Improvement of Transmission Propagation of Multimode Optical Fibers using CDMA Techniques

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Abstract— **Multimode fibers are characterized by multipath propagation of optical signals which leads to severe Inter Symbol Interference (ISI) at the output of the fiber. In this work, approaches based on the spread spectrum (SS) techniques are proposed to overcome this drawback. An optimization algorithm is developed and appropriate software is employed to apply the proposed methodology on a specific multimode fiber. Extensive simulation results are produced and are presented herein. The numerical results have shown that the order of magnitude of the maximum data rate, *R*, supported at different CDMA gains, in order to achieve a bit error rate (BER) value smaller or equal to a convergent point, is related to the length of the multimode fiber, L, and the CDMA technique used. The Hybrid CDMA type direct sequence/frequency hopping (DS/FH) is applied to eliminate the disadvantage of DS which is the near-far effect (different power levels of users at optical fiber input).**

Index Terms— Intersymbol interference, optical orthogonal frequency division multiplexing, wireless optical communications.

I. INTRODUCTION

Optical fibers are widely used as transmission channels in communication networks because of their high bandwidth and small values of attenuation at the two wavelength regions of 1.3 and 1.55 μm, achieving up to Terabit high bit data rates. However, dispersion [1, 2] constitutes the main restrictive factor for signal transmission over single mode fibers (SMFs) as well as multimode fibers (MMFs). This problem is more severe in the latter. An MMF is considerably thicker, with a core diameter 50 or 62.5 μm against 4 to 9 μm for than an SMFs. This allows the excitation of multiple modes at the usual wavelengths. Multiple modes can be represented geometrically by the propagation of multiple light rays in a MMF, with each ray arriving at the output of the fiber at a different time depending on the distance it covers in the fiber. Therefore, excited modes have different group delays and, consequently, multiple delayed copies of the transmitted signal arrive at the output of the fiber. This phenomenon results in a significant ISI when many successive light pulses have to be transmitted, each pulse corresponding to a bit of information. Therefore, under normal circumstances an SMF can support much higher data rates than the MMF. Despite the above limitations, MMFs dominate in most backbone networks (LANs, WANs, MPLS…) because of the lower cost of installation and maintenance of MMF networks. Also, due to their large core diameter and flexibility, MMFs are resilient against mechanical distress. In this context, there has been much research effort over the last years to improve the distance to bandwidth product of MMFs. Substantial improvement has been achieved in this respect by applying techniques such as the use of graded index MMFs, selective modal excitation via sophisticated launch approaches [3] or by using hypocycloidal optical waveguides with helical winding [4], multiple input-multiple-output (MIMO) techniques [5–7], the combination of wavelength division multiplexing (WDM) with subcarrier multiplexing (SCM) [8]. Nevertheless, the capacity of multimode fibers has not been fully exploited and research is ongoing.

In this paper, we propose an alternative method to enhance the data rates that can be supported by MMFs. This is performed by the implementation of the spread spectrum techniques [9–13].

This paper is organized as follows. In Section II, the CDMA techniques and their features are introduced. The proposed MMF fiber model is described and derived in Section III. Section IV presents the proposed DS-CDMA model and the Hybrid SFH/DS-CDMA is presented in Section V. Simulation results are given in Section VI followed by conclusions in section VII.

II. SPREAD SPERCTUM TECHNIQUES

A CDMA system may overcome some of propagation problems depending on the type of CDMA used. For example, a DS CDMA system is highly resistant to multipath propagation, an FH CDMA system combats the near-far effects, and a hybrid DS/FH CDMA system can combine the effectiveness of DS systems against multipath fading with the avoidance property of FH systems to reduce the near-far problem.

In a star connected CDMA network, the base station consists of a bank of SS transmitters/receivers, one for each active user. Each user is assigned a unique SS code sequence for DS CDMA or a unique hopping pattern for FH CDMA, or a unique spread-spectrum code sequence and a hopping pattern in hybrid DS/SFH CDMA. This means that CDMA offers simultaneous transmission by multiple terminals with successful reception of packets. It may be noted that in the case of Advocates Of Linux Opensource Hawaii Association (ALOHA), there is a packet collision if there are simultaneous transmissions Thus, ALOHA is a special limiting case of CDMA systems with only one packet transmission at a time with successful reception.

However, in the case of CDMA, there is also a threshold value for simultaneous active users. When the number of simultaneous users exceeds the threshold value, all packets are lost due to excessive errors. The lost packets are rescheduled according to retransmission delay distribution [14].

III. PROBLEM FORMULATION

The MMF studied in this work is a graded index one with a parabolic distribution of the core refractive index, having, $\Delta = (n_1 - n_o)/n_1 = 0.02$ where n_1 and n_0 are the refractive indices at the center of the core and at the cladding of the fiber. Considering $n_0 = 1.41$, it follows that $n_1 = 1.439$. Also, the core diameter is taken as 62.5 μm. For wave guiding in an MMF with parabolically distributed refractive index, the propagation constant of each mode, β, is given by [12]:

$$\beta = k_0 n_1 \sqrt{1 - \frac{\sqrt{2\Delta}}{a k_0 n_1} 2(2l + |m| + 1)} \qquad (1)$$

where the k is the free space propagation constant, α is the core radius and $2l + |m| + 1$, with $l = 0, 1, 2 \ldots$, and $m = 0, \pm 1, \pm 2 \ldots \}$. , reflects the class of the mode being wave guided. The wavelength of operation is taken $\lambda_0 = 1300$ nm, corresponding to a radial frequency of operation $\omega_0 = 14.5 \times 1014$ rad/s.

For a particular mode to be guided in the fiber, the quantity under the square root of Eq. (1) must be positive, while it becomes zero at the critical frequency, ω_c, which defines the transition from attenuation to waveguiding. Thus, for a given mode, the critical frequency is

$$\omega_c = \frac{\sqrt{2\Delta}}{n_1 a \sqrt{\varepsilon_0 \mu_0}} 2(2l + |m| + 1) \qquad (2)$$

where ε_0 and μ_0 are the permittivity and permeability of the vacuum, respectively. Replacing the parameters with their arithmetic values gives:

$$\omega_c = 0.027 \times 1014(2l + |m| + 1) \text{ rad/sec} \qquad (3)$$

To determine the number of guide modes at a frequency ω_0, one recalls that $\omega_0 \geq \omega_c$ which leads in combination with Eq. (3) to

$$(2l + |m| + 1) \leq 537 \qquad (4)$$

Therefore, approximately 537 mode groups are guided in the considered MMF. Each group includes different modes, i.e., modes with different l and m values but with the same propagation constant. The group delay per unit length of fiber is defined by the derivative

$$\tau_g = \frac{d\beta}{d\omega}\Big|_{\omega = \omega_0} \qquad (5)$$

Using Eq. (1) and replacing parameters with their arithmetic values, the following expression is obtained for the group delay (in ns)

$$\tau_g = 4.8\sqrt{1 - 0.00184(2l + |m| + 1)} + \frac{0.0044(2l + |m| + 1)}{\sqrt{1 - 0.00184(2l + |m| + 1)}} \qquad (6)$$

Thus, the group delay ranges from 4.8 to 22.1656 ns per unit length of fiber.

The simulation of the SS technique (CDMA) on the MMF considered above was performed using the MATLAB 7.0 Software. To this aim, program codes were developed to simulate the production of an SS signal, its transmission through the MMF studied above and its processing by the matched filters at the output of the fiber. It is also used to calculate the BER at the output of the receiver with the help of a simple decision device. As shown earlier [7], the MMF studied can be modeled as a multipath Rayleigh channel with a transfer function given by

$$y(t) = \sum_{k=1}^{N} h_k x(t - \tau_{gk}) \qquad (7)$$

where N is the total number of modes-paths in the fiber, τ_{gk} is the group delay of mode k and h_k is the attenuation because of mode k. Figure 1 displays the probability distribution function (PDF) for a Rayleigh distribution at different values of the attenuation constant, σ [14].

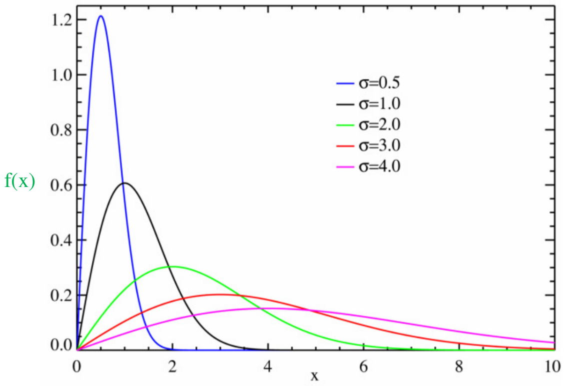

Fig. 1 Rayleigh PDF distribution

For the fiber considered here the attenuation of each mode is considered to be equal to 0.4 dB/km.

IV. DIRECT SEQUENCE DS-CDMA OVER OPTICAL FIBER

The following model is suggested to simulate the behavior of the optical fiber with DS CDMA technique.

$$s_k(t) = A\, a_k(t)\, b_k(t) \cos(\omega_c t + \theta_k) \qquad (8)$$

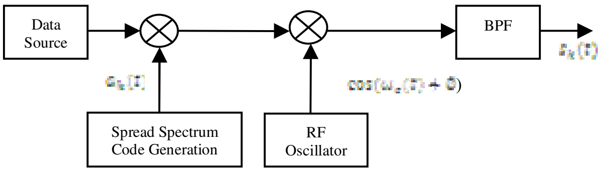

Fig. 2 Block diagram of transmitter k.

$$r(t) = \sum_{k=1}^{N} \sum_{l=1}^{L} A h_k a_k(t - \tau_{lk}) b_k(t - \tau_{lk}) \cos(\omega_c t + \theta_{lk}) \qquad (9)$$

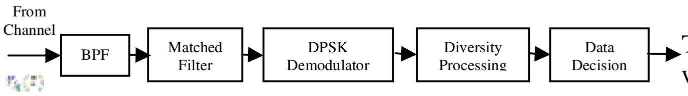

Fig. 3 Receiver block diagram.

V. HYBRID DS/FH-CDMA OVER OPTICAL FIBER

Hybrid CDMA system is attractive because it can combine the advantages of both DS and FH while avoiding some of their disadvantages. A hybrid system can combine the anti-multipath effectiveness of DS with the good antinear-far problem features of FH. Hybrid systems may also use shorter signature sequences and hopping pattern, thus reducing the overall acquisition time. A disadvantage of hybrid system is the increased complexity of their transmitters and receivers [14].

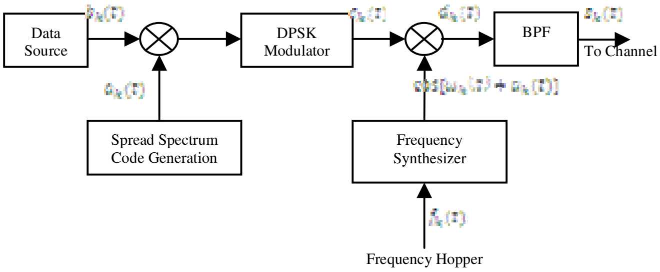

Fig. 4 Block Diagram of a Hybrid DS/SFH Transmitter.

$$s_k(t)=\sqrt{2P}\, a_k(t)\, b_k(t) \cos[\omega_c t+\omega_k(t)t+\theta_k+\alpha_k(t)] \tag{10}$$

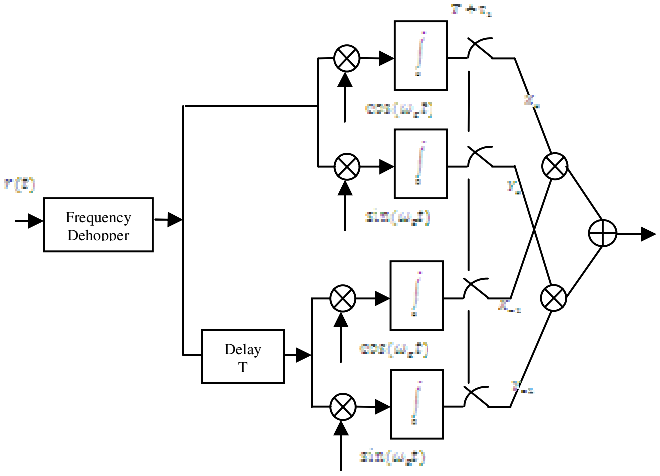

Fig. 5 Block Diagram of a Hybrid DS/SFH Receiver.

$$r(t) = \sqrt{2P}\sum_k \sum_i h_{ik}\, a_k(t-\tau_{ik})\, b_k(t-\tau_{ik}) \cos[\omega_c t+\omega_k(t-\tau_{ik})+\varphi_{ik}] \tag{11}$$

VI. SIMULATION RESULTS

The system was studied initially for CDMA gain equal to 50, while the number of information bits was set to 100. Thus, the achievement of BER ≤ 0.01 can be considered as the condition for successful operation of the system, i.e., the maximum number of acceptable false bit decisions is one.

The basic conclusion arising from the MATLAB simulation is that in order to achieve a BER ≤ 0.01, the CDMA code chip period (equivalently, the inverse of data rate in the fiber) must be at least equal to the order of magnitude of the group delays of excited modes paths. For our study, we considered fiber lengths from 1m to 100 km, and, as mentioned earlier, for each meter of fiber the group delays of the 537 excited mode groups range from 4.8 to 22.1656 × 10^{-9} s. The results concerning the mode group delays for the studied fiber lengths are presented in Table 1.

Fiber length (m)	Range of group Delays (s)
1	(4.8 - 22.1656) x 10^{-9}
10	(4.8 - 22.1656) x 10^{-8}
10^2	(4.8 - 22.1656) x 10^{-7}
10^3	(4.8 - 22.1656) x 10^{-6}
10^4	(4.8 - 22.1656) x 10^{-5}
10^5	(4.8 - 22.1656) x 10^{-4}

Table 1. Ranges of group delays for different fiber lengths.

The order of magnitude of maximum data rates, *R*, that can be supported by the fiber in order to achieve a BER ≤ 0.01 for CDMA gain equal to 50 are given in Table 2 and are presented schematically in Fig. 6 as a function of fiber length, *L*. Actually, this diagram represents the transition from the area of successful operation (BER $\leq$ 0.01) to the area of unsuccessful operation of the system where a BER smaller or equal to 0.01 is unachievable.

Fiber length (m)	Chip period (s)	Data rate (Kb/s)
1	10^{-9}	10^6
10	10^{-8}	10^5
10^2	10^{-7}	10^4
10^3	10^{-6}	10^3
10^4	10^{-5}	10^2
10^5	10^{-4}	10

Table 2. Minimum chip period and respective data rate in the fiber for CDMA gain equal to 50.

The results obtained demonstrate clearly that, as the fiber length increases the maximum data rate (order of magnitude) that can be supported decreases. Specifically, data fitting shows that *R* and *L* are related by the expression:

$$R = dL^{-1} \tag{12}$$

where d (bps.m) is the constant of proportionality.

In order to increase the data rate by one order of magnitude and still have an acceptable bit error rate (BER ≤ 0.01), it is necessary to increase the CDMA gain. We have tested the system for CDMA gain equal to 500. Table 3 presents the obtained order of magnitude of the maximum data rates that can be supported in order to achieve BER ≤ 0.01 (0 or 1 false bit decisions) for CDMA gain equal to 500.

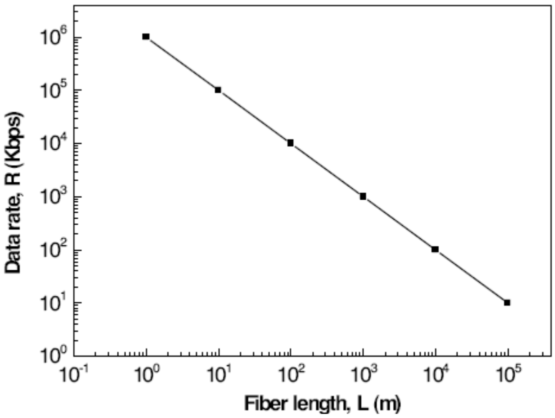

Fig. 6 Order of magnitude of maximum data rate, *R*, for different fiber lengths, *L*, in order to achieve BER ≤ 0.01 (CDMA gain = 50).

Fiber length (m)	Chip period (s)	Data rate (Kb/s)
1	10^{-10}	10^4
10	10^{-9}	10^3
10^2	10^{-8}	10^2
10^3	10^{-7}	10
10^4	10^{-6}	1
10^5	10^{-5}	10^{-1}

Table 3. Minimum chip period and respective data rate in the fiber for CDMA gain equal to 500.

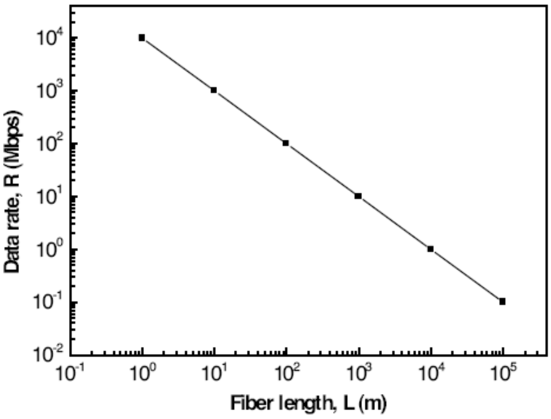

Fig. **7.** Order of magnitude of maximum data rate, *R*, for different fiber lengths, *L*, in order to achieve BER ≤ 0.01 (CDMA gain = 500).

The results of Table 3 are shown schematically in Fig. 7 versus fiber length. It is found that the data rate and the fiber length for CDMA gain = 500 obey also Eq. (12) with $d=10^7$ kbps.m. Thus, the proportionality constant between data rate and the inverse of fiber length increases by an order of magnitude when CDMA increases by one order of magnitude Thus, it is found that the CDMA gain is a crucial parameter, the increase of which allows for higher data rates for the MMF studied in this work.

VII. CONCLUSION

In this paper, a modulation based on hybrid (DC/FH) CDMA techniques is proposed. The results yields to a promising improvement from BER point of view in eliminating the effect of multi- path fading due to nature of multi mode fiber. It has been established that, for DS CDMA gain equal to 50, when the CDMA code chip period is at least equal to the order of magnitude of the group delays of the wave guided modes then the system operates successfully. Attempts to increase the data rate without modifying the CDMA gain showed that the system does not operate successfully. The results demonstrated that higher data rates can be achieved by increasing the CDMA gain, and still retaining the BER value smaller than the convergent point. For the MMF investigated in this work, it was found that the maximum data rate supported, *R*, is related to the fiber length, *L*, by $R = dL-1$ with d varying from 10^6 (Kbps. m) to 10^7 (Kbps. m) when CDMA gain increases from 50 to 500. Hybrid CDMA DS/FH technique is improving the BER due Multiple Access MA which increases the number of users. Similar results, with a fair agreement, have been achieved by Kamitsos [13] using DS-CDMA and Rake receivers. The proposed DS-CDMA models in this paper are less complex.

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