Experimental Demonstration and Simulation Results of Frequency Encoded Optical CDMA

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Abstract—In this paper, we present an experimental demonstration and simulation results of frequency encoded code division multiple access (FE-CDMA) using a broadband source, fiber Bragg gratings for encoding/decoding of unipolar m-sequence codes and balanced detection. The bit error rate is measured for up to four simultaneous users, at 155 Mb/s and 622 Mb/s. Exploiting the excellent match between simulation and experiment, we conclude with a prediction of potential system capacity of an optimised FE-CDMA system.

Keywords- Optical code division multiple access, frequency encoding, fiber Bragg gratings, intensity noise.

I. INTRODUCTION

Several optical code division multiple access (OCDMA) techniques have been proposed and demonstrated to offer flexible solutions for local area networks. OCDMA systems allow asynchronous access to the network while providing enhanced security. Among the different types of OCDMA systems, frequency encoded (FE) OCDMA [1]-[11] of broadband sources has the advantage of canceling multiple access interference (MAI) when a balanced detection is employed. Furthermore, contrary to direct-sequence CDMA and fast-frequency hopping CDMA that require high electrical bandwidth for the detection of short pulses, the receiver bandwidth in FE-CDMA is limited to the data rate therefore offering low cost and secure transmission.

In this paper, a novel FE-OCDMA approach using superimposed fiber Bragg gratings (FBG) for encoding/decoding operations is proposed and demonstrated both experimentally and theoretically. Previous studies of FE-OCDMA had limited experimental validation [2]-[7], or purely theoretical analyses [8]-[11]. Here we present bit error rate (BER) measurements at 155 Mb/s and 622 Mb/s showing that MAI is properly eliminated, but that the performance is limited by intensity noise (also called phase-induced-intensity-noise). Excellent match between experiment and simulation is shown for up to four simultaneous users.

In section II we present the experimental setup. In section III we predict BER performance by analysis of the various noise sources. In section IV we present experiment results that verify our simulations. Finally, in section V we investigate the performance of FE-OCDMA with various modified system configurations such as 1) Bragg grating encoding in transmission instead of reflection [7], and 2) orthogonal codes that have fixed cross-correlation such as m-sequence [2]-[3], [8], [12], Hadamard [5]-[9] or modified quadratic congruence (MQC) codes [10]-[11].

II. EXPERIMENTAL SETUP

The experimental setup is shown in Fig. 1. At the transmitter, an erbium doped broadband fiber source is modulated with a standard non return to zero format using a $2^{21}$-1 pseudo random bit sequence. The optical signal then passes through a circulator and a $1\times4$ coupler before being reflected by four superimposed FBG encoders. This architecture emulates CDMA signals coming from 4 distinct users. The data streams are de-correlated using fiber delay lines of various lengths before the encoders. The multiplexed signals are then pre-amplified with an erbium doped fiber amplifier (EDFA) that is chosen such that its combination with the broadband source results in a flat spectrum at detection. After propagation, an attenuator is used to adjust the received signal power during BER measurements and to compensate the EDFA gain variations when changing the number of active users. The signals are copolarized by individually adjusting the polarization controllers placed before the encoders. This operation is verified by maximizing the power after a 10% tap coupler and a polarization beam splitter. Note that alignment of polarization among users is a worst-case situation for BER performance, but is used here to facilitate comparison of experimental and simulation results. At the receiver side, the CDMA coded signal is split by a 3 dB coupler, whose first output is connected to a decoder identical to encoder 1, whereas the second output is connected to a decoder complementary to encoder 1. A synchronization fiber delay line is placed after the complementary decoder in order to synchronize the signals in the two photo-detector inputs. The 830 MHz balanced photo-detector radio frequency (RF) output provides an electrical signal proportional to the power difference of the two optical inputs. The RF signal is amplified and low-pass filtered to remove the out of band high frequency noise. The bandpass of the filter is $\sim 0.75 \times R_T$, where $R_T$ is the transmission rate.

For frequency encoding, an m-sequence code [12] is used, which in theory allows for the complete elimination of MAI when combined with balanced detection. The code length is 15 and its weight 8. The frequency bins are spaced 50 GHz apart, and range from $\lambda = 1542.0$ nm to $\lambda = 1548.0$ nm. In order to
perform preliminary tests of the proposed system, only four users are experimentally implemented, although the proposed codes might accommodate up to 15 users. In the system, user #1 is chosen as the desired user and users #2, #3 and #4 are interferers. All codes are shown in Fig. 1. The reflectivity of the individual gratings is 85±5 %, the bandwidth is 12.5±1.5 GHz and the peak frequency accuracy is ±2.2 GHz. A deeper description of the gratings is given in [2]. Experimental results are presented in section IV.

III. BER ANALYSIS

In order to tighten the correspondence between results and theory, all the noises that might influence the system performance are considered. In the next paragraphs, we present the mathematical model of each noise source and the experiments used to parameterize these models.

A. Characterization of Noise Sources

The most important noise for the system at high optical power is the intensity noise associated with the use of incoherent broadband sources. For a given signal to noise ratio (SNR) represented by $\gamma$, the conditional probability density function (pdf) of the integrated optical power, $W$, when conditioned on the average integrated optical power, $\overline{W}$, is gamma distributed [14], that is for $W \geq 0$,

$$f(W|\overline{W}) = \left(\frac{W}{\overline{W}}\right)^{W-1} \exp\left(-\frac{W}{\overline{W}}\right) \frac{1}{\Gamma(\overline{W})},$$  \hspace{1cm} (1)

where $\Gamma$ is the usual gamma function and where the integrated optical power, $W$, corresponds to the time integral of the instantaneous optical power, over the time constant of the electrical filter. For optical and electrical filters having a rectangular shape, it can be shown that the signal to noise ratio is $\gamma = m \times B_o / (2 B_e - B_o) B_e$, [13], where $m = 1$ for a polarized signal and $m = 2$ for an unpolarized signal while $B_o$ and $B_e$ are the optical and electrical bandwidth respectively. For $B_o >> B_e$, the SNR is approximated by $\gamma \approx m \times B_o / 2 B_e$.

For electrical and optical filters of arbitrary spectral shapes, the power spectral density (PSD) of both the signal and noise are given in [15]. In this case, the PSD of the noise is the autocorrelation of the optical spectrum, and the signal power is the square of the integrated optical spectrum. The resulting SNR is thus given by

$$\gamma = \frac{m \cdot H(0) \left( \int_{-\infty}^{\infty} S(v) dv \right)^2}{\int_{-\infty}^{\infty} \int_{-\infty}^{\infty} S(v)S(v + f) df dv H(f) df},$$  \hspace{1cm} (2)

where $v$ and $f$ are the optical and baseband frequencies respectively, $S(v)$ is the optical spectrum, $H(f)$ is the electrical filter transfer function and where $m = 1$ for a polarized signal and $m = 2$ for an unpolarized signal. This expression for the SNR is equivalent to that in [14] for a polarized signal, but allows the use of any electrical filter.

The noise from the modulating system (pattern generator and modulator) is characterized using a digital communication analyzer (DCA) and modeled as Gaussian distributed. That is, $\overline{W}$, the average integrated intensity, varies from bit to bit with a normal distribution with mean and variance measured experimentally. As this modulation noise appears before detection, the intensity noise is dependent on it and this dependence is treated in the next section.
The other noise sources considered are the photo-detector thermal noise, the RF amplifier noise and the error detector intrinsic noise. We assume all are independent of one and another and each has a Gaussian distribution. The photo-detector thermal noise is measured with a DCA. The RF amplifier noise and gain are characterized for different input levels. The error detector intrinsic noise is measured by sending a pattern composed exclusively of “1”s, and then detecting the errors at different thresholds. This measurement directly provides the cumulative distribution function of the voltage noise around the threshold.

B. Noise Dependencies

In order to predict the BER, we find the resultant pdf that includes all the noise sources. For the FE-OCDMA system studied here, the shape of the optical spectrum at both inputs of the balanced detector depends on the number of active users and on the bits sent by them. If \( K \) users are active, the number of possible spectrum shapes at the input of each photo-detector is \( 2^K \). By measuring the power and spectrum incident on each of the two photo-detector inputs for each user taken one at a time, the corresponding received power and optical spectrum for any given combination of bits can be deduced. For instance, let \( d \) be the binary column vector of data bits, where \( d_i \) is the bit of the \( i \)th user. The optical spectrum in this case is

\[
S_\mathbf{d}(\upsilon) = \mathbf{d}^T \cdot \mathbf{F}(\upsilon),
\]

where \( \mathbf{F}(\upsilon) = [F_1(\upsilon) \ F_2(\upsilon) \ ... \ F_K(\upsilon)]^T \) is the column vector of each user spectrum measured individually. Using (2) we calculate the SNR for a given \( \mathbf{d} \) (note a Bessel-Thomson electrical filter was used in the experiment and in \( h(\upsilon) \) for this calculation). From the SNR and average received power, we calculate the pdf in (1) conditioned on a given \( \mathbf{d} \). The optical spectrums \( (F_i(\upsilon) and S_i(\upsilon)) \) and pdfs at the complementary decoder are found following the same steps. Assuming equiprobable data, the final pdf is found by averaging over all vectors \( \mathbf{d} \).

Since \( \mathbf{W} \) in (1) is not deterministic (it varies with the modulation noise), the intensity noise pdfs are individually combined with the modulation noise pdf using

\[
f(\mathbf{W}_\mathbf{d}) = \int f(\mathbf{W}_\mathbf{d} | \mathbf{W}_\mathbf{d}) f(\mathbf{W}_\mathbf{d}) d\mathbf{W}_\mathbf{d}
\]

(4)

Recall \( f(\mathbf{W}_\mathbf{d}) \) is Gaussian with measured variance \& mean. The pdfs are computed at the output of each of the two photodiodes. The balanced photo-detector then subtracts the electrical outputs (independent since the power comes from different spectral regions). The resultant pdf is calculated by taking the cross-correlation between the two pdfs at each output. Finally, the noises coming from the photo-detector, RF amplifier and error detector are modeled as independent additive white Gaussian noises.

Once the resultant pdf is computed for each possible vector \( \mathbf{d} \), the final pdf for a “0” is computed by averaging the pdfs when a “0” is sent by the desired user and equivalently for a “1”. The BER is calculated by integrating the tails of these final pdfs; numerical methods are used to find the optimal threshold.

IV. EXPERIMENTAL RESULTS

Fig. 2 presents BER versus desired user power for systems with 1, 2, 3 and 4 simultaneous users. The figure contains experimental results from the setup described in section II and simulation results following the methodology of section III. Note that the desired user power is the mean optical power difference between decoder 1 and complementary 1 (not the total received optical power). The curves in Fig. 2-a are for a transmission rate of 155 Mb/s and those of Fig. 2-b are for a rate of 622 Mb/s. In both graphs, no BER floor is noticeable for a single user system out to a BER of \( 10^{-12} \). At 155 Mb/s we see a BER floor for 3 users and at 622 Mb/s the floor is apparent with only 2 users. These experimental results are not optimized to show maximum system capacity (see section V), but rather to validate theoretical and simulation results.
In the experiment, the BER is measured for up to 4 simultaneous users and the intensity noise theory is used to fit the BER curves. Excellent match is found between simulation and experiment. However, the slight differences at high power might come from the calculation of the intensity noise that assumes a Bessel-Thomson filter instead of the exact transfer function of the whole electrical system. Also, the polarizations of the 4 users have been co-aligned, but with a limited precision, causing lower BER than predicted.

V. PREDICTION OF FE-CDMA CAPACITY

In the previous section, we show that the intensity noise from incoherent broadband sources causes a serious limitation to the system performance. In order to better define the exact limitation, we present results from a computer simulator that considers only the intensity noise. For ease of interpreting results, we consider optical slices and electrical filters of ideal rectangular shapes. FBGs, or any frequency selective components, are simulated either in reflection or in transmission, and the optical signal is taken as unpolarized. We simulate both unipolar as well as bipolar systems. For both modes, when a logical “1” is transmitted, light is sent to the encoder. For the unipolar case, when a logical “0” is transmitted, nothing is sent, while for the bipolar case, a logical “0” is represented by light sent to the complementary encoder.

The experimental validation of our simulation allows us to predict with confidence the performance attainable when optimizing system parameters that were not available for this experiment. Several lessons are clear

1) The analysis of FE-CDMA capacity given in [9] is confirmed by our experiments and simulations. As proposed in [9], a code that partitions all the available optical bandwidth will yield the best system performance. In our experiment significant guard frequencies were employed between frequency bins in the code, so that only 25% of the available optical bandwidth was used. However, the Hadamard codes proposed by [8] and [9] and m-sequence codes used in our experiments do not yield optimal performance.

2) As proposed in [10]-[11], the MQC codes offer significant improvement over Hadamard codes (same properties as m-sequence) by reducing intensity noise and maintaining code orthogonality for a receiver using balanced detection. While [10]-[11] predictions of BER are optimistic based on our experimental and simulation results (see details in following discussion), they still offer considerable performance improvement, on the order of twice the capacity of Hadamard codes.

3) As proposed in [7], FE-CDMA can be accomplished using FBGs in transmission, simplifying the technical demands on FBG fabrication, and enabling the use of MQC codes. The capacity predictions in [7] are overly optimistic, as the FBGs used are too narrow to be used in transmission; a large uncoded energy is transmitted, increasing intensity noise. That energy is incident both on the decoder and the complementary decoder and does not contribute to the signal, but only to the noise. Also, the analysis used to predict capacity is that of [9], while the encoders used in fact included significant guard frequencies that would reduce system performance.

Taking into account these lessons, in Fig. 3 we present simulation results for systems with bit rates of 155 Mb/s, 415 Mb/s, 622 Mb/s and 1.25 Gb/s. We assume the use of FBG encoders/decoders in transmission, MQC codes, and a code that partitions the entire available optical bandwidth (10 nm and 30 nm are simulated). The MQC codes have a weight of $p+1$ and a length of $p(p+1)$. Therefore, an available optical bandwidth of $B_o$ would be partitioned into $B_o/p(p+1)$ logical frequency bins. However, a code consists of $p+1$ peaks of one bin width and $p+2$ gaps of various multiples of a bin width. When writing an encoder as a FBG in transmission, we would...
have $p+2$ peaks of various multiples of a bin width and $p+1$ gaps of one bin width. We select $p=13$ as a reasonable fabrication complexity that yields good system capacity. In Fig. 3-a we present the BER versus the number of system users when the available bandwidth is 10 nm; the long dashed line is for transmission rate of 1.25 Gb/s, short dashed line 622 Mb/s, solid curve 415 Mb/s and dashed dotted line 155 Mb/s. The same data is presented in Fig. 3-b for $B_c=30$ nm plus a solid dotted curve that represents Hadamard codes at 415 Mb/s.

The codes proposed by [10]-[11] have lower fixed in-phase cross-correlation than Hadamard codes. Therefore, they should be less subject to intensity noise. These codes must be used in a unipolar system and are orthogonal when combined with balanced detection. Theoretical predictions have been made by [10] based on the model developed by [9]. We refine their BER calculations as, in a unipolar system [10]-[11] as opposed to a bipolar one [9], there are many different pdfs possible after the balanced detection depending on the data sent and each of these must be considered in the BER calculation.

In [11], an MQC code ($p=13$) with an optical bandwidth of 30 nm in a unipolar, unpolarized system at a transmission rate of 622 Mb/s ($B_c=311$ MHz) is predicted to support around 55 users with a BER of $10^{-5}$. We introduce these parameters in the simulator with $R_c=415$ Mb/s and $B_c=311$ MHz (in the simulator, the electrical filter is $B_e \sim 0.75 \times R_c$ while in [9]-[11], it is taken to be $B_e \sim 0.5 \times R_c$). A maximum of 42 users (Fig. 3-b) could be accommodated, while a bipolar system with Hadamard codes could only support up to 18 users (Fig. 3-b) at such a BER. Even if the predictions of [10]-[11] are too optimistic, the proposed codes can considerably improve the performance of an FE-OCDMA system, as shown by the $R_c=415$ Mb/s curves.

When simulating the system described in [7], assuming unpolarized light, which should give the best results, it is found that such a system could accommodate less than half of the users predicted by [7]. Nevertheless, the proposition in [7] to use the FBGs in transmission allows the writing of gratings in series as opposed to superimposing them in the fiber. In transmission, there is no delay imposed by the FBGs. This allows more flexibility in the codes, as the number of FBGs placed in series and their optical bandwidth are unlimited. However, in order to reduce the intensity noise, it is important to write wide FBGs. In conclusion, the best FE-OCDMA system with incoherent sources and balanced detection would use MQC codes implemented with FBGs in transmission, and the whole optical bandwidth would have to be used (no guard bands).

VI. CONCLUSIONS

A novel and simple coding approach using superimposed FBGs to achieve FE-OCDMA is demonstrated experimentally as well as theoretically. A good MAI rejection is obtained using balanced photo-detection. This system is limited by the intensity noise inherent to the incoherent FE-OCDMA approach. A simulator is developed and its accuracy is validated by a comparison with both experimental results and an analytical prediction [9]. It is shown that codes using low fixed cross-correlation could improve the performance of an FE-OCDMA system. These codes can significantly reduce the effect of intensity noise, but cannot eliminate it completely. Future work should focus on decreasing the intensity noise effect by using components such as coherent sources and non-linear optical effects.

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