A Systematic review of Multi-Mode Fiber based on Dimensional Code in Optical-CDMA

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Abstract. This paper deals with optical code division multiple access (optical-CDMA) and provides a general analysis of multi-mode fiber (MMF). The purpose of this work is to classify the works in the literature that are related to Optical-CDMA based on MMF and to find the limitation of the researches done in this field. Several challenges that occur in the medium such as multiple-access interference (MAI), pulse dispersion (PD) and nonlinearity in optical fibers deteriorate system performances and become a major performance-limiting factor.

1. Introduction

Optical fiber is considered as one of the most integral constituent of current networking architectures. Telecommunication uses this technology because of its vast advantages such as low cost, high capacity, huge bandwidth, and no electromagnetic interferences. Also, it can support transmission of exceptionally high data rate in the range of Gbps. Optical communication are becoming more popular for both long-haul and local wired transmission [1-3]. Along with the increasing demand for fiber optic system is the rapid advancement of its relative technology. As predicted by Cisco, the IP traffic increases from 59.9 exabytes per month in 2014 to reach 168 exabytes per month by 2019, which will be remarkably greater than the three-decade old Internet years from 1984 to 2015 [4, 5]. Moreover, high-definition video streaming, multimedia file sharing, online gaming, mobile networking, and other information technologies are other applications of the technology. However, the continued growth of data traffic will lead the fiber optical system to reach its limit [6-8].

There are two main types of optical fiber, single-mode fiber (SMF) and multi-mode optical fiber (MMF). Since it is able to maintain transmitted signals for long distances, SMF supports higher capacity
to transmit information over long distances. Single mode fiber is mostly used in long-haul networks. Furthermore, SMF will reach their capacity limit in near future [6, 7], thus motivating researchers to use MMF for high capacity data transmission [9]. MMF differs from the SMF by its core diameter. The larger core diameter of the MMF makes possible to have more modes propagating through this core [10, 11].

Typically, the core plus cladding of a standard optical fiber has diameter of about 125 μm; however, the core has three different sizes that are determined according to the application of the fiber [12]. An optical fiber is called multimode fiber when it has a diameter of 50 μm and supports several propagation modes. Whereas, it is called single mode fiber when it has a diameter that ranges from 8.6 to 9.5 μm and supports only one propagation mode. [9, 12, 13]. Different multiplexing techniques has been explored and have already been implemented in optical systems to increase the capacity. schemes such as frequency division multiplexing (FDM) and wavelength division multiplexing (WDM) [14]. These multiplexing schemes present, which have now reached a point where they need to be complimented by MMF have reached their limit also known as the ‘Shannon Limit’ [15] which explains the maximum limit of bits of data that a communications channel can carry for a particular noise level.

According to Shannon limitation [16], the capacity increases with a signal to noise ratio, [17] which can be expressed as

\[ C = W \log(1 + SNR) \]

where (W) is the channel’s bandwidth of and (SNR) is the signal-to-noise ratio, the SMF will rich their capacity in near future [6, 18, 19].

In comparison, recent research into the use of optical-CDMA in communication systems has shown incoherent optical-CDMA as the most popularly demonstrated system in the optical domain. Incoherent optical-CDMA system depends on intensity modulation for encoding/decoding as well as uses an optical source that is incoherent. Also, is designs are based on simpler techniques of intensity modulation [20, 21].

2. Systematic Literature Review

This study explains a methodical systematic literature review (SLR) of a dimensional code in optical-CDMA based on multi-mode fiber. Data has been collected from different sources to present the SLR. In this section, an explanation to the SLR is presented including the procedure used to achieve the SLR process and the main points that led to this study.

2.1. Research Question

The study deals with the following research issues that have been recognized and are discussed later in this paper.

**RQ1.** What are the existing types of MMF, the maximum distance and users that have used in optical-CDMA based on MMF?

**RQ2.** What are the limitation of using optical-CDMA over MMF?

**RQ3.** What are the existing code and measurement performance that have been applied for optical-CDMA?

2.2. Inclusion & Exclusion

This paper studies the research papers in which different multimode fibers based on optical CDMA have been used. Papers that are included are from various online resources, journals, and conferences. In addition to that, papers that are not relevant to the multi-mode fiber, papers that are not written in English, book chapters, and reports are excluded from the study.
2.3. Search Process & Study selection

The search process starts with selecting the four databases which are available online to search for target articles. The databases are the IEEE Xplore library, Science Direct database, Optical Society of America library, and Scopus. Indexing cross-disciplinary research in information technology and communication, computer sciences, and computer communication engineering. This selection was made to cover all information technology and communication to provide wider view of researchers’ efforts in relevant disciplines’ range. In the searching process, two groups of keywords were used, the first group contained “Optical-CDMA OR OCDMA”, combined by the “OR” operator whereas the second group contained “multimode fiber OR multi-mode fiber OR MMF” combined by the “OR” operator. The two groups then combined by an AND operator.

As shown in Figure 1 the results of the systematic review articles from IEEE Xplore library, 17 articles from Science Direct database, 28 articles from the Optical Society of America library, and 75 articles from Scopus database, from all years. The first step is filtering based on limits years from 2008 to 2018 resulted in 110 articles. The second step is filter based on journal and conference and writing in English resulted in 89 articles. The third step by remove the duplication resulted in 63 articles. The fourth step is the study selection based on the title, abstract and keyword resulted in 45 articles will exclude before going through quality assessment of selected papers to get the final set of papers in next section. The final step is reading the full articles and only articles content optical-CDMA and MMF in this study will be included as primary study which resulted in 6 articles that will be reviewed in this study as shown in Figure 1 search process & study selection and Figure 2 taxonomy of multiplexing & medium protocol. The initial query search resulted in 173 articles: 53

![Diagram of search process and study selection](image_url)
3. Exploration Of Research Concerns

The following research concerns will be reviewed and discussed individual:

**RQ1.** What are the existing types of MMF, the maximum distance and users that have used in optical-CDMA based on MMF?

Following Table.1 represents an analytical view of the available MMF, the maximum distance and users that have used in optical-CDMA based on MMF. The table content different column that represent various data, first column illustrates several items which are (“Authors- Citation-Years”) and listed according to year. The second column explain various types of MMF that have developed in optical-CDMA and the third column illustrate different users and distance that used in MMF based on optical-CDMA. Moreover, papers in optical-CDMA over MMF has been consider only the last ten year’s which are from 2008 – 2018, as we can see from the table that in 2011 is the first paper that used MMF in optical-CDMA. In addition, there are a few studies on optical-CDMA over MMF due to a number of limitation that will explain more in detail in table 2.

Further, there are two types of MMF that have developed to enhance the capacity and distance of communication system which are step index and graded-index. There are several characteristics of both types, which are the core’s refractive index in MMF, such as uniform throughout and experiencing sudden changes at the boundary in step index. However, in graded index it is made to vary gradually such that being maximum at the center of the core. The diameter of the core is about 50-200μm in step index, in graded index the diameter of the core is about 50μm in the case of MMF as shown in Figure 3. Attenuation is more for step index MMF compare to graded index MMF is attenuation is less.

Furthermore, graded index has higher bandwidth compared to the other which is less bandwidth. As shown in Table.1 there is one study in step index that applied in MMF over optical-CDMA [20], in other hand the study which used graded index are [22-26]. In addition, there are a more studies on optical-CDMA over MMF based on graded index.
Figure 3. MMF types

Table 1. represent different kinds of MMF, the maximum distance and users in optical-CDMA based on MMF.

| No | Authors- Citation-Years | MMF types | Users-Distance |
|----|-------------------------|-----------|----------------|
| 1  | Youssef A. Diab [20] 2018 | MMF Step Index | 20 users |
| 2  | Hichem Mrabet [22] 2016 | MMF Graded-index | 5.14 Km - 10.82 Km (Mb/s to 10 Gb/s user 17) |
| 3  | Aliaa Mamoun [23] 2014 | SMF – MMF Graded-index | 1km |
| 4  | Aliaa Mamoun [24] 2013 | MMF Graded-index | 1.5km |
| 5  | Mohammad Hossein [25] 2013 | MMF Graded-index | 1168 m |
| 6  | Tolulope B [26] 2011 | MMF Graded-index | 17 km |

Moreover, the number of accommodating users is severely limited, because of several issues and challenges in MMF. Also, the noise increases when the number of users increases. Figure 4 represent the number of the users for each study. In 2018 Youssef A. Diab [20] their study used 20 users over step index MMF, 2016 Hichem Mrabet [22] their study try to transmit 17 users over 5.14km MMF based on LED and 10.82km MMF based on VCSEL in range capacity between (10 Mb/s to 10 Gb/s). At the Tx it’s better to use VCSEL for MMF. And, can support from 10 Mb/s to 10 GB/s capacity. However, the performance of OCDMA systems has been improved by using electrical detection. In 2014 Aliaa Mamoun [23] their study used one user over 1km graded index MMF, 2013 same author try to transmit 2 users over 1168 m MMF, and used selective excitation of LPOI and LP02 modes to improve the signal and mitigate noise [25]. The last paper in this study [26] 2011 Tolulope try to transmit 4 users over 17 km graded index MMF based on power re-equalization of wavelength pulses inside of optical-CDMA Codes.
RQ2. What are the limitation of using OCDMA over MMF?

As shown in Table 2, an analytical view of the available limitation in MMF based on optical-CDMA is demonstrated. The table contains several columns that represent various data, first column explains items which are (“Citation- Authors -Years”) and listed according to year. The second column explains various types of MMF that have developed in optical-CDMA and the third column illustrates different limitation in MMF based on optical-CDMA.

| No | Citation | Years- Authors | MMF types       | Limitation                                                                 |
|----|----------|----------------|-----------------|-----------------------------------------------------------------------------|
| 1  | [20] 2018 Youssef A. Diab | Step Index | MMF             | Intermodal dispersion total pulse broadening strongly increases as the number of active users increase |
| 2  | [22] 2016 Hichem Mrabet    | Graded-index | MMF             | MAI and modal dispersion caused by the MMF channel in LAN context           |
| 3  | [23] 2014 Aliaa Mamoun      | Graded-index | MMF             | Modal dispersion                                                            |
| 4  | [24] 2013 Aliaa Mamoun      | Graded-index | MMF             | Modal dispersion                                                            |
| 5  | [25] 2013 Mohammad Hossein  | Graded-index | MMF             | Multi-user interferences                                                    |
| 6  | [26] 2011 Tolulope B        | Graded-index | MMF             | Multi-user interferences                                                    |

Because of its information security, more attention has been given to the OCDMA recently. Spectral efficiency has been improved by decentralized and simplified network control. This enables several users to share the same transmission medium synchronously and simultaneously as well as increases flexibility in the provisioned granularity of bandwidth. However, during propagation of data over the MMF based on OCDMA, an inevitable issue encountered is pulse dispersion, nonlinearity and MAI due to mode coupling [21-23, 27, 28]. The most critical damage of OCDMA is pulse dispersion that should
be compensated to avoid data MAI [21]. Pulse dispersion occurs due to the difference in the fiber’s propagation constants which is called mode dispersion. This is a time varying phenomenon [22, 24, 28-31]. As see in Table.2, which shows the limitation of MMF, the first study illustrates that increasing number of active users increases total pulse broadening. Differences between modes for multimode fiber of propagation delay results in pulse broadcasting that is detected by intermodal dispersion. Furthermore, when only single mode is allowed, pulse broadening is resulted from intermodal dispersion [20]. MAI and modal dispersion are caused by MMF channel in LAN context as represented in 2016, the performance of OCDMA systems has been improved by using electrical detection. However, the performance will be effected when the number of users and distance increase then MAI is increasing [20], [22].

Moreover, in 2014 and 2013 they try to improve the performance by used selective excitation of LP01 and LP02 modes to improve the signal and mitigate noise [24, 25]. Other study used power re-equalization and other detection technique of wavelength pulses inside of optical-CDMA codes to reduce the noise. To improve pulse dispersion, different approaches are used to recover signal [32, 33] in optical communication system such as space diversity, optimization and coding were needed to reducing the effects of fading and MAI [34]. However, this domain need more attention to improve the bandwidth and to transmit more data over more distance in MMF.

**RQ3. What are the existing code and measurement performance that have been applied for optical-CDMA?**

Following Table.3 explain the existing code and measurement performance that have been applied for optical-CDMA. The table content different column that demonstrate various data, first column explains items which are (“Citation- Authors -Years”) and listed according to year. The second column explain the existing code that have developed in optical-CDMA and the third column illustrate different measurement performance that applied in MMF based on optical-CDMA.

**Table 3.** demonstrate the existing code and measurement performance

| No | Citation   | Years- Authors | Code types       | D-code | Measurement performance         |
|----|------------|----------------|------------------|--------|----------------------------------|
| 1  | [20] 2018  | Youssef A. Diab | APHCs            | 2D     | Pulse broadening                 |
| 2  | [22] 2016  | Hichem Mrabet  | PHS and HC       | 2D     | BER                              |
| 3  | [23] 2014  | Aliaa Mamoun   | MD               | 1D     | Eye diagram                      |
| 4  | [24] 2013  | Aliaa Mamoun   | MD               | 1D     | Q factor and BER and Eye diagram |
| 5  | [25] 2013  | Mohammad Hossein | MPC, PMPC and UC-MPC | 1D | BER                              |
| 6  | [26] 2011  | Tolulope B     | WH/TS            | 2D     | BER                              |

Incoherent optical-CDMA encoding process is realised either in the spectral domain, time domain, space domain as one-dimensional (1D) code sequences [34-36], or a combination of both is called two-dimensional coding (2D coding) [37-40] which can be time-wavelength, time-space and wavelength-space [34]. Because of the larger 2D code set and the better correlation properties of 2D code sequence, compared to 1D, 2D coding both supports larger number of users and has better system performance [41, 42].

As show in Figure.4 and Table.3 illustrate the different measurement and different types of code that have been developed for optical-CDMA based on MMF. As explain above that in optical-CDMA the coding have to be based on spectral domain, time domain, space domain as one-dimensional (1D) code sequences [34-36] or two-dimensional coding (2D-coding) [37-40] which can be time-wavelength, time-space and wavelength-space [34]. One-dimensional (1D) code that have explained in Table.1 are (Multi-
diagonal (MD) codes in 2013 [24], Modified prime code (MPC), double-padded modified prime code (DPMPC) and Uniform Cross-Correlation Modified Prime Code (UC-MPC) in 2013 [25], in 2014 [23] have used Multi-diagonal (MD) codes, all the code are developed for optical-CDMA based on MMF. Moreover, the two-dimensional code that have been developed for optical-CDMA to improve the MAI are Wavelength-hopping time-spreading (WH/TS) in 2011 [26]. in 2016 [22] Prime hop system and hybrid code (PHS and HC), asymmetric prime-hop codes (APHCs) in 2018 [20]. The evaluation of the previous study in optical-CDMA based on MMF are based on different measurement, most of them used BER [22-26], the other performance measurement are Q factor [24], Eye diagram [24], and pulse broadening [20] as show in Figure.4 below.

![Figure 4](image)

**Figure 5.** represent the different measurement and different types of code

4. Conclusion

In this study, we present a systematic review of optical-CDMA over MMF. A number of different articles are included in the study showing an analytical study resulted from the analyzation of the authors. It was found that few articles are available out there that work on the MMF field. This is because of several challenges that occur in the medium such as MAI, pulse dispersion, and nonlinearity due to mode coupling.

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