# Trellis-Coded Modulation in PSK and DPSK Communications

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**Abstract** *Coded modulation is for the first time investigated in phase-modulated systems, with coherent as well as differential detection. We find coding gains of 3.0 and 1.7 dB, already with the simplest possible trellis code.*

## Introduction

Coded modulation is the technique of codesigning error-correcting codes and modulation formats, so that the strongest error protection is applied to the bits that would be most error-prone in an uncoded system [1]. Because any such method has to build upon a multilevel modulation format, a relatively large coding overhead can be accepted without sacrificing bandwidth and dispersion tolerance. One attractive approach is to simply cascade a multilevel modulator with an error-correcting code, as was proposed for fiber-optical systems in [2,3]. With coded modulation, however, similar coding gains can be achieved with less overhead or lower complexity.

The only study of coded modulation for optical systems so far is [4], where a trellis-coded modulation (TCM) system based on 8-level polarization shift keying was investigated. In this paper, we demonstrate, for the first time, the use of coded modulation in a phase-modulated fiber-optical system. This setting differs from the corresponding wireless systems in the implementation of the transmitter, the optical and electric receiver filters, and the optical noise source. In addition to coherent reception, we also study noncoherent (differential) modulation which is of particular interest in optical systems due to the simplified optical receiver implementation, but which has almost never been used for TCM.

## Simulation Setup

A back-to-back fiber system is studied, and we focus our discussion on the linear regime. Fig.1 illustrates the transmitter and receiver structures of the coded systems, where the TCM encoder has a code rate of 2/3, i.e., the coding overhead is 50 percent. As shown in the figure, the encoded data stream with a rate of 30 Gb/s is modulated into a symbol stream of rate 10 Gsymbols/s by the optical 8PSK transmitter, which has same setup as in [5, fig.3 (a)]. The differential precoder (dashed in Fig.1) exists only in noncoherent systems. Note that the coded systems use natural bit mapping rather than Gray mapping, as the consequence of the set partitioning (see below).

In the receiver, the gain and noise figure of the EDFA pre-amplifier are set to be 30 dB and 5 dB, and we use 1550 nm carrier wavelength. The optical bandpass filter has a Gaussian shape and a 40 GHz 3 dB bandwidth. For coherent systems, the optical

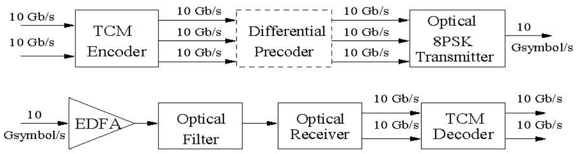


*Fig.1 Transmitter and receiver structure of the simulated coded systems.*

receiver uses a local oscillator to recover the carrier phase and obtain the transmitted signal phase (see [6] for more details), while for the differential detection systems, since soft information is required by the TCM decoder, two delay interferometers with 0 and $\pi/2$ phase difference are used to recover the real and imaginary information of the transmitted signal. The TCM decoder is a conventional Viterbi decoder, which has been widely used in wireless communications [7, sec. 8.2.2]. We will compare the performance of the TCM coded system with a QPSK modulated system, which has the same transmitted information rate of 20 Gb/s.

## Trellis-Coded Modulation

Trellis-coded modulation (TCM) has been well developed in digital transmission over bandwidth-limited channels. By combining coding and modulation techniques, using a simple convolutional encoder and a conventional Viterbi decoder, TCM achieves coding gains from 3 dB to 6 dB without sacrificing transmission bandwidth [1].

The core of constructing TCM is a signal mapping method called set partitioning, which aims at maximizing the signal separation between the modulation levels in signal space. The separation determines the bit-error-rate (BER) performance at high signal-to-noise ratio. We show an 8PSK set partitioning in Fig.2, where eight modulation levels are partitioned bitwise from set A into subsets B, C, and D such that the signal separation within each subset is maximized. Note that the signal separation in set B, d2, corresponds to the uncoded QPSK system. The idea behind 8PSK TCM is to combine coding with bit mapping such that the signal separation is increased compared with d2. For example, the signal separation of the simplest possible TCM 8PSK (its encoder has 4 trellis states [1]) is equal to d3, which gives an asymptotic coding gain of 3dB [1]. In this paper, the simplest 4-state TCM, as well as a rather simple 16-state TCM (their encoders can be found in [1]), are applied to 8-level PSK and DPSK fiber systems.

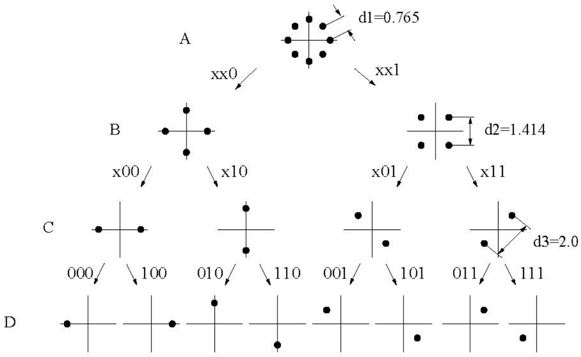


*Fig.2 Set partitioning of 8PSK signals. The indices of the arrows represent the encoded bits (x stands for unkown bits).*

**Simulation Results**

The back-to-back coded system described above is investigated with Monte-Carlo simulations, for both coherent and differential receivers. We use random independent data for all the simulations and each BER was estimated until 50-100 bit errors had occurred.

The simulated BER of coded and uncoded systems versus the EDFA input power is shown in Fig.3. Details on implementing the transmitters and receivers of uncoded DQPSK systems can be found in [3]. For uncoded 8DPSK system, we used the transmitter in [5] and the receiver in [8]. For coherent systems, the coded systems obtain coding gains of 3.0 dB (4-state TCM) and 3.5 dB (16-state TCM) when targeting a BER of $10^{-7}$ compared with the uncoded QPSK system. For noncoherent systems, the TCM 8DPSK at a BER of $10^{-7}$ gains about 1.7dB (4-state TCM) and 2.2 dB (16-state TCM) compared to the uncoded DQPSK system.

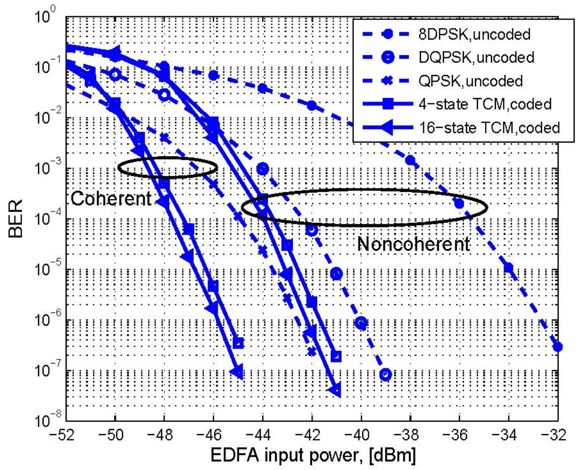


*Fig.3 Performance of the coded and uncoded systems with coherent and noncoherent detection.*

When comparing the spectrum of the optical signal in the coded and uncoded systems, as seen in Fig.4, we see the similarity of the spectrum width and side-lobes. This property indicates that the dispersion effects for the coded system should be similar to the uncoded systems when they have the same symbol rate. In addition, coded multilevel DPSK systems have been found to have an increased dispersion robustness compared to 2-level DPSK systems [3].

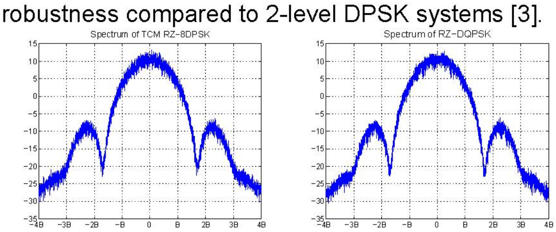


*Fig. 4 Spectrum of coded and uncoded systems.*

**Discussion**

The use of 8PSK TCM in a back-to-back fiber-optic communication system was investigated numerically. A more than 3 dB (for coherent systems) or 2 dB (for noncoherent systems) coding gain is achieved with simple encoders and decoders, without sacrificing transmission bandwidth. Much higher gains can be attained at the price of more complex TCM schemes. If the quantization of soft information in the decoder is taken into account, a penalty of 0.2 dB for 4-bit quantization is incurred [2].

We are aware of no other systems that obtain the same power and bandwidth efficiencies with a comparable transceiver complexity. A rate 2/3 convolutional code cascaded with 8PSK modulation would use the same bandwidth, but the implementation of such a code is more complex. The reason is not only that puncturing or parallel input streams are needed [7, Sec. 8.2], but also that it wastes strong error protection on bits that are well separated in signal space. Compared with Reed-Solomon (RS) coding, TCM offers a simpler encoder and works better at low power levels [3]. Furthermore, the relatively short memory of the TCM-coded bits streams studied in this paper makes TCM an attractive candidate for the inner code in a serially concatenated coding scheme, without the need for a large interleaver.

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