Spectrally Encoded CDMA System Using Mach-Zehnder Encoder Chains

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Abstract

Spectrally encoded code division multiple access (CDMA) systems using a complementary bipolar encoding mechanism has been considered the most suitable way to implement CDMA on optical fiber systems by many people. In this paper, we present a proposed bipolar complementary spectrally encoded optical CDMA system based on a cascaded Mach-Zehnder encoder chain filter and give an analysis on the capacity limit of such systems.

Keywords: optical CDMA, spectral encoding, Mach-Zehnder encoder, shot noise

1. Introduction

Spread spectrum communication systems have been successfully deployed in wireless radio communications. The optical fiber is a broadband medium with 30 to 100THz potential bandwidth. The bandwidth available in optical fiber is very much under-utilized at present. Recently, there has been tremendous interest in applying spread spectrum communications to fiber optic communications. Many spread spectrum optical code division multiple access (CDMA) systems have been proposed [1-5]. In a CDMA system, all users share the same time bandwidth concurrently. Different users are distinguished from each other by superimposing codes which are orthogonal to each other to individual data streams. The receiver removes the code by correlating the received signal with an exact copy of the code of the desired channel. Radio CDMA systems employ electrical field encoding and correlation. Since the electrical field can be both positive and negative, good codes exist which give true orthogonality and perfect cancellation of unmatched channels.

Because of the implementation difficulties of coherent optical communication systems, most of the optical communication systems are non-coherent intensity modulation and direct detection systems. Therefore, most of the optical CDMA proposals use intensity correlation of long sparse codes [1-3] which in turn require using very narrow optical pulses. Perfect orthogonality is never achieved in these systems because of the lack of negative quantities in code correlation. This gives rise to significant crosstalk penalty in these optical CDMA schemes. In order to achieve full orthogonality in a non-coherent system, a differential intensity encoded CDMA system making use of a balanced receiver that calculates the difference of two encoded spectra was introduced[4-5]. In this paper, we introduce a bipolar non-coherent spectrally encoded CDMA system using both a balanced transmitter and a balanced detector. A cascaded Mach-Zehnder chain is used as the encoder to produce

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complementary encoded spectra which represent 0 and 1 bit information in the transmission.

2. System Description

The block diagram of the system is shown in Figure 1. The transmitter consists of a pair of broadband light sources connected in a balanced fashion. The input data differentially modulate the intensity of the two balanced light sources. Examples of the broadband sources are super luminescent light emitting diodes (SLDs) and erbium doped fiber amplifiers (EDFAs) biased into super luminescent modes. The spectrum from the broadband source passes through an intensity encoder, which selectively transmits or blocks certain spectral components. When a 0 bit is transmitted, the encoder encodes the direct spectrum for transmission. When a 1 bit is transmitted, the complementary spectrum is encoded. The proposed cascaded Mach-Zehnder encoder is shown in Figure 2. In a Mach-Zehnder configuration, the two outputs are complementary to each other. Moreover, the output spectra at the two output ports switch to the complementary when the input light source is changed from one input port to the other. So by differentially turning on and off the two light sources in the balanced transmitter, complementary outputs are generated for binary input digits.

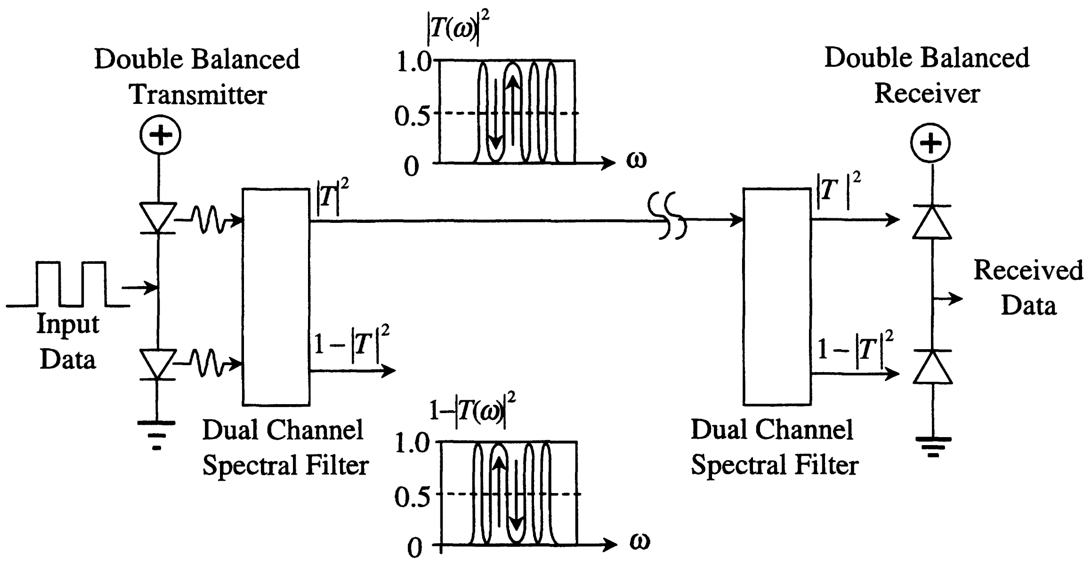

Figure 1. Block diagram of spectrally encoded fiber optic CDMA system

Each stage of the Mach-Zehnder encoder is made programmable by incorporating a phase-shifter in one arm of the Mach-Zehnder configuration. The phase shifters can be made using eletro-optic or thermo-optic effects. Changing the bias to the phase shifters produces different codes. The output spectral intensity changes in a complicated way with the phase shifter biases.

The intensity encoded spectra are broadcast to the receivers using a star coupler. The receiver uses the same spectral encoder to recover the data from the transmitter whose code setting matches the receiver code setting. In this case, the balanced receiver will detect a positive or negative output depending on whether the direct spectrum or its complementary is transmitted. If the receiver code setting is not matched to the transmitter code setting, the received energy will split equally at the two output ports of the receiver and will be cancelled at the balanced transmitter output.

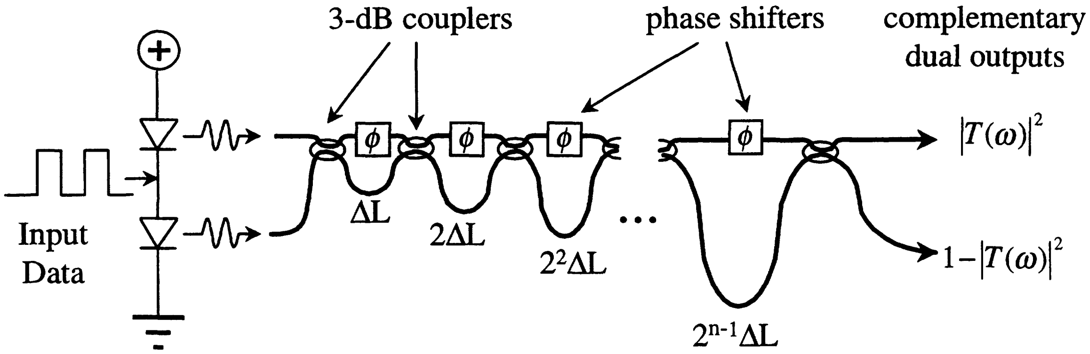

Figure 2. Multi-stage Mach-Zehnder spectral encoder

3. Theory

Optical systems using intensity modulation and direct detection are unipolar systems. The intensity transfer function of the spectral filter has a frequency dependent value between 0 and 1. We also know that the two outputs of a Mach-Zehnder interferometer are complementary to each other and they interchange when the input light source is changed from one input port to the other. The complementary transfer functions of the ith encoder can thus be represented as:

$$T_i(\omega) = \frac{1}{2} + f_i(\omega) \quad (1)$$

and $$\overline{T_i(\omega)} = \frac{1}{2} - f_i(\omega) \quad (2)$$

where ω is the angular frequency and $-½ \le f_i(\omega) \le ½$. We have chosen ½ as the reference level for the transfer function.

If the broadband source has a power spectral density $s(\omega)$ in the frequency range from ω_1 to ω_2, the encoded signals for the ith channel when a 0 bit and a 1 bit are transmitted are:

$$X_i^0(\omega) = s(\omega) \bullet T_i(\omega) \quad (3)$$

and $$X_i^1(\omega) = s(\omega) \bullet \overline{T_i(\omega)} \quad (4)$$

The balanced detector output of the jth receiver due to the ith transmitter is:

$$Y_{ji} = \int_{\omega_1}^{\omega_2} \Re X_i(\omega)\left[T_j(\omega) - \overline{T_j(\omega)}\right]d\omega \quad (5)$$

where $\Re$ is the responsivity of the balanced photodetectors.

Assuming $s(\omega)=1$ and the responsivity $\Re$ is constant in the frequency range of interest, the output is:

$$Y_{ji} = \begin{cases} \Re\int_{\omega_1}^{\omega_2} f_j(\omega) + 2f_i(\omega)f_j(\omega)d\omega & \text{0 bit} \\ \Re\int_{\omega_1}^{\omega_2} f_j(\omega) - 2f_i(\omega)f_j(\omega)d\omega & \text{1 bit} \end{cases} \quad (6)$$

For big enough encoding spectral range ω_2-ω_1, i.e. ω_2-ω_1 >> $1/\tau_{min}$ where τ_{min} is the time delay introduced by the encoder stage with the least propagation path imbalance, $\int_{\omega_1}^{\omega_2} f_i(\omega)d\omega \approx 0$. Therefore, orthogonal codes are obtained when $f_i(\omega)$ and $f_j(\omega)$ are orthogonal:

$$\int_{\omega_1}^{\omega_2} f_i(\omega)f_j(\omega)d\omega = 0 \qquad i \neq j \tag{7}$$

In this case, the input power spectrum due to an unmatched channel is split equally at the two optical output ports of the receiver.

For the matched transmitter and receiver pairs, the detected signal is:

$$Y_i = Y_{ii} = \begin{cases} +2\Re\int_{\omega_1}^{\omega_2} f_i^2(\omega)d\omega & 0\text{ bit} \\ -2\Re\int_{\omega_1}^{\omega_2} f_i^2(\omega)d\omega & 1\text{ bit} \end{cases} \tag{8}$$

which is bipolar.

In our encoder set-up, different codes are produced by adding $\pi/2$ phase shifts to individual Mach-Zehnder stages.

4. Multiple Access Interference

In this section, we discuss the multiple access crosstalk induced by shot noise. We assume that each receiver receives equal power P from each transmitter. In the best case, all the codes are orthogonal to each other and we assume this is the case. Ideally, when the transmitter code and the receiver codes are matched to each other, all the received power P goes to either the upper or the lower photodetector of the receiver (which happens when $f_i(\omega)=\pm½$ in equations (1) and (2)) depending on whether a 0 or 1 is sent by the transmitter. Otherwise, the balanced receiver will receive equal power P/2 by both of its photodetectors. This is true whether the unmatched transmitter transmits a 0 or a 1.

Suppose there are K+1 active users of which K are unmatched interfering users. If a 0 is detected, the upper and lower detectors will detect power,

$$P_U = P_U^0 = P + \frac{K}{2}P \tag{9a}$$

and $$P_L = P_L^0 = \frac{K}{2}P \tag{9b}$$

respectively.

Similarly, if a 1 is transmitted:

$$P_U = P_U^1 = \frac{K}{2}P \tag{10a}$$

and $$P_L = P_L^1 = P + \frac{K}{2}P \tag{10b}$$

The output photocurrent for a transmitted 0 is:

$$
\begin{aligned}
I_{sig} &= I_U - I_L \\
&= \Re P_U - \Re P_L \\
&= \begin{cases} +\Re P & \text{for a 0 bit} \\ -\Re P & \text{for a 1 bit} \end{cases}
\end{aligned} \tag{11}
$$

In either case, the shot noise in the output is given by [6]:

$$
\begin{aligned}
\langle I_{sh}^2 \rangle &= \langle I_{sh-U}^2 \rangle + \langle I_{sh-L}^2 \rangle \\
&= 2qI_U B + 2qI_L B \\
&= 2q\Re P(1+K)B
\end{aligned} \tag{12}
$$

where q is the electronic charge and B is the bandwidth of the receiver. Thus the shot noise is multiplied by the total number of active users (K+1). The signal detected is $I^2_{sig} = \Re^2 P^2$ which goes as the square of the input optical power.

Another major source of noise in optical communication is the receiver front-end thermal noise. This is given by [6]:

$$
\langle I_{th}^2 \rangle = \frac{4kT}{R_L} B = 8\pi kTB^2 C \tag{13}
$$

where k is the Boltzman constant, T the temperature and R_L the receiver load resistance. We have also used $B = 1/T_b = 1/2\pi R_L C$ in (13) where T_b is the bit period and C is the load capacitance. For state of the art technology, C is in the order of 0.02pF.

The total noise is:

$$
\langle I_n^2 \rangle = \langle I_{sh}^2 \rangle + \langle I_{th}^2 \rangle \tag{14}
$$

Assuming a large number of active users so that the Poisson distribution of shot noise can be approximated as Gaussian, for a bipolar signaling scheme, the bit error rate is given by [7]:

$$
BER = Q\left(\sqrt{\frac{2E_b}{N_0}}\right) \tag{15}
$$

where

$$
Q(x) = \frac{1}{2}[1 - erf(\frac{x}{\sqrt{2}})] \tag{16}
$$

and $E_b = \wp T_b$. Here, $\wp$ is the electrical power proportional to I^2_{sig}. N_0 is the two-sided noise spectral density. Therefore,

$$
\begin{aligned}
\frac{E_b}{N_0} &= \frac{\wp T_b}{N_0} = \frac{I_{sig}^2 R_L}{BN_0} \\
&= \frac{I_{sig}^2}{\langle I_n^2 \rangle}
\end{aligned} \tag{17}
$$

Assuming a received optical power of -20dBm (10μW) per active user, the photodetector responsivity 0.8(A/W) for an InGaAs PIN photodiode working at 1.5μm wavelength range, and a receiver bit rate of 10Gbps, the thermal noise is $\langle I^2_{th} \rangle = 2.09\times10^{-13}$ A^2 for C = 0.02pF and the shot noise is $\langle I^2_{sh} \rangle = 2.56\times10^{-14}$ A^2 in the absence (K = 0) of interfering unmatched users. It can be seen that the shot noise quickly overwhelms the thermal noise when more than eight (K > 7) users are simultaneously transmitting on the network. Figure 3 plots the BER against the number of active users for different received power levels per channel at 10Gbps per channel. It is seen from Figure 3 that for -20dBm received power per channel, 71 concurrent users are allowed for a BER less than 10^{-15} and 130 concurrent users are allowed for a BER less than 10^{-9}. It is worth noticing that this is the worst case situation. For a system with bursty traffic, the number of concurrent users will likely to be much less than the total number of subscribers most of the time.

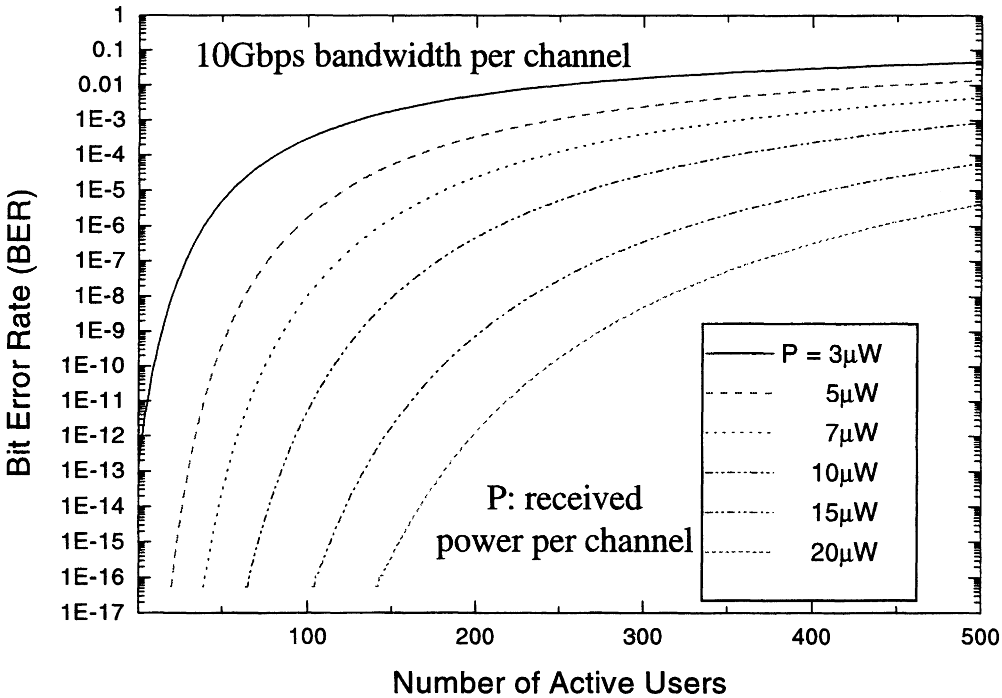

Figure 3. Bit Error Rate (BER) vs. the number of active users in the network for different received power (P) per channel. Assume 10Gbps data rate in each channel.

It is seen from the above analysis that the SNR is shot noise limited when the total received optical power P(K+1) is large and is approximately given by:

$$SNR \approx \frac{I^2}{\langle I_{sh}^2 \rangle} = \frac{\Re P}{2q(K+1)B} \tag{18}$$

The total network throughput is given by (K+1)B. For a given BER performance requirement, the minimum allowed SNR is fixed. The network throughput scales linearly as the per channel received optical power increases.

From the transmitter's point of view, the transmitted signal from each transmitter is broadcast to all the users in the network by the passive optical star coupler. Suppose the network size is the same as the total number of active users. Then the splitting loss is 10log(K+1) dB. Neglecting the transmission loss and other non-idealities, the network throughput scales as the square root of the available transmitter power P_t:

$$SNR \approx \frac{I^2}{\langle I_{sh}^2 \rangle} = \frac{\Re P_t}{2q(K+1)^2 B} \quad (19)$$

The total throughput is given by:

$$(K+1)B \approx \frac{\Re P_t}{2q(K+1)SNR} \quad (20)$$

For a given available transmitter power, to obtain higher throughput, the total number of users needs to be smaller, which also means that each channel needs to handle a bigger bandwidth. Assuming 10mW available optical power at the transmitter output and 256 concurrent users, the network can support a total capacity from 3.1THz to 5.3THz for bit error rates from 10^{-15} to 10^{-9} where each channel has a bandwidth B from 12GHz to 21GHz. Figure 4 plots the achievable throughput for different output powers per transmitter (P_t). The transmitter power is assumed to be evenly distributed among all the subscribers which are all active at the same time (worst case). The BER is assumed to be 10^{-9}. In figure 5, the achievable capacity and the bandwidth per channel against the number subscribers at 10^{-9} BER and 10mW available transmitter power per channel are plotted. The same worst case assumption that the transmitter power is equally distributed to all the subscribers that are simultaneously active is applied.

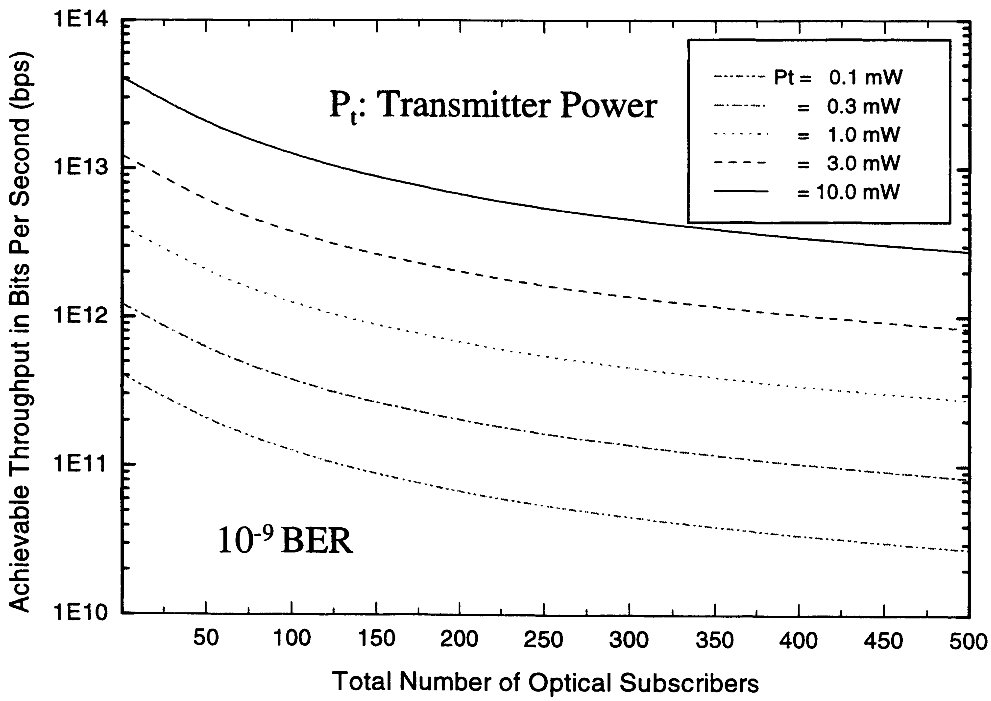

Figure 4. **Achievable total throughput at 10^{-9} BER vs. number of subscribers in the network (assumed all active at the same time). P_t in the plot represents the available power per transmitter which is split equally among all the subscribers.**

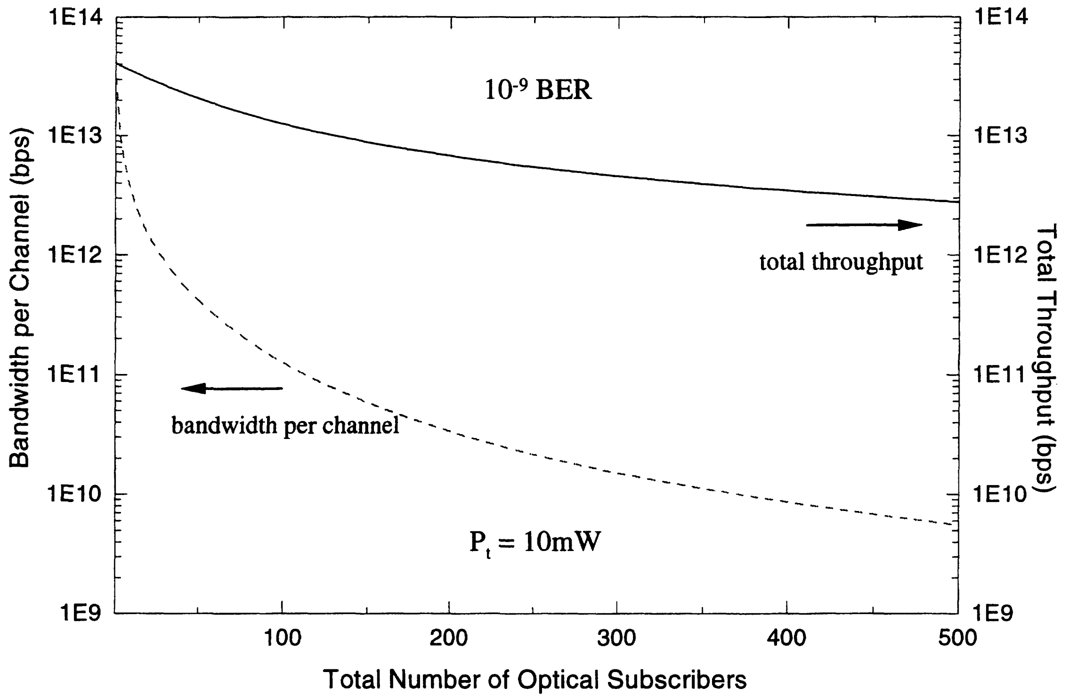

Figure 5. Bandwidth per channel required to achieve the throughput limit vs. number of subscribers in the network at 10mW transmitter power and 10^{-9} BER.

5. Security Considerations

Security has become more and more important for optical fiber networks. The easiest way to eavesdrop an intensity modulated optical fiber channel is to bend the fiber and place a photodetector next to it. Because the bipolar spectrally encoded optical CDMA system always transmits half of the spectral energy whether a 0 or 1 bit is transmitted, a simple photodetector will detect constant power. In order to listen to the signal, the eavesdropper can filter out a spectral component and listen to the modulation of the particular component. While this is easy at the fiber path close to the transmitter and before the star coupler, it is not so easy at the receiver side because all the transmitters transmit on the whole spectrum asynchronously and all the channels are multiplexed together. In addition, a scrambler channel which transmits continuous random signal can be used to further enhance the difficulty of eavesdropping.

6. Future Research

In this paper, we introduced a new implementation idea for spectrally encoded bipolar CDMA systems using cascaded Mach-Zehnder interferometers. The ultimate capacity limitation due to multiple access interference has been estimated based on the assumption of perfect code orthogonality. Perfectly orthogonal codes have been proposed by other authors[4-5]. We still need to investigate the mathematical properties of the codes generated by cascaded Mach-Zehnder interferometer chains more thoroughly. At the same time, experiments are being carried out at UCLA to study these systems experimentally. Monolithic silica waveguide multi-stage Mach-Zehnder interferometer circuits incorporated with thermo-optic phase shifters have been fabricated and are being tested to prove the concepts.

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