of these source-stream fractions can be chosen with the aid of EXtrinsic Information Transfer (EXIT) charts in order to shape the EXIT curve of the IrVLC codec, so that an open EXIT chart tunnel may be created even at low E_b/N_0 values that are close to the capacity bound of the channel. These schemes are shown to be capable of operating within 0.9 dB of the DSTS-SP channel's capacity bound using an average interleaver length of $113,100$ bits and an effective bandwidth efficiency of 1 bit/s/Hz, assuming ideal Nyquist filtering. By contrast, the equivalent-rate regular VLC-based benchmarker scheme was found to be capable of operating at 1.4 dB from the capacity bound, which is about 1.56 times the corresponding discrepancy of the proposed IrVLC-aided scheme.**

I. Introduction

Alamouti [1] proposed a simple transmit diversity scheme employing Space-Time Block Codes (STBC) [2], which was capable of achieving a substantial diversity gain. Inspired by the philosophy of STBC, Hochwald $et\ al.$ [3] proposed the transmit diversity concept known as Space-Time Spreading (STS) for the downlink of Wideband Code Division Multiple Access (WCDMA) [4]. As a further advance, the concept of combining orthogonal STBCs with the principle of sphere packing (SP) modulation was introduced by Su $et\ al.$ in [5], where it was demonstrated that the proposed SP-aided STBC system was capable of outperforming the conventional orthogonal design based STBC schemes of [1, 2]. The SP-aided STBC scheme of [5] was further developed by Alamri $et\ al.$ [6] by invoking an iterative turbo receiver.

The above-mentioned STBC and STS schemes use coherent detection, which requires channel estimation at the receiver. In practice, the Channel Impulse Response (CIR) of each link between each transmit and receive antenna pair has to be estimated at the receiver either blindly or using training symbols. However, channel estimation increases both the cost and complexity of the receiver. Furthermore, when the channel experiences fast fading, an increased number of training symbols has to be transmitted, potentially resulting in an undesirably high transmission overhead and wastage of transmission power. Therefore, it is beneficial to develop low-complexity techniques that do not require channel estimation. Hence, in this contribution, we use a Differential Space-Time Spreading (DSTS) scheme [7] dispensing with CIR estimation. Naturally, this is achieved at the cost of a 3 dB performance loss in comparison to the more sophisticated coherent receiver. In this contribution we refer to the DSTS-aided SP system as DSTS-SP.

Furthermore, in analogy to Irregular Convolutional Coding (IrCC) [8], the family of so-called Irregular Variable Length Codes (IrVLC) employs a number of VLC component codebooks having different coding rates [9] for encoding particular fractions of the input source symbol stream. More specifically, the appropriate fractions may be selected with the aid of EXtrinsic Information Transfer (EXIT) chart analysis [10], by ensuring that the EXIT curve of the composite IrVLC may be accurately matched to that of a precoded DSTS-SP system. In this way, an open EXIT chart tunnel [11] may be created even at low E_b/N_0 values, which implies approaching the capacity bound of the channel.

The novelty and rationale of the proposed system can be summarised as follows:

1) *We employ a non-coherent STS scheme for eliminating the potentially high complexity of Multiple-Input Multiple-Output (MIMO) channel estimation together with the multidimensional SP modulation in order to achieve an increased diversity product.*
2) *We amalgamate the merits of the DSTS-SP system with those of the IrVLC in order to potentially allow operation within* 0.4 *dB from the DSTS-SP channel capacity [7] as compared to the* 0.9 *dB distance from capacity recorded for the system employing an equivalent-rate conventional VLC code. This is achieved with the aid of EXIT chart analysis. Furthermore, we provide simulation results using an interleaver having an average length of* $113,100$ *bits for demonstrating that the system was capable of operating within* 0.9 *dB from channel capacity, while employing the proposed IrVLC-aided system as compared to* 1.4 *dB from capacity for the system employing conventional VLC.*

The rest of this paper is organised as follows. In Section II we introduce the proposed serially concatenated and iteratively decoded IrVLC-DSTS-SP scheme as well as the appropriate regular VLC-DSTS-SP benchmarker. Section III describes how the DSTS scheme can be combined with SP modulation, followed by Section IV that details the design and EXIT chart aided characterisation of these schemes. Finally, the attainable performance of these schemes is studied comparatively in Section V, followed by our conclusions in Section VI.

II. System Overview

The schematic of the proposed system is shown in Figure 1, where the VLC-encoded bits $\mathbf{u}$ are interleaved by a random bit interleaver and then the interleaved bits $\mathbf{d}$ are precoded by a Unity-Rate Code (URC) encoder. After URC encoding, the DSTS-SP modulator maps B number of coded bits $\mathbf{b} = b_0, \ldots, b_{B-1} \in \{0, 1\}$ to a SP symbol $v \in V$, so that we have $v = map_{sp}(\mathbf{b})$, where $B = \log_2 L$, as outlined in [6]. Subsequently, we have a set of SP symbols that can

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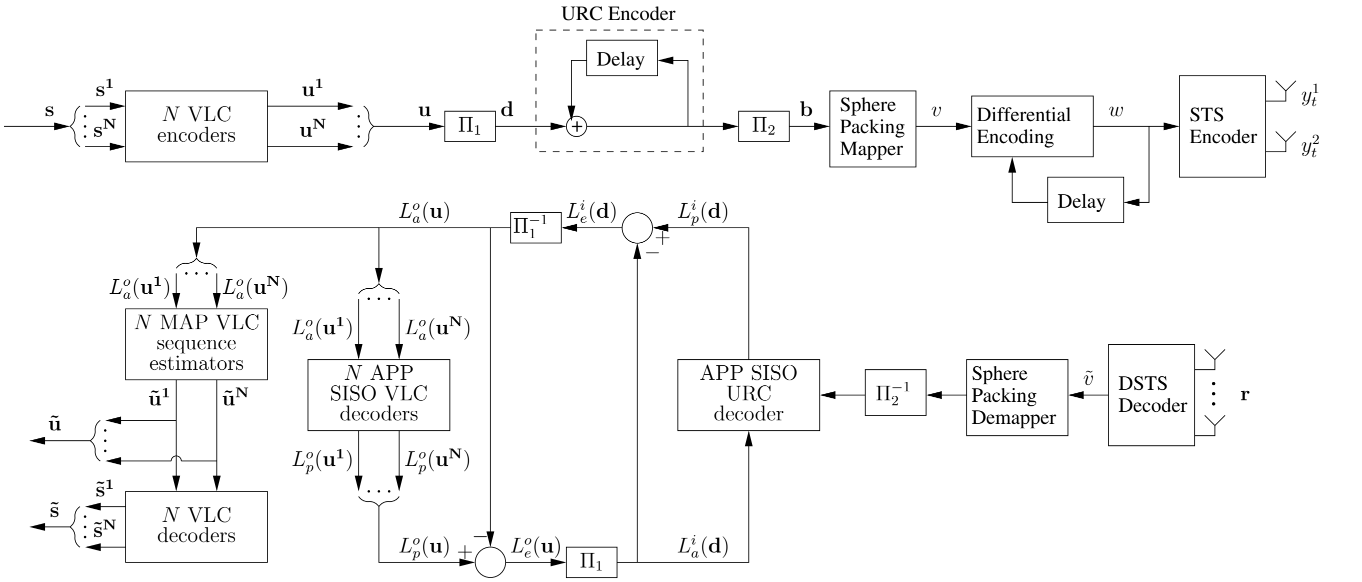

Fig. 1. Schematic of the IrVLC- and VLC-DSTS-SP schemes. In the IrVLC-DSTS-SP scheme we have $N = 15$ different irregularly encoded protection classes, whilst $N = 1$ in the VLC-DSTS-SP scheme.

be transmitted with the aid of DSTS within two time slots using two transmit antennas. The schemes considered in this paper differ in their choice of the outer source codec. Specifically, we consider a novel IrVLC codec and an equivalent-rate regular VLC-based benchmarker. We refer to these two schemes as the IrVLC- and VLC-DSTS-SP arrangements, as appropriate.

A. Joint source and channel coding

The schemes considered are designed for facilitating the near-capacity transmission of source symbol sequences over a correlated narrowband Rayleigh fading channel, associated with a normalised Doppler frequency of $f_D = f_d T_s = 0.01$, where f_d is the Doppler frequency and T_s is the symbol duration. We consider $K = 16$-ary source symbol values that have the probabilities of occurrence resulting from the Lloyd-Max (LM) quantisation [12] of independent Gaussian distributed source samples. More explicitly, we consider the 4-bit LM quantisation of a Gaussian source. Note that these occurrence probabilities vary by more than an order of magnitude between 0.0082 and 0.1019. These probabilities correspond to entropy or average informations values between 3.29 bits and 6.93 bits, motivating the application of VLC and giving an overall source entropy of $E = 3.77$ bits/VLC-symbol.

In the transmitter shown in Figure 1, the source symbol frame $\mathbf{s}$ comprises $J = 15,000$ 4-bit source symbols having the $K = 16$-ary values $\{s_j\}_{j=1}^{J} \in [1 \ldots K]$. These 4-bit source symbols are decomposed into N number of different protection classes $\{\mathbf{s^n}\}_{n=1}^{N}$, where we opted for $N = 15$ in the case of the IrVLC-DSTS-SP scheme and $N = 1$ in the case of the VLC-DSTS-SP scheme. The number of symbols in the source symbol frame $\mathbf{s}$ that are decomposed into the source symbol frame component $\mathbf{s^n}$ is specified as J^n, where we have $J^1 = J$ in the case of the VLC-DSTS-SP scheme. By contrast, in the case of the IrVLC-DSTS-SP scheme, the specific values of $\{J^n\}_{n=1}^{N}$ may be chosen in order to shape the inverted EXIT curve of the IrVLC codec, so that it does not cross the EXIT curve of the precoder, as will be detailed in Section IV.

Each of the N number of source symbol frame components $\{\mathbf{s^n}\}_{n=1}^{N}$ is VLC-encoded using the corresponding codebook from the set of N number of VLC codebooks $\{\mathbf{VLC}^n\}_{n=1}^{N}$, having a range of coding rates $\{R^n\}_{n=1}^{N} \in [0, 1]$. The specific source symbols having the value of $k \in [1 \ldots K]$ and encoded by the specific VLC codebook $\mathbf{VLC}^n$ are represented by the codeword $\mathbf{VLC}^{n,k}$, which has a length of $I^{n,k}$ bits. The J^n number of VLC codewords that represent the J^n number of source symbols in the source symbol frame component $\mathbf{s^n}$ are concatenated to provide the transmission frame component $\mathbf{u^n} = \{\mathbf{VLC}^{n,s^n_{j^n}}\}_{j^n=1}^{J^n}$.

Owing to the variable length of the VLC codewords, the number of bits comprised by each transmission frame component $\mathbf{u^n}$ will typically vary from frame to frame. In order to facilitate the VLC decoding of each transmission frame component $\mathbf{u^n}$, it is necessary to explicitly convey its length $I^n = \sum_{j^n=1}^{J^n} I^{n,s^n_{j^n}}$ to the receiver with the aid of side information. Furthermore, this highly error sensitive side information must be reliably protected against transmission errors. This may be achieved using a low rate block code or repetition code, for example. For the sake of avoiding obfuscating details, this is not explicitly shown in Figure 1.

In the transmitter of Figure 1, the N number of transmission frame components $\{\mathbf{u^n}\}_{n=1}^{N}$ are concatenated. As shown in Figure 1, the resultant transmission frame $\mathbf{u}$ has a length of $\sum_{n=1}^{N} I^n$ bits. Following interleaving Π_1, the transmission frame $\mathbf{u}$ is precoded [13] by the URC and then interleaved again before being SP modulated for transmission using DSTS.

B. Iterative Decoding

In the receiver, the A Posteriori Probability Soft-In Soft-Out (APP SISO) decoder of the precoder- and the VLC-decoder iteratively exchange extrinsic information, as shown in Figure 1. Both of these decoders invoke the Bahl-Cocke-Jelinek-Raviv (BCJR) algorithm [14] on the basis of bit-based trellises [15]. All BCJR calculations are performed in the logarithmic probability domain and using an eight-entry lookup table for correcting the Jacobian approximation in the Log-MAP algorithm [16].

The extrinsic soft information, represented in the form of Logarithmic Likelihood Ratios (LLRs) [17], is iteratively exchanged between the precoder's decoder and the VLC decoding stages for the sake of assisting each other's operation, as detailed in [18]. In Figure 1, $L(\cdot)$ denotes the LLRs of the bits concerned, where the superscript i indicates the inner precoder's decoder, while o corresponds to outer VLC decoding. Additionally, the corresponding subscript denotes the dedicated role of the LLRs, with a, p and e indicating *a priori*, *a posteriori* and extrinsic information, respectively.

In parallel to the formation of the bit-based transmission frame $\mathbf{u}$ from N number of components, the *a priori* LLRs $L_a^o(\mathbf{u})$ are decomposed into N number of components, as shown in Figure 1. Each of the N number of VLC decoding processes is provided with the *a priori* LLR sub-frame $L_a^o(\mathbf{u^n})$ and in response it generates the *a posteriori* LLR sub-frame $L_p^o(\mathbf{u^n})$, $n \in [1 \dots N]$. These *a posteriori* LLR sub-frames are concatenated in order to provide the *a posteriori* LLR frame $L_p^o(\mathbf{u})$, as shown in Figure 1.

During the final decoding iteration, N number of bit-based MAP VLC sequence estimation processes are invoked instead of APP SISO VLC decoding, as shown in Figure 1. In this case, each transmission frame component $\mathbf{u^n}$ is estimated from the corresponding *a priori* LLR frame component $L_a^o(\mathbf{u^n})$. The resultant transmission frame component estimates $\tilde{\mathbf{u}}^\mathbf{n}$ may be concatenated to provide the transmission frame estimate $\tilde{\mathbf{u}}$. Additionally, the transmission frame component estimates $\tilde{\mathbf{u}}^\mathbf{n}$ may be VLC decoded to provide the source symbol frame component estimates $\tilde{\mathbf{s}}^\mathbf{n}$.

III. DSTS Design Using Sphere Packing Modulation

According to Figure 1, it becomes clear that the DSTS encoder can be divided into two main stages. The differential encoding takes place before the space-time spreading and the differentially encoded symbols are then spread according to the STS scheme of [3], where orthogonal spreading codes are used for spreading each symbol of duration T_s to an interval of $2T_s$.

The DSTS encoding/decoding algorithm is described in detail in [7]. The channel is modeled as a correlated narrowband Rayleigh fading channel, associated with a normalised Doppler frequency of $f_D = f_d T_s = 0.01$, where f_d is the Doppler frequency and T_s is the symbol duration. The complex-valued Additive White Gaussian Noise (AWGN) of $n = n_I + jn_Q$ contaminates the received signal, where n_I and n_Q are two independent zero-mean real-valued Gaussian random variables having a variance of $\sigma_n^2 = \sigma_{n_I}^2 = \sigma_{n_Q}^2 = N_0/2$ per dimension, with $N_0/2$ representing the double-sided noise power spectral density expressed in W/Hz. Furthermore, assuming the channel to be narrowband, the decoded signal can be represented as:

$$\tilde{v}_t^1 = (|h_1|^2 + |h_2|^2) \times \sqrt{|w_{t-1}^1|^2 + |w_{t-1}^2|^2} \times v_t^1 + N_1 \quad (1)$$

$$\tilde{v}_t^2 = (|h_1|^2 + |h_2|^2) \times \sqrt{|w_{t-1}^1|^2 + |w_{t-1}^2|^2} \times v_t^2 + N_2, \quad (2)$$

where h_1 and h_2 denote the CIRs between transmitter antenna 1 as well as transmitter antenna 2 and the receive antenna respectively, N_1 and N_2 are zero-mean complex-valued Gaussian random variables having variances of $\sigma_N^2 = \sigma_{N_1}^2 = \sigma_{N_2}^2 \approx 2 \cdot h \cdot \sigma_n^2$, and we have $h = (|h_1|^2 + |h_2|^2) \times \sqrt{|v_{t-1}^1|^2 + |v_{t-1}^2|^2}$.

According to Equations (1) and (2), the decoded signals represent scaled versions of v_1 and v_2 corrupted by the complex-valued AWGN. This observation implies that the diversity product of DSTS-aided systems is determined by the minimum Euclidean distance of all legitimate vectors (v_1, v_2), as shown in [5]. The idea is to jointly design the legitimate vectors (a_1, a_2, a_3, a_4) so that they are represented by a single phasor point selected from a sphere packing constellation corresponding to a 4-dimensional real-valued lattice having the best known minimum Euclidean distance in the 4-dimensional real-valued space $\mathbb{R}^4$. For the sake of generalising our treatment, let us assume that there are L legitimate vectors $(v_{l,1}, v_{l,2})$, $l = 0, 1, \dots, L-1$, where L represents the number of sphere-packed modulated symbols. The transmitter, then, has to choose the modulated signal from these L legitimate symbols, which have to be transmitted over the two antennas, where the throughput of the system is given by $(\log_2 L)/2$ bits per channel use. Our aim is to design $v_{l,1}$ and $v_{l,2}$ jointly, so that they have the best minimum Euclidean distance from all other $(L-1)$ legitimate SP symbols, since this minimises the system's SP symbol error probability. Let $(a_{l,1}, a_{l,2}, a_{l,3}, a_{l,4})$, $l = 0, 1, \dots, L-1$, be legitimate phasor points of the four-dimensional real-valued Euclidean space $\mathbb{R}^4$. Hence, $v_{l,1}$ and $v_{l,2}$ may be written as

$$\begin{aligned} \{v_{l,1}, v_{l,2}\} &= T(a_{l,1}, a_{l,2}, a_{l,3}, a_{l,4}) \\ &= \{a_{l,1} + ja_{l,2}, a_{l,3} + ja_{l,4}\}. \end{aligned} \quad (3)$$

In the four-dimensional real-valued Euclidean space $\mathbb{R}^4$, the lattice $\mathbb{D}_4$ is defined as a SP having the best minimum Euclidean distance from all other $(L-1)$ legitimate constellation points in $\mathbb{R}^4$ [19]. More specifically, $\mathbb{D}_4$ may be defined as a lattice that consists of all legitimate sphere-packed constellation points having integer coordinates $[a_{l,1}\ a_{l,2}\ a_{l,3}\ a_{l,4}]$ uniquely and unambiguously describing the legitimate combinations of the modulated symbols $v_{l,1}$ and $v_{l,2}$, but subject to the sphere packing constraint of $a_{l,1} + a_{l,2} + a_{l,3} + a_{l,4} = \kappa$, where κ is an even integer. Assuming that $V = \{v^l = [a_{l,1}, a_{l,2}, a_{l,3}, a_{l,4}] \in \mathbb{R}^4 : 0 \le l \le L-1\}$ constitutes a set of L legitimate constellation points from the lattice $\mathbb{D}_4$ having a total energy of $E \triangleq \sum_{l=0}^{L-1}(|a_{l,1}|^2 + |a_{l,2}|^2 + |a_{l,3}|^2 + |a_{l,4}|^2)$, and upon introducing the notation

$$C_l = \sqrt{\frac{2L}{E}}(v_{l,1}, v_{l,2}), \qquad l = 0, 1, \dots, L-1, \quad (4)$$

we have a set of complex constellation symbols, $\{C_l : 0 \le l \le L-1\}$, whose diversity product is determined by the minimum Euclidean distance of the set of L legitimate constellation points in V.

IV. IrVLC Design Using EXIT Chart Analysis

As described in Section II, the IrVLC-DSTS-SP scheme employs $N = 15$ component VLC codebooks $\{\mathbf{VLC}^n\}_{n=1}^N$ having approximately equally spaced coding rates in the range $[0.26, 0.95]$. In each case, we employ a Variable Length Error Correcting (VLEC) codebook [9] that is tailored to the source symbol values' probabilities of occurrence described in Section II and having the maximum minimum free distance that can be achieved at the particular coding rate considered. By contrast, in the VLC-DSTS-SP scheme, we employ just $N = 1$ VLC codebook, which is identical to the VLC codebook $\mathbf{VLC}^{10}$ of the IrVLC-DSTS-SP scheme, having a coding rate of $R = 0.5$, as shown in Figure 2. Note that this coding rate results in an average interleaver length of $J \cdot E/R = 113,100$ bits and a bandwidth efficiency of 1 bit/s/Hz, if we ignore the negligible overhead of conveying the side information and assume ideal Nyquist filtering having a zero excess bandwidth. We note furthermore that for the proposed DSTS-SP system, this bandwidth efficiency is associated with an E_b/N_0 channel capacity bound of 5.1 dB [7].

In Figure 2 we provide the inverted EXIT curves that characterise the bit-based APP SISO VLC decoding of the VLC codebooks together with the precoder's EXIT curves recorded for E_b/N_0 values of 5.5 and 6.0 dB. The EXIT curves were generated in all cases using uncorrelated Gaussian distributed *a priori* LLRs, under the assumption that the transmitted bits have equiprobable values. This

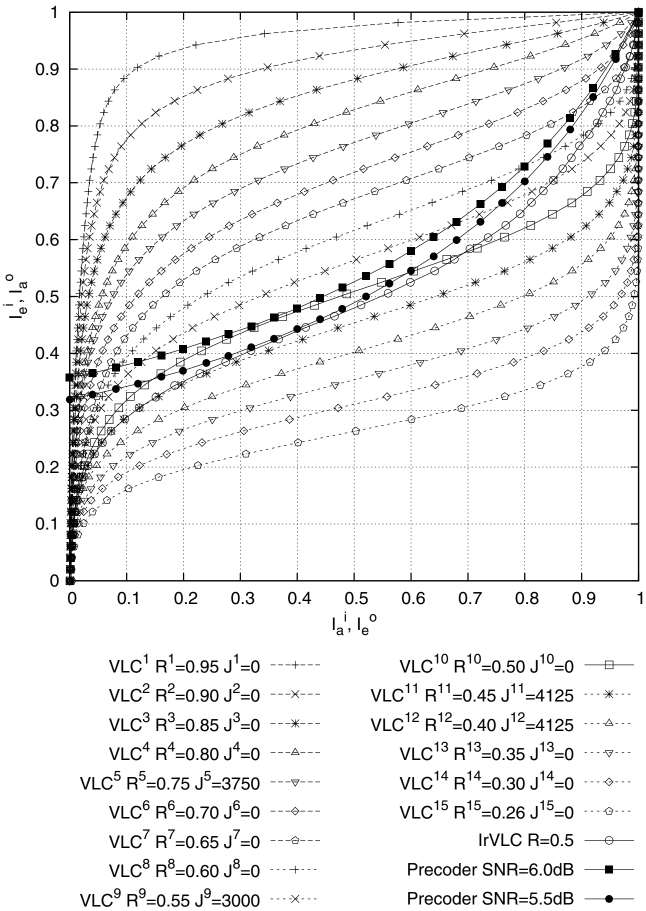

Fig. 2. Inverted VLC EXIT curves and precoder EXIT curves.

is justified, because we employ a long interleaver and because the entropy of the VLC encoded bits was found to be at a negligible distance from unity for all the VLC codebooks considered. All mutual information values were recorded using the histogram-based PDF-estimation method [10].

Figure 2 also shows the inverted EXIT curve of the IrVLC scheme. This is obtained as the appropriately weighted superposition of the $N = 15$ unequal protection component VLC codebooks' inverted EXIT curves, where the weight applied to the inverted EXIT curve of the component VLC codebook $\mathbf{VLC^n}$ is related to the number of source symbols that it is employed for encoding J^n [8]. Using the approach of [8], the values of $\{J^n\}_{n=1}^{N}$ given in Figure 2 were designed for ensuring that the IrVLC coding rate matches that of our regular VLC scheme, namely VLC^{10}, and so that the inverted IrVLC EXIT curve does not cross the precoder's EXIT curve at an E_b/N_0 value of 5.5 dB. We note that only four out of the $N = 15$ VLC components were chosen by the proposed EXIT-chart matching procedure for encoding a non-zero number of source symbols. As shown in Figure 2, the presence of the resultant open EXIT chart tunnel implies that an infinitesimally low Symbol Error Ratio (SER) may be achieved by the IrVLC-DSTS-SP scheme for E_b/N_0 values in excess of 5.5 dB, which is just 0.4 dB from the channel capacity bound of 5.1 dB [7]. By contrast, no open EXIT chart tunnel is maintained for E_b/N_0 values below 6.0 dB in the case of the VLC-DSTS-SP benchmarker scheme. This value of E_b/N_0 is 0.9 dB from the DSTS-SP capacity bound, representing a discrepancy that is 2.25 times that of the IrVLC-DSTS-SP scheme.

V. Performance Results

We consider a SP modulation scheme associated with $L = 16$ and employing Gray Mapping (GM) for assigning the source bits to the SP symbols, in conjunction with a two-antenna-aided DSTS system and a single receiver antenna, in order to demonstrate the performance improvements achieved by the proposed system.

Figure 3 shows the inverted EXIT curve of the IrVLC scheme employed as well as the EXIT curves of the precoded DSTS-SP system together with the decoding trajectories at both E_b/N_0 values of 5.5 dB and 6.0 dB. The system communicates over a correlated narrowband Rayleigh fading channel associated with a normalised Doppler frequency of $f_D = 0.01$ and employs a random interleaver having an average length of $113,100$ bits. The decoding trajectory recorded for $E_b/N_0 = 6.0$ dB and shown in Figure 3 is the one we obtained from simulations, where the system did not converge below an E_b/N_0 value of 6.0 dB, although the EXIT curve of Figure 2 predicted an open tunnel at E_b/N_0 of 5.5 dB. The EXIT-chart predictions are accurate, if we employ a long interleaver that is capable of removing the correlation of the data imposed by both the correlated channel employed as well as by the differential encoding that introduces more correlation to the data. Figure 3 also shows the decoding trajectory at $E_b/N_0 = 5.5$ dB. However, this trajectory was generated by simulating the effect of a long interleaver, i.e. by generating uncorrelated LLRs at the input of the precoder's decoder. Therefore, the EXIT curve predictions can be fulfilled, if we succeed in designing a special interleaver having a reasonable length that can be used for eliminating the correlation imposed by the DSTS scheme and by the channel employed. Satisfying this objective will be the focus of our future research.

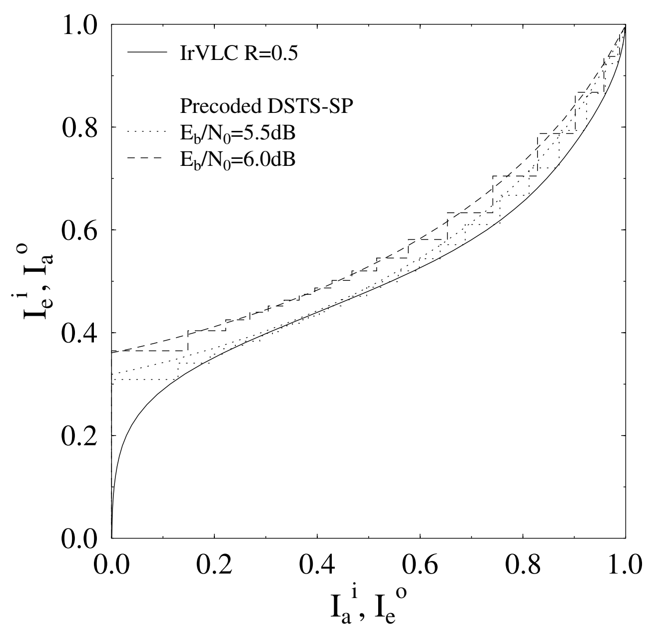

Fig. 3. Decoding trajectory of the iteratively-detected IrVLC-DSTS-SP scheme operating at $E_b/N_0 = 5.5$ dB and $E_b/N_0 = 6.0$ dB.

Figure 4 compares the attainable performance of the IrVLC-aided and of the VLC-aided DSTS-SP systems, when communicating over a correlated narrowband Rayleigh fading channel with a normalised

Doppler frequency of $f_D = 0.01$. The EXIT analysis of Figure 2 predicted a difference of 0.5 dB between the performance of the two systems. In Figure 4 we present the corresponding BER curves having the same E_b/N_0 difference as the EXIT curve prediction, however with a shift of 0.5 dB from the prediction. In other words, as mentioned in the previous paragraph, owing to the employment of an interleaver that is incapable of eliminating the effect of correlation, the IrVLC-aided system converges at $E_b/N_0 = 6.0$ dB and the VLC-aided system at $E_b/N_0 = 6.5$ dB. The BER curves presented in Figure 3 were recorded after 40 decoding iterations between the VLC decoder and the precoder's decoder, as shown in Figure 1.

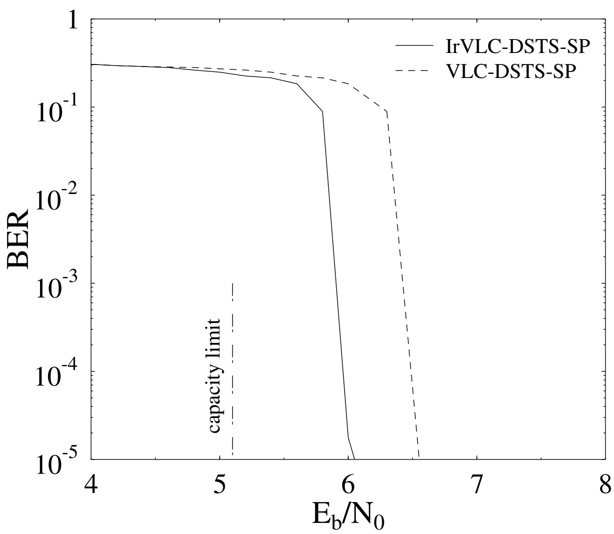

Fig. 4. Performance comparison of the IRVLC- and VLC-DSTS-SP systems while employing an average interleaver length of 113100 bits and 40 iterations.

VI. Conclusion

In this contribution we presented a serially concatenated and iteratively decoded Irregular Variable Length Coding (IrVLC) and precoded Differential Space-Time Spreading (DSTS) aided multi-dimensional Sphere Packing (SP) modulation scheme designed for near-capacity joint source and channel coding. Our EXIT chart analysis demonstrated that the IrVLC-aided system is capable of operating within 0.4 dB from the DSTS-SP channel capacity, as compared to operating at 0.9 dB from capacity for the regular VLC-aided system. However, the bit-by-bit simulation results show that the IrVLC-aided system is capable of operating within 0.9 dB of the DSTS-SP channel's capacity bound using an average interleaver length of $113,100$ bits at an effective bandwidth efficiency of 1 bit/s/Hz, when assuming ideal Nyquist filtering. By contrast, the equivalent-rate regular VLC-based benchmarker schemes required a higher E_b/N_0 value since they were found to be capable of operating at 1.4 dB from the capacity bound, which is about 1.56 times the discrepancy of the proposed IrVLC-aided scheme. Our future research will focus on the design of specific interleavers that are capable of eliminating the effect of correlation inevitably introduced by both the channel as well as by the differential scheme employed.

References

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

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

[3] B. Hochwald, T. Marzetta, and C. 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] L. Hanzo, L.-L. Yang, E.-L. Kaun, 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, NY, USA, 2003.

[5] W. Su, Z. Safar, and K. Liu, "Space-time signal design for time-correlated Rayleigh fading channels," in *IEEE International Conference on communications*, vol. 5, pp. 3175–3179, 2003.

[6] O. Alamri, B. L. Yeap, and L. Hanzo, "A turbo detection and sphere packing modulation aided space-time coding scheme," *IEEE Transactions on Vehicular Technology*, January 2007.

[7] 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." to appear in IEEE Transaction on Wireless Communications.

[8] M. Tüchler and J. Hagenauer, "EXIT charts of irregular codes," in *Conference on Information Science and Systems*, (Princtone, NJ), pp. 748–753, March 2002.

[9] V. Buttigieg and P. G. Farrell, "Variable-length error-correcting codes," *IEE Proceedings- Communications*, vol. 147, pp. 211–215, Aug. 2000.

[10] S. ten Brink, "Convergence of iterative decoding," *Electronics Letters*, vol. 35, no. 13, pp. 1117–1119, 1999.

[11] A. Ashikhmin, G. Kramer, and S. ten Brink, "Extrinsic information transfer functions: model and erasure channel properties," *IEEE Transactions on Information Theory*, vol. 50, no. 11, pp. 2657–2673, 2004.

[12] S. Lloyd, "Least squares quantization in PCM," *IEEE Transaction on Information Theory*, vol. 28, pp. 129–137, Mar. 1982.

[13] D. Divsalar, S. Dolinar, and F. Pollara, "Serial concatenated trellis coded modulation with rate-1 inner code," in *IEEE Global Telecommunications Conference (GLOBECOM)*, vol. 2, (San Francisco, CA), pp. 777–782, 2000.

[14] L. Bahl, J. Cocke, F. Jelinek, and J. Raviv, "Optimal decoding of linear codes for minimizing symbol error rate (Corresp.)," *IEEE Transactions on Information Theory*, vol. 20, no. 2, pp. 284–287, 1974.

[15] V. B. Balakirsky, "Joint source-channel coding with variable length codes," in *IEEE International Symposium on Information Theory*, (Ulm, Germany), June 1997.

[16] L. Hanzo, T. H. Liew, and B. L. Yeap, *Turbo coding, turbo equalisation and space time coding: for transmission over fading channels*. Chichester, UK: Wiley: IEEE Press, 2002.

[17] J. Hagenauer, E. Offer, and L. Papke, "Iterative decoding of binary block and convolutional codes," *IEEE Transactions on Information Theory*, vol. 42, no. 2, pp. 429–445, 1996.

[18] S. Benedetto and G. Montorsi, "Serial concatenation of block and convolutional codes," *Electronics Letters*, vol. 32, pp. 887–888, May 1996.

[19] J. H. Conway and N. J. Sloane, *Sphere Packings, Lattices and Groups*. Springer-Verlag, 1999.