

# Performance comparison of the cascaded MZI based OCDMA system using multimode and singlemode fibers

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*In this paper we compare the performances of the spectrally encoded optical CDMA system with respect to optical beat noise (OBN) and dispersion limitation for two different types of optical fibers, namely singlemode and multimode. The analyzed OCDMA system is based on cascades of MZIs and uses broadband light sources and integrated optical components. Modulation is performed in the electrical domain. Although the use of multimode integrated components in combination with multimode fibers seems to be a better solution with respect to OBN, their poor performance in the presence of dispersion necessitates the use of singlemode counterparts.*

## Introduction

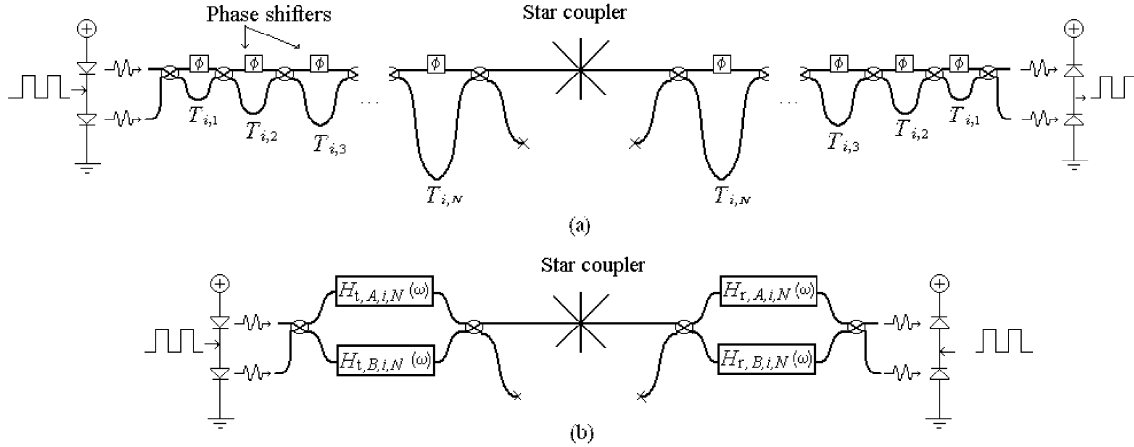
In order to make the optical CDMA system economically attractive the researchers now mainly focus their work on spectral coding of broadband light sources [1, 2]. Such a system has the advantage of being simple, inexpensive and can be realized using optical integrated components. The spectral coding is performed in the optical domain by passive optical filters.

In our system modulation is performed in electrical domain at the data rate and the spectrum of the signal is encoded and decoded using Mach-Zehnder (MZ) filters. This is presented in Fig. 1(a). In the same figure we have presented this system as a generalized coherence multiplexing system [3] for the sake of simplicity of analysis.

Presented system can best be applied in access and local area networks (LANs), due to their relatively short span and bit rates up to 1 Gbps. Its practical implementation can rely on singlemode fibers and singlemode devices, or their multimode counterparts. The interest in using multimode fibers in the "last mile" rises from the fact that they are less sensitive to misalignment and dust particles, can be easily coupled to the light sources and other integrated multimode devices and can be used in combination with low cost short wavelength LEDs and VCSELs. Moreover, as the research and development of new multimode integrated optical components becomes more attractive, the multimode fibers are supposed to be significant in bringing information to the user.

On the other side, it is well known that modal dispersion and high chromatic dispersion at short wavelength limit the performance of multimode graded-index fibers. However, in combination with LEDs they still can operate satisfactorily in short-distance, higher bandwidth systems.

In this paper we will investigate the performance of the OCDMA system presented in Fig. 1. based on multimode fibers and compare it with its single-mode counterparts. We will show that modal dispersion in multimode fibers reduces the optical beat noise



**Figure 1: (a) Schematic diagram of the spectrally encoded OCDMA system based on a MZ en/decoder, (b) equivalent generalized coherence multiplexing scheme.**

(OBN), the main limiting factor in the spectrally encoded OCDMA systems, but at the same time hinders the decoding process disabling the practical implementation of the system for larger distances. This provokes the necessity of using single-mode fibers that are more susceptible to OBN, but have much smaller chromatic dispersion.

### Analysis of the system with multimode fiber

The dispersion effect on signal transmission in multimode fiber has already been calculated in [4]. This will help us to analyze how the OCDMA system, presented in Fig. 1. will perform in the presence of dispersion. We will mainly concentrate on the effect of the modal dispersion on OBN and material dispersion on decoding process in which the wanted signals have to be separated from the interfering ones, based on orthogonality of codes.

To simplify the analysis we will assume that all the modes in the fiber are guided without mutual mode coupling and that the transmitted power is equally distributed among modes. For the broadband light source model we have taken the circular complex Gaussian bandpass process with the pre-envelope of the electrical field:

$$x(t) = [u(t) + jv(t)] e^{j2\pi f_c t} \quad (1)$$

where  $f_c$  is the carrier frequency and  $u(t)$  and  $v(t)$  are the in-phase and the quadrature components of  $x(t)$ , respectively. These components are real Gaussian lowpass wide-sense stationary processes with the spectral profiles that are symmetrical around zero. Since all the modes in the fiber are actually characterized by the fields that are spatially orthogonal to each other, interference among them cannot take place. This is very important for the calculation of the total current at the output of the correlator that consists of the last splitter and the balanced detector, which is presented in Fig. 1. This current is obtained as the result of the interference of the lightwaves in the upper and the lower branches of the MZ interferometer in the receiver after the filters. Although only the same modes in each of the branches in the MZ interferometer can interfere,

the mean value of the output current will remain the same as in the case of the system based on a single-mode fiber. Only the optical beat noise (OBN) will reduce by the factor of  $N$  where  $N$  is the number of modes in the multimode MZIs, assuming that power is equally distributed over the different modes. The final result that we have obtained for SNR is

$$\text{SNR} = \frac{E[I_r(t)]^2 T_b}{S_{I_r I_r}(0)} = \frac{N}{3 M^2 + M} \cdot \frac{T_b}{\tau_c} \quad (2)$$

where  $T_b$  is the bit period of the modulating signal and  $M$  represents the total number of users in the system.  $I_r(t)$  is the current at the output of the balanced detector. Comparing this result with the one obtained for the single-mode fiber [3] we see that SNR has improved  $N$  times. This goes in favor of the realization of the system shown in Fig. 1 using multimode fiber and components.

However, the merit of using multi-mode fibers cannot be estimated without investigating the dispersion effect on the decoding process. To do that we have to calculate the dispersion effect on the orthogonality of codes.

Modifying the expression that orthogonal codes have to satisfy [3] by invoking the dispersive multi-mode fiber transfer function we get

$$\int_0^\infty |H_c|^2 \Re(C_{t,i}^{(N)}) \Re(C_{r,j}^{(N)}) S_{x^*x}(f) df = \begin{cases} 0, & i \neq j \\ C_r, & i = j, C_r = \text{const.} \neq 0 \end{cases} \quad (3)$$

where we assumed that  $S_{x^*x}(f) = S_{x_1^*x_1}(f) = S_{x_2^*x_2}(f)$  is the psd of the input light from upper or the lower diode and subscripts  $t, i$  and  $r, j$  denote  $i$ -the transmitter and  $j$ -th receiver, respectively.  $\Re(C_{t(r),i(j)}^{(N)})$  is the real part of the complex code that always consists of the sum of products of sine and cosine functions with the argument that depends on frequency and the phase shifts

$$\Re(C_{t(r),i(j)}^{(N)}) = \sum_{i=1}^M g_i [\sin(f, \phi_{t(r),i(j)}), \cos(f, \phi_{t(r),i(j)})] \quad (4)$$

To evaluate the expression (3) we have calculated that

$$\begin{aligned} \int_0^\infty |H_c(f)|^2 S_{x^*x}(f) \Re(C_{t,i}^{(N)}) \Re(C_{r,j}^{(N)}) df = \\ = K \cdot \Re(C_{t,i}^{(N)}) \Re(C_{r,j}^{(N)}) \Big|_{f=0} \cdot \int_0^\infty e^{-\frac{2\pi f^2 (2\pi + \tau_c^2 \sigma^2)}{\sigma^2}} df \end{aligned} \quad (5)$$

where  $K$  is a constant and  $\tau_c$  is the coherence time of the source. Parameter  $\sigma$  is calculated from [3]

$$\sigma = \frac{\tau_c}{\sqrt{\pi \beta''(f_c) \cdot l}} \quad (6)$$

where  $\beta''(f_c)$  and  $l$  are the dispersion coefficient and the length of the fiber, respectively. Since  $\tau_c^2 \sigma^2 \ll 2\pi$ , for the broadband sources and  $T \ll 1/\sigma$ , we can simplify (5). The exponential term will now depend on the squared ratio  $f/\sigma$ . In the system with a negligible fiber dispersion this exponential term is a squared product of  $\tau_c f$ .

This means that we can approximate the dispersive fiber system with the one with negligible dispersion, in which the light source has a much narrower spectrum. Since, the performance of the spectrally encoded OCDMA system is directly proportional to the spectral width of the source [3], we will have a degradation in the SNR for the amount that is equal to the ratio between the dispersion coefficient and the coherence time of the source.

In order to achieve full orthogonality of codes (3), we have two possibilities.

The first possibility is to change the phase shifts from 0 to  $\pi/2$  provided that the delay lines in MZIs are carefully chosen such that their values avoid a certain pattern [3], must be much larger than the coherence time of the source and much smaller than the bit time of the modulating signal [3]. Since  $\beta''(f_c)$  is high for a graded-index multi-mode fiber at short wavelengths [5], we obviously have a significant degradation in SNR.

The second possibility to achieve orthogonality is to avoid dispersion dependence by only changing the phase shifts in one of the arms of the MZIs. In this case we have tried to find the combination of the phase shifts that will not necessarily be from  $[0, \pi/2]$  but still satisfy the following conditions:

$$\Re_0(C_{t,i}^{(N)})\Re_0(C_{r,j}^{(N)}) = 0, \Re_0^2(C_{t,i}^{(N)}) \neq 0, \Re_0^2(C_{r,j}^{(N)}) \neq 0, \Re_0(C_{t,i}^{(N)}) = 0, \Re_0(C_{r,j}^{(N)}) = 0 \quad (7)$$

where subscript 0 denotes that  $f = 0$ . Solving this system of equations we have found no solution for the phase shifts that satisfies (7), which means that we cannot achieve full orthogonality of codes by only changing the phase shifts, for any given number of stages  $N$ . This reveals the necessity of using the combination of delay lines for the code orthogonality and low dispersion fiber.

## Conclusion

In this paper we have analyzed the OCDMA system based on cascades of MZ filters and multi-mode fibers and compared it with single-mode counterpart. We have shown its much better performance with respect to OBN, but the limitation in the bit-rate (or the fiber length) imposed by the presence of dispersion puts the fiber choice in favor of the single-mode one, since it has a negligible dispersion at short distances that are typical for access and local area networks.

## References

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