OFDM based fiber nonlinear impairment compensation for long-reach passive optical networks

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Orthogonal frequency division multiplexing (OFDM) is an extensive technology in commercial communication because of its ability to mitigate channel distortions. OFDM technique achieves high spectral efficiency and requires simple channel equalization. It has received significant interest to photonics community as an attractive solution for long-reach transmission, as it offers a reduced signal bandwidth and enables simple digital equalization. This paper investigates the performance of optical OFDM (OOFDM) system using fiber nonlinear effects. A new approach named impairment factor is introduced to reduce the fiber nonlinear impairments of the system. The simulation results have been provided for dual polarization OOFDM system with multi-level quadrature amplitude modulation (M-QAM) applied to the optical signal subcarriers. The performance of the proposed OOFDM system is compared to the conventional single carrier optical system with M-QAM for the same number of information bits.

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1. Introduction

Passive optical networks (PONs) are considered as a cost-effective fiber-to-the-home (FTTH) solution. However, the increasing bandwidth enabled by fiber access network means that metro and core networks will also need to be updated. Next generation PONs (NG-PONs), in particular the long-reach PON (LR-PON) addresses this issue and has gained significant interest to the photonics community recently as a profitable solution. LR-PON is a network access technology that fully exploits the low loss of optical fiber to build a cost effective and energy efficient broadband access network. By expanding the optical reach to about 100 km, the number of required network nodes can be reduced by as much as two orders of magnitude, eliminating most of the local exchanges and thereby reducing both cost and energy consumption. The number of users per PON is reached from 32 to over 500 or even 1000, which increases the resource sharing and reduced cost makes the LR-PON as a potential solution [1, 2]. The main characteristics of LR-PON are [3]: (a) Use a power-split optical distribution network that leads to resource sharing over a larger number of users. (b) Increase distance between user and the core system that reduces the number of central systems by orders of magnitude. (c) Use a flat optical core and smart traffic management that reduce core traffic by turning traffic around at the metro/core node.

According to the CISCO IP traffic forecasting research, households with high-speed fiber connectivity generated more traffic than households connected by DSL or cable broadband. The average FTTH household generated 67 GB/month in 2015 and will generate 138 GB/month in 2020 as shown in Table 1. Thus, it is necessary to develop an optical system with higher spectral efficiency.

Table 1. Fiber-connected traffic vs other broadband traffic

Year	FTTH (GB/month)	Other broadband (GB/month)
2014	61	28
2015	67	35
2019	120	78
2020	138	83

2. Literature Review

Orthogonal frequency division multiplexing (OFDM) is a method of digital modulation commonly used in commercial communications, shows great potential to be used in optical systems. Although OFDM has been recently studied in the photonics field, it has not so widely been studied for LR-PON rather than few efforts [4-9]. An OFDM signal consists of several orthogonal sub-carriers that are simultaneously emitted over a single transmission path. Each sub-carrier occupies a small portion of the entire signal bandwidth [10]. Various system designs have been proposed in the literature to build efficient LRPONs. Transmission impairments compensation using broadband channel sounding in multi-format OFDM-based LR-PONs is introduced in [11]. Transmission of baseband OFDM and multi-band UWB-OFDM signals along LR-PONS using directly modulated lasers (DML) is experimentally demonstrated in [12]. Spectrally efficient ER-PON using 4 Gbps OFDM-QAM for both upstream and downstream signals was proposed and demonstrated in [13]. OFDM for high-speed optical transmission has been studied in [14] and it was shown that optical OFDM in combination with the subcarrier multiplexing offers a significant improvement in spectral efficiency. Adaptive four-band OFDM modulation with 40 Gbps downstream and 10 Gbps upstream signals for next generation LR-PON is investigated in [15]. Spectrally efficient 100 Gbps LR-PON based on 64-QAM and frequency interleaved directly detected OOFDM was proposed in [16] to solve the scalability issues of existing PONs. We see that OFDM based LR-PONs has been getting significant interest in optical applications.

In this paper, OFDM based LR-PON system using M-QAM is introduced and the effect of fiber nonlinear impairments such as four-wave mixing (FWM) has been compensated using the proposed system. A new approach is developed by partial utilization of the OFDM sub-carriers for minimizing the nonlinear impairment is also presented and impairment factor is introduced.

The structure of the paper is as follows. Section 3 describes the conceptual design of OFDM based LR-PON system. Section 4 presents the proposed technique for fiber nonlinear impairment reduction. Section 5 provides the simulated results using the proposed technique and comparison of the results with the conventional single carrier system. Final conclusions are given in Section 6.

3. OFDM based LR-PON System

Fig. 1 shows the block diagram of the proposed system using OFDM over an optical channel. Each data stream is presented as N parallel data paths to the OFDM transmitter. The N paths are modulated by N equally spaced OFDM subcarriers using QAM. A cyclic prefix is inserted to each transmitted block after the IFFT so that the relative delays between the received OFDM subcarriers due to fiber dispersion can be compensated by preserving the orthogonality among the OFDM subcarriers. After equalization, each symbol is demodulated to obtain N parallel data streams. These can be converted into single data stream by parallel to serial conversion.

In the OFDM transmitter, the input data stream is mapped into information symbols of the OFDM subcarriers. To efficiently reduce the transmitter and receiver bandwidth, the subcarrier frequency of OFDM symbol is chosen between $-f_{bw/2}$ and $f_{bw/2}$, where, f_{bw} is the bandwidth of OFDM symbols. The baseband OFDM signal can be given as [17].

$$s(t) = \sum_{i=-\infty}^{\infty} \sum_{k=-\frac{N_{SC}}{2}+1}^{k=\frac{N_{SC}}{2}} X_{ik} \Pi\left(t-iT_S\right) e^{j2\pi f_k \left(t-iT_S\right)} \quad (1)$$

where, X_{ik} is the i^{th} information symbol at the k^{th} subcarrier, f_k is the frequency of the subcarrier, N_{sc} is the number of OFDM subcarriers and T_s is the OFDM symbol period respectively.

The transmitted signals for a dual-polarized OOFDM system can be given as

$$s(t) = [s_1(t), s_2(t)]^T \quad (2)$$

The received signal is then expressed as

$$\begin{gathered} r(t) = \quad (t) \otimes s(t) + n(t) \\ (t) = \begin{bmatrix} {}_{11}(t) & {}_{12}(t) \\ {}_{21}(t) & {}_{22}(t) \end{bmatrix} \end{gathered} \quad (3)$$

where, $h(t)$ is the fiber impulse response and $h_{ij}(t)$ denotes the response of the i^{th} output polarization to an impulse in the j^{th} input polarization. The terms $r(t)$ and $n(t)$ represents the received signal and noise respectively can be given as

$$n(t) = [n_1(t), n_2(t)]^T \quad (4)$$

$$r(t) = [r_1(t), r_2(t)]^T \quad (5)$$

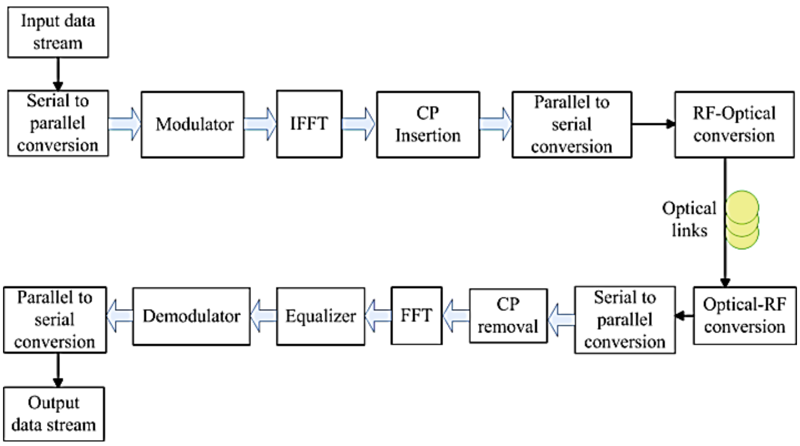


Fig. 1. Conceptual diagram of an Optical OFDM system

LR-PONs suffers from two main types of fiber linear impairments: (i) chromatic dispersion (CD), which creates inter-symbol interference (ISI). CD is independent of polarization, i.e., identically affects the channels carried by both polarizations and (ii) polarization mode dispersion (PMD), is a time varying phenomenon which requires adaptive equalization techniques for its mitigation [18].

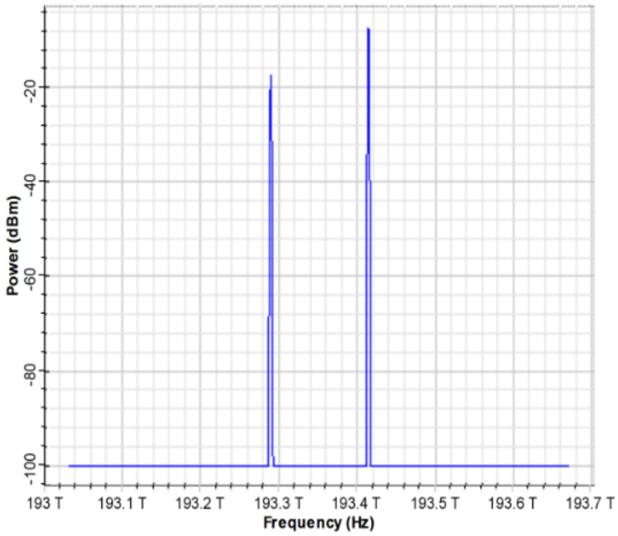
4. Nonlinear Impairment Reduction

The basic operational principles of optical transmission are commonly explained assuming that optical fiber medium is linear. However, the linearity assumption is valid if launched power does not exceed several milliwatts in a single channel system. In modern multichannel optical system, high-power semiconductor lasers and optical amplifiers are used, and the impact of fiber nonlinearities becomes important. The most significant nonlinear impairment occurs in optical system is known as four-wave mixing (FWM) that occurs due to the dependence of the index of refraction on light intensity. FWM is an inter-modulation phenomenon in non-linear optics, whereby interaction between two wavelengths produces two extra wavelengths in the signal as shown in Fig. 2.

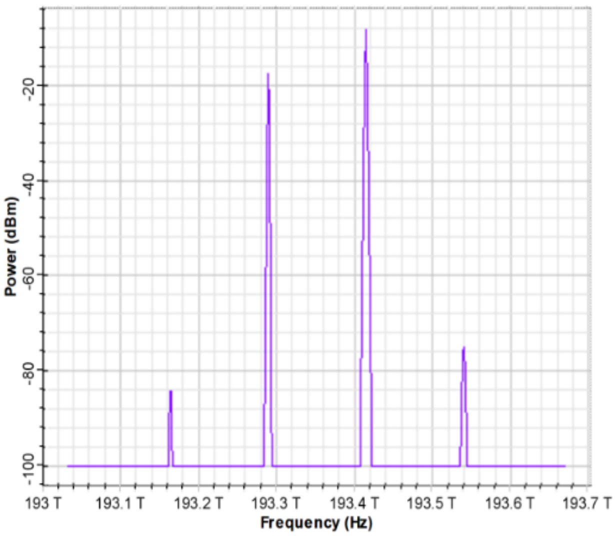
Let us consider two input frequency components f_1 and f_2 (with $f_2 > f_1$), a refractive index modulation at the difference frequency occurs, which creates two additional frequency components. In this case, the phase modulation creates two sidebands (at frequencies given by their difference) but at a lower intensity. In effect, two new frequency components are generated as $f_3 = f_1 - (f_2 - f_1) = 2f_1 - f_2$ and $f_4 = f_2 + (f_2 - f_1) = 2f_2 - f_1$.

In FWM, several wavelength channels interact to create new channels. FWM occurs in optical fibers during the propagation of a composite optical signal such as OFDM signal. It gives rise to the optical signals. FWM can be minimized either by reducing the power per channel or increasing the channel spacing. FWM affects the signal-to-noise ratio and thus the bit error rate.

The fiber nonlinear effects can be compensated by OFDM based partial sub-carrier utilization so that the system can be modeled with a linear channel. The impact of system nonlinearity on the OFDM symbol can be compensated by partial utilization of the OFDM subcarriers. This can be done by assigning redundant zeros to certain OFDM subcarrier as shown in Fig. 3. It shows that there are zero subcarriers between every two data subcarriers.



(a)



(b)

Fig. 2. Four-wave mixing (a) Two adjacent optical frequencies (b) Signal with FWM (color online)

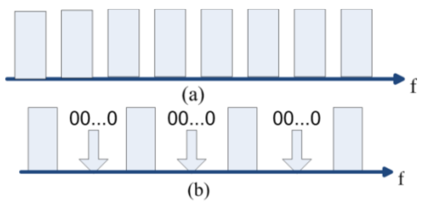


Fig. 3. (a) Original OFDM subcarriers (b) OFDM with partial subcarrier utilization

To implement the partial subcarrier utilization, OFDM frequency-domain sample vector for N sub-carriers can be generated using the sequences as shown in Table 2. The sequence in Table 2 generates the orthogonal signals based on the placement of 1's and 0's. We observe that in each column, if we have a 1, the other elements are 0's and the next column is filled with all 0's to prevent oversampling.

This procedure not only preserves the zero subcarrier properties but also ensure the orthogonality between the signals in a dual-polarized optical system. As an example, the spectrum of an original OFDM signal with 16 subcarriers is shown in Fig. 4(a) where each subcarrier has a null at the center of its adjacent subcarriers. Fig. 4(b) shows the spectrum of an OFDM signal with 16 subcarriers which is generated based on the scheme shown in Fig. 5 by spreading the digital frequency domain vector shown in Table 2 and the modulation symbol from random integer generator. The order of modulation (*M*) may be chosen as $M = 2^k$.

Table 2. OFDM frequency-domain sample vector for partial subcarrier utilization (color online)

	1	2	3	-	-	-	-	N
Ψ_{ω_1}	1	0	0	0	1	0	0	0
Ψ_{ω_2}	0	0	1	0	0	0	1	0

We develop a procedure to design the optimal pulse shaping technique that ensures orthogonality by imposing the rules shown in Table 2. This approach preserves the orthogonality based on the placement of null sub-carrier with 0's. Significant portion of the distortion components caused by fiber nonlinearity will be located in the null (zero) subcarriers, which has no impact on the effective data subcarriers. Therefore, inter-subcarrier and inter-channel interference due to fiber nonlinearity are reduced by partial utilization of the OFDM sub-carriers. This technique takes advantage of the efficient signal processing capability of the multicarrier OFDM system which is difficult to implement in single-carrier system, where a large number of electrical filters are required for the same purpose.

We define an impairment factor as the ratio of the number of effective subcarriers (data subcarriers) divided by the total number of the subcarriers in each OFDM symbol. The impairment factor can be given as

$$\eta = \frac{N_s - N_0}{N_s} \times 100\% \quad N_s > N_0 \tag{6}$$

where, (N_s - N_0) is the number of effective data sub-carriers, N_0 is the number of null sub-carriers and N_s is the total OFDM sub-carriers used in the system.

We observe that as long as we increase the number of null sub-carriers, the impairment factor is decreased which in turn decreases the fiber nonlinear impairments. This is because the increment in null-subcarriers causes significant amount of distortions located in the null subcarriers. However, the trade-off is bandwidth consumption on null sub-carriers.

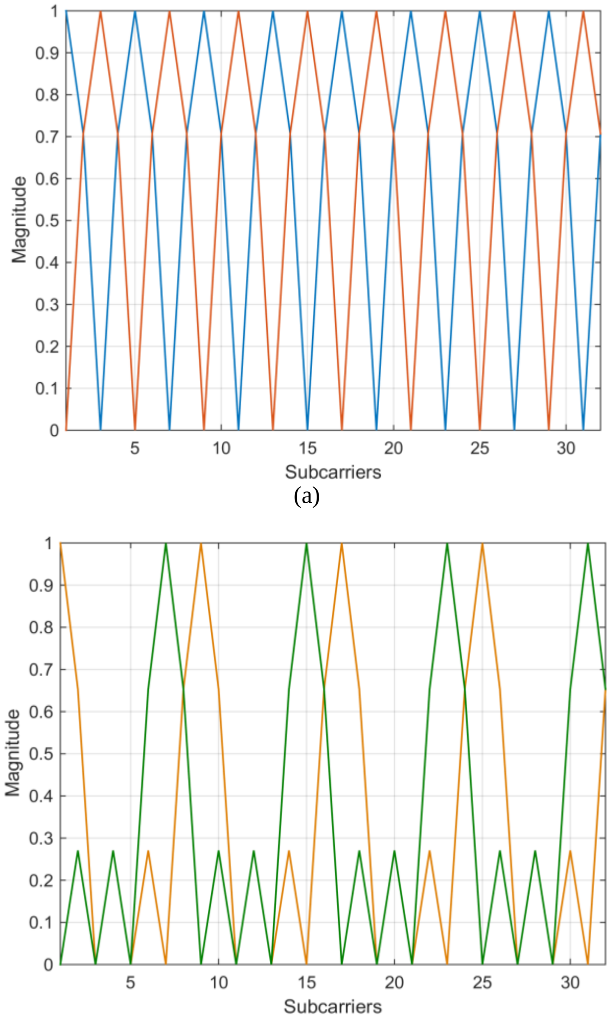


Fig. 4. OFDM signal spectrum (a) Generic OFDM (b) OFDM with partial subcarrier utilization (color online)

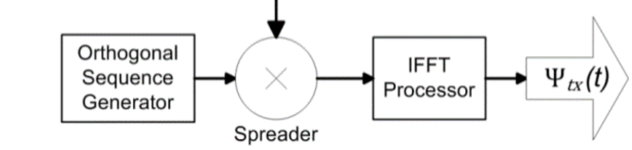


Fig. 5. OFDM signal generator with partial subcarrier utilization

5. Results and discussion

In simulation, randomly generated data were packed into OFDM subcarriers; each subcarrier symbol was in a QAM format. By using IFFT, these subcarrier symbols were converted to a time domain signal. Cyclic prefix insertion is then performed. The effect of nonlinear impairment such as FWM was applied and AWGN is added based on the OSNR in 0.1 nm. In the receiver, cyclic prefix has been removed and FFT is applied. Finally, QAM demodulation was applied to retrieve the data and BER was computed. Table 3 shows the parameters used during simulation.

Table 3. Simulation parameters

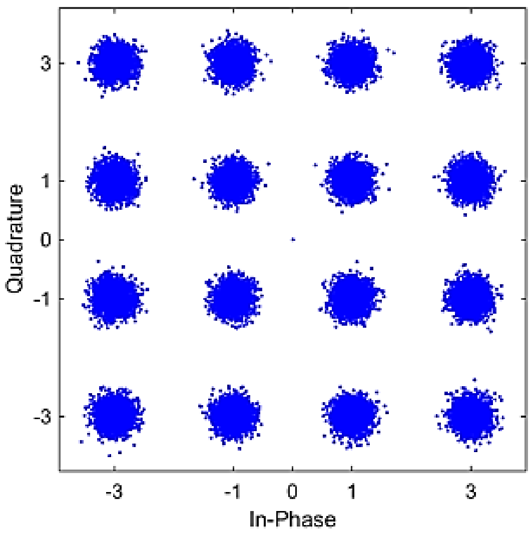
Parameters	Value
Baud rate	14 Gbaud/s
Fiber length	110 Km
Wavelength	1550 nm
OFDM Subcarriers	4096
Subcarrier spacing	3.4 MHz
Cyclic prefix length	64

The proposed system has been evaluated by two scenarios such as (a) multicarrier optical OFDM system and (b) OOFDM system with proposed partial subcarrier utilization technique. Initially we have evaluated the OOFDM system performance in terms of constellation recovery using 16-QAM. Fig. 6(a) shows the recovered symbols constellation for the proposed OOFDM system. We observe that the estimation error is comparatively large i.e. equalized symbols are not well concentrated. For comparison, the recovered symbol constellation of OOFDM using partial subcarrier utilization of 50% is shown in Fig. 6(b), where equalized symbols are more concentrated on their expected position and their bias are much smaller.

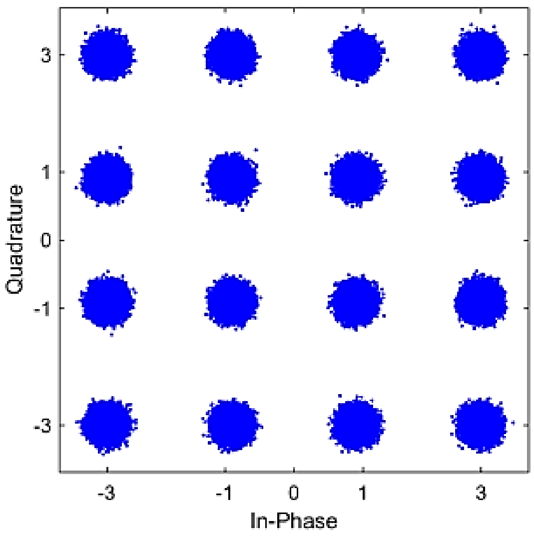
Fig. 7 shows the BER performance of the proposed system using received data versus the OSNR for conventional single carrier with 16-QAM, multicarrier OFDM using 16-QAM and OFDM with partial subcarrier utilization (impairment factor of 50%). We observe that, with the increase of OSNR, the improvement of BER performance increases. If we consider the BER of 10^{-3}, the required SNR is 16 dB using OFDM whereas single carrier 16-QAM system requires 17 dB. This can further be improved by partial subcarrier utilization for same BER and required SNR is reduced to 13 dB.

Fig. 8 shows the BER performance of the proposed system using received data versus the OSNR for conventional single carrier with 64-QAM, multicarrier OFDM using 64-QAM and OFDM with partial subcarrier utilization (impairment factor of 50%). As expected, with the increase of OSNR, the improvement of BER performance increases. If we consider the BER of 10^{-3}, the required SNR is 22 dB using OFDM whereas single carrier 64-QAM system requires 23 dB. The performance is further improved by the proposed partial subcarrier utilization technique for the same BER and required SNR is reduced to approximately 19 dB.

Fig. 9 shows the BER performance of the proposed multicarrier OOFDM system with 16-QAM for different impairment factors. As the impairment factors increases, the BER decreases. Increasing the impairment factor results in increase of electrical and optical bandwidth of transmitting data. Although the proposed partial subcarrier utilization technique broadens the bandwidth of an OFDM signal, due to its high spectral efficiency, the OOFDM system with an impairment factor of 50% is still comparable with conventional single carrier system.



(a)



(b)

Fig. 6. Constellation of 16-QAM symbols after equalization (a) Generic OOFDM (b) OOFDM with partial subcarrier (color online)

6. Conclusion

Performance for optical OFDM systems is analyzed considering the fiber non-linearity effect. Simulation results show that the proposed system is able to compensate the nonlinear impairment based on the proposed partial subcarrier utilization technique. The proposed system may simplify the long-reach system design and maintenance without a need for CD compensation. OFDM based system can provide higher spectral efficiency. Although partial utilization of the subcarriers broadens the bandwidth of an OFDM signal, the proposed OOFDM system provides better performance than the conventional single carrier optical systems.

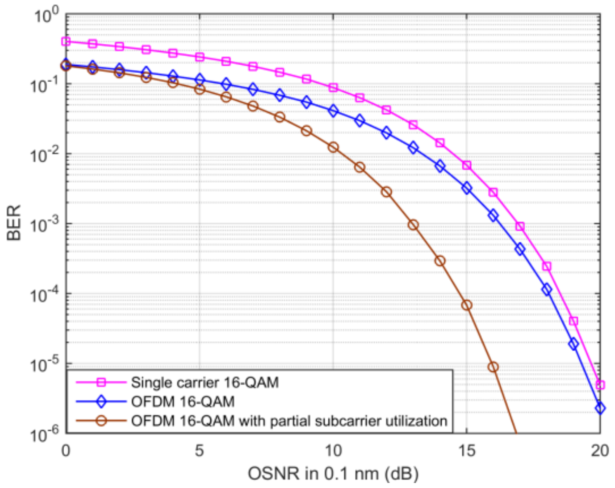


Fig. 7. OSNR vs BER in OOFDM system with 16-QAM (color online)

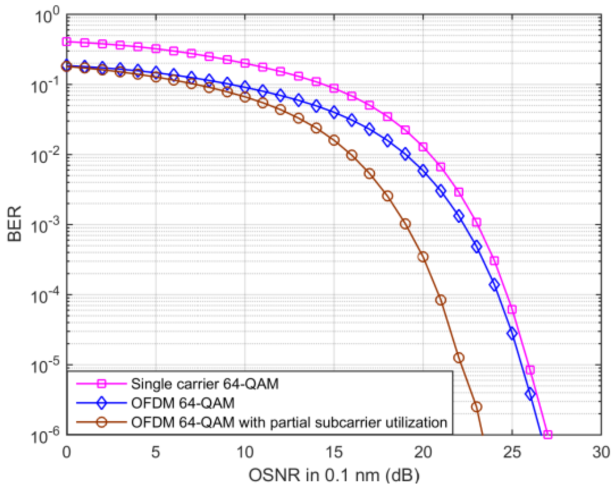


Fig. 8. OSNR vs BER in OOFDM system with 64-QAM (color online)

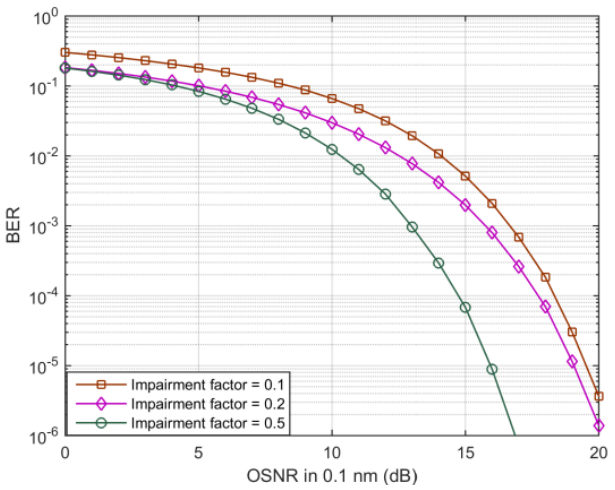


Fig. 9. BER vs OSNR in OOFDM system for different impairment factors (color online)

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