A NEW METHOD FOR BLOCK DEMODULATION WITHOUT CHANNEL ESTIMATION

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ABSTRACT
For communication channels exhibiting fading and interference, noncoherent maximum likelihood (ML) block demodulation generally requires the knowledge of received signal strength, fading levels, and the phase offset introduced by the channel. Furthermore, ML block demodulation can be computationally prohibitive. This paper presents a sub-optimal block demodulation method based on a computationally simple and efficient clustering algorithm known as the K-means algorithm. The performance of noncoherent block demodulation based on this algorithm is determined for various phase and amplitude-phase modulation techniques. This demodulation scheme does not require knowledge of the received signal strength, fading levels, or channel phase offset. Numerical results show significant improvement over classical differential demodulation techniques.

I. INTRODUCTION
Many approaches of varying complexity have been applied to the demodulation of inphase-quadrature modulation in the presence of fading and an unknown channel phase offset. Implementation of coherent or partially coherent demodulation has taken forms from approximate phase recovery via decision-aided and non-decision-aided techniques [1] to iterative joint estimation of the data sequence and channel parameters [2]. Frequently, maximum likelihood estimation of the channel parameters is complicated, computationally expensive, or even intractable.

Demodulation without the estimation of channel parameters necessitates noncoherent demodulation techniques. Noncoherent demodulation of many modulation schemes requires differential encoding. Classical symbol-by-symbol demodulation of differentially encoded waveforms uses successive pairs of received decision statistics. For example, a classical differential phase shift keying (DPSK) demodulator makes pairwise phase decisions. Demodulators of higher order modulation techniques such as differential amplitude phase shift keying (DAPSK) also rely on pairwise decisions of phase and amplitude [3], [4].

If the channel phase offset is constant over $N$ successive symbols, then phase estimation techniques can be used on the block of $N$ received decision statistics. Clearly, for noncoherent differential detection, pairwise decision techniques are suboptimal. Given a block of $N$ received decision statistics, the optimal differential block demodulator operates on all $N$ statistics. The resulting performance approaches that of coherent demodulation of the differentially encoded signal as $N \to \infty$ [5].

A design consideration with noncoherent block demodulation is the tradeoff between blocklength and computational complexity. In general, as $N$ increases (and, thus, performance increases), the number of operations necessary to implement the optimal block demodulator increase exponentially [6]. However, for a specific modulation technique and corresponding block demodulator, the computational complexity may be reduced. For example, an algorithm exists for optimal block demodulation of noncoherent differential detection of DPSK over an additive white Gaussian noise (AWGN) channel that requires operations on the order of $N \log_2 N$ [7].

This paper presents a novel block demodulation method that is readily adaptable to a wide variety of modulation schemes. This demodulation method facilitates easy digital implementation and has very low complexity with regard to data manipulation and computational costs.

II. SYSTEM MODEL
The analyzed system employs a combination of phase and amplitude modulation. The general form of the $k$th transmitted symbol is

$$s(t) = a_x A_x \cos(\omega_c t + \theta_k),$$

$$(k - 1)T_s < t \leq kT_s$$

(1)

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where $\omega_c$ is the carrier frequency, $T_s$ is the symbol duration, $a_j A_3$ is the amplitude of the signal, and $\theta_3$ is the phase of the signal. The phase $\theta_i$ is one of $M_1$ values, and the amplitude $a_j$ is one of $M_2$ positive values. The indices $i$ and $j$ satisfy the conditions $0 \leq i \leq M_1 - 1$ and $0 \leq j \leq M_2 - 1$. The number of points in the signal space is $M = M_1 M_2$.

The data sequences are denoted by $\{a^{(k)}\}$ and $\{\theta^{(k)}\}$ for $k = 0, 1, 2, \ldots$ where $a^{(n)}$ and $\theta^{(n)}$ represent the amplitude and phase of the $n$\textsuperscript{th} transmitted symbol, respectively. The data sequences are differentially encoded. The maximum amplitude value corresponds to $a_{M_2-1} = 1$, and the minimum amplitude value corresponds to $a_0 = \rho$. The amplitude values are assumed to have equal separation between the maximum and minimum amplitude values. Thus, the $M_2$ amplitude values are $a_0 = \rho + \alpha\ell$, $\ell = 0, \ldots, M_2 - 1$, where $\alpha = (1 - \rho)/(M_2 - 1)$. In a block of $N$ symbols, the $k$\textsuperscript{th} transmitted amplitude level is

$$a^{(k)}_n = \Delta a^{(k)}_p + a^{(k-1)}_p,$$

where $\Delta a^{(k)}_p \in \{\alpha p : p = 0, \ldots, M_2 - 1\}$ and $\ell = (p + \nu) \mod M_2$. The $M_1$ phase angles are given by $\theta_n = \frac{2\pi}{M_1} n$, $n = 0, \ldots, M_1 - 1$, and the $k$\textsuperscript{th} transmitted phase angle is given by

$$\theta^{(k)}_n = \Delta \theta^{(k)}_d + \theta^{(k-1)}_d,$$

where $\Delta \theta^{(k)}_d \in \{\frac{2\pi}{M_1} d : d = 0, \ldots, M_1 - 1\}$ and $b = (d + \nu) \mod M_1$.

A modulation scheme described by (1) that employs differential encoding is differential amplitude phase shift keying (DAPSK). DPSK modulation is a subset of DAPSK for which the amplitude is constant for all symbols (i.e., $M_2 = 1$). For the DAPSK constellations considered in this paper, $M_1$ and $M_2$ are powers of two, and the first $m_1$ bits of the $\log_2 M$ bits comprising an $M$-ary DAPSK symbol are conveyed in differentially encoded $2^{m_1}$-ary PSK, and the remaining $m_2 := \log_2 M - m_1$ bits are conveyed by differentially encoded amplitudes $[3]$. As an example, if $M_1 = 4$ and $M_2 = 2$, then the 8-ary DAPSK constellation in Fig. 1 results. If the phase bits employ Gray coding, then each symbol’s nearest neighbor(s) differs in only one bit position. A Gray-coded bit assignment is also shown in Fig. 1.

The channel is modeled as a random phase, fading channel with additive Gaussian noise and Rayleigh fading statistics. The fading level and the channel phase offset are assumed to be constant throughout the duration of a block of $N$ transmitted symbols. For the corresponding block of received symbols, the fading level is denoted by $A_f$, and the channel phase offset is denoted by $\phi$. The fading level $A_f$ is modeled as a Rayleigh random variable, and the channel phase offset $\phi$ is modeled as a uniform random variable over the range $[0, 2\pi)$.

The $k$\textsuperscript{th} inphase and quadrature received decision statistics are given by

$$y^{(k)}_i = \int_{(k-1)T_s}^{kT_s} y(t) \cos(\omega_c t) dt$$

and

$$y^{(k)}_q = \int_{(k-1)T_s}^{kT_s} y(t) \sin(\omega_c t) dt,$$

respectively, where $y(t)$ is the received signal given by

$$y(t) = A_f a^{(k)} a A_3 \cos(\omega_c t + \theta^{(k)} + \phi) + n(t),$$

where $n(t)$ is a white Gaussian noise process with spectral density $N_0/2$. A transformation from rectangular to polar coordinates is given by

$$\xi^P(x, y) = \left(\sqrt{x^2 + y^2}, \arctan(y/x)\right) = (\rho, \varphi),$$

and the corresponding transformation from polar to rectangular coordinates is given by

$$\xi^R(\rho, \varphi) = (\rho \cos(\varphi), \rho \sin(\varphi)),$$

where the arctan is interpreted over $[0, 2\pi]$. Thus, the magnitude and phase decision statistics of the $k$\textsuperscript{th} signal

\[\text{Fig. 1. An 8-ary DAPSK signal constellation with Gray coding.}\]
(r(k) and ψ(k), respectively) are given by (r(k), ψ(k)) = εp(yI(k), yQ(k)).

The fading level and the channel phase offset are not known at the receiver. The following sections investigate demodulation schemes that can operate well despite this lack of information.

III. CLASSICAL DIFFERENTIAL DETECTION

Classical differential detection bases decisions on successive pairs of statistics (yI(k−1), yQ(k−1)) and (yI(k), yQ(k)). Differential detection of the phase of DAPSK modulation is straightforward: hard decisions are made on consecutive phases ψ(k−1) and ψ(k), the differential phase is Δψ(k) = ψ(k) − ψ(k−1), and the estimated transmitted differential phase is arg min {Δψ(k) : i = 0, ..., M1 − 1}.

Pairwise differential detection of the amplitude information requires some sort of threshold test; e.g., the detector chooses the amplitude corresponding to a if

\[ r_{j,\ell}^{(k+1)} < \frac{r_{j,\ell}^{(k+1)}}{r(k)} \leq r_{j,u}^{(k+1)}, \]

where the choice of the thresholds r_{j,\ell}^{(k+1)} and r_{j,u}^{(k+1)} depends on the fading levels and the previous amplitude decision. For M2 = 2, only one threshold is necessary. In this case, if the current amplitude decision is a, then the next amplitude decision is a if

\[ \max(r(k), r_{j,\ell}^{(k+1)}) - \min(r(k), r_{j,u}^{(k+1)}) \leq \tau; \quad (2) \]

otherwise the detector chooses the alternative amplitude.

Pairwise detection for differentially encoded waveforms is suboptimal. Since fading is constant over a block of N symbols, the joint statistics can be used to estimate the received signal strength explicitly or implicitly. Optimal block demodulation of differentially encoded data performs implicit channel estimation. The following section describes a suboptimal block demodulation technique that also performs implicit channel estimation. This suboptimal method has lower complexity than the optimal block demodulator and performs significantly better than classical differential demodulation techniques.

IV. THE K-MEANS ALGORITHM

A. General Description

Demodulation of DAPSK may be viewed as a pattern recognition problem in two dimensions. The K-means test is a well-known algorithm used in pattern recognition for data clustering [8]. The test can be described as follows:

1. Begin with an arbitrary assignment of samples to clusters.
2. Determine the average value of the samples in each cluster.
3. Reassign each sample to the cluster with the nearest average value.
4. Stop if no samples have changed clusters; otherwise, return to step 2.

The samples used in this test are the coordinate pairs z_k = (yI(k), yQ(k)), 1 ≤ k ≤ N.

For some set of samples (z_1, ..., z_K), the average value is defined as

\[ \left( \frac{1}{K} \sum_{j=1}^{K} y_{I(j)}, \frac{1}{K} \sum_{j=1}^{K} y_{Q(j)} \right). \]

Differential detection follows the application of the clustering algorithm. Knowledge of the transmitted signal structure leads to modifications of the algorithm that improve the accuracy of the algorithm and increase the rate of convergence of the algorithm.

B. Block Demodulation of DPSK

The transmitted amplitude is constant for M-ary PSK signals, and the symbols are equally spaced on [0, 2π). This knowledge of the transmitted signal suggests an obvious modification of the K-means algorithm for block demodulation. Step 1 is replaced by the following:

1a. Determine the average amplitude of the N samples, say Центр. 
1b. Initiate the cluster means to be εp(Центр, [2πn + arg(z_1)]) for n = 0, ..., M − 1. 
1c. Goto step 3.

C. Block Demodulation of DAPSK

Similar to the modification for DPSK, a K-means algorithm that implements block demodulation

1Equivalent to, differential detection can be performed first such that the samples used in this test are the differences between successive coordinate pairs.
of DAPSK can make educated guesses on the initial assignment of samples to clusters. For example, for the 8-ary DAPSK signal constellation shown in Fig. 1, step 1 in the K-means algorithm is replaced by the following:

1a. Determine the average amplitude of the N samples, say $\bar{a}$.

1b. Initiate the cluster means to be $a_n^p \left( (1 + \beta)a_n^{(2\pi n + \text{arg}(z_1))} \right)$ and $a_n^p \left( (1 - \beta)a_n^{(2\pi n + \text{arg}(z_1))} \right)$ for $n = 0, \ldots, M-1$, where $\beta$ is proportional to the distance between $\max_j(a_j)$ and $\min_j(a_j)$.

1c. Goto step 3.

The K-means algorithm obviates differential encoding of the amplitudes.

D. Variations of a Theme

Many variations of the K-means algorithm are readily evident. For instance, the algorithm can be applied in stages. An alternative to the algorithm given in Section IV-C is the following:

1. Apply the modified K-means algorithm given in Section IV-B ($K = 4$) to the $N$, 8-ary DAPSK samples.
2. For $i = 0, \ldots, (2^{m_1} - 1)$, apply the general K-means algorithm ($K = 2$) to the $i$th cluster from step 1.

In this case, step 1 performs differential phase detection of the DAPSK signal. Step 2 performs differential amplitude detection of the samples in each of the four clusters determined in step 1.

For this alternative approach, a reduction in the number of iterations of the algorithm and an improvement in accuracy can be obtained if the samples in step 2 are sorted. The clustering algorithm labels the received statistics $\{r^{(k)}\}$ as arising from either $a_0$ or $a_1$. Clearly, each $r^{(k)}$ is real-valued. If an ordered version of the $r^{(k)}$s is used in step 2, then samples only change clusters in one direction. In other words, if the $i$th ordered statistic is reassigned from the cluster of lower mean to the cluster of higher mean, then the $j$th ordered statistic cannot move from the cluster of higher mean to the cluster of lower mean for any $j > i$ [9]. The improvements in performance come at the operational cost of sorting the statistics (on the order of $N \log_2 N$).

Equally justifiable is a process in which the K-means algorithm first makes amplitude decisions and then phase decisions. The logical order in which the staging occurs depends on the structure of the signal constellation. If the minimum distance between adjacent symbols is with respect to phase and not amplitude, then for best performance the K-means test should be applied to the $r^{(k)}$s first. Conversely, if the minimum distance between adjacent symbols is with respect to amplitude and not phase, then for best performance the K-means test should be applied to the $\psi^{(k)}$s first.

V. NUMERICAL RESULTS

System performance is measured by the bit error rates of the DAPSK data. The nature of the K-means algorithm requires simulations to determine performance results. Numerical results are restricted to two constellations — differential quadrature phase shift keying (DQPSK) and the 8-ary constellation shown in Fig. 1. The block demodulation algorithm given in Section IV-B is applied to the DQPSK constellation with $a_0 = 1.0$. The algorithm given in Section IV-C is applied to the 8-ary DAPSK constellation having amplitude values corresponding to $a_0 = 0.425$ and $a_1 = 1.0$.

Fig. 2 presents the bit error probabilities for DQPSK in an AWGN channel for classical pairwise demodulation, the modified K-means block demodulation, and coherent demodulation of differentially encoded QPSK. The bit error probabilities are shown as a function of $E_b/N_0$, where $E_b$ is the average bit energy. For $N = 100$, the K-means block demodulation scheme yields significant improvement over the classical pairwise demodulation, providing approximately a 1.5 dB gain at a probability bit error of $10^{-3}$ — the same gain as coherent demodulation.

Fig. 3 presents the bit error probabilities for 8-ary DAPSK in an AWGN channel for classical pairwise demodulation, the K-means block demodulation, and coherent phase/noncoherent differential amplitude
demodulation. In contrast to the block demodulation technique, consecutive pairs of received statistics provide little reliable amplitude information. The ratio test given in (2) measures the amount of change between consecutive decision statistics. Simulations show that the threshold $\tau = 1.6$ performs well for $E_b/N_0 \leq 12$ dB. The pairwise decision performance in Fig. 3 correspond to this threshold.

Fig. 4 shows the probabilities of bit error for 8-ary DAPSK over a Rayleigh fading channel. The relative performance of the classical and K-means demodulation methods over a Rayleigh fading channel are similar to their relative performance over an AWGN channel. For either channel, the probability of bit error is dominated by the error performance of the demodulation of the differentially encoded amplitudes. Since the fading over pairs of consecutive symbols is constant, the performance issues for the amplitude decisions based on the ratio given in (2) is the same for a Rayleigh channel as for an AWGN channel. Thus, the performance of the pairwise demodulation scheme in Fig. 4 is similar to that in Fig. 3. In the simulations, the K-means algorithm always converged in no more than two iterations.

In conclusion, this paper has evaluated block demodulation techniques based on the K-means algorithm. These techniques treat the demodulation of DAPSK as a pattern recognition problem in two dimensions.

The results show that block demodulation techniques based on the K-means test perform significantly better than classical pairwise demodulation schemes for DAPSK (and DPSK). A major advantage of these algorithms is that no explicit channel estimation is required. Furthermore, these algorithms have very low complexity and facilitate easy digital implementation.

REFERENCES


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2Coherent phase/noncoherent differential amplitude demodulation has a perfect phase reference for phase demodulation (assuming the phase information is not differentially encoded) but performs noncoherent differential amplitude demodulation as described in Equation (2). In contrast, the optimal coherent demodulator has “perfect” amplitude reference for amplitude demodulation.