On Noncoherent Sequence Detection of Coded QAM

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***Abstract*— In this letter, new noncoherent sequence detection algorithms for combined demodulation and decoding of coded linear modulations transmitted over additive white Gaussian noise channels are presented. These schemes may be based on the Viterbi algorithm and have a performance which approaches that of coherent detection for increasing complexity. The tradeoff between complexity and performance is simply controlled by a parameter referred to as *implicit phase memory* and the number of trellis states.**

***Index Terms*—Maximum-likelihood detection, noncoherent sequence detection, trellis-coded modulation.**

I. Introduction

NONCOHERENT detection of digital signals is an attractive strategy in situations where carrier phase recovery is difficult. Differential detectors, the simplest noncoherent receivers, are frequently employed to detect M-ary phase-shift keying (M-PSK) modulations, with good performance only in the case of binary signaling (BPSK) [1]. Although differential detection eliminates the need for carrier acquisition and tracking, it suffers from a performance penalty when compared to ideal coherent detection.

The performance of ideal coherent detection may be approached by more complex noncoherent receivers based on *multiple-symbol differential detection*. This approach was presented in [2]–[4] for PSK modulation and extended to trellis-coded PSK [5] and quadrature-amplitude modulation (QAM) [6]. A trellis-based noncoherent detection scheme is proposed in [7] for PSK modulations based on *maximally overlapped observations*.

In this letter, starting from the branch metrics of the optimal coherent detector, we derive new noncoherent detection schemes based on the Viterbi algorithm, for coded linearly modulated signals transmitted through additive white Gaussian noise (AWGN) channels. Being noncoherent, the proposed schemes do not have all the drawbacks of conventional approximation of coherent detection based on the use of synchronization schemes, such as acquisition problems, sensitivity to phase jitter, phase slips, false locks, loss of lock caused by severe fading or oscillator frequency instabilities, etc.

The proposed schemes may exhibit performance gains with respect to existing noncoherent receivers with an acceptable complexity level—the tradeoff between complexity and performance being simply controlled by two parameters: *implicit phase memory* and number of trellis states. Applications for coded and uncoded linear modulations are explicitly considered. The complexity reduction issue is further investigated by reduced-state sequence detection techniques based on per-survivor processing (PSP) [8]. This letter expands upon previous work reported in [9] and [10].

II. Noncoherent Sequence Detection

Under the assumption of a constant channel phase model, it may easily be shown that the sampled output of a filter matched to the basic pulse of a linear modulation is a sufficient statistic for optimal detection of the information sequence. This conclusion holds for both known phase and a stochastic phase model (see [1, Appendix 4C] for the relevant background). For an unknown deterministic phase model, adopting joint maximum-likelihood estimation of data and phase as a heuristic detection approach, this sampled output is still a sufficient statistic (this conclusion turns out to hold even for other heuristic approaches).

Assuming absence of intersymbol interference (ISI), the samples $\{x_k\}$ at the output of this matched filter may be expressed as

$$x_k = c_k e^{j\theta} + n_k \tag{1}$$

where symbols $\{c_k\}$ are assumed to belong to an alphabet with M points, θ is the phase shift introduced by the channel, and $\{n_k\}$ are independent, identically distributed, zero-mean, complex, Gaussian random variables with independent, equal-variance real and imaginary components. Symbols $\{c_k\}$ are assumed to be derived from information symbols $\{a_k\}$, independent and identically distributed, by means of some coding rule.

The optimal coherent receiver selects the sequence $\{c_k\}$ which maximizes the sum of metrics

$$\mathrm{Re}\{x_k \tilde{c}_k^* e^{-j\theta}\} - \frac{1}{2}|\tilde{c}_k|^2 \tag{2}$$

in which θ is the known channel phase [1] and $\{\tilde{c}_k\}$ is a hypothetical code sequence. The proposed noncoherent detection algorithm is based on the use of a data-aided maximum-likelihood estimate of the phase θ, based on the previous $N-1$ received signal samples, to approximate the metrics of the coherent receiver. It is easy to verify that the resulting estimator of the unknown phase is such that

$$e^{-j\hat{\theta}} = \frac{\sum_{i=1}^{N-1} x_{k-i}^* c_{k-i}}{\left|\sum_{i=1}^{N-1} x_{k-i}^* c_{k-i}\right|}. \tag{3}$$

Manuscript received November 18, 1997. The associate editor coordinating the review of this letter and approving it for publication was Prof. C. Douligeris. This letter was presented in part at the International Symposium on Information Theory, Ulm, Germany, July 1997.

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Publisher Item Identifier S 1089-7798(98)06468-0.

This estimator is used to replace the unknown phasor $e^{-j\theta}$ in (2). To circumvent the need for the correct data sequence, the general technique of per-survivor processing (PSP) [8] is adopted. The resulting receiver selects the sequence $\{\tilde{c}_k\}$ which maximizes the sum of metrics

$$\lambda_k = \frac{\mathrm{Re}\left\{\displaystyle\sum_{i=1}^{N-1} x_k x_{k-i}^* \tilde{c}_k^* \tilde{c}_{k-i}\right\}}{\left|\displaystyle\sum_{i=1}^{N-1} x_{k-i}^* \tilde{c}_{k-i}\right|} - \frac{1}{2}|\tilde{c}_k|^2. \qquad (4)$$

The maximization of the sum of these metrics may be performed recursively on a properly defined trellis diagram using a Viterbi algorithm with branch metrics expressed by (4). For a given coding rule, the code symbols $\{c_k\}$ may be expressed in terms of the information symbols $\{a_k\}$ and a trellis state defined accordingly. Since (4) depends on N code symbols, in general the number of trellis states is larger than that of the code trellis. However, this complexity increase may be limited by a possible use of techniques for state-complexity reduction without excessively reducing the value of N, as described at the end of this section. Moreover, even using small values of N (a few units) a performance very close to that of coherent detection may be obtained, as shown in the numerical results. In the limit as $N \rightarrow +\infty$, coherent detection performance is obtained. On the other hand, in the case of time-varying phase models, an estimation based on the most recent observations may have greater accuracy—under dynamic channel conditions, receivers employing values of N of a few units may have a robustness to phase jitter and frequency offsets similar to that of differential detectors. Integer N affects the number of previous symbols which aid an implicit per-survivor phase estimator and is intimately related to the definition of trellis state. For this reason, we refer to N as *implicit phase memory* parameter.

The state-complexity of the proposed detection schemes may be limited by reduced-state sequence detection (RSSD) [8], [11], [12]. As an example, considering a trellis state defined in terms of ζ information symbols as $\delta_k = (\tilde{a}_{k-1}, \tilde{a}_{k-2}, \cdots, \tilde{a}_{k-\zeta})$,[1] the number of states is $S = M^\zeta$. A reduced state $\delta'_k = (\tilde{a}_{k-1}, \tilde{a}_{k-2}, \cdots, \tilde{a}_{k-\beta})$ with $\beta < \zeta$ may be defined. The resulting number of states is reduced to $S = M^\beta < M^\zeta$. More complex techniques based on set partitioning may also be employed [11], [12]. In order to compute the branch metrics (4) in a reduced trellis, the necessary symbols not included, or not completely specified, in the state definition may be found in the survivor history according to PSP [8]. We note that, in the limiting case of $\beta = 0$, the trellis diagram degenerates and symbol-by-symbol detection with decision-feedback is performed.

III. Numerical Results

The performance of the proposed receivers is assessed, by means of computer simulation, in terms of bit-error rate (BER) versus E_b/N_0, E_b being the received signal energy per information bit and $N_0/2$ the noise power spectral density.

[1] Symbols $\tilde{a}_k$ are defined in analogy with symbols $\tilde{c}_k$.

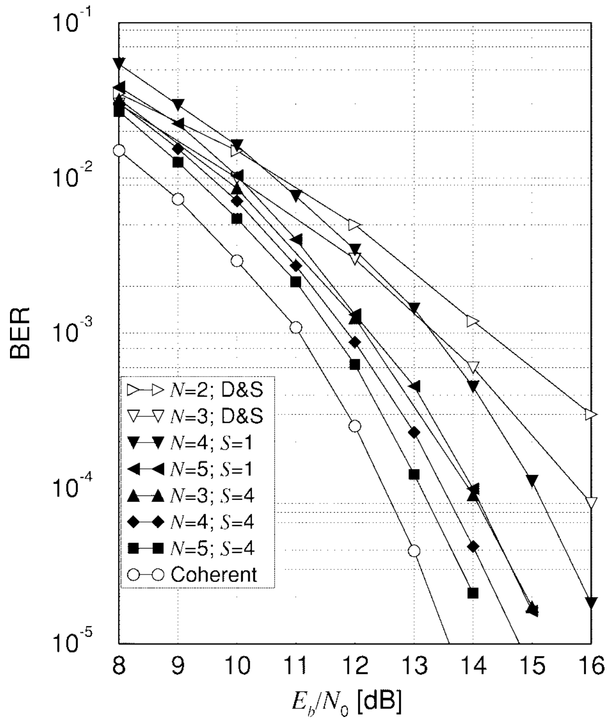

Fig. 1. BER of the proposed detection schemes for 16-DQAM with various degrees of complexity and comparison with receivers in [6] (D&S).

Besides "full-state" receivers, reduced-state techniques have also been considered. The channel phase is assumed constant.

The first considered coding rule is as follows. We assume symbols $\{c_k\}$ belong to an M-ary square QAM alphabet and are derived from information symbols $\{a_k\}$, belonging to the same alphabet, by means of the following *quadrant differential encoding* rule. The generic information symbol is uniquely represented as $a_k = \mu_k p_k$, where μ_k belongs to the first quadrant and $p_k \in \{\pm 1, \pm j\}$. The encoded symbol c_k is given by $c_k = \mu_k q_k$, where $q_k \in \{\pm 1, \pm j\}$ are defined by $q_k = p_k q_{k-1}$, i.e., the usual differential encoding rule for quadrature phase-shift keying (QPSK) applied to symbols $\{p_k\}$. For differentially encoded 16-QAM (16-DQAM), we only consider schemes with a number of states $S = 4$ (i.e., the state is defined as $\delta'_k = \tilde{\mu}_k$[2]) and $S = 1$ (i.e., symbol-by-symbol detection with decision-feedback). Fig. 1 shows the relevant performance, obtained by computer simulation, for various values of N and S and compares it with that of optimal coherent detection. The receivers proposed in [6] by Divsalar and Simon (D&S in the figure) are also considered for comparison, assuming N is the block length. It is worth to note that a different type of differential encoding was adopted in [6], which, however, modifies an original M-point square QAM constellation into one characterized by a larger number of points. It may be observed that the proposed receivers perform better and exhibit a loss of only 0.8 dB at a BER of 10^{-5} with respect to coherent detection, with an affordable level of complexity. For larger complexity, the performance approaches that of coherent detection. We also note that the

[2] Symbols $\tilde{\mu}_k$ are defined in analogy with symbols $\tilde{c}_k$.

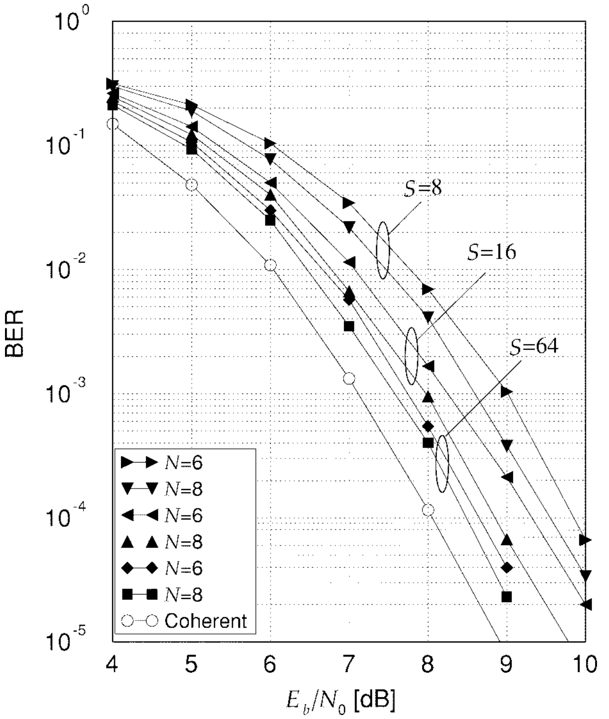

Fig. 2. BER of the proposed detection schemes for eight-state TC-16-QAM.

performance tends to that of coherent detection with a rate which is independent of the signal-to-noise ratio.

Noncoherent sequence detection has also been applied to trellis-coded (TC) modulation. An eight-state TC 16-QAM scheme with 90° rotationally invariance and differential encoding has been considered [13]. Various noncoherent receivers with different complexity have been analyzed. Fig. 2 shows the performance of the considered receivers along with that of coherent detection. Receivers based on the code trellis ($S = 8$) exhibit a performance loss of about 1.5 dB (for $N = 8$) but with an increase in the number of states up to $S = 64$ the performance loss becomes negligible. The state of the receivers with $S = 16$ is defined by a complete representation of the previous information symbol $\tilde{a}_{k-1}$ and a partial representation of the symbol $\tilde{a}_{k-2}$ by four-point subsets according to RSSD.

IV. Conclusions

In this letter, new algorithms for combined noncoherent detection and decoding of coded linear modulations have been presented based on an approximation of the branch metrics of an optimal coherent receiver. Under this approximation, trellis diagrams which represent both the code memory and an implicit phase memory may be defined and searched by a Viterbi algorithm. State reduction techniques may also be employed. The tradeoff between performance and complexity may be controlled by the implicit phase memory parameter and the level of state-complexity reduction.

The proposed detection schemes have been assessed by computer simulation for some cases of practical significance. These schemes have a performance which can be made arbitrarily close to that of coherent detection. The necessary complexity increase may be kept at affordable levels. The proposed schemes compare favorably with other solutions previously proposed in the literature. Being noncoherent, they do not have all the drawbacks of conventional approximation of coherent detection based on the use of phase-locked loops and are especially attractive for burst-mode transmissions.

Acknowledgment

This work was performed within a research cooperation between the Dipartimento di Ingegneria dell'Informazione, Università di Parma, Italy, and Italtel S.p.A., Milan, Italy [14].

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