Research on mode-coupled multi-mode Fiber mode-division in multiplexing transmission system

Yang Zhou ¹* and Han Su¹

¹ College of Information Engineering, Engineering University of PAP, Xi’an, shaanxi, 710086, China
*Corresponding author’s e-mail: 1870673402@163.com

Abstract. The mode coupling and random loss between different modes have important effects on the reliability of the multimode fiber-based mode division multiplexing transmission system. Using the VPI optical communication simulation platform, a short-distance analog-division multiplexing transmission system based on multimode fiber was designed and built. By setting the relevant parameters of mode coupling and random loss caused by bending, the quality of the eye diagram of the received signal is analyzed by the photoelectric signal analyzer at the receiving end. The experimental results show that the mode coupling has great influence on the anti-noise performance and anti-inter-symbol interference performance of the multimode fiber-based transmission system, and the random loss has great influence on the anti-noise performance of the system, this effect is more obvious in high-order linear polarization mode fiber.

1. Introduction

Since the outbreak of the new crown pneumonia, Internet applications such as distance education and video conferencing have ushered in unprecedented development. These services are mainly carried in the optical fiber transmission network, and the optical fiber communication system mainly uses single-mode optical fiber for transmission [1]. In order to increase the system bandwidth, people use the five dimensions of light wave time slot, frequency, phase, amplitude, and polarization to improve the system transmission capacity [2], but with the continuous increase in bandwidth demand, single-mode fiber gradually approaches the nonlinear Shannon Limit [3]. Therefore, people seek to use the dimension of space for capacity expansion, which is called space division multiplexing. Space division multiplexing is divided into two types, one is to aggregate multiple fiber to form a multi-core fiber, and the other is to multiplex by mode in a few-mode fiber or multi-mode fiber, that is, mode division multiplexing (MDM) [4]. In the MDM system, due to factors such as fiber bending, the signal of one mode enters another mode, resulting in a decrease in signal quality. This phenomenon is called mode coupling (MC) [5].

In recent years, many researchers have studied the MDM system and achieved some results. Literature [6] focuses on the study of the mode selection coupler in the large-capacity optical fiber communication system and the discussion of the experimental conditions, but it does not study the MC phenomenon in MDM. Literature [2] realized the production and experiment of the mode conversion and multiplexing device of photon lantern for the first time in China, but it also did not study the influence of MC on MDM. Literature [7] began to study the MC phenomenon in the MDM system, focusing on the MC in the few-mode fiber, and realized the corresponding few-mode fiber link transmission simulation, but did not involve the MDM system based on the multi-mode fiber.
Literature [8] also studied the MDM system based on few-mode fiber, built 3×3 and 6×6 MDM transmission systems based on photon lanterns, and studied the damage mechanism of MC during transmission. Therefore, most of the current research results have never studied the MC phenomenon existing in MDM, and have developed to study MDM systems based on few-mode fiber mode coupling, and there are few studies on MDM systems based on multi-mode fiber mode coupling. Therefore, the influence of mode coupling and random fiber loss on the reliability of the transmission system under this system is still unclear.

The main innovations of this paper are as follows: Firstly, design and build a short-distance MDM system based on multimode optical fiber by using the VPI optical communication simulation platform. Secondly, it is verified through experiments that random loss has a greater impact on the anti-noise performance of short-distance MDM systems, and this effect is more obvious in high-order linear polarization mode fibers.

2. A short-distance MDM transmission system based on VPI
The MDM transmission system model based on multi-mode fiber is shown in Figure 1. The signal is processed by modulated laser and transmitted in single-mode fiber, and then converted into a high-order mode by a mode converter. The commonly used linear polarization (LP) mode multiplexing, and then the optical signals of different modes are multiplexed on a multi-mode optical fiber through a multi-mode multiplexer, after corresponding de-multiplexing and mode conversion at the receiving end, and then through the multi-input multi-output digital signal processing The loss in the signal transmission process is compensated, and finally the electric receiver is used for signal reception.

As shown in Figure 2, this paper builds a short-distance MDM transmission system on the VPI platform. Two 400-meter-long optical fiber transmission paths A and B are set up, and two multimode couplers 2 and 3 are set up on the A path. It is used to simulate the position of fiber bending, so as to compare whether the fiber bending causes MC; compare the influence of MC on the MDM system by changing the Bending Induced Coupling Factor (BICF) parameter caused by bending. Finally, observe the influence of random loss on the MDM system by turning on the switch of the random loss parameter Mode Dependent Loss. The functions and descriptions of each module in Figure 2 are as follows:

Signal sending module: This module is composed of three modulated lasers and two optical white noise sources with Gaussian distribution. Three modulated lasers generate three signals of 10Gb/s with the same emission frequency, and the noise source generates white noise. The three signals are respectively transmitted through three channels of LP01 mode, LP21 mode and LP31 mode.

Couplers: Five couplers are set up, among which the parameters BICF and mode correlation loss coefficients between the LP modes in couplers 1, 4 and 5 are specified in the file. In the file, the coupling coefficient between LP01 mode input and LP11 output is set to 0.5, and the coupling coefficients between the other LP modes are all 0.025; the values of random loss parameters in LP01 mode, LP21 mode and LP31 mode are 0.287987dB and 1.18434 respectively dB and 1.25267dB. The coupling coefficient and random loss parameters between the LP modes of couplers 2 and 3 are changed according to the experimental scenario.
Multimode fiber: This module simulates the transmission of any transverse refractive index distribution in a multimode fiber. The input signal can be regarded as a single incident beam or multiple single fields of different fiber modes with good coupling. The output signal can represent the total power of all modes or the fields of the fiber mode. Among them, the multimode fiber 1 and 3 are 100 meters, the multimode fiber 2 is 200 meters, and the multimode fiber is 400 meters.

Combining and shunting devices: including BusMerge and BusFork combining devices.

Signal analyzer: Connect two photoelectric signal analyzers at the ends of the two optical fibers A and B for quality analysis of the eye diagrams of the signals on different channels.

3. Experiment and Performance Analysis

3.1 System default simulation settings
The parameter settings of the system are shown in Table 1. The value of the MC coefficient BICF caused by bending is between 0 and 5. The random loss is a switch type parameter. The signal transmission frequency and the sampling center frequency remain the same, and the sampling mode bandwidth is $1.28 \times 10^{12}$, other parameters are system default values.

| Default parameters         | Value       | Unit  |
|----------------------------|-------------|-------|
| Time Window                | 64 e-9      | s     |
| BICF                       | 0-5         |       |
| Mode Dependent Loss        | ON/OFF      |       |
| Emission Frequency         | 193.1e12    | Hz    |
| Laser Power                | 1e-3        | W     |
| Sample Mode Bandwith       | 1280e9      | Hz    |
| Sample Mode Center Frequency | 193.1e12   | Hz    |
| Sample Rate Default        | 16*10e9     | Hz    |
| Bit Rate Default           | 10e9        | bit/s |

3.2 The influence of MC on MDM system caused by fiber bending
Set the random loss parameter Mode Dependent Loss to OFF, set the MC coefficient BICF caused by the fiber bending of the multimode couplers 2 and 3 to 0.01, and the other parameters remain unchanged. The optical signal analyzers A and B obtain two optical fiber links. The eye diagram of the signal is shown in Figure 3.
It can be seen from the analysis of Fig. 3 that the signal eye diagram of signal analyzer A with MC caused by bending is compared with the signal eye diagram obtained by signal analyzer B without bending caused by MC. In the three modes, LP01, LP21, and LP31, there is a certain degree of line broadening and blurring. The opening of the "eye" is significantly smaller than the signal eye diagram of MC without bending, which shows that the MC caused by bending is reduced. The anti-noise performance of the MDM system; in addition, when MC is caused by bending, the time jitter of the signals obtained from the three modes is significantly increased. When there is no bending caused by MC, the time jitter of the eye diagram is very small, which indicates that there is bending the resulting MC causes inter-code crosstalk in the system and affects the reliability of system transmission.

3.3 The influence of MC coefficient caused by fiber bending on MDM system

Set the random loss parameter Mode Dependent Loss to OFF, set the mode coupling coefficient parameter BICF caused by the fiber bending of the multimode couplers 2 and 3 to 0.02, and obtain the eye diagrams of the two optical fiber link signals by the optical signal analyzer A and B. As shown in Figure 4.
It can be seen from the analysis of Fig. 4 that when the BICF is increased to 0.02, comparing Fig. 3(b) and Fig. 4(b), it can be found that the eye diagrams of the three modes have no obvious changes under the condition of no bending; compare Fig. 3(a) As shown in Figure 4(a), the opening degree of the “eye” of the signal eye diagram under the three modes does not change much, and the broadening and blurring of the lines are not obvious, but the time jitter increases significantly. This shows that with the MC coefficient BICF As the inter-symbol interference of the received signal continues to increase, the interference to the MDM system is also stronger.

3.4 The influence of random loss on the mode division multiplexing system
Set Mode Dependent Loss to ON, and set the mode coupling coefficient BICF caused by the bending of the fiber of multimode couplers 2 and 3 to 0.01, and the optical signal analyzers A and B can obtain the two optical fiber link signals. The picture is shown in Figure 5.

![Figure 5. Received signal eye diagram](image)

It can be seen from the analysis of Figure 4 that when random loss is added to the system, comparing Figure 3 and Figure 4, we find that regardless of whether there is mode coupling caused by bending, the opening of the "eye" of the received signal eye diagram in the three modes is significantly reduced. This shows that when random losses are added to the system, the anti-noise performance of the system is severely degraded, especially in higher-order modes, such as LP_{21} and LP_{31} modes, the opening of the "eyes" decreases greatly, and the anti-noise performance decreases even more. Obvious; but the eye diagram time jitter of the received signal under the three modes does not increase significantly, which shows that the addition of random loss has a small impact on the system's anti-inter-symbol interference performance.

4. Conclusion
This paper uses the VPI optical network simulation platform to build a short-distance multimode fiber-based mode division multiplexing transmission system. Through experimental parameter settings, the influence of mode coupling and random loss on the reliability of the MDM transmission system is compared. The experimental results show that the mode coupling has a greater impact on the anti-noise performance and anti-inter-symbol interference ability of the MDM transmission system. The larger the mode coupling coefficient, the weaker the anti-noise performance and anti-inter-symbol interference ability of the MDM transmission system. Secondly, random loss has a greater impact on the anti-noise performance of the MDM system, and this impact is more obvious in high-order LP
mode fibers. The focus of the next step is how to perform corresponding time-domain equalization at the receiving end to compensate for the distortion of the signal caused by mode coupling and random loss.

Acknowledgments
Authors wishing to acknowledge assistance by the Armed Police Engineering University Scientific Research Capability Enhancement Program (NO: WKY202127) and Basic Research Fund Project of Information Engineering College of Armed Police Engineering University (NO: XYJC202112).

References
[1] M. Li et al. (2020) Single-Mode VCSEL Transmission Over Graded-index Single-Mode Fiber Around 850 nm. In: 2020 Optical Fiber Communications Conference and Exhibition (OFC), San Diego, CA, USA, pp.1-3.
[2] Zeng X.L. (2018) Research on several key technologies of multi-dimensional multiplexing optical fiber communication system. Beijing: Beijing University of Posts and Telecommunications, pp. 1-10.
[3] Chen H.M, Zhuang Y.Y. (2018) Research progress on key technologies of modular multiplexing systems. Journal of Nanjing University of Posts and Telecommunications (Natural Science Edition), 38(01): 37-44.
[4] Ma C. (2019) Research on Mode Converter in Optical Fiber Mode Multiplexing Communication System. Yunnan University, pp.23-29.
[5] G. Guerra, M. Santagiustina, A. Galtarossa and L. Palmieri. (2019) Analysis of intra-mode coupling length in few-mode fibers. In: 45th European Conference on Optical Communication (ECOC 2019), Dublin, Ireland, pp.1-4.
[6] Ma H.T. (2018) Research on key technologies of pattern multiplexing communication system. Jinan University, pp. 3-10.
[7] Huang H.W. (2018) Research on mode coupling and equalization technology of multi-rate mode multiplexing system. Beijing Jiaotong University, pp. 37-66.
[8] Chen J.k. (2019) Experimental research on mode division multiplexing system based on photon lantern. Jilin University, pp. 35-45.