Signal Processing 90 (2010) 3242–3255

Contents lists available at ScienceDirect

Signal Processing

journal homepage: www.elsevier.com/locate/sigpro

# Classification of linear and non-linear modulations using the Baum–Welch algorithm and MCMC methods ☆

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ARTICLE INFO

*Article history:*
Received 25 September 2009
Received in revised form
11 May 2010
Accepted 25 May 2010
Available online 4 June 2010

*Keywords:*
Digital modulation classification
Linear and non-linear modulations
Bayesian classifiers
Markov chain Monte Carlo methods
Baum–Welch algorithm

ABSTRACT

Satellite transmissions classically use constant amplitude linear modulation schemes, such as M-state phase shift keying (M-PSK), because of their high robustness to amplifier non-linearities. However, other modulation formats are interesting in a satellite transmission context. For instance, non-linear modulations such as Gaussian minimum shift keying (GMSK) present a higher spectral efficiency and appear in new standards for telemetry/telecommand satellite links. Another example is offset-QPSK (OQPSK) modulation that allows one to decrease the out-of-band interference due to band limiting and the non-linearity of the amplifier. To get a compromise between the robustness to amplifier non-linearities provided by MPSK modulation and the spectral efficiency given by QAM modulation, the recent broadcasting satellite standard (DVB-S2) proposes new modulation schemes called APSK. Obviously, all satellite systems that use various modulation schemes will have to co-exist. In this context, modulation recognition using the received communication signal is essential. In that context, this paper studies two Bayesian classifiers to recognize linear and non-linear modulations. These classifiers estimate the posterior probabilities of the received signal, given each possible modulation, and plug them into the optimal Bayes decision rule. Two algorithms are used for that purpose. The first one generates samples distributed according to the posterior distributions of the possible modulations using Markov chain Monte Carlo (MCMC) methods. The second algorithm estimates the posterior distribution of the possible modulations using the Baum–Welch (BW) algorithm. The performance of the resulting classifiers is assessed through several simulation results.



## 1. Introduction

Satellite transmissions classically use constant amplitude modulation schemes because of their high robustness to amplifier non-linearities. Linear phase modulation, or M-state phase shift keying (M-PSK), are the most widely used. However, some non-linear modulation formats appear in new standards for satellite communications. For example, Gaussian minimum shift keying (GMSK) is a new modulation standard for telemetry/telecommand satellite links. This class of modulation is very interesting for satellite transmissions. It is actually very robust to amplifier non-linearities. With proper choice of parameters, it also allows one to obtain higher spectral efficiency than that obtained with the traditional M-PSK schemes. Particularly, the choice of a pre-modulation Gaussian filter, associated to a modulation index $h=\frac{1}{2}$,

☆ This work was partially supported by the French Space Agency (CNES, Toulouse, France).

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doi:10.1016/j.sigpro.2010.05.030

leads to a modulation with a very interesting compact power spectral density. Two different GMSK schemes, characterized by two different normalized bandwidths *BT*, have been adopted by the consultative committee for space data system (CCSDS) for future space missions [1]. More precisely, for the packet telemetry for space-to-earth links, the CCSDS recommends the GMSK modulation with $BT=0.25$ (denoted GMSK25) for spacecrafts orbiting at the altitude below $2\times 10^6$ km and the GMSK modulation with $BT=0.5$ (denoted GMSK50) at the altitude above $2\times 10^6$ km. Another interesting modulation for satellite transmissions is the offset-QPSK or OQPSK. This modulation is a linear phase modulation similar to QPSK, except that some phase changes are not allowed between two consecutive symbols. This property leads to OQPSK modulated signals that are less sensitive to spectral sidelobe spreading than QPSK signals.

Thus the out-of-band interfering due to band limiting and the non-linearity of the amplifier is decreased. Quadrature amplitude modulations (QAM) are very interesting compared to PSKs because of their higher spectral efficiency. However, they are not use in a satellite context because of their sensitivity to amplifier non-linearities. The new satellite standard for broadcasting referred to as DVB-S2 defines a kind of compromise between PSK and QAM modulations called APSK. APSK are amplitude and phase modulations defined by a reduced set of possible amplitude values compared to QAM. As all satellite systems using various modulation formats will have to co-exist, it is important to be able to recognize the modulation associated to the received communication signal. In particular, identifying the modulation is important for spectrum monitoring to check whether the user is authorized to send this modulation. The modulation classification problem is also interesting in non-cooperative scenarios where there is an emerging need for intelligent modem capable of quickly discriminated signal types [2]. The application considered in this paper is spectrum monitoring. Our objective is to identify the constellation of a received communication signal assuming this constellation belongs to a known dictionary. Various strategies have been proposed in the literature for the classification of linear modulations. The most popular modulation classifier (often referred to as *optimal classifier*) is probably the Bayes classifier that minimizes the average probability of error (or an appropriate average cost function). However, the Bayes classifier is difficult to implement due to its high computational complexity. Moreover, it is not robust to model mismatch due to transmission impairments, such as synchronization errors or residual channel. To overcome the difficulties inherent to the Bayesian classifier, several suboptimal likelihood-based classifiers have been proposed in the signal processing and communication literature (see for example [3–6]). An alternative to likelihood based classifiers is to extract interesting features from the observations and to use these features for classification. In this case, the key point is to find the "appropriate" set of features depending on the considered communication system. Many features have been proposed in the literature, including statistical moments [7] or higher-order statistics [2].

This paper studies new strategies to classify linear and non-linear modulations. The first strategy is based on a practical suboptimal Bayes classifier using a "plug-in" rule initially proposed in [8]. It can be applied to recognize *M*-PSK classical schemes, as well as *M*-QAM (*M* states QAM) or *M*-APSK (*M* states APSK) modulations. The main idea is to estimate the unknown model parameters by Bayesian estimation combined with Markov chain Monte Carlo (MCMC) methods. The estimated parameters are then plugged into the posterior probabilities of the received modulated signal (conditionally to each class). The classical maximum *a posteriori* (MAP) classification rule is finally implemented with these estimated probabilities. Unfortunately, the complexity of this MCMC classifier may be prohibitive for some practical applications. To overcome this difficulty, we consider a new digital modulation classifier based on hidden Markov models (HMMs) to classify linear modulations transmitted through an unknown finite memory channel and corrupted by additive white Gaussian noise (AWGN). This classifier is based on a state trellis representation, allowing one to use a modified version of the Baum–Welch (BW) algorithm (proposed in [9] for speech recognition) to estimate the posterior probabilities of the possible modulations. These posterior probabilities are then plugged into the optimal Bayes decision rule. This BW classifier, initially introduced in [10], is interesting since it can be used to recognize OQPSK modulation from other linear phase modulations. Indeed, since some transitions are not allowed in case of OQPSK, a distinct state trellis representation from QPSK can be defined. The BW classifier then exploits this state trellis representation for modulation classification.

Classifying non-linear modulations has received less attention in the literature. Several methods for classifying full response binary CPMs with rectangular pulse shape and different modulation indexes have been studied in [11,12]. A classifier based on an approximate likelihood function for a multiple M-ary frequency shift keying (MFSK) signal propagating through a Rayleigh fading channel has been developed in [13]. However, classification problems involving GMSK modulations have not been considered in the literature (to the best of our knowledge). Exploiting the fact that GMSK modulation is a modulation with memory, the BW classifier can be used for classifying the two non-linear GMSK modulations recommended by CCSDS. Finally, we show that linear modulations used in satellite systems (BPSK, QPSK, 8PSK, OQPSK), as well as the non-linear standardized GMSK modulation schemes, can be identified using the same recognition process (the problem was initially introduced in [14]). By associating a first order HMM to the received baseband communication signal, the BW classifier can be used to estimate the posterior distribution of the received GMSK communication signals. The BW method for HMM can also provide as a by-product the sequence of estimated transmitted symbols using the MAP criterion.

This paper is organized as follows: Section 2 gives some useful information regarding the linear and non-linear modulations considered in this study. Section 3 presents a model of the received baseband communication