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Analyses of constraints on high speed optical code division multiplexing access (OCDMA) link parameters due to fiber optic chromatic dispersion

Y. Zouine [c], I. Dayoub [a], S. Haxha [b,*], J.M. Rouvaen [a]

[a] *IEMN DOAE (UMR CNRS 8520) UVHC, Le Mont-Houy, 59313 Valenciennes Cedex 9, France*
[b] *Photonics Group, Department of Electronics, University of Kent, Canterbury CT2 7NT, UK*
[c] *LEIMP Laboratoire d'électroniques, d'instrumentations et mesures physiques, Faculty of Science and Technology, BP 509 Boutalamine, Errachidia, Morocco*

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Abstract

In direct sequence-optical code division multiplexing access (DS-OCDMA) system networks, data rate and data spreading technique involved in such systems require a high chip rate. Transmission link in these systems is significantly affected by the fiber chromatic dispersion. In this study, we have developed and employed a simple model to estimate the G652 fiber dispersion effects. OCDMA technique has been employed to investigate fiber chromatic dispersion effects on multiple access interference (MAI). We have found that, at a short optical fiber length, the optical fiber dispersion has a significant impact on the high data rate transmission systems (higher than 750 Mbit/s). The performance and optimization of optical orthogonal code (OOC) in the OCDMA system is reported. We have demonstrated that, for a high data rate, even if dispersion compensated devices are not deployed, the BER can be significantly improved when the OOC desired length is selected. We have shown that when compensation dispersion devices are not deployed in the system, there is a trade off between the limited dispersion effects and the MAI.

1. Introduction

The success and extensive application of code division multiple access (CDMA) in the wireless area has renewed attention in exploring its application in the optics communication systems. Optical CDMA (OCDMA) has for a long time been the subject of research because of its inherent ability to support asynchronous burst communications. Initially it was employed for local area [1], then for access network applications [2,3] and more recently for emerging networks such as generalized multiprotocol label switching [4–6].

Optical communication networks are widely reported in the literature, particularly, in the access of optical transmission systems such as fiber-to-the-home (FTTH) or fiber-to-the-curb (FTTC). OCDMA is broadly studied as a possible solution to provide high quality transmission [7–11]. It is already known that several network topologies can be employed for FTTH such as single star, active double star and passive star (PDS). The PDS also know as a passive optical network (PON) is used as a result of flexible configuration and low cost [12,13]. Depending on the signal multiplexing techniques, various PONs can be employed. In time division multiple access (TDMA) which uses a time-division-multiplexing (TDM) technique, N time slots are assigned to N corresponding users. However, there are serious limitations of this technique. The increase of the bandwidth is restricted by the bandwidth limitations of the electronic devices, and only synchronous network configurations can be used. The next technique is wavelength division multiple access (WDMA), where a wavelength is assigned to each user. In this case the bandwidth is used efficiently and the asynchronous transmission can be

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[*] Corresponding author. Tel.: +44 (0) 1227 827257; fax: +44 (0) 1227 456084.
E-mail address: S.Haxha@kent.ac.uk (S. Haxha).

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maintained. However, limitations of this technique are that current coarse-wavelength-division-multiplexing (CWDM) technique supports only 18 wavelengths, which is not suitable for existing PON systems which have up to 32 users. Thus, in order to increase the number of users, the equipment cost will significantly increase. In this context, the OCDMA is a promising technique which requires no electronics for synchronization and offers a low cost, all optical processing, simplified network control and bandwidth efficiency [9,14–16]. Additionally, the OCDMA technique allows several users to access the network simultaneously and asynchronously by allocating a specific code to each user [8,9]. In the case of an optical incoherent network, the spreading codes are unipolar, not strictly orthogonal. This introduces a limitation to the performances known as MAI [17]. However, the MAI is not the only restriction in the OCDMA optical link networks. In reality, there are many impairments involved in transmission of optical signals [18,19]. In the optical fiber systems, the main deprivation is caused by dispersion and attenuation. This dispersion is caused by combined effects of material and waveguide dispersion. The chromatic dispersion of the transmission fibre is a major factor causing optical pulse broadening. In the case when dispersion is positive, shorter wavelengths propagate faster than longer wavelengths. In the opposite case of negative dispersion, this regime is considered to be normal. This creates the interference inter different chip transmitted over optical fiber which can affect the system performances.

In this paper, we developed and employed a numerical model based on DS-OCDMA where single mode fiber (SMF) chromatic dispersion effects in the access networks are taken into consideration. This numerical model is developed in Matlab and then incorporated in the COMSIS simulator [20]. A study of a complete system parameters using system simulation is considered to be time consuming. Thus, the proposed model allows us to effectively investigate several system parameters at the same time. To the best of our knowledge there is no study reported in estimation of the fiber optic chromatic dispersion impact on the OCDMA performance at a high data rate in the access networks.

This paper is organized as follows: In the introduction, a brief description of the state of the art of the OCDMA technique and its advantages over TDMA and WDMA is presented. In Section 2, a study of a DS-OCDMA system is reported. Section 3 is devoted to fiber optic chromatic dispersion effects on the OCDMA and validity of the proposed model. Section 4 is dedicated to dispersion effects on the MAI. Finally, conclusions are drawn in Section 5.

2. DS-OCDMA system description

In this study, we considered a synchronous DS-OCDMA system with N users $b_i^{(k)}$, as shown in Fig. 1. The data corresponding to the user k is spread by the user's code $c_k(t)$. The code signature of the kth user is described by [8]

$$c_k(t) = \sum_{i=1}^{F} d_{k,j} P(t - j \cdot T_c) \tag{1}$$

where $P(t)$ denotes a unit rectangular pulse with a T_c duration and $d_{k,\,j} \epsilon \{0, 1\}$ is the jth value of the kth user spreading code. The contribution of each user is summed together and sent into the optical fiber link. The transmitted signal $s(t)$ at the input of the optical fiber, shown in Fig. 1, can be expressed by [21]

$$s(t) = \sum_{k=1}^{N} b_i^{(k)} c_k(t) \tag{2}$$

The received signal $r(t)$ at the front end of each receiver is the superimposed sum of N delayed photodetector outputs. At the end, a correlation receiver is employed to recover the data.

In order to be able to extract the data at the end of the receiver, the sequence code must be specified to each user. In this study, the Optical Orthogonal Codes (OOCs) with their parameters (F, W, λ_a, λ_c) [8] are considered as sequence codes. Where, F is the code sequence length, W is the code weight which represent "1"s in the code sequence, λ_a and λ_c is auto-correlation and cross-correlation constraint, respectively. In order to minimize the MAI, the auto-correlation and cross-correlation constrain λ_a and λ_c should be equal to "1".

The OOCs are modeled by a quasi orthogonal unipolar sequence $c_k(t)$ and divided into F intervals with a weight W. For a given OOC (F, W), the maximum number of users N that can be accommodated in the OOC system can be expressed as [9]

$$N = \left| \frac{(F-1)}{W(W-1)} \right| \tag{3}$$

In this study we employed a Conventional Correlation Receiver (CCR) and we assumed it to be an ideal optical component, as shown in Fig. 2. The received signal $r(t)$ is the sum of all coded signals sent through the fibre optic and can be expressed as [9]

$$r(t) = \sum_{k=1}^{N} b_k c_k(t) \tag{4}$$

At the receiver end, the optical demodulator provides the signal $r(t)$ which is proportional to the received optical power. This signal is recovered by multiplying it with the desired user's code, then integrated and detected by adjusting the decision threshold S, which is equal to W. In an ideal system, for example, when the encoder is directly connected to the decoder, the only system limitation is the MAI. In this case, errors can only occur when the data sent is "0" and the decision variable $Z_i^{(k)}$ is too large. This is due to the contribution of the other users.

The probability of error P_{ES} for an ideal chip in synchronous system can be expressed as [9]

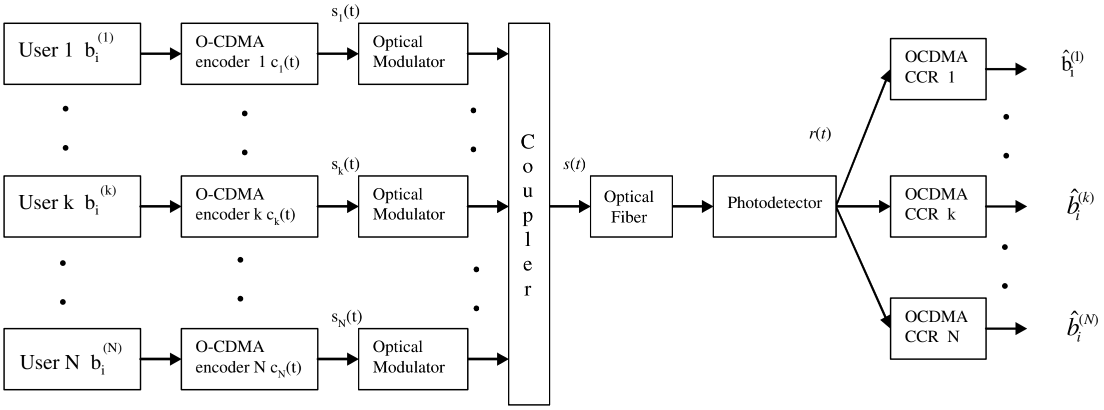

Fig. 1. The optical DS-OCDMA system.

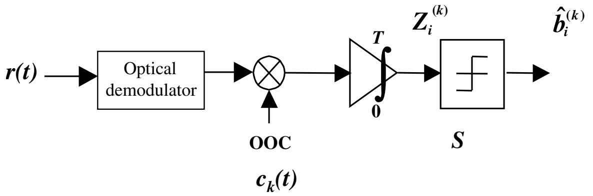

Fig. 2. Conventional correlation receiver (CCR).

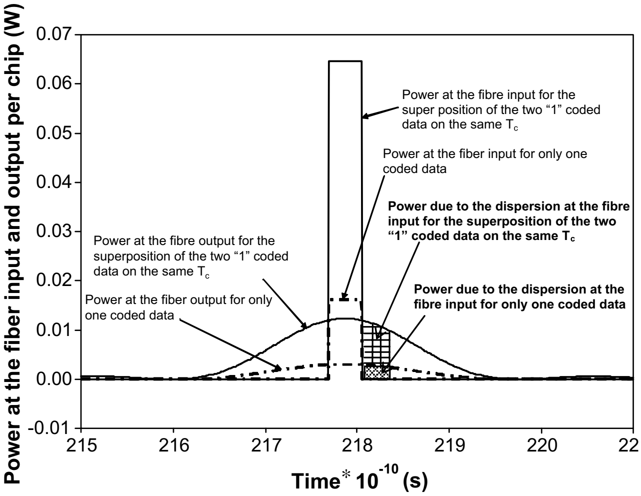

Fig. 3. Spreading of the data due to optical fiber dispersion when two coded data are transmitted.

$$P_{\mathrm{ES}} \leqslant \frac{1}{2}\sum_{i=S_{\mathrm{Th}}}^{N-1}\binom{N-1}{i}\left(\frac{W^2}{2F}\right)^{i}\left(1-\frac{W^2}{2F}\right)^{N-1-i} \tag{5}$$

As can be observed from Eqs. (3) and (5), there is a trade of between the number of users and bit error ratio (BER) in the OCDMA system modeling. In the last two decades, the performance of the OCDMA for optical access networks has been demonstrated in the literature [8,9,14, 22,23], where MAI effects on the system performance have been investigated. However, so far chromatic fiber dispersion in such systems has not been considered. Therefore, in this study we have investigated fiber chromatic dispersion effects on the OCDMA performance.

3. Fiber chromatic dispersion effects on OCDMA

A study of optical pulse spreading as a result of chromatic dispersion in the input and output of the optical fiber is carried out and presented in Fig. 3. Simulated results of the power at the input and output of the optical fiber are shown with a solid and dash-dotted curve, respectively. The optical power represents the power per chip T_c. From Fig. 3, it can be observed that the data is not spread uniformly. This phenomenon is as a result of an increase in power which corresponds to the superposition of two data coded at the same chip T_c (chip duration), and the power which corresponds to the one coded data. One can see that more coded superposition data per chip would result in further spreading of the coded data. This will affect adjacent chips and result in the further increase of errors. This will significantly reduce the performance of the system, especially when the number of users is increased.

The increase of data rate and the spreading data technique used in OCDMA contribute to shorten the light pulses. In this case, it is necessary to take into account fiber dispersion effects and to compare to MAI limitations. This is essential, in particular, when short optical fibers are used in access network.

3.1. Description of dispersion model

The MAI is not the only restriction factor in OCDMA networks. Other impairments such as thermal noise, shot noise, attenuation and dispersion also have a negative impact on these networks. In this context, we investigate the fiber dispersion effects on the MAI. Dispersion is generally classified as intermodal, chromatic and polarization mode dispersion (PMD). The propagation distance in the access networks is usually short. In general, in these networks G652 monomode fiber optics are deployed [18]. Therefore, intramodal dispersion is not a problem. The

PMD is caused by asymmetries and stress distribution in fiber core, which leads to birefringence. It affects only long-haul communications systems. Nonlinear effects in optical fiber can also cause negative effects on system performance, but mainly for long-distance communication. Such nonlinearities are dependent on the signal intensity, which are not significant at the low power. Therefore, for a short access optical link, chromatic dispersion effect is an important factor which needs to be addressed.

In the access network applications, high data rate should be available to a large number of users. In order to reduce the MAI limitations, the OOC length F should be increased in OCDMA analysis. For a given data rate D, the chip rate D_c can be expressed as: $D_c = D \cdot F$. Hence, as F increases the chip rate increases. Consequently, the chip duration decreases, as a result of this the signal becomes more susceptible to dispersion. Accordingly, the optical power contained in the emitted chip "1" causes optical signal broadening, this signal is then received at several chips. In communication systems, intersymbol interference (ISI) is a result of distortion of a signal that causes the previously transmitted data to have an effect on the received data. The ISI affect results in more chips containing non-zero optical power than expected. As for conventional decisions, we selected the decision threshold level $S = W \cdot P_{cen}$, where P_{cen} is the optical power level which corresponds to the chip center. Thus, the data sent "1" is always well-detected. The only error that can occur in this situation is when the data sent is "0", as in the ideal case.

In order to effectively estimate the impact of the chromatic dispersion in the system, we developed a simple model of optical fiber dispersion by using Matlab. The main objective in this study was to evaluate the perturbation on chips of the OCDMA code sequence, for example, the number of adjacent chips disturbed by the spreading effect due to the dispersion and the corresponding optical power. In reality, pulse broadening generates additional contributions in the decision variable value $Z_i^{(k)}$ that could lead to more errors on '0' data.

In this study, we considered the most obvious values of the signal broadening due to distortions, as shown in Fig. 4. The central lobe of the received signal with the width T and height H is illustrated in this figure. The central lobe contains the largest part of the optical power. The width T describes the number of adjacent chips in the OCDMA sequence disturbed by the effects of the dispersion; whereas the height H describes the level of optical power in the lobe. These two parameters (T and H) are included in our model. To determine these two parameters, we transmitted a rectangular impulse through the optical fiber and then measured the central lobe width T and height H at the fiber output using COMSIS system simulator [20]. From Fig. 4 one can see that majority of the power is contained in the central lobe. Therefore, for this reason, we have modeled the spreaded signal by a triangle with base T and height H. The values of T and H depend on the width of the impulse T_c, the length of the fiber and the value of chromatic dispersion. The spreading of the impulse creates co-chips interferences (temporal). The number of chips disturbed by the spreading of the considered chip is obtained by dividing T per T_c (as shown in the insert Fig. 4). Then we calculate the percentages of power disturbed in each impulse chip. Using this method, we can produce a signal composed of rectangular impulses of duration T_c of decreasing amplitudes relative to the amount of spreading.

Variation of the central lobe width T and height H as a function of the rectangular emitted pulse duration T_c for the G652 optical fiber is illustrated in Fig. 5. The G652 fiber length is 50 km with its dispersion of 17 ps/nm km. The emitted pulse normalized height is equal to '1'. It appears that, according to Ref. [18] the shorter the emitted pulse is, the larger and the lower the dispersed pulse will be. Therefore, in this study, we considered these parameters to be essential in modeling of the dispersion effects. In this model, the received dispersed signal has a triangle form with a base T, and height H. As can be seen from Fig. 5, when T_c is 35 ps, the corresponding T is 380 ps. This clearly shows that 5 adjacent chips on both sides of the central chip are disturbed. The corresponding optical power is

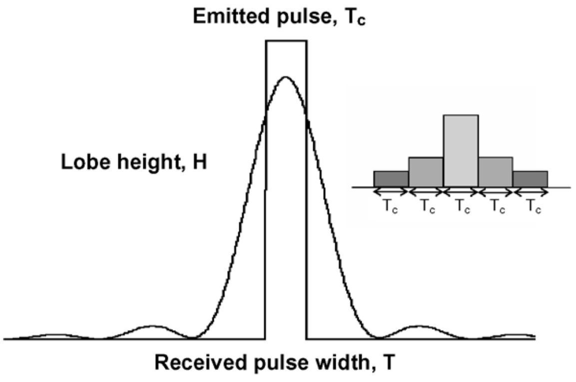

Fig. 4. Waveform of a pulse before and after spreading.

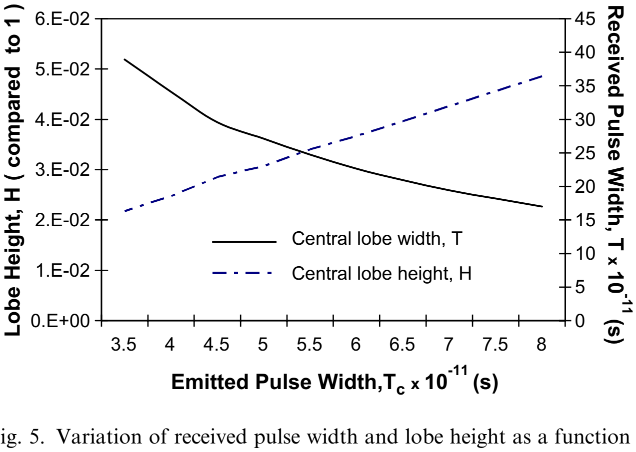

Fig. 5. Variation of received pulse width and lobe height as a function of the emitted pulse duration T_c when the G652 optical fiber length $L = 50$ km.

estimated as the optical power contained in the triangle hit by the chip.

3.2. Model validation

In order to validate our numerical model, simulation results are compared to the system simulator [20] and to the theoretical BER of the OCDMA conventional receiver, expressed by the Eq. (5). Compared results of the BER are illustrated in Fig. 6. These system simulations are time consuming. Therefore, in order to carry out rapidly system simulations, the OOC simulations are performed for $F = 181$, $W = 4$ and $N = 5$ (users). The threshold level is set to $S = 2 \cdot P_{\mathrm{cen}},$ and the fiber length is $L = 50$ km.

From Fig. 6 One can see that dispersion has a significant impact on the system performance when the data rate D increases. According to theory expressed by Eq. (5), when the data rate increases the BER is constant. However, our simulations results indicate that the system performance is deteriorated by about one order of magnitude, shown here by the dashed curve. A similar trend is shown by the system simulator [20], illustrated by the dotted curve. It can be anticipated that our model allows superior bound of fiber dispersion impact on the system performance and describes dispersion evolution. Furthermore, in this study we developed a reliable and a faster dispersion model than the system simulator reported in [20]. The proposed model can be effectively employed to investigate and optimize the system parameters.

4. Dispersion effects and MAI

Pulse spreading due to dispersion is related to several system parameters, such as optical fiber type, fiber length L, and the pulse duration T_c. It also depends on the data rate D and the code length F, which can be expresses as: $T_c = 1/(D \cdot F)$. Based on the fact that MAI is a function of the code parameters and the number of active users, the impact of the dispersion on the system performance is significant. In this study, we investigated the system performance with different active numbers of users N with and without inclusion of dispersion effects.

We analyzed and optimized the data rate D, fiber length L, and OOC code length F, in order to reduce the BER without the need to deploy compensated dispersion devices. For example, in the case when a Dispersion Compensated Fiber (DCF) is deployed, attenuation will be increased. Also, additional optical amplification devices are required. This could have a negative effect on the local access deployment. Therefore, in our simulations, we considered the G652 fibers with dispersion of 17 ps/nm km. In order to minimize the MAI impact, the optimum decision threshold is set to $S = 2 \cdot P_{\mathrm{cen}}$ [8]. Dispersion impact on the system performance as a function of the number of users N is illustrated in Fig. 7.

As can be observed from this figure the trend of the BERs with and without dispersion is the same. One can see that for $N = 5$ active users and 10 km fiber length, the MAI is low. In this case chromatic dispersion is the main limiting factor of the system performance. However, when the number of users is increased to 15, MAI is the main limiting factor, whereas the chromatic dispersion effect is very small. This is the reason why there is a difference of 1 decade between the two cases, $N = 5$ and $N = 10$ users. Therefore, the system performance is more susceptible to dispersion when the number of users is reduced (i.e. low MAI). In order to upper-bound the dispersion effect, simulations for $N = 5$ are performed.

4.1. System performance as a function of fiber length and data rate

A study of the system performance as a function of the fiber length and the data rate is carried out. Variation of the BER as a function of the data rate D, for various fiber lengths, when $N = 5$ and $F = 181$, is illustrated in Fig. 8.

From Fig. 8, it can be observed that the system performance is significantly deteriorated by the dispersion effects, when the data rate and fiber length is increased. It can be seen that, for example, when the fiber length is 20 km, the data rate limit is 100 Mbit/s, whereas when the fiber

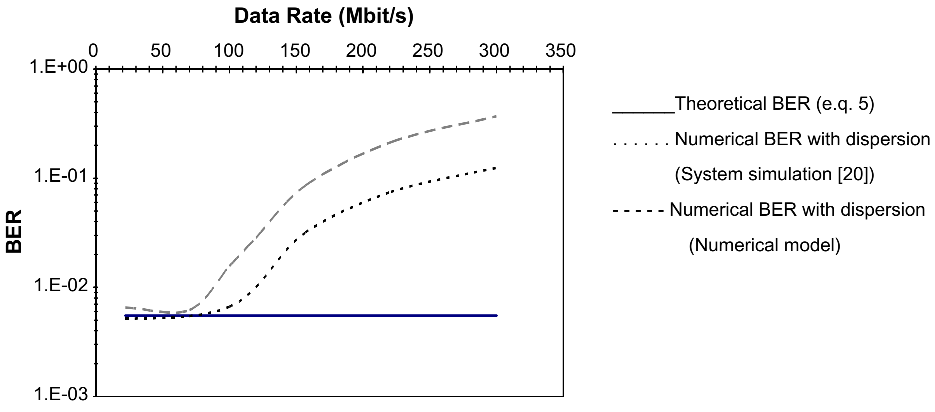

Fig. 6. Variation of BER as a function of data rate.

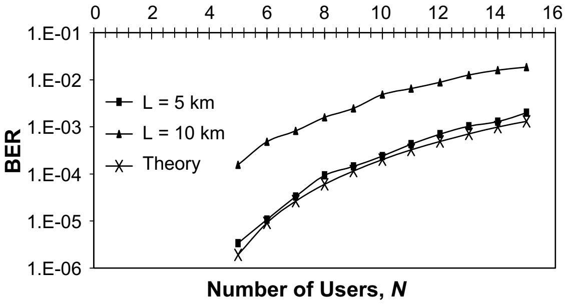

Fig. 7. Variation of BER as a function of the number of users when $F = 181$ and $D = 220$ Mbit/s.

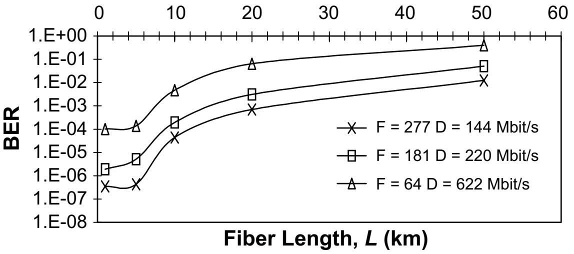

Fig. 9. Variation of BER as a function of fiber length, where T_c $(F, D) = 2.51 \times 10^{-1}$ s and $N = 5$.

length is 1 km, the data rate limit is 600 Mbit/s. In fact, when the fiber length decreases, the date rate should increase to recover a similar degradation of the signal form. Thus, in order to design and optimize link parameters, the maximum fiber length should be defined as short as possible, to obtain high data rate and to achieve a desired system performance without dispersion compensation device.

Next, a study of the code length for a given L and D, when there is no dispersion compensation device deployed, is carried out. Variation of the BER as a function of the fiber length for 3 codes with various F and D, is illustrated in Fig. 9. The pulse duration is fixed to $T_c = 1/(F \cdot D) = 2.51 \times 10^{-11}$ s, and the number of active users is $N = 5$.

It can be noted that the dispersion effect increases as the fiber length increases. However, for this particular chip duration, the dispersion has no impact on the BER for optical fibers shorter than 5 km. On the other hand, when the fiber's length is greater than 5 km, system performance is deteriorated. One can see, that the system performance improves for a longer code and a low data rate. Indeed, for a given emitted chip duration, i.e. a given dispersion, the dispersion effect would disturb a given number of adjacent chips. As the code length increases, the disturbed chips become less frequent. So, when a desired user sends a "0", its signal is statistically less disturbed. Thus, for a given dispersion and the fiber length, longer code improves the system performance.

Next, investigation of the code length for various data rates and fiber lengths is carried out. Variation of the BER as a function of the code length, when data rate is kept fixed to $D = 220$ Mbit/s, for fiber lengths of 1, 5, 10 and 20 km, is illustrated in Fig. 10. From this figure, one can see that for a given fiber length, the BER initially decreases and then, after a while, it starts to increase. This is due to the fact that when the code length is small, the chip duration is long, so the dispersion effect is almost negligible. Therefore, results are almost identical to the theoretical results presented in the Eq. (5). When the code length increases, the chip duration is short, and as a result the signal is dispersed. Using longer code, improves the system's performance; however, in the output fiber, the signal will be spread further. Consequently, the chromatic dispersion effect will increase. As a result of this, BER will be further degraded compared to the ideal system. In the case, when no dispersion compensation device is deployed, our simulation results show a constraint on the selection of the OOC parameters. However, there is an optimum value of the code length F, where the system performance can be improved.

Furthermore, it can be noted that the systems performance is deteriorated when the fiber length is increased. It can also be observed that the code length increases as the fiber length decreases. When the fiber length decreases, the systems performance can be improved by using the optimal code.

Considering the fact that the access link is typically 5 km long, we focus on investigating of these types of systems. Variation of BER as a function of code length for various data rates, when $L = 5$ km is illustrated in Fig. 11. One can see that for a particular data rate, there is an optimum code length, which can be used to improve the system performance. It can be observed that, in order to improve the system performance, the optimal code length should be

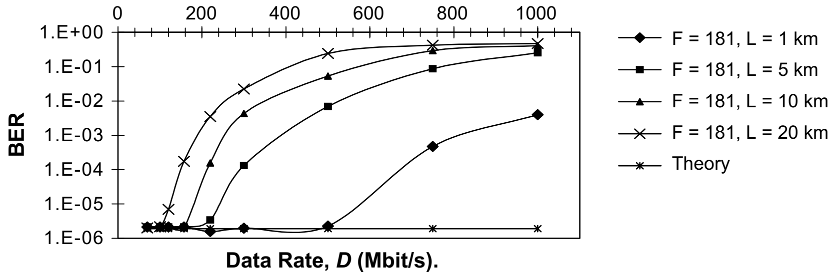

Fig. 8. Variation of BER as a function of data rate and fiber length when $F = 181$ and $N = 5$.

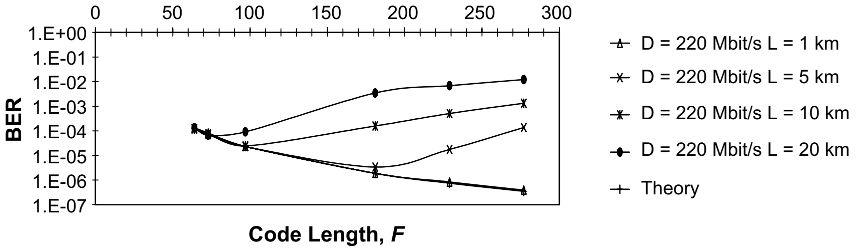

Fig. 10. Variation of BER as a function of code length F, when $D = 220\text{Mbit/s}$ and L is 1 km, 5 km, 10 km and 20 km.

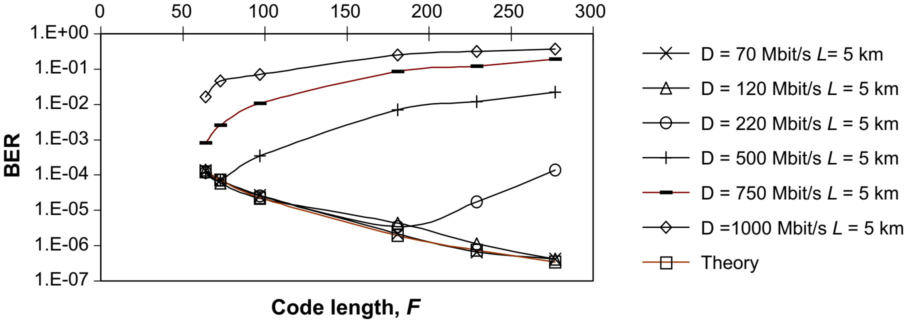

Fig. 11. Variation of BER as a function of code length for various data rates when $L = 5$ km.

increased and the data rate should be decreased. However, it can be seen that, for a data rate higher than 750 Mbit/s, even when a short code length is used, the dispersion is still significant. In these situations, a desired system performance can not be achieved without deploying dispersion compensation devices. On the other hand for a data rate smaller than 120 Mbit/s, the dispersion has no effect on the system performance.

5. Conclusion

A simple model using OOC codes is developed and employed to investigate dispersion effects on the DS-OCDMA access links. The impact of the fiber chromatic dispersion effects on the MAI is reported. The developed model is used to analyze and optimize the OCDMA parameters such as data rate, optical fiber length, and code sequence parameters. It is demonstrated that chromatic dispersion has a significant negative effect on system performance which cannot be neglected for systems with short a fiber length and a high data rate. It is reported that system performance can be significantly overestimated if chromatic dispersion is ignored. It is found that for a high data rate even if dispersion compensated devices are not deployed, the BER can be significantly improved when the OOC optimal length is carefully selected (even for short fiber length). Our simulations show that this optimal code length should be less than 100. The MAI is also an important system limitation which must be reduced. Thus, in an access optical network, when the OCDMA technique is used it is necessary to use either dispersion compensated devices or interference cancellation receivers in order to obtain desired system performance.

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