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# IMPROVEMENT OF TRANSMISSION PROPERTIES OF MULTIMODE FIBERS USING SPREAD SPECTRUM TECHNIQUE AND A RAKE RECEIVER APPROACH

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**Abstract**—Multimode fibers are characterized by multipath propagation of optical signals and this leads to severe intersymbol interference at the output of the fiber. In this work an approach based on the Rake receiver is proposed to overcome this drawback. An optimization algorithm was developed and appropriate software was employed to apply the proposed methodology on specific multimode fiber. Extensive simulation results were 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 value smaller or equal to a convergent point, is related to the length of the multimode fiber, $L$, by the expression $R = dL^{-1}$ with $d$ increasing from $10^6$ to $10^7$ (Kbps. m) when CDMA gain increases from 50 to 500.

## 1. INTRODUCTION

Optical fibers are widely used as transmission channels in communication networks because of their high bandwidth, small values of attenuation at the two wavelength regions of 1.3 and 1.55 $\mu$m, achieving up to Terabit high bit data rates. However, dispersion [1, 2] constitutes the main restrictive factor for signal transmission over singlemode fibers (SSFs) as well as multimode fibers (MMFs), this problem being more severe in the latter. A MMF is considerably thicker than a SSF, with core diameter 50 $\mu$m or 62.5 $\mu$m vs. ca. 9 $\mu$m, and this allows for 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 significant intersymbol interference (ISI) when many successive light pulses have to be transmitted, each pulse corresponding to a bit of information. Therefore, under normal circumstances a SSF can support much higher data rates than a MMF.

Despite the above limitations, MMFs dominate in most backbone networks (LANs and WANs) because of the lower cost of installation and maintenance of MMF networks. Also, because of 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 MMF, 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. It is shown in this work that the implementation of the spread spectrum technique [9–11], along with a Rake receiver at the output of the fiber, compensates effectively for the negative effects of multipath propagation of optical signals that characterizes multimode fibers.

## 2. THE RAKE RECEIVER AND THE SPREAD SPECTRUM TECHNIQUE

The architecture of a Rake receiver allows for an optimum combination of the energy received from the paths of a multipath transmission channel like a MMF. In addition, it inhibits fading caused by the arrival of multiple signal copies with phase divergence. Actually, a Rake receiver takes advantage of the multipath propagation by combining properly the arriving signal copies and producing a stronger signal, leading to the improvement of the throughput of the system.

A block diagram of a Rake receiver is shown in Figure 1, where $r(t)$ is a spread spectrum modulated signal that enters the multipath channel for transmission, i.e., a MMF in this case. For the production of $r(t)$ the following procedure has been applied. Initially, a narrowband signal has been multiplied with a pseudorandom code sequence $c(t)$, the CDMA code, under the condition that the chip's period in this sequence is CDMA gain times smaller than the period of each bit of information. As a consequence, a spread spectrum signal is produced. It is noted that each bit of the pseudorandom sequence is called chip, while the CDMA gain denotes the ratio of the spread spectrum signal bandwidth over the bandwidth of the initial narrowband signal. Afterwards, the spread spectrum signal modulates a high-frequency carrier and the $r(t)$ signal is produced.

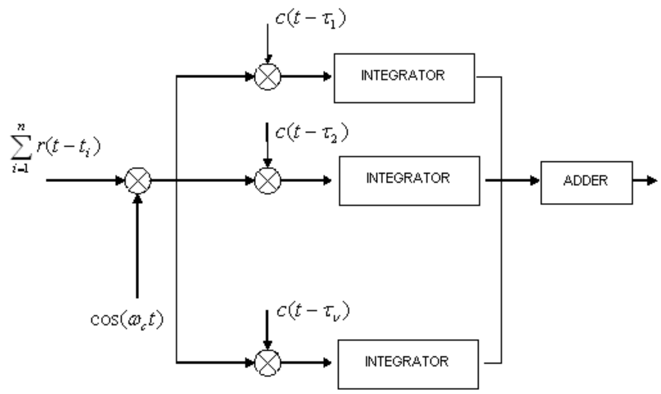


**Figure 1.** A simplified block diagram of a Rake receiver.

With the assumption that the transmission channel consists of n paths, the signal arriving at the output of this channel is $\sum_{i=1}^{n} r(t - t_i)$, where $t_i$ is the delay of path $i$. After demodulation, this signal is transferred to the fingers of the Rake receiver. If the number of channel paths, n, is relatively small, then the number of fingers, $\nu$, equals to $n$ (case 1). If $n$ is high then $v < n$ (case 2).

For case 1, the received demodulated signal at finger $i$ is multiplied by $c(t - \tau_i)$, which represents the CDMA code shifted by $\tau_i$, where $\tau_i = t_i$ for every $i = 1, 2 \ldots \nu (= n)$. This multiplication leads to the recompression of the multipath signal, and the recompressed signal is integrated with the help of an integrator. Finally, the signals produced by this procedure at each finger are weighed over an appropriate criterion and then they are added. A commonly used weigh criterion is the combination of maximum ratio, i.e., the signal produced from finger $i$ is weighed over the attenuation coefficient of path $i$. The optimum output of the Rake receiver is equal to the sequence of information bits produced at the transmitter of the system. Equivalently, the achievable Bit Error Rate (BER) is very low because there is always the possibility of a false bit decision. It is noted that the output of the Rake receiver is sent to a decision device to decide on the transmitted bits.

For case 2, it is not practical to use a Rake receiver with the number of fingers equal to the number of paths. For this case, the number of fingers is much smaller than the number of paths, while at the same time the CDMA code's shifting times $\tau_1, \tau_2, \ldots, \tau_\nu$ are chosen according to a BER optimization algorithm.

## 3. PROBLEM FORMULATION

The multimode fiber studied in this work is a graded index fiber with a parabolic distribution of the core refractive index, having $\Delta = \frac{n_1 - n_0}{n_1} = 0.02$ 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 $62.5\,\mu$m and the total fiber diameter is $125\,\mu$m. For waveguiding in a multimode fiber with parabolically distributed refractive index the propagation constant of each mode, $\beta$, is given by the expression [12]:

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

where the propagation constant in free space is $k_0 = \frac{\omega}{c}$, $\alpha$ 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 waveguided. The wavelength of operation is taken $\lambda_0 = 1300\,\text{nm}$, corresponding to a radial frequency of operation $\omega_0 = 14.5 \times 10^{14}\,\text{rad/sec}$.

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

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

where $\varepsilon_0$ and $\mu_0$ are the permittivity and permeability of the vacuum, respectively. Replacing the parameters with their arithmetic values gives:

$$\omega_c = 0.027 \times 10^{14} (2l + |m| + 1) \text{ rad/sec} \tag{3}$$

To determine the number of modes waveguided at the frequency of operation $\omega_0$ we recall that $\omega_0 \geq \omega_c$ which leads in combination with Eq. (3) to:

$$(2l + |m| + 1) \leq 537 \tag{4}$$

Therefore, approximately 537 mode groups are waveguided in the considered multimode fiber. 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 given by the derivative:

$$\tau_g = \frac{d\beta}{d\omega} \mid \omega = \omega_0 \tag{5}$$

By calculating this derivative from Eq. (1), and replacing parameters with their arithmetic values, the following expression is obtained for the group delay (in nsec):

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

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

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

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

where $N$ is the total number of modes-paths in the fiber, $\tau_{gk}$ is the group delay of mode $k$ and $h_k$ is the attenuation because of mode $k$. For the fiber considered here the attenuation of each mode is considered to be equal to 0.4 dB/Km.

Because of the large number of mode groups excited at the wavelength of 1300 nm (i.e., 537), the Rake receiver used is not possible to have so many fingers. As a consequence, the performance of the system was studied for number of fingers ranging from 2 to 10. In this context, the optimization algorithm presented below was developed in order to obtain the CDMA code shifting times that correspond to the receiver fingers, on the basis of which a BER value smaller or equal to the convergent point was achieved.

## 4. OPTIMIZATION ALGORITHM

For each number of fingers of the Rake receiver an initial condition is considered for the CDMA code shifting times, and the BER at the output of the fiber is calculated. If the BER is smaller or equal to a convergent point (e.g., $10^{-2}$ for 100 bits of information, $10^{-3}$ for 1000 bits of information etc.) the algorithm is considered to converge and the specific shifting times (expressed in number of chips) are chosen. Otherwise, the algorithm keeps constant the shifting time of the first finger and increases by 1 the shifting times of the remaining fingers. If the new calculated BER is not smaller or equal to the convergent point, the algorithm keeps constant the new shifting time of the second finger and increases by 1 the shifting times of the rest of the fingers (third, fourth etc.). This constitutes the basic loop of the algorithm, and it is repeated as many times as the number of the receiver fingers ($\nu$). If the basic loop is repeated $\nu$ times and a BER smaller or equal to the convergent point is not obtained, the first cycle of the algorithm closes. Meanwhile, if the algorithm is found to converge it terminates and the corresponding shifting times are selected. If the algorithm has not terminated, the second cycle begins, where the shifting times equal to the shifting times at the beginning of the previous cycle plus one (the beginning of the first cycle is the initial condition). During the second cycle, the basic loop is repeated as many times as the number $\nu$ of the receiver's fingers. Then, the third cycle begins etc. If after 100 cycles the algorithm does not converge, it is considered that with the specific number of fingers a BER smaller or equal to the convergent point cannot be achieved. In this case, the smaller among all BERs calculated, and stored in a matrix, is chosen to describe the system's performance.

Regarding the initial condition for the CDMA code shifting times, it was chosen that the initial shifting time for every finger is given by the ratio [group delay of the first mode group ($l = m = 0$)]/[CDMA code chip period]. This ratio is approximated by the closest integer because each shifting time at a receiver finger is expressed in chip numbers.

## 5. NUMERICAL RESULTS AND DISCUSSION

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 $\leq 0.01$ 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 BER $\leq 0.01$ 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 1 m 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 $22.1656 \times 10^{-9}$ sec.

The results concerning the mode group delays for the studied fiber lengths are presented in Table 1. The order of magnitude of maximum data rates, $R$, that can be supported by the fiber in order to achieve BER $\leq 0.01$ for CDMA gain equal to 50 are given in

**Table 1.** Range of group delays for different fiber lengths.

| **Fiber length (m)** | **Range of group delays (sec)** |
|---|---|
| 1 | $(4.8 - 22.1656) \times 10^{-9}$ |
| 10 | $(4.8 - 22.1656) \times 10^{-8}$ |
| $10^2$ | $(4.8 - 22.1656) \times 10^{-7}$ |
| $10^3$ | $(4.8 - 22.1656) \times 10^{-6}$ |
| $10^4$ | $(4.8 - 22.1656) \times 10^{-5}$ |
| $10^5$ | $(4.8 - 22.1656) \times 10^{-4}$ |

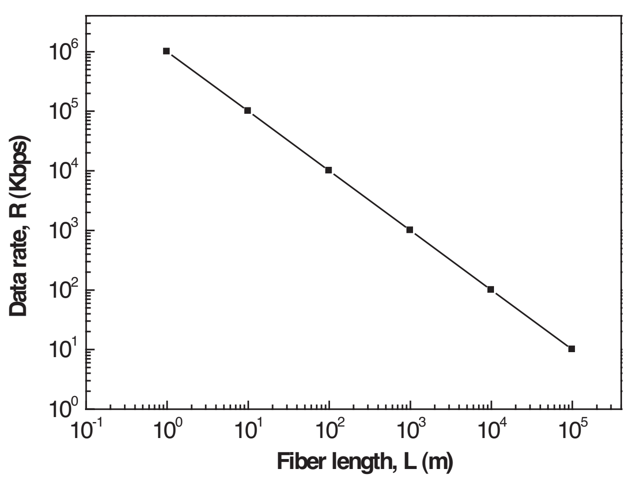


**Figure 2.** Order of magnitude of maximum data rate, $R$, for different fiber lengths, $L$, in order to achieve BER $\leq 0.01$ (CDMA gain = 50).

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

| Fiber length (m) | Chip period (sec) | Data rate (Kbps) |
|---|---|---|
| 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, and are presented schematically in Figure 2 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. 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:

$$R = dL^{-1} \tag{8}$$

with $d = 10^6$ (Kbps. m) when CDMA = 50. When the CDMA code chip period is at least equal to the order of magnitude of the group delays of the waveguided modes then the system operates successfully for every number of fingers of the Rake receiver, i.e., 2 to 10 fingers which is of practical interest. It is of interest to note that the more fingers simulated for each fiber length studied the harder it is for the optimization algorithm to converge. Nevertheless, for 2 to 6 fingers the algorithm converges with the initial condition. Table 3 gives the number of iterations needed for the algorithm to converge for each fiber length investigated in this work.

When at the given CDMA gain (e.g., 50) the data rate is increased by one order of magnitude over the maximum value possible, it is ascertained that the system does not operate properly for any number of fingers. For example, when we simulate the system at the data rate of 100 Mbps for a 100 m fiber, where the maximum data rate supported is 10 Mbps, the minimum BER achieved is 0.42 for 4 fingers. Of course, such a value is extremely high and, thus, it indicates that the operation of the system is not acceptable.

**Table 3.** Number of iterations for the optimization algorithm to converge in proportion to the fiber length and the number of fingers (CDMA gain = 50).

| **Number of fingers** | **Number of algorithm iterations for convergence** | | | | | |
|---|---|---|---|---|---|---|
| | **100 Km (10 Kbps)** | **10 Km (100 Kbps)** | **1 Km (1 Mbps)** | **100 m (10 Mbps)** | **10 m (100 Mbps)** | **1 m (1 Gbps)** |
| 2 | 1 | 1 | 1 | 1 | 1 | 1 |
| 3 | 1 | 1 | 1 | 1 | 1 | 1 |
| 4 | 1 | 1 | 1 | 1 | 1 | 1 |
| 5 | 1 | 1 | 1 | 1 | 1 | 1 |
| 6 | 1 | 1 | 1 | 1 | 1 | 1 |
| 7 | 2 | 2 | 2 | 2 | 2 | 3 |
| 8 | 5 | 3 | 5 | 4 | 7 | 6 |
| 9 | 8 | 6 | 5 | 7 | 17 | 9 |
| 10 | 17 | 7 | 6 | 7 | 25 | 10 |

**Table 4.** Minimum chip period and respective data rate in the fiber for CDMA gain equal to 500.

| **Fiber length (m)** | **Chip period (sec)** | **Data rate (Mbps)** |
|---|---|---|
| 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 |
| $10^5$ | $10^{-5}$ | $10^{-1}$ |

In order to increase the data rate by one order of magnitude and still have an acceptable bit error rate (BER $\leq$ 0.01), it is necessary to increase the CDMA gain. We have tested the system for CDMA gain equal to 500. Table 4 presents the obtained order of magnitude of the maximum data rates that can be supported in order to achieve BER $\leq$ 0.01 (0 or 1 false bit decisions) for CDMA gain equal to 500. The results of Table 4 are shown schematically in Figure 3 versus fiber length. It is found that the data rate and the fiber length for CDMA gain = 500 obey also Eq. (8) with $d = 10^7$ (Kbps. m). Thus, the proportionality constant between data rate and the inverse of fiber

**Table 5.** Number of iterations for the optimization algorithm to converge in proportion to the fiber length and the number of fingers (CDMA gain = 500).

| **Number of fingers** | Number of algorithm iterations for convergence | | | | | |
|---|---|---|---|---|---|---|
| | 100 Km (100 Kbps) | 10 Km (1 Mbps) | 1 Km (10 Mbps) | 100 m (100 Mbps) | 10 m (1 Gbps) | 1 m (10 Gbps) |
| 2 | 1 | 1 | 1 | 1 | 1 | 1 |
| 3 | 1 | 1 | 1 | 1 | 1 | 1 |
| 4 | 1 | 1 | 1 | 1 | 1 | 1 |
| 5 | 1 | 1 | 1 | 1 | 1 | 1 |
| 6 | 1 | 1 | 1 | 1 | 1 | 1 |
| 7 | 1 | 1 | 1 | 1 | 1 | 1 |
| 8 | 1 | 1 | 1 | 1 | 1 | 1 |
| 9 | 2 | 1 | 2 | 2 | 2 | 2 |
| 10 | 3 | 3 | 2 | 2 | 3 | 3 |

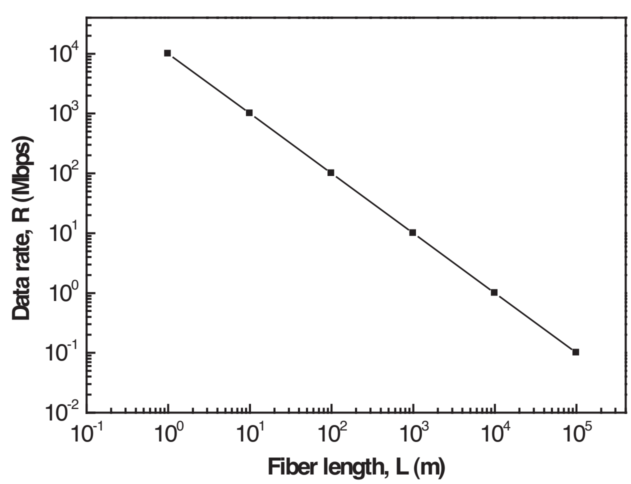


**Figure 3.** Order of magnitude of maximum data rate, $R$, for different fiber lengths, $L$, in order to achieve BER $\leq 0.01$ (CDMA gain = 500).

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.

When the system operates successfully for CDMA gain equal to 500 this is done for every number of fingers of the Rake receiver, i.e., from 2 to 10 which is again of practical interest. Also, the optimization algorithm developed converges very rapidly, as shown in Table 5 which presents the numbers of iterations needed for the algorithm to converge for each fiber length. As it is found, for a number of fingers from 2 to 8 the algorithm converges just with the initial condition, while for 9 and 10 fingers the maximum number of iterations needed is three. Such a quick convergence results from the high CDMA gain considered.

## 6. CONCLUSION

We have shown in this paper that the spread spectrum technique, along with the use of a Rake receiver, can be employed as an alternative method to compensate for the negative effects caused by the multipath propagation of optical signals in multimode fibers. Using MATLAB 7.0 software, we have simulated this technique on a specific multimode fiber. We have studied several lengths of this fiber and investigated the data rates that can be supported for different CDMA gains, in order to achieve at the output of the Rake receiver a BER value smaller or equal to a convergent point. Also, an optimization algorithm was developed to obtain the CDMA code shifting times at the different fingers of the receiver with which such a BER value is achieved.

It has been established that, for 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 waveguided modes then the system operates successfully (i.e., BER is smaller or equal to the convergent point) for every number of fingers of the Rake receiver (from 2 to 10 fingers, which is of practical interest). It has been also found here that upon increasing the number of fingers it becomes progressively more difficult for the optimization algorithm to converge. 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.

We note that the data rates achieved with the method proposed here are lower than those obtained with methods mentioned earlier in this paper. However, some disadvantages of such methods cannot be neglected. For example, the high cost of multi-wavelength systems renders the WDM approach very expensive [7], while the limitation of the excited modes in an optical waveguide requires difficult to implement micromachining techniques [4]. Also, sophisticated launch schemes could result in increased attenuation in a MMF link and lead to higher power budget [3]. On the other hand, the Rake receiver approach proposed in this work is a less expensive technique. Although the equipment needed for its implementation is simpler and less sophisticated, the proposed method is very reliable. The data rates achieved, although lower, are sufficient for applications involving shorter fiber links. This approach could potentially allow for more than one user to transmit reliably in the MMF, and this aspect of the method would lead to practically improved data rates.

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