Soft-Decision Star-QAM Aided BICM-ID

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***Abstract*—Differentially detected noncoherent Star Quadrature Amplitude Modulation (Star-QAM) is ideal for low-complexity wireless communications, since it dispenses with high-complexity channel estimation. We conceive soft-decision based demodulation for 16-level Star-QAM (16-StQAM), which is then invoked for iterative detection aided Iteratively-Detected Bit-Interleaved Coded Modulation (BICM-ID). It is shown that the proposed 16-StQAM based BICM-ID scheme achieves a coding gain of approximately 14 dBs in comparison to the 16-level identical-throughput Differential Phase-Shift Keying (16DPSK) assisted BICM scheme at a bit error ratio of 10^{-6}.**

***Index Terms*—BICM-ID, correlated Rayleigh fading channel, iterative detection, soft-decision, star QAM.**

I. Introduction

COHERENT detection aided Quadrature Amplitude Modulation (QAM) requires accurate Channel State Information (CSI) in order to avoid false-phase locking, especially when communicating over Rayleigh fading channels [1]–[4]. As a remedy, differentially detected noncoherent Star-QAM was proposed in [5] in order to dispense with high-complexity CSI estimation. More specifically, 16-level Star-QAM (16-StQAM) is based on two concentric 8-level Phase-Shift Keying (8PSK) constellations having two different amplitudes. Differential detection has also been investigated recently in wireless relay networks [6]–[8]. The significance of this low-complexity detection method may be expected to increase in the cooperative communications era, since it might be unrealistic to expect from a relay station constituted by a cooperating mobile phone to estimate the channel of the link it is relaying [7], [8].

Star-QAM schemes having more than two PSK constellations are also referred to as Differential Amplitude and Phase-Shift Keying (DAPSK) schemes [9], [10]. The authors of [9], [10] have further improved the performance of DAPSK/Star-QAM schemes [9], [10]. However, despite its attractive performance versus complexity characteristics, soft-decision based demodulation has not been conceived for these Star-QAM and DAPSK schemes. This also implies that without soft-decision based demodulation, the potential power of sophisticated channel coding or coded modulation schemes cannot be fully exploited. Hence, when channel coding is incorporated into Star-QAM as in [5], its performance is far from the channel capacity due to the employment of hard-decision based demodulation. More specifically, powerful channel coding, such as Bit-Interleaved Coded Modulation (BICM) [11], [12] and Iteratively-Detected BICM (BICM-ID) [13], [14] heavily relies on the exploitation of soft-decision based demodulation.

Our novel contribution is that we will first derive the soft-decision demodulation formula for 16-StQAM. Secondly, the performance benefits of using this new formula will be demonstrated in the context of BICM and BICM-ID schemes invoked for communications over correlated Rayleigh fading channels. Note, however, that the proposed soft-decision based 16-StQAM demodulation principles may be readily extended to DAPSK schemes having more than two concentric PSK constellations. This letter is organized as follows. In Section II, the soft-decision demodulation of 16-StQAM will be presented. Our results will be discussed in Section III and our conclusions are offered in Section IV.

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II. System Model and Analysis

Fig. 1 shows the simplified schematic of the proposed 16-StQAM aided BICM-ID scheme. A sequence of 3-bit information symbols is encoded by a rate-3/4 BICM encoder for yielding a sequence of 4-bit coded symbols. The Most Significant Bit (MSB) of the 4-bit encoded symbol will be used for selecting the amplitude of the Phase-Shift-Keying (PSK) ring, while the remaining 3 bits will be used for selecting the phase of the complex-valued 16-StQAM symbol x_k, where the subscript k denotes the symbol index. The BICM-encoded 16-StQAM symbol is corrupted by both the Rayleigh fading channel h_k and the Additive White Gaussian Noise (AWGN) n_k, when it is transmitted to the receiver, as shown in Fig. 1. Iterative detection is then carried out by exchanging extrinsic information between the 16-StQAM soft demapper and BICM decoder based on the received sequence $\{y_k\}$ without the any need for CSI.

A. Star-QAM Mapper

As seen in Fig. 1, the 16-StQAM mapper consists of three components, namely the amplitude selector, the 8PSK mapper and a differential encoder. The 8PSK mapper and the differential encoder jointly form a conventional 8-level DPSK (8DPSK) mapper. The MSB of the BICM-encoded symbol, namely b_3, is used for selecting one of the two possible amplitudes. The remaining 3 bits, namely $b_2\, b_1\, b_0$, are used by the 8DPSK mapper. Note that similar to any DPSK scheme, we insert a reference symbol at the beginning of each frame before the 16-StQAM mapper.

1) Amplitude Selection: The MSB, b_3, is used for selecting the amplitude of the PSK ring, a_k. The two possible amplitude

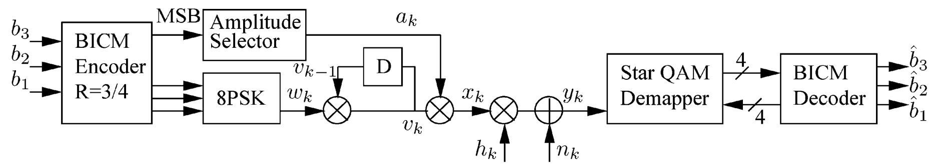

Fig. 1. Schematic of the 16-StQAM aided BICM-ID scheme, where the parallel bit interleavers between the encoder/decoder and mapper/demapper are not shown for avoiding obfuscating details.

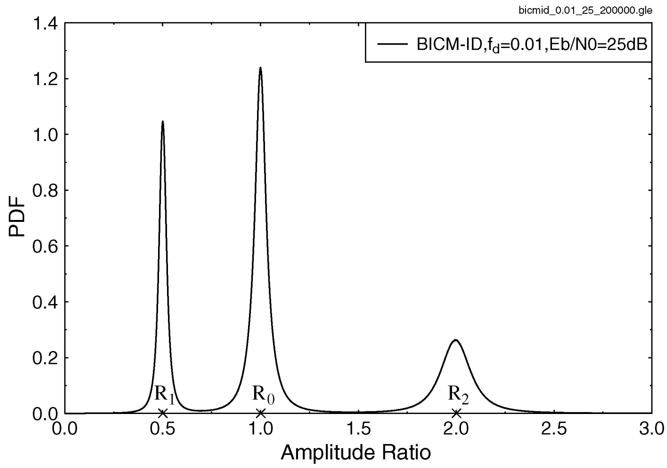

Fig. 2. The PDF of the received signal amplitude ratios of 16StQAM $|y_k|/|y_{k-1}|$ based on (6), when communicating over correlated Rayleigh fading channels having an E_b/N_0 of 25 dB.

values are denoted as $a^{(1)}$ and $a^{(2)}$, respectively. When the MSB of the kth BICM-encoded symbol is given by $b_3 = 0$, the amplitude of the PSK ring will remain the same as that of the previous value $a_k = a_{k-1}$. The amplitude of the PSK ring will be switched to another value, if $b_3 = 1$. This amplitude selection mechanism may be referred to as 2-level Differential Amplitude Shift Keying (2DASK). After normalisation for maintaining a symbol energy of unity, we have $a^{(1)} = 1/\sqrt{2.5}$ and $a^{(2)} = 2/\sqrt{2.5}$. The amplitude value of the reference symbol is given by $a_0 = a^{(1)}$.

2) Phase Selection: The kth differentially encoded symbol v_k can be expressed as

$$v_k = v_{k-1} w_k, \tag{1}$$

where $x_k = \mu(b_2\ b_1\ b_0)$ is the kth 8PSK symbol based on the 8PSK mapping function of $\mu(.)$, while v_{k-1} is the $(k-1)$st 8DPSK symbol and $|v_k|^2 = 1$. The reference symbol for the 8DPSK part is given by $v_0 = \mu(0\,0\,0)$.

The kth 16-StQAM symbol is then given by

$$x_k = a_k v_k, \tag{2}$$

where $a_k \in \{a^{(1)}, a^{(2)}\}$.

B. Star-QAM Soft Demapper

The soft-decision based 16-StQAM block is placed in front of the BICM decoder of Fig. 1. The kth received symbol may then be written as

$$y_k = h_k x_k + n_k = h_k a_k v_k + n_k \tag{3}$$

where h_k is the Rayleigh fading channel's coefficient, while n_k represents the AWGN having a variance of $N_0/2$ per dimension. Assuming a slow Rayleigh fading channel, where $h_k \approx h_{k-1}$, we can rewrite (3) using (1) as

$$\begin{aligned} y_k &= h_{k-1} a_k v_{k-1} w_k + n_k, \\ &= \frac{a_k}{a_{k-1}} (y_{k-1} - n_{k-1}) w_k + n_k, \\ &= p_k y_{k-1} w_k + \tilde{n}_k \end{aligned} \tag{4}$$

where $p_k = a_k/a_{k-1}$ is the ratio of the kth and $(k-1)$ st amplitudes, while $\tilde{n}_k = -(a_k/a_{k-1}) n_{k-1} w_k + n_k$ is the effective noise.

1) Amplitude Detection: Three amplitude ratios can be derived from the two PSK ring amplitudes of 16-StQAM as follows:

$$p_k = \begin{cases} R_0 = \frac{a^{(1)}}{a^{(1)}} \text{ or } \frac{a^{(2)}}{a^{(2)}} = 1 \\ R_1 = \frac{a^{(1)}}{a^{(2)}} \\ R_2 = \frac{a^{(2)}}{a^{(1)}}. \end{cases} \tag{5}$$

When the noise power is low, the amplitude ratio p_k may be approximated as

$$\frac{|y_k|}{|y_{k-1}|} = \frac{|h_k a_k v_k + n_k|}{|h_{k-1} a_{k-1} v_{k-1} + n_{k-1}|}, \tag{6}$$

$$\begin{aligned} &\approx \frac{|a_k|}{|a_{k-1}|}, \\ &\approx p_k. \end{aligned} \tag{7}$$

Fig. 2 shows the Probability Density Function (PDF) of the received signal amplitude ratios $|y_k|/|y_{k-1}|$. It becomes plausible from Fig. 2 that the PDF peak, which is characteristic of each amplitude ratio experiences a different noise variance, although all the 16-StQAM symbols experience the same AWGN at the same E_b/N_0 value of 25 dB.

Probability Computation: The effective noise variance of $\tilde{n}_k$ in (4) depends on the amplitude ratio used at time instant k, which can be computed as

$$\widetilde{N}_0 = N_0 + |p_k|^2 |w_k|^2 N_0 = N_0 \left(1 + |p_k|^2\right) \tag{8}$$

where $\widetilde{N}_0 = 2N_0 = N_0^{(0)}$ if $b_3 = 0$, while $\widetilde{N}_0 = (1+R_1^2)N_0 = N_0^{(1)}$ or $\widetilde{N}_0 = (1+R_2^2)N_0 = N_0^{(2)}$ for $b_3 = 1$. Based on (4) we can express the probability of receiving y_k conditioned on the transmission of b_0, b_1, b_2 and b_3 as follows:

$$P(y_k | w^{(m)}, b_3 = 0) = \frac{1}{\pi N_0^{(0)}} e^{\frac{-\left|y_k - y_{k-1} R_0 w^{(m)}\right|^2}{N_0^{(0)}}}, \tag{9}$$

TABLE I
SIMULATION PARAMETERS. NOTE THAT WE DECLARE "AN ITERATION" BEING COMPLETED WHEN BOTH THE DEMAPPER AND DECODER WERE ACTIVATED ONCE

Coded Modulation	BICM	BICM-ID
Modulation Scheme	16-StQAM, 16PSK 16QAM, 16DPSK	16-StQAM
Mapper type	Gray-labelled	Set-Partitioned
Number of iterations	1	1,2,4
Code Rate	3/4	
Code Memory	3	
Code Polynomial (octal)	$G = [4\,4\,4\,4\,;\ 0\,6\,2\,4\,;\ 0\,2\,5\,6\,]$	
Decoder type	Approximate Log-MAP	
Symbols per frame	1,200	
Number of frames	20,000	
Channel	Correlated Rayleigh channel	
Normalised Doppler Frequency (f_d)	0.01	

$$P(y_k|w^{(m)}, b_3=1) = \frac{1}{\pi N_0^{(1)}} e^{\frac{-\left|y_k - y_{k-1} R_1 w^{(m)}\right|^2}{N_0^{(1)}}} + \frac{1}{\pi N_0^{(2)}} e^{\frac{-\left|y_k - y_{k-1} R_2 w^{(m)}\right|^2}{N_0^{(2)}}} \quad (10)$$

where $w^{(m)} = \mu(b_2\ b_1\ b_0)$ and μ is the conventional 8PSK mapping function. However, when the *a priori* bit probabilities $P^a(b_i)$ become available from the BICM decoder, the extrinsic bit probability that can be gleaned from the 16-StQAM demapper becomes

$$P^e(b_i=b) = \sum_{w^{(m)} \in \chi(i,b)} \left(P\left(y_k|w^{(m)}, b_3=0\right) + P\left(y_k|w^{(m)}, b_3=1\right)\right) \prod_{\substack{j=0 \\ j\neq i}}^{3} P^a(b_j),$$
$$\text{for } i \in \{0,1,2\}, b \in \{0,1\} \quad (11)$$

where b_i denotes the ith coded bit of the symbol and $\chi(i,b)$ is the set of constellation points having the ith bit set to b. The extrinsic bit probability of the MSB may be formulated as

$$P^e(b_3 = b) = \sum_{w^{(m)}}^{\text{all}} P\left(y_k|w^{(m)}, b_3 = b\right) \prod_{j=0}^{2} P^a(b_j) \quad (12)$$

where the summation term considers all possible 8PSK constellation points, because the MSB b_3 influences only the amplitude selection. The extrinsic bit probabilities can then be employed for generating the Log-Likelihood Ratios (LLRs) [15] of all BICM-coded bits, which are then fed back to the BICM decoder.

III. SIMULATION RESULTS

Monte-Carlo simulations have been performed for characterising the proposed soft-decision based 16-StQAM demodulation technique in the context of BICM and BICM-ID coding schemes. The simulation parameters are shown in Table I.

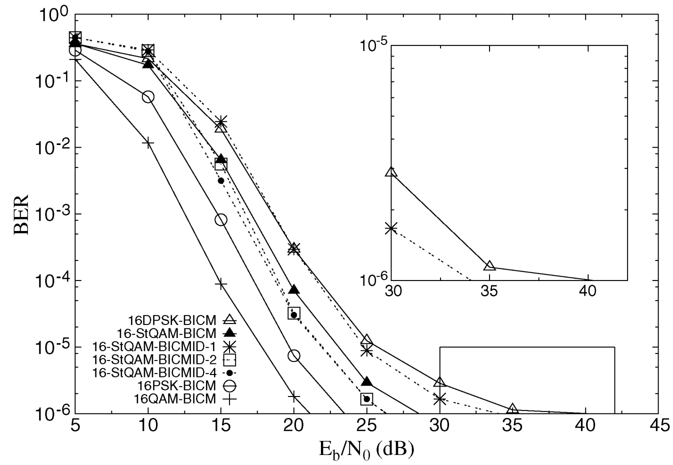

Fig. 3. BER versus E_b/N_0 performance of the 16DPSK-BICM, 16-StQAM-BICM, 16-StQAM-BICM-ID, 16PSK-BICM, and 16QAM-BICM schemes. The simulation parameters are shown in Table I.

Fig. 3 portrays the E_b/N_0 performance of the 16DPSK aided BICM, 16-StQAM assisted BICM, 16PSK aided BICM, 16QAM BICM, and 16-StQAM based BICM-ID schemes, when communicating over correlated Rayleigh fading channels. Solid lines are used for illustrating the performance of Gray-labelled BICM, while the dotted lines represent the Set-Partitioning (SP) based 16-StQAM BICM-ID. As seen from Fig. 3, the 16DPSK-BICM scheme suffers from a high BER floor, since the minimum Euclidean distance of a 16-point constellation ring is lower than that of the classic square 16QAM or 16-StQAM schemes. The 16-StQAM-BICM scheme outperforms the 16DPSK-BICM scheme by approximately 12 dBs at a BER of 10^{-6}. The coherently detected 16QAM-BICM and 16PSK-BICM are considered here as our benchmark schemes, while assuming perfect CSI. During the *first iteration*, the SP-based 16-StQAM-BICM-ID scheme performs worse than the Gray-labelled 16-StQAM-BICM, since the SP-based mapper has a lower minimum Euclidean distance compared to that of the Gray-label-based mapper. Note that both the 16-StQAM-BICM-ID and 16-StQAM-BICM schemes use the bit-probabilities of (9) and (10) during the first iteration. However, after the *second iteration* the 16-StQAM-BICM-ID outperforms the noniterative 16-StQAM-BICM by approximately 2 dB with the aid the extrinsic bit-probabilities of (11) and (12).

IV. CONCLUSIONS

In this letter, soft-decision based demodulation was conceived for 16-StQAM in order to enable the employment of power-efficient channel codes and coded modulation. The performance of soft-decision 16-StQAM assisted BICM and BICM-ID schemes was investigated, when communicating over correlated Rayleigh fading channels. The proposed soft-decision aided 16-StQAM demodulation techniques can be extended for assisting DAPSK schemes having more than two PSK constellations.

REFERENCES

[1] E. Issman and W. Webb, "Carrier recovery for 16-level QAM in mobile radio," in *IEE Colloq. Multi-Level Modulation*, Mar. 1990, pp. 9/1–9/8.

[2] L. Hanzo, S. X. Ng, T. Keller, and W. Webb, *Quadrature Amplitude Modulation: From Basics to Adaptive Trellis-Coded, Turbo-Equalised and Space-Time Coded OFDM, CDMA and MC-CDMA Systems Digital Communications*, 2nd ed. Hoboken, NJ: Wiley-IEEE Press, 2004.

[3] L. Chen, H. Kusaka, and M. Kominami, "Blind phase recovery in QAM communication systems using higher order statistics," *IEEE Signal Process. Lett.*, vol. 3, no. 5, pp. 147–149, May 1996.

[4] Y. Wang and E. Serpedin, "A class of blind phase recovery techniques for higher order QAM modulations: Estimators and bounds," *IEEE Signal Process. Lett.*, vol. 9, no. 10, pp. 301–304, Oct. 2002.

[5] W. Webb, L. Hanzo, and R. Steele, "Bandwidth-efficient QAM schemes for Rayleigh-fading channels," *Proc. Inst. Elect. Eng.*, vol. 138, no. 3, pp. 169–175, June 1991.

[6] Y. Jing and H. Jafarkhani, "Distributed differential space-time coding for wireless relay networks," *IEEE Trans. Commun.*, vol. 56, no. 7, pp. 1092–1100, Jul. 2008.

[7] L. Wang and L. Hanzo, "The amplify-and-forward cooperative uplink using multiple-symbol differential sphere-detection," *IEEE Signal Processing Letters*, vol. 16, no. 10, pp. 913–916, 2009.

[8] L. Wang and L. Hanzo, "The resource-optimized differentially modulated hybrid af/df cooperative cellular uplink using multiple-symbol differential sphere detection," *IEEE Signal Process. Lett.*, vol. 16, no. 11, pp. 965–968, Nov. 2009.

[9] C.-D. Chung, "Differentially amplitude and phase-encoded QAM for the correlated Rayleigh-fading channel with diversity reception," *IEEE Trans. Commun.*, vol. 45, no. 3, pp. 309–321, Mar. 1997.

[10] Y. Ma, Q. T. Zhang, R. Schober, and S. Pasupathy, "Diversity reception of DAPSK over generalized fading channels," *IEEE Trans. Wireless Commun.*, vol. 4, no. 4, pp. 1834–1846, Jul. 2005.

[11] E. Zehavi, "8-PSK trellis codes for a Rayleigh fading channel," *IEEE Trans. Commun.*, vol. 40, pp. 873–883, May 1992.

[12] G. Caire, G. Taricco, and E. Biglieri, "Bit-interleaved coded modulation," *IEEE Trans. Inf. Theory*, vol. 44, no. 3, pp. 927–946, May 1998.

[13] X. Li and J. A. Ritcey, "Bit-interleaved coded modulation with iterative decoding using soft feedback," *Electron. Lett.*, vol. 34, pp. 942–943, May 1998.

[14] N. Tran, H. Nguyen, and T. Le-Ngoc, "Multidimensional subcarrier mapping for bit-interleaved coded ofdm with iterative decoding," *IEEE Trans. Signal Process.*, vol. 55, no. 12, pp. 5772–5781, Dec. 2007.

[15] L. Hanzo, T. H. Liew, and B. L. Yeap, *Turbo Coding, Turbo Equalisation and Space-Time Coding for Transmission Over Fading Channels*. Hoboken, NJ: Wiley-IEEE Press, 2002.