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M-ary (D)PSK modulation in coherence multiplex systems

Arjan Meijerink, Geert Heideman and Wim van Etten
University of Twente, Department of Electrical Engineering,
Telecommunication Engineering Group,
P.O. Box 217, 7500 AE Enschede, The Netherlands
`a.meijerink@ieee.org`

Coherence multiplexing (CM) is a relatively unknown form of optical CDMA, which is particularly suitable in medium bitrate, small-scale optical networks like access networks, LANs or optical interconnects. Previously proposed CM systems for transporting digital data were based either on binary (D)PSK or OOK modulation. In this paper, it will be shown how M-ary (D)PSK modulated signals (with $M > 2$) can be demodulated in a CM receiver, using a 4×4 optical hybrid. Expressions for the BER floor will be derived, both for a phase synchronous as well as a phase diversity receiver.

1 Introduction

Coherence multiplexing (CM) is a simple form of optical code division multiplexing, in which broadband sources and delay-lines are used to multiplex signals from distinct users over one optical fiber cable [1]-[4]. An example of a well-known CM-configuration is shown in Figure 1, which depicts one transmitter and one receiver. The transmitter consists of a broadband lightsource (for example an LED) and a Mach-Zehnder interferometer (MZI) having a path-imbalance T_{tr} which is much larger than the coherence time τ_{c} of the source. Moreover, one of the paths contains an in-line modulator which inpresses a phase modulation $\phi_{\text{mod}}(t)$ on the lightwave taking the lower path of the MZI. Therefore, the two lightwaves that are launched into the transmission fiber are mutually incoherent, such that the phase modulation $\phi_{\text{mod}}(t)$ does not result in a visible intensity modulation in the transmitted signal. The receiver consists of an MZI, having path-imbalance $T_{\text{re}} \gg \tau_{\text{c}}$, and a balanced photodiode pair. It can be proven that the combination of the rightmost 2×2-coupler and the photodiodes acts as a balanced mixer [1, 2]. Hence, the output signal of the receiver only contains zero-mean interferometric noise when the difference between T_{tr} and T_{re} is much larger than τ_{c}, as all lightwaves mix incoherently in that case. When that difference is much smaller than τ_c, however, the lightwave taking the upper path in the transmitter and the lower path in the receiver mixes coherently with the lightwave taking the lower path in the transmitter and the upper path in the receiver. The resulting output signal has an expected value which is then given

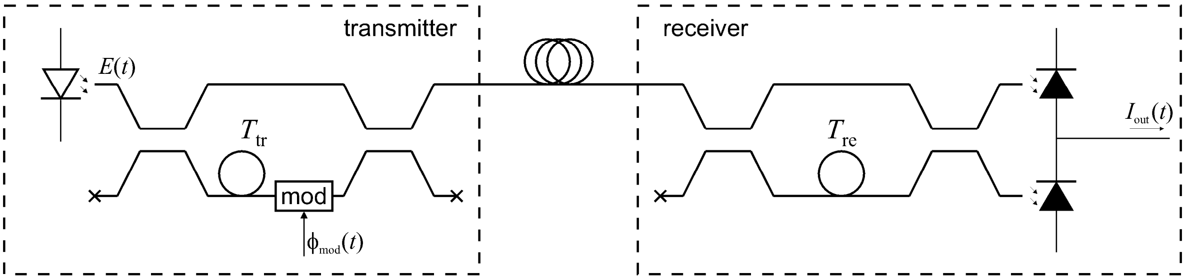

Figure 1: Coherence multiplex system with one transmitter and one receiver

by $\mathrm{E}[I_{\mathrm{out}}(t)] = A\sin(\Delta\phi(t))$, where A is proportional to the received power and the responsivities of the photodiodes [2]. $\Delta\phi(t)$ is the phase difference between the coherently mixed lightwaves, which is given by $\Delta\phi(t) = 2\pi f_{\mathrm{c}}\,(T_{\mathrm{re}} - T_{\mathrm{tr}}) + \phi_{\mathrm{mod}}(t) + \frac{\pi}{2}$, where f_{c} is the carrier frequency of the light. Hence, information transmission can be accomplished by performing binary phase shift keying (BPSK) modulation in the transmitter ($\phi_{\mathrm{mod}} = 0$ for a binary one and $\phi_{\mathrm{mod}} = \pi$ for a binary zero), and by carefully controlling the relation between T_{tr} and T_{re}, for example by means of a feedback loop from the output signal to T_{re}. In that case, the expected output signal is $A\cos(\phi_{\mathrm{mod}}(t))$, which is a baseband polar NRZ signal taking values $+A$ and $-A$ that correspond to the transmitted information. Using multiple transmitters, several channels can be multiplexed onto an optical fiber cable, provided that the values of the delays in the transmitters are mutually separated by a value that is much larger than τ_{c}. So far, the only alternative modulation schemes published were OOK modulation [1]-[3] (which is not considered in this paper) and binary DPSK modulation [4]. Although the phase synchronous balanced mixer is suitable for detecting binary PSK-modulated signals, special measures are needed for detecting M-ary PSK with $M > 2$. In this paper, two methods will be described, and expressions for the corresponding BER-floors will be derived.

2 Phase synchronous detection of M-ary PSK

Phase synchronous detection of M-ary PSK can be performed by replacing the balanced mixer in Figure 1 by a double balanced mixer (see Figure 2), which consists of a 4×4 optical hybrid and two balanced photodiode pairs. It is assumed that the geometry of the optical hybrid (for example a 4×4 MMI) is such that the output currents $I_{\mathrm{I}}(t)$ and $I_{\mathrm{Q}}(t)$ have expected values $\mathrm{E}[I_{\mathrm{I}}(t)] = A\cos(2\pi f_{\mathrm{c}}(T_{\mathrm{re}} - T_{\mathrm{tr}}) + \phi_{\mathrm{mod}}(t))$ and $\mathrm{E}[I_{\mathrm{Q}}(t)] = A\sin(2\pi f_{\mathrm{c}}(T_{\mathrm{re}} - T_{\mathrm{tr}}) + \phi_{\mathrm{mod}}(t))$, respectively. These currents are matched-filtered, resulting in decision samples i_n and q_n, from which the transmitted bits can be extracted by conventional PSK-decoding [5], provided that the relation between T_{re} and T_{tr} is carefully controlled.

3 Phase diversity detection of M-ary DPSK

A detection method that does not require optical phase synchronisation is phase diversity detection [2]-[4]. In that case, differential PSK (DPSK) modulation should be performed instead of PSK [5]. For demodulation, the same configuration as in section 2 can be used, with the difference that, after matched filtering and prior to decoding, the decision samples i_n and q_n are transformed into $i'_n = i_n i_{n-1} + q_n q_{n-1}$ and $q'_n = q_n i_{n-1} - i_n q_{n-1}$, where (i_n, q_n) and (i_{n-1}, q_{n-1}) are succesive sample pairs at the outputs of the matched filters and (i'_n, q'_n) is the pair of decision samples that is applied to the decoder.

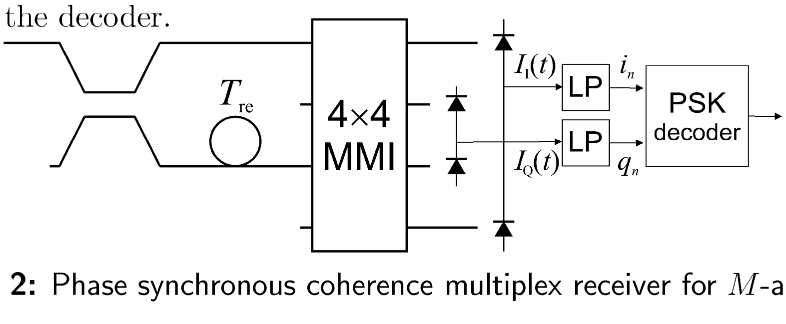

Figure 2: Phase synchronous coherence multiplex receiver for M-ary PSK

4 Performance comparison

When the received power is large, it can be proven that shot noise and receiver noise can be neglected, resulting in a system performance that is mainly limited by source-induced noise, which consists of interferometric noise (beat noise) and source intensity noise. For symbol rates R_s that are much lower than the inverse of the path-imbalances of the MZIs (which have to be much smaller than the 3-dB bandwidth of the source Δf), the double-sided power spectral density (psd) function of the noise can be shown to be flat over the information band. When the lightwaves are modeled as polarized thermal light with a Gaussian spectrum, and when it is assumed that the lightwaves entering the receiver have matched polarization states and identical power, then it can be proven that the output currents of the two photodiode pairs have only negligible correlation and have approximately identical noise psds that are given by [4]

$$S_{I_\mathrm{I}}(0) \approx S_{I_\mathrm{Q}}(0) \approx \sqrt{\frac{\ln 2}{2\pi}} \left(4N^2 + 2N + 1\right) \frac{A^2}{\Delta f} \quad , \tag{1}$$

where N is the number of simultaneous active users. Consequently, the signal-to-noise ratio per symbol is given by

$$\gamma_\mathrm{s} = \frac{E_\mathrm{s}}{N_0} = \frac{A^2 T_\mathrm{s}}{2 S_{I_\mathrm{I}}(0)} = \frac{k\sqrt{\frac{\pi}{2\ln 2}}}{4N^2 + 2N + 1} \frac{\Delta f}{R_\mathrm{b}} \quad , \tag{2}$$

where T_s is the symbol time, k is the number of bits per symbol (so $M = 2^k$) and R_b is the bitrate. As the matched filter bandwidth R_s is much smaller than the bandwidth of the noise (which is in the order of the source bandwidth Δf), the decision samples i_n and q_n can be assumed to be Gaussian distributed and -since they have only negligible correlation- independent. As a result, the BER floors can be found by using the general results for coherent detection of PSK and non-coherent detection DPSK in AWGN [5]. Hence, the BER floors for phase synchronous detection of M-ary PSK are

$$\mathrm{P}_{\mathrm{e,BPSK,ps}} = \mathrm{P}_{\mathrm{e,QPSK,ps}} = \mathrm{Q}\left(\sqrt{\frac{2\gamma_\mathrm{s}}{k}}\right) \quad , \tag{3}$$

and

$$\mathrm{P}_{\mathrm{e,MPSK,ps}} \approx \frac{2}{k} \mathrm{Q}\left(\sqrt{2\gamma_s} \sin\left(\frac{\pi}{M}\right)\right) \quad , \tag{4}$$

and the BER floors for phase diversity detection of M-ary DPSK are

$$\mathrm{P}_{\mathrm{e,2-DPSK,pd}} = \frac{1}{2} \exp\left(-\gamma_\mathrm{s}\right) \quad , \tag{5}$$

$$\mathrm{P}_{\mathrm{e,DQPSK,pd}} = \frac{1}{2} \exp\left(-\gamma_\mathrm{s}\right) \left(\mathrm{I}_0\left(\frac{\gamma_\mathrm{s}}{\sqrt{2}}\right) + 2\sum_{n=1}^{\infty} \left(3 - 2\sqrt{2}\right)^n \mathrm{I}_n\left(\frac{\gamma_\mathrm{s}}{\sqrt{2}}\right)\right) \quad , \tag{6}$$

and

$$\mathrm{P}_{\mathrm{e,M-DPSK,pd}} \approx \frac{2}{k} \mathrm{Q}\left(\sqrt{\gamma_\mathrm{s}} \sin\left(\frac{\pi}{M}\right)\right) \quad , \tag{7}$$

where Q(z) is defined as

$$\mathrm{Q}\left(z\right) \triangleq \frac{1}{\sqrt{2\pi}} \int_{z}^{\infty} \exp\left(-\frac{x^2}{2}\right) \mathrm{d}x \tag{8}$$

and $\mathrm{I}_n(x)$ is the modified Bessel function of the first kind and order n. Note that (3) corresponds to the result that Pendock [1] found for BPSK modulation, and (5) was previously found in [4]. (4) and (7) are approximations which only hold for small BERs. The numerical values for the SNR per symbol γ_s that are required in order to achieve $\mathrm{P_e} = 10^{-9}$ are shown in Table 1, for several values of M, both for phase synchronous detection of PSK and phase diversity detection of DPSK.

Table 1: Required γ_s for $\mathrm{P_e} = 10^{-9}$ when M-ary (D)PSK modulation is used

M	2	4	8	16	32
Required γ_s for PSK	18	36	120	455	1781
Required γ_s for DPSK	20	60	240	910	3562

The corresponding bitrates R_b can be found using (2). (So, for example, a system with $N = 8$ users and source linewidths of $\Delta f = 5$ THz (which corresponds to 40 nm around a center wavelength of 1.55 μm), performing (D)QPSK modulation, can achieve bitrates R_b of at most 1.5 Gbps when a phase synchronous receiver is used and 0.9 Gbps when a phase diversity receiver is used.)

5 Conclusion and discussion

It is shown that it is possible to demodulate coherence-multiplexed M-ary (D)PSK modulated signals, by using either a phase synchronous receiver or a phase diversity receiver. The BER analysis shows, however, that in a coherence multiplex system with negligible dispersion and high received power, both detection methods result in network capacities that decrease with increasing M. The difference in performance between the two detection methods is small, particularly for $M = 2$. A particular advantage of increasing M, however, is that the symbol time increases, such that both the modulation speed and the clock frequency of the detection electronics can be reduced. Moreover, increasing the symbol time causes the detected signal to become less susceptible for fiber dispersion; this will be considered in a later paper. A disadvantage is that the receiver's processing complexity increases with increasing M, and that a higher accuracy of the modulator in the transmitter and the phase synchronisation mechanism in the receiver is required.

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