ADDRESSABLE SPECTRALLY ENCODED OPTICAL CDMA SYSTEM FOR APPLICATION IN ACCESS AND LOCAL AREA NETWORKS

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ABSTRACT

In this paper we present the recursive expressions for calculating the spectral intensity codes for an OCDMA system based on cascaded MZIs. Since the sets of orthogonal codes are not unique for a specific number of sections, we present a general expression for all the possible sets of codes that might lead to a different performance of the system. We also present a general analytic expression for the SNR by calculating the psd of optical beat noise, making a framework for more thorough analysis of the system.

INTRODUCTION

The optical code-division multiple access (OCDMA) technique provides random asynchronous communication access arnong many users and is therefore very attractive for use in the access part of the PSTN and local area network (LAN) environment. In order to make the OCDMA system economically attractive and easy to implement we use spectral intensity encoded OCDMA based on encoding of the spectrum of noncoherent optical sources: such as edge emitting LEDs or Super luminescent diodes [1]-[3]. Such a system has the advantage of being simple, inexpensive and can be realized using integrated optical components. The basic elements of the system are the Mach-Zehnder (MZ) encoder and decoder.
The MZ encoder and decoder reported in [1] consist of a cascade of MZI stages designed in such a way that the path length difference (PLD)of each stage doubles that of the previous one. We have recently shown in [4], that this architecture does not represent the best solution, since it does not provide the maximum number of orthogonal codes. To obtain the maximum number of orthogonal codes the PLD values rnust avoid a certain pattern. The best pattern is the one that provides the shortest possible PLDs in order to enable practical realization of the system [4].

SPECTRAL INTENSITY CODING OCDMA BASED ON CASCADED MZIs

The OCDMA system based on spectral intensity coding is presented in Figure 1.

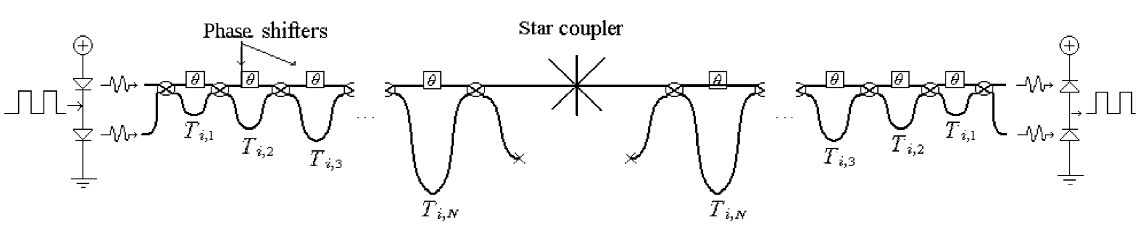

Figure 1: Schematic diagram of the spectrally encoded OCDMA system based on a MZ en/decoder.

We assume that all the delays in each stage of the MZ en/decoder are much smaller than the bit tirne.
We have to stress that spectral intensity codes are made indirectly by phase coding, i.e. changing one or more phases in the phase shifters from 0 to $\pi/2$[4]. The index i denotes the i-th transmitter and receiver that belong to 2 different users, between which a connection is established.

In this system we can associate each orthogonal code with a connection between two users with the same physical address (phase codes), so the maximal number of duplex connections between the two users with the same physical address equals maximal number of orthogonal codes.
The duplex tranrnission is enabled by placing the modulator in front of the encoder, so the complete structure is symmetrical, i.e. the same physical device can be used for transmitting and receiving signals. Modulation in the electrical dornain makes the system economically more attractive and facilitates its realization.
The greatest advantage of the architecture is that all the users use the same addressable physical device, both for transrnission and reception of signals. The addresses of the users are changed by means of changing the phase shifts, thus indirectly changing the spectral intensity code of the signal that is transmitted through the passive optical star network.
In this paper we present the possibilities for making different sets of orthogonal codes by using an analytical expression for the average received signal. The SNR will depend on the chosen set of orthogonal codes. By giving the general expression for the SNR, we made a framework for more thorough analysis of the system.

ANALYTICAL EXPRESSIONS FOR COMPLEX SPECTRAL CODES

The architecture bresented in Figure 1 can be constituted as the generalized coherence rnultinlexing scheme with two filters in'each of the branches of one MZ interferometer [6]. This is presented in Figure 2.

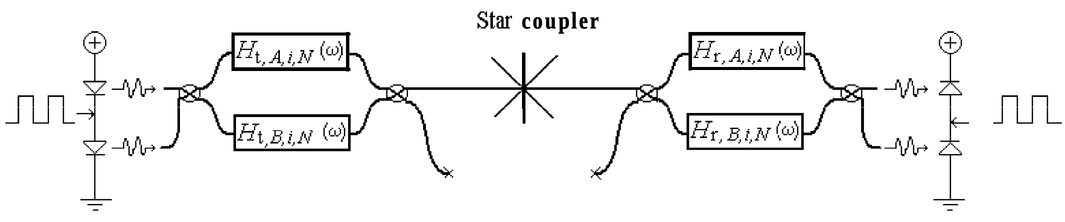

Figure 2: A generaiized coherence multiplexing system.

$H_{t(r),A,i,N}(\omega), H_{t(r),B,i,N}(\omega)$ are generalized field transfer functions of the filters in the transmitter (receiver). These transfer functions in their turn are constituted by the delays and phase shifts from each stage of the N-stage MZ transmitter (receiver). The delays and phase shifts can be represented by the filters with transfer functions:

$$\begin{aligned} H_{t(r),a,i,k}(\omega) &\triangleq e^{j\phi_{i,k}} \\ H_{t(r),b,i,k}(\omega) &\triangleq e^{j\omega T_{i,k}} \end{aligned} \tag{1}$$

where $\phi_{i,k} \in \{0, \pi/2\}, i = 1, \ldots M_{\max}$ indicates the index of a particular transmitter (receiver) when cascades are made reversed to each other, $M_{\max}$ is the maximal number of orthogonal codes (connections) [4] and $k = 1, \ldots, N$ the index of a particular stage in the N-stage MZ en/decoder. $T_{i,k}$ denotes the delays in each stage of the MZ en/decoder.
It can be shown that the generalized transfer functions of an N-stage MZ en/decoder can be obtained from the generalized transfer function of the $(N-1)$-stage MZ en/decoder as

$$\begin{aligned} H_{A,i,N}(\omega) &= \tfrac{1}{\sqrt{2}}(H_{A,i,N-1}(\omega) - H_{B,i,N-1}(\omega))H_{a,N}(\omega), \qquad N > 2 \\ H_{B,i,N}(\omega) &= \tfrac{1}{\sqrt{2}}(H_{A,i,N-1}(\omega) + H_{B,i,N-1}(\omega))H_{b,N}(\omega), \qquad N > 2 \end{aligned} \tag{2}$$

where $H_{a,N}(\omega)$ and $H_{b,N}(\omega)$ are given in (1) and the index that associates the transfer function with the transmitter or the receiver is omitted since we made this recursive formula for the receiver due to simplicity of notations.
We will now introduce the complex spectral codes, defined as

$$C_i^{(N)}(\omega) = H_{A,i,N}(\omega) H^*_{B,i,N}(\omega) \tag{3}$$

We introduced this complex spectral codes in order to facilitate the SNR calculation.

Since the recursive expressions for the generalized transfer functions $H_{A,i,N}(\omega)$ and $H_{B,i,N}(\omega)$ are known, *after* lengthy but straightforward calculation we can write (3) as

$$\begin{aligned} C_i^{(N)} &= \tfrac{1}{2}[(H_{A,i,N-1}H^*_{B,i,N-1} - H^*_{A,i,N-1}H_{B,i,N-1}) - (H_{A,i,N-2}H^*_{B,i,N-2} + H^*_{A,i,N-2}H_{B,i,N-2})]H_{a,i,N}H^*_{b,i,N} \\ &= [-\Re(C_i^{(N-2)}) + \mathrm{j}\Im(C_i^{(N-1)})]e^{-\mathrm{j}(\omega T_{i,N} - \phi_{i,N})}, \qquad N > 2 \end{aligned} \tag{4}$$

where the dependence of the transfer functions on w is omitted in the first row of **(4)** for the sake of simplicity of representation. The spectral intensity code is equal to the real part of the complex spectral code.
It is easy to conclude that it is possible to calculate complex spectral codes for the N-stage MZ en/decoder when complex spectral codes for (N -1)- and (N $-$ 2)-stage MZ en/decoder are known. Real and irnaginary parts of the complex code can be **represented as**

$$\begin{aligned} \Re(C_i^{(N)}) &= -\Re(C_i^{(N-2)})\cos(\omega T_{i,N} - \phi_{i,N}) + \Im(C_i^{(N-1)})\sin(\omega T_{i,N} - \phi_{i,N}) \\ \Im(C_i^{(N)}) &= \Re(C_i^{(N-2)})\sin(\omega T_{i,N} - \phi_{i,N}) + \Im(C_i^{(N-1)})\cos(\omega T_{i,N} - \phi_{i,N}) \end{aligned} \tag{5}$$

In order to check the orthogonality of codes we have to prove the validity of the following expression:

$$\int_0^\infty \Re(C_{\mathrm{t},i}^{(N)})\Re(C_{\mathrm{r},j}^{(N)})S_{x^*x}(\omega)\,\mathrm{d}w = \frac{C}{2\pi}\int_0^\infty S_{x^*x}(\omega)\,\mathrm{d}w = \begin{cases} 0, & i \neq j \\ C_\mathrm{r}, & i = j, C_\mathrm{r} = \mathrm{const} \neq 0 \end{cases} \tag{6}$$

where we assumed that S_{x^*x}(w) = $S_{x_1^*x_1}$ (w) = $S_{x_2^*x_2}(\omega)$ 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. With this expression we can also calculate the mean value of the current at the output of the balanced detector [4,6]:

$$\mathrm{E}[I_\mathrm{r}(t)] = \frac{R_\mathrm{pd}}{2\pi \cdot 4\ M^2_{\max}} m_i \int_0^\infty \{\Re(C_{\mathrm{t},i}^{(N)})\}^2\, S_{x^*x}(\omega)\,\mathrm{d}w \tag{7}$$

where m_i is the transmitted bit that can be ± 1 depending on whether upper or lower diode is transmitting. $M_{\max}$ is the maximal number of active users and R_pd is the responsivity of the photodiode.
The products of the real parts of the complex spectral codes will always be a sum of products of cosines [4]. After integration only the products of cosines with the arguments $\phi_{i,k} - \phi_{j,k}, k$ = 1, ... N will remain.
In order to achieve the orthogonality of codes we rnust choose the phase shifts combination at the transmitter and receiver such that at least one of the cosines in each product equals zero. For an odd number of stages (N > 1), there are more possibilities to choose these combinations and the choice should be such that it gives maximum SNR at the output of the balanced detector. For example, for the 3-stage MZ en/decoder the result of (6) will be

$$\mathrm{C} = \frac{1}{4}\cos(\phi_{i,1} - \phi_{j,1})\cos(\phi_{i,3} - \phi_{j,3}) + \frac{1}{8}\cos(\phi_{i,1} - \phi_{j,1})\cos(\phi_{i,2} - \phi_{j,2})\cos(\phi_{i,3} - \phi_{j,3}) \tag{8}$$

Vve see that this expression equais zero if either $\Delta\phi_1 = \phi_{i,1} - \phi_{j,1}$ or $\Delta\phi_3 = \phi_{i,3} - \phi_{j,3}$ is $\pi/2$ and that $\Delta\phi_2 = \phi_{i,2} - \phi_{j,2}$ is not relevant. But we can also change $\Delta\phi_2$ together with either $\Delta\phi_1$ or $\Delta\phi_3$, if that will irnprove the SNR in the system. In this example the total number of the code sets is equal to 2, but the number will increase with larger number of stages. For even number of stages the code sets are unique.

SNR CALCULATION

The rnain limiting factor in the performance of the OCDMA system is the optical beat noise (OBN). We will assume in our calculations that for the N-section MZ en/decoder, all possible duplex connections are established. In order to determine the power spectral density (psd) of OBN we will use the expression for the psd of OBN in a coherence multiplexing system [6]. Here we suppose that psd of OBN is flat in a wide frequency range and that is the reason we will evaiuate this function in zero:

$$S_{I_\mathrm{r}I_\mathrm{r}}(0) = \frac{R^2_\mathrm{pd}}{2\pi \,.\, 256\ M^4_{\max}} \sum_{i=1}^{M}\sum_{j=1}^{M}\int_0^\infty ([H_{\mathrm{r},A,l}H^*_{\mathrm{r},B,l} + H^*_{\mathrm{r},A,l}H_{\mathrm{r},B,l}]^2 |H_{\mathrm{t},A,i} - m_i H_{\mathrm{t},B,i}|^2 |H_{\mathrm{t},A,j} - m_j H_{\mathrm{t},B,j}|^2 S^2_{x^*x})\,\mathrm{d}\omega \tag{9}$$

We omitted here again the dependence on w for the sake of simplicity of representation. $m_{i(j)}$ can be ± 1 depending on whether the upper or the lower diode is transmitting and M represents the number of active users. Indexes i, j, l denote different transmitters and receivers. We again assume that the bit time T_b is much larger then the delays $T_{ik}, k = 1, \ldots. N$ in the MZ en/decoders.

Invoking (3) and simplifying the last expression we get

$$S_{I_r I_r}(0) = \frac{R_{pd}^2}{16\ M_{max}^4} \int_0^\infty \left(M^2 [\Re(C_{r,l}^{(N)})]^2 + [\Re(C_{r,l}^{(N)})]^2 \sum_{i=1}^{M} [\Re(C_{t,i}^{(N)})]^2 \right) S_{x^*x}^2(\omega)\ d\omega \tag{10}$$

Evaluating the real parts of the complex spectral codes for different number of stages N, we find that (10) can be approximated by

$$S_{I_r I_r}(0) \approx \frac{R_{pd}^2}{16\ M_{max}^4} \left(M^2 . K + M . K^2 \right) \int_0^\infty S_{x^*x}^2(\omega)\ dw. \tag{11}$$

K is a number that converges to $1/3$ for large N. We see that the first term within the brackets is the dominant one due to multiplication with a squared number of active users. We can also conclude from (11) that the psd of the OBN stays constant no matter what the number of stages in the MZ en/decoder is, provided that the number of active users is the same.

The signal-to-beat noise ratio after the integrate-and-dump filter is given by:

$$SNR = \frac{E[I_r(t)]^2\ T_b}{S_{I_r I_r}(0)} = \frac{1}{3\ M^2 + M} \cdot \frac{T_b}{\tau_c} \tag{12}$$

where T_b is the bit period and τ_c coherence time of the source [7]. We see that for a large number of users SNR decreases with three times the squared number of active users, which is two thirds worse than the SNR in the one stage coherence multiplexing system [6].

CONCLUSIONS

We gave a general representation of an OCDMA system based on MZ interferometers. Based on recursive expressions for the complex spectral codes one can easily determine the number and all possible sets of orthogonal codes and based on SNR analysis determine which one gives the best performance. We calculated that the SNR is inversely proportional to three times the squared number of active users. It is important to emphasize that the obtained results are only valid if the bit time is much larger than the delays in the MZ interferometers, which is the case in most practical realizations.

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