Radio-over-Fiber system capacity improvements by using Wavelength Division Multiplexing and Subcarrier Multiplexing Techniques

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Received on: 19/1/2015 & Accepted on:7/5/2015

Abstract:

Radio-over-Fiber (RoF) system refers to the radio signals which are modulated with optical signal and transmitted over optical fiber link from Central Office (CO) to the Remote Nodes (RN_s). In this paper, RoF system with Wavelength Division Multiplexing (WDM) and Subcarrier Multiplexing (SCM) techniques, has been designed and simulated with different modulation schemes (such as: 4-QAM-OFDM, 16-QAM-OFDM and 64-QAM-OFDM schemes) to increase the capacity of the system by 20×8 Gbps data rate. The simulation results show that the SCM-WDM-RoF with 16-QAM-OFDM scheme gives better performance with symbol error rate (SER) equal to 10^{-9}, and reduces the power consumption compared with SCM-WDM-RoF system with other modulation schemes which have been used in this work. The software package "Optisystem version 12" has been used to simulate this system.

تحسين قدرة نظام الراديو عبر الالياف باستخدام تقنيات مضاعفة تقسيم الطول الموجي و مضاعفة الناقل الثانوي

الخلاصة

يشير نظام الراديو عبر الالياف الى تضمين الاشارات الراديوية بواسطة الاشارة الضوئية و تنقل عبر قناة الالياف البصرية من المركز الرئيسي إلى النقاط البعيدة. في هذه المقالة، تم تصميم و محاكاة نظام الراديو عبر الالياف مع تقنيات مضاعفة تقسيم الطول الموجي (WDM) و مضاعفة الناقل الثانوي (SCM) مع مخططات التضمين المختلفة مثل (4-QAM-OFDM ، 16-QAM-OFDM ، 64-QAM-OFDM) لزيادة قدرة النظام بنسبة 8× 20 جيجابت في الثانية معدل البيانات. حيث بينت نتائج المحاكاة ان نظام SCM-WDM-RoF مع 16-QAM-OFDM يعطي اداء افضل مع SER تساوي 10^{-9} ويقلل من استهلاك الطاقة مقارنة مع نظام SCM-WDM-RoF مع مخططات التشكيل الأخرى التي استخدمت في هذا العمل. وقد استخدامت حزمة البرامج التي تدعى "Optisystem Ver. 12" لمحاكاة هذا النظام.

INTRODUCTION

Radio-over-Fiber (RoF) systems can be described as the modulation process of microwave data signals onto an optical carrier and then transported to remote sites or base station using an optical fiber channel [1]. Radio-over-Fiber

https://doi.org/10.30684/etj.33.6A.11
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technology has been developed since the late 20^{th} century and has been used efficiently in a range of applications for communication systems such as cellular networks, WiMax, wireless local area networks (WLANs), cable television systems, indoor distributed antenna systems and other RF applications [2]. Radio over fiber system is the next generation of communication systems because it has many advantages compared with conventional system with low attenuation, a large bandwidth, immunity to radio frequency interference, operational flexibility, reduced power consumption, a long signal transmission distance and extension of existing coverage and capacity [3]. The main elements of the RoF system are; the Central Office (CO), the Optical Link and the Remote Node (RN) [4].

Theoretical Analysis

This section presents a brief overview of the Radio over Fiber system, Quadrature Amplitude Modulation (QAM), Orthogonal Frequency Division Multiplexing (OFDM) technique, multiplexing techniques, and other techniques related to this work.

Quadrature Amplitude Modulation (QAM)

Quadrature Amplitude Modulation (QAM) is a combination of Amplitude Shift Keying (ASK) and Phase Shift Keying (PSK) modulations [5]. The correct detection of the signal depends upon the separation distance between the signal points in the signal constellation. In PSK systems, all points located on the circumference of the circle because of PSK signal has constant amplitude throughout. In QAM systems, phase and amplitude of the signal are varied, thus the points will place inside the circle also on the constellation diagram. Furthermore, increase the noise immunity of the system and with a higher order form of modulation as a result of its ability to carry more bits of information per symbol, this system can be used for high bit rate transmission [6, 7]. The transmitted QAM signal for symbol *k* is defined by [6]:

$$s_k(t) = \sqrt{\frac{2E_0}{T}}\, a_k \cos(2\pi f_c t) - \sqrt{\frac{2E_0}{T}}\, b_k \sin(2\pi f_c t) \qquad ...(1)$$

where
$0 \le t \le T$, $k = 0, \pm 1, \pm 2, \ldots M$, a_k and b_k are integers, and E_0 is the energy of the signal with the lowest amplitude. Let $(d_{min}/2) = \sqrt{E_0}$, where d_{min} is the minimum distance between any two message points in the constellation.

Orthogonal Frequency Division Multiplexing (OFDM)

OFDM is used extensively in communication systems because it is an effective solution to Inter-Symbol Interference (ISI) problem caused by a dispersive channel. Another advantage of OFDM is that it transfers the complexity of transmitters and receivers from the analog to the digital domain [8]. The basic concept of OFDM is to split a high data rate stream into multiple lower data rate streams that are transmitted simultaneously over a number of orthogonal subcarriers. As a result the relative amount of dispersion in time caused by dispersive channels such as optical fibers is decreased. OFDM based design has an inherent capability to include a cyclically extended guard time in every OFDM symbol. In the guard time, the OFDM symbol is cyclically extended to avoid and eliminate intercarrier interference. An OFDM signal consists of a sum of subcarriers that are modulated by using phase shift keying (PSK) or quadrature amplitude modulation (QAM). If d_i are the complex QAM symbol, then one OFDM symbol starting at $t = t_s$ can be written as [9]:

$$s(t) = \mathrm{Re}\left\{\sum_{i=-\frac{N_s}{2}}^{\frac{N_s}{2}-1} d_{i+\frac{N_s}{2}} \exp\left(j2\pi\left(f_c - \frac{i+0.5}{T}\right)(t-t_s)\right)\right\}, t_s \leq t \leq t_s+T \quad \ldots(2)$$

$$s(t) = 0, \quad t < t_s \text{ and } t > t_s+T \quad \ldots(3)$$

where

N_S is the number of subcarriers, T is the symbol duration, and f_c is the carrier frequency.

The block diagrams of the basic OFDM transmitter and receiver is shown in Figure (1), the input data can be in different modulation formats, such as: BPSK, QPSK, QAM, etc. The first processes in the transmitter are interleaving and coding. All OFDM systems use some formats of error correction or detection because, if there is frequency selective fading in the channel, some of the parallel data streams will experience deep fading. After coding, the data is mapped onto complex numbers representing the QAM or PSK constellation being used for transmission. The sequence of complex numbers output from the constellation mapping are then serial to parallel converted to form a vector suitable for input to the IFFT. The complex vector $\mathbf{X} = [X_0\ X_1\ X_2 \ldots X_{N-1}]^T$ is the input to the IFFT, the vector has length N where N is the size of the IFFT. Each of the elements of $\mathbf{X}$ is a complex number representing a particular QAM constellation point. The complex vector $\mathbf{x} = [x_0\ x_1\ x_2 \ldots x_{N-1}]^T$ is the output of the IFFT. The remaining processes of the OFDM transmitter is the front end as combining filtering, parallel to serial conversion and digital-to-analog conversion (DAC). After that, the output complex signal is passed to an IQ modulator for upconversion to the carrier frequency [8-10].

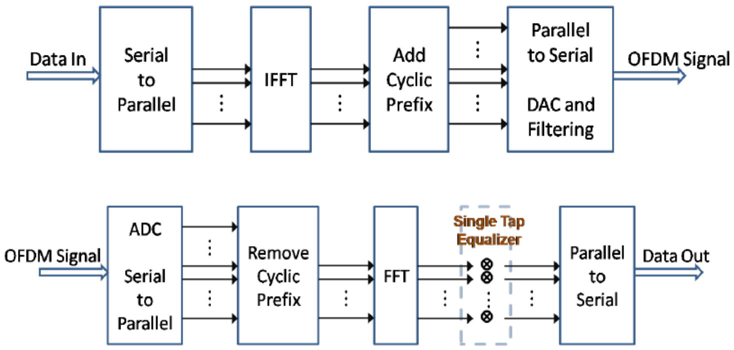


Figure (1): The block diagram of OFDM system [9]

Optical Modulation

The electrical signal is modulated onto an optical carrier in RoF system by an optical intensity modulation (IM). The Mach–Zehnder Modulator is preferred to be used as an external modulator due to many advantages such as its refractive index, which is changed linearly with applied voltage and its stability at normal electronic operating temperatures. The electrical signal $E_{RF}(t)$, as given in Eq. (4), is divided into two branches in-phase $E_i(t)$ and quadrature-phase $E_q(t)$ components, via a 3 dB splitter [11].

$$E_{RF}(t) = V_{RF}\ \cos(\omega_{RF}(t) + \theta(t)) \qquad \ldots(4)$$

where
V_{RF} is the electrical signal amplitude in volts, $\omega_{RF}(t)$ is the electrical carrier frequency, and $\theta(t)$ is the signal phase in radians. The Mach–Zehnder Modulator (MZM) is shown in Figure (2). The output of MZM which is denoted as $E_{O/P}(t)$ as given in Eq. (5):

$$E_{O/P}(t) = \frac{V_{LD}}{\sqrt{2}\times 10^{L_M/20}}\left(\exp\left(j\left(\omega_c(t) + \frac{\pi V_{dc}}{\sqrt{2}\times V_\pi} + \Phi_{in}(t) + \frac{E_i(t)}{\sqrt{2}}\right)\right) + \exp\left(j\left(\omega_c(t) + \Phi_{in}(t) + \frac{E_q(t)}{\sqrt{2}}\right)\right)\right) \qquad \ldots(5)$$

Where
V_{LD} is the laser source voltage in mV, L_M is the insertion loss of MZM, $\omega_c(t)$ is the optical carrier frequency, V_{dc} is the threshold voltage and V_π is the switching voltage for MZM in volts. $\Phi_{in}(t)$ is the phase difference of optical carrier within MZM in radian.

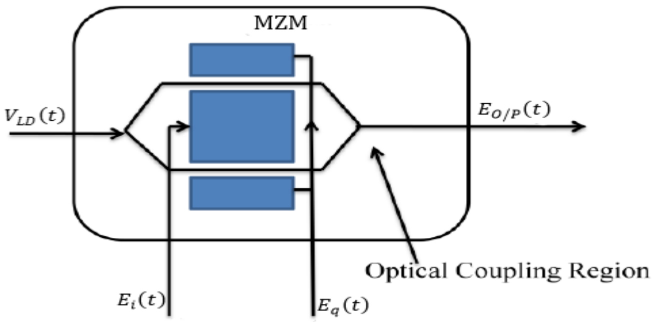
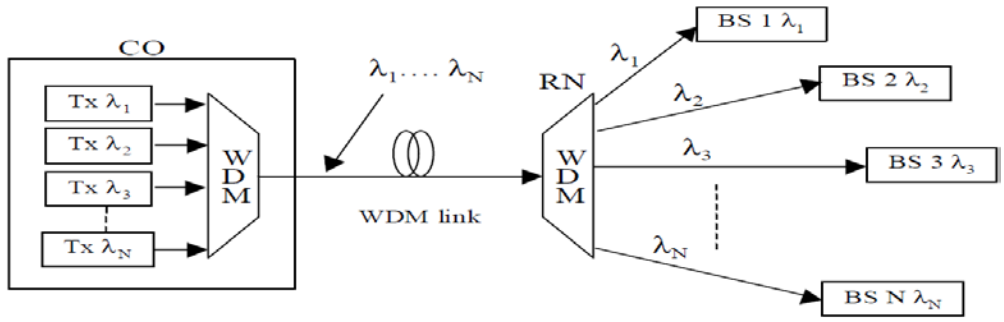


Figure (2): Mach–Zehnder Modulator (MZM) [11]

Wavelength Division Multiplexing (WDM)

The basic operation of WDM, is the combination of multiple optical channels with different wavelengths, coming from different optical sources into a single fiber using multiplexers at the transmitter end, and demultiplexers in the receiver to split WDM channels [12]. The capacity of the Radio-over-Fiber (RoF) systems can be increased by applying Wavelength Division Multiplexing (WDM) technology in the optical fiber feeder network, and also increases the number of base stations supported by a central



office. In addition to that it is an effective way to increase the usable bandwidth of the fiber [13]. WDM-RoF networks topologies are similar to the network topology for other optical networks, such as star network, ring network and bus network. In this work, star network has been used as shown in Figure (3) [14].

Figure (3): Generic WDM-RoF star network architecture [14]

Subcarrier Multiplexing (SCM)

Subcarrier Multiplexing (SCM) is one of multiplexing techniques that can be applied in optical system in order to increase the efficiency of the bandwidth utilization. In SCM technique of RoF system the multiple Radio Frequency (RF) signals are multiplexed in frequency domain and transmitted by a single wavelength. The combination of subcarrier multiplexing (SCM) and Wavelength Division Multiplexing (WDM) may provide a more flexible for high speed optical transmission with high optical bandwidth efficiency and high dispersion tolerance. The SCM is more sensitive to noise effects, disadvantage, which limits the maximum subcarrier frequencies and data rates. The basic configuration of SCM optical system is shown in Figure (4) [15-18].

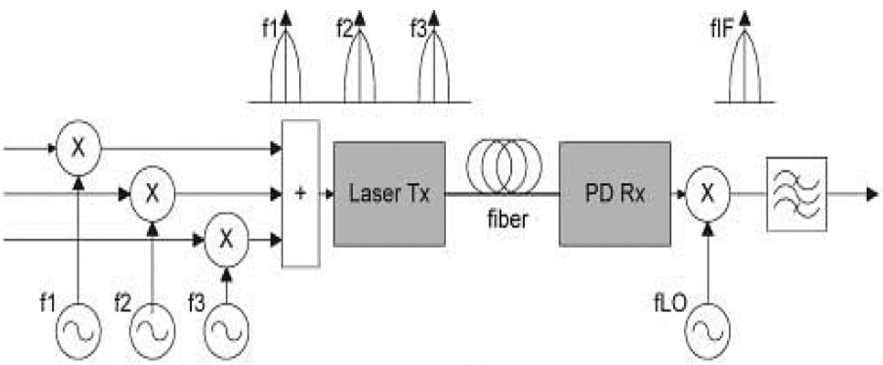


Figure (4): Subcarrier multiplexing in optical system architecture [16]

Simulation Setup

Radio-over-Fiber (RoF) system consists of three main parts are; transmitter, fiber channel and receiver. The transmitter consists of two main parts: electrical side to generate RF signal with SCM, and optical side to generate optical signal with WDM. The receiver consists of optical part and RF part. Figure (5) shows the transmitter part of four RF channels (2.4 GHz, 5.8 GHz, 10.8 GHz and 18 GHz) with different modulation schemes such as: 4-QAM, 16-QAM and 64-QAM schemes, in addition to orthogonal frequency division multiplexing (OFDM) technique.

The transmitter part of 8-Ch-WDM and optical fiber channel is shown in Figure (6), each optical channel consist of 4 RF channels at 5 Gbps data rate for each RF channel, and thus a 32-channel RF is produced. The simulation parameters of the transmitter model and fiber channel of RoF system are listed in Table (1).

Table (1): Simulation parameters of transmitter part of RoF system

Parameter	Value	Parameter	Value
Bit rate of one optical channel	20 Gbps	channel spacing of WDM MUX	100 GHz
No. of Subcarriers of OFDM modulator	128	BW channel of WDM MUX	25 GHz
No. of FFT point of OFDM modulator	1024	length of fiber	10 – 100 km
RF	2.4, 5.8, 10.8, 18 GHz	fiber attenuation	0.2 dB/km
power of CW laser	-5 to 0 dBm	dispersion coefficient	16 (ps/nm.km)

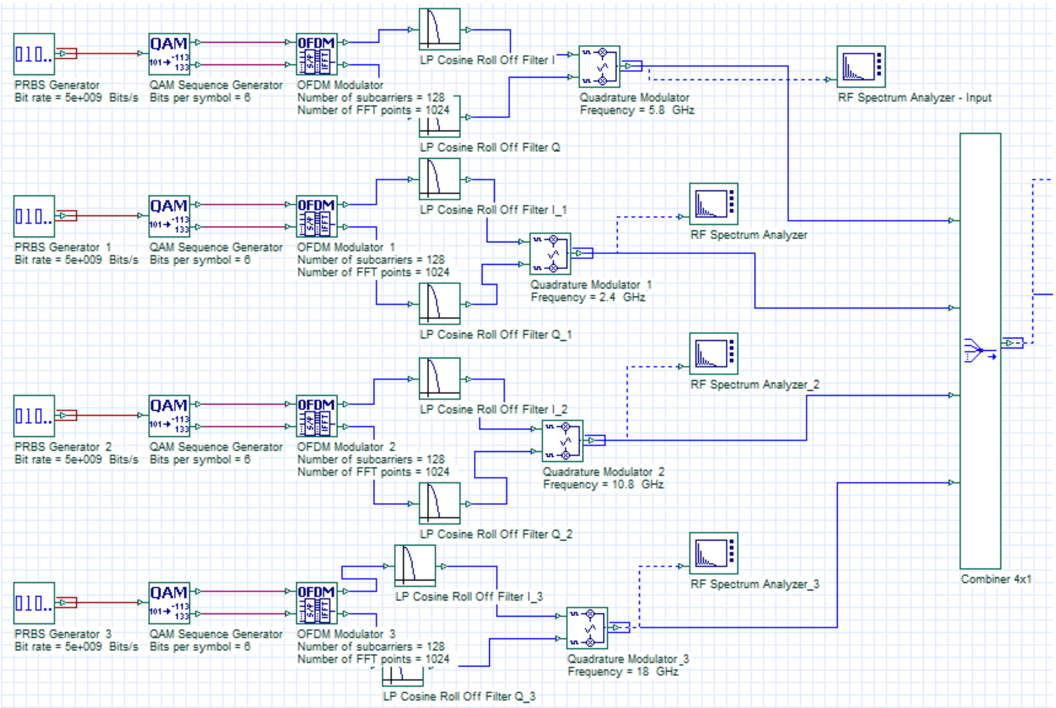


Figure (5): Transmitter side of SCM with 64-QAM-OFDM

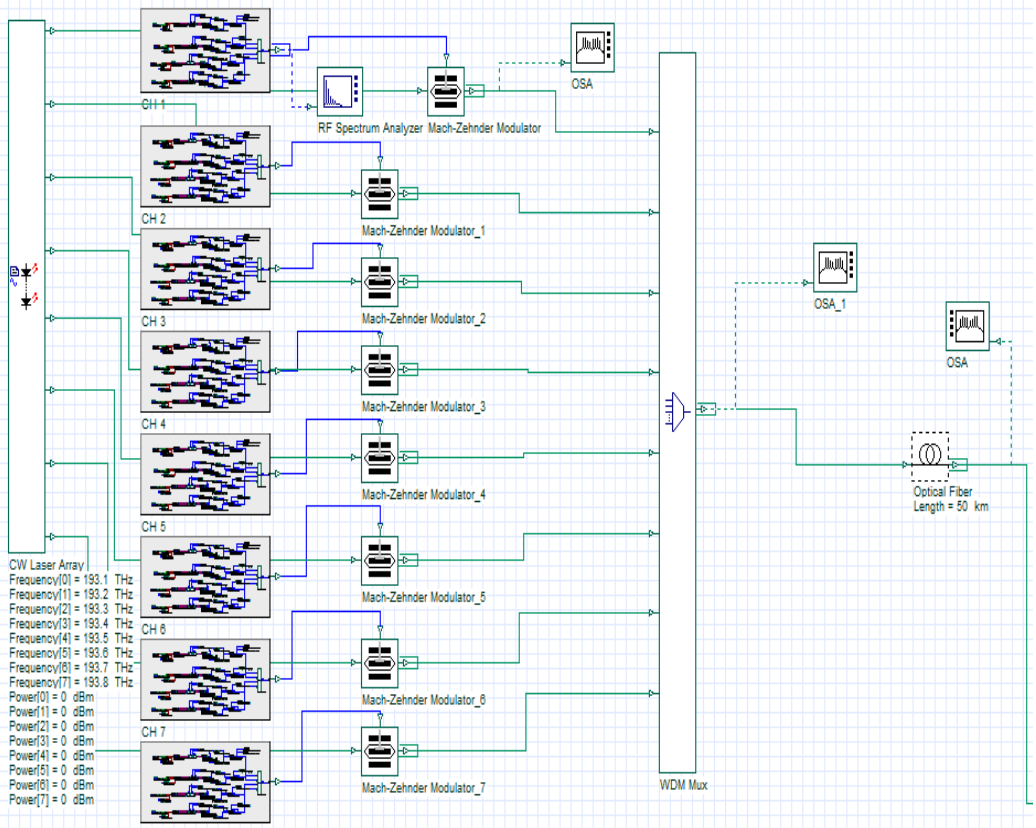


Figure (6): Transmitter part of SCM/WDM RoF system

The receiver part of SCM/WDM RoF system is shown in Figure (7-a) and Figure (7-b) illustrates the RF receiver of the system. After the signal converted from an optical form into an electrical form by a photodetector with responsivity of 1 A/W, the received signal is amplified by an electrical amplifier to compensate the power which is wasted due to the fiber attenuation. In addition, it is passed through Fork to duplicate the input signal into 4 output signals. Band pass cosine roll off filter is utilized to choose the desired signal (defined RF) from other signals. A quadrature demodulator is used to demodulate the signal from the RF modulated wave, then the signal is demodulated by an OFDM demodulator to extract the symbols and then decoded to get the original bits.

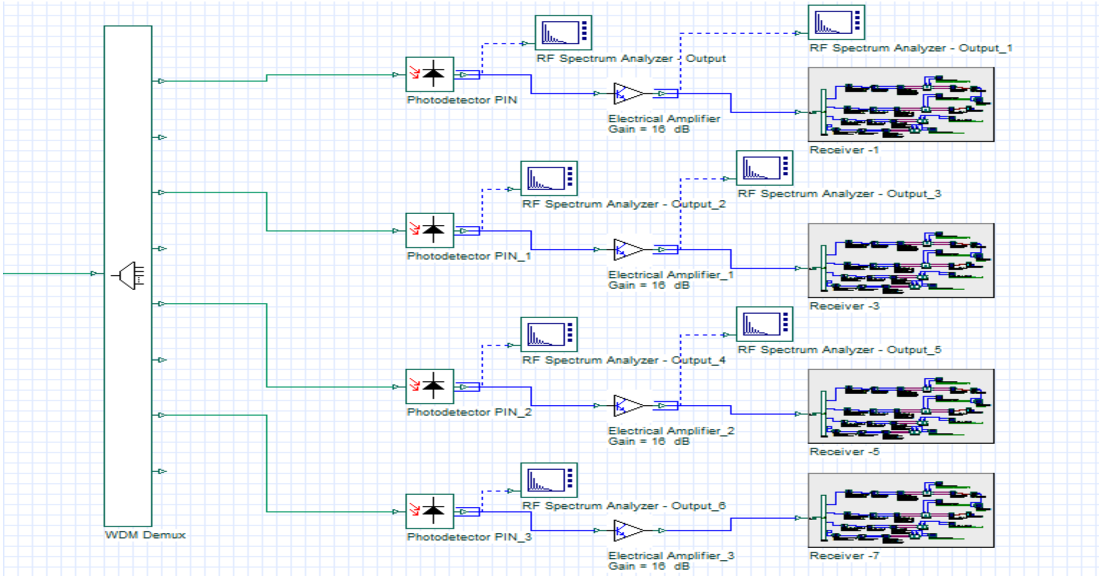


Figure (7-a): Receiver part of SCM/WDM RoF system

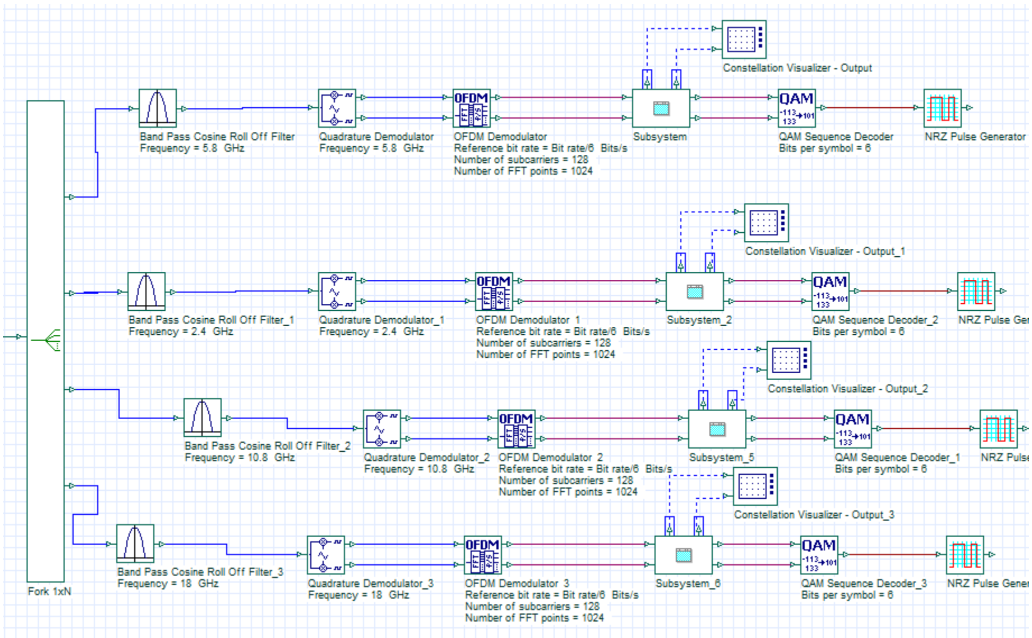
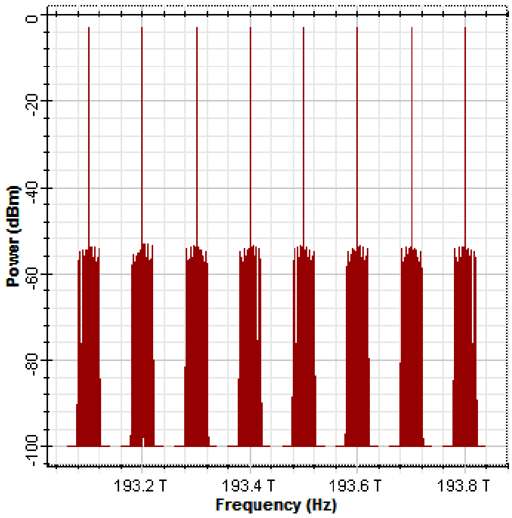


Figure (7-b): The RF receiver part of SCM/WDM RoF system

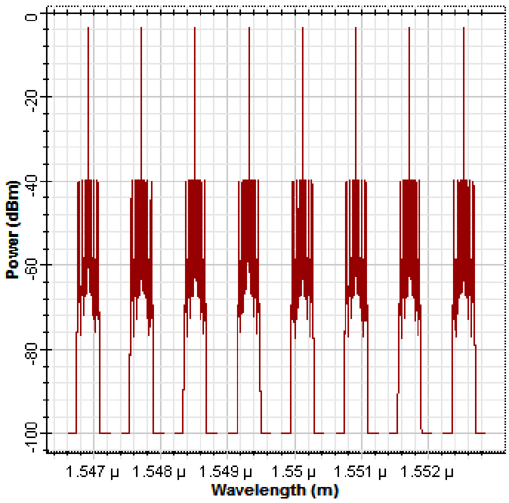
Simulation Results

In this section, the simulation results are presented for the combination of wavelength division multiplexing (WDM) with subcarrier multiplexing (SCM) techniques for radio over fiber (RoF) link.

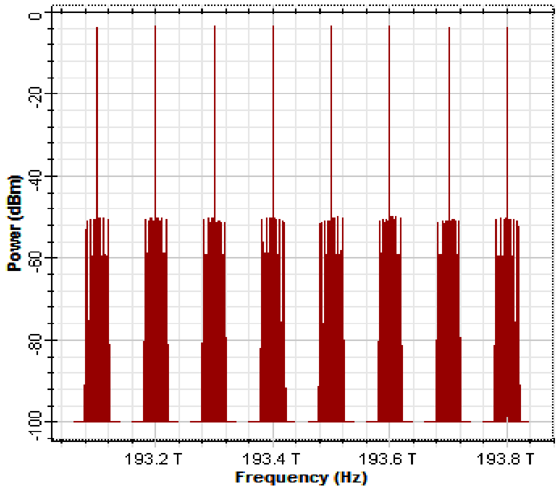
Figure (8) shows the optical spectrum of transmitted signal for 32-channel RF (32 RF channel carried by eight optical channels) of 4-QAM, 16-QAM and 64-QAM schemes with OFDM technique.



(a) with 4-QAM-OFDM



(b) with 16-QAM-OFDM



(c) **with 64-QAM-OFDM**

Figure (8): Optical spectrum of SCM/WDM RoF link

Figure (9) shows the constellation diagram of SCM/WDM RoF link with 4-QAM-OFDM, 16-QAM-OFDM and 64-QAM-OFDM for the first and the fourth RF channel carried by third optical channel after 20 km of fiber length.

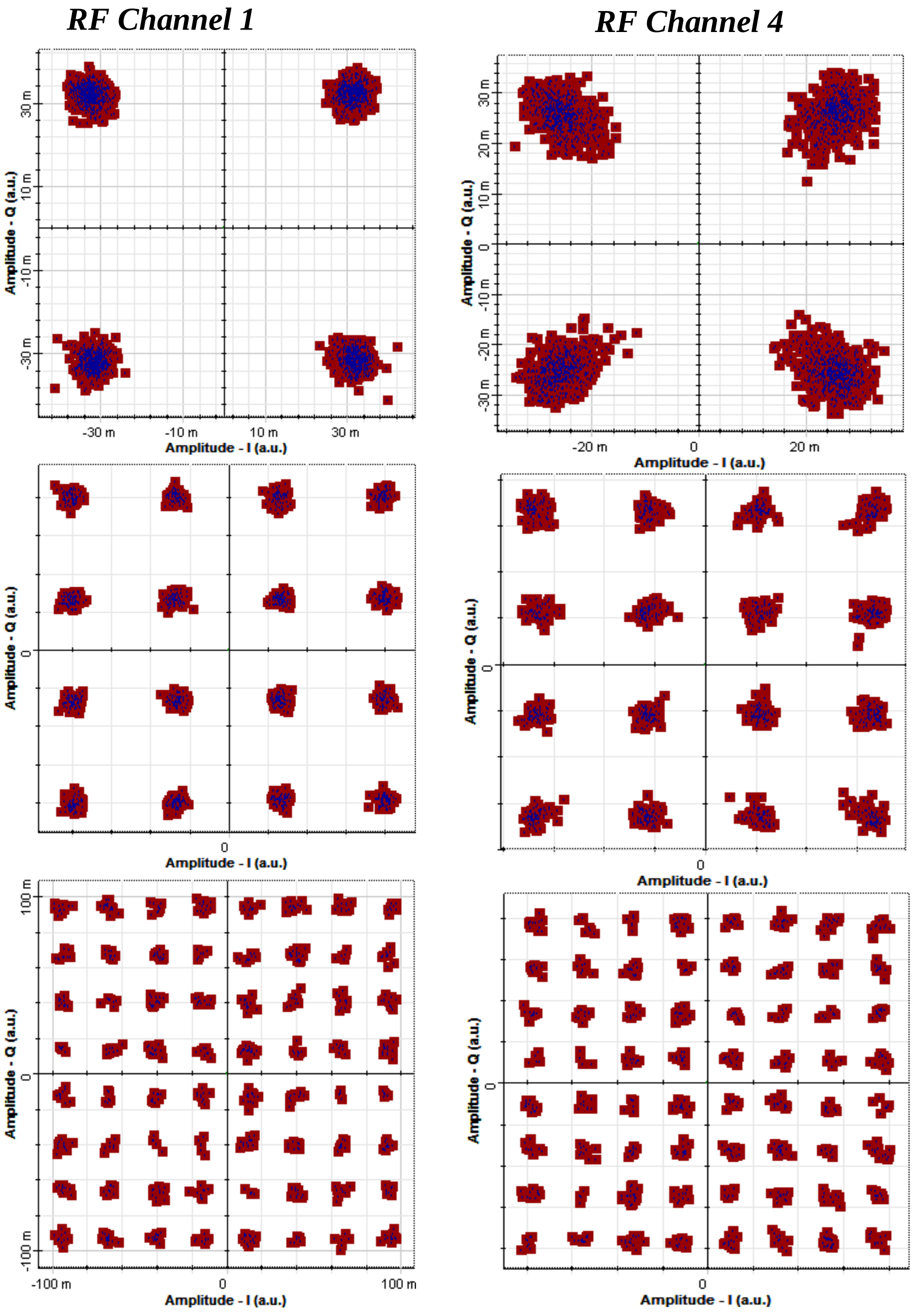


Figure (9): The constellation diagram of SCM/WDM RoF link

Each RF channel has 5 Gbps data rate, and thus the data rate for each optical channel equal to 20 Gbps. The data rate of this system equal to 20×8 Gbps. These systems have a high capacity due to combine the properties of the Wavelength Division Multiplexing (WDM) and the Subcarrier Multiplexing (SCM) techniques.
The symbol error versus the received optical power for SCM/WDM RoF link with different modulation schemes (4-QAM, 16-QAM and 64-QAM) with OFDM technique after 50 km of fiber length is shown in Figure (10). The performance of SCM/WDM RoF system with 16-QAM scheme and OFDM technique is better than the performance of this system with 4-QAM-OFDM and 64-QAM-OFDM. The symbol error of 16-QAM-OFDM at -14 dBm received optical power equal to $10^{-8.5}$ while it is equal 10^{-7} for 64-QAM-OFDM at the same received optical power. In addition, the RF signal power of 4-QAM, 16-QAM and 64-QAM with OFDM technique versus fiber length is shown in Figure (11). The RF signal power for SCM/WDM with 64-QAM-OFDM is higher than the RF signal power for this system with 16-QAM-OFDM and 4-QAM-OFDM. It can be concluded that the RF signal power increases with the increase of the level of M-ary QAM for the same bit error rate

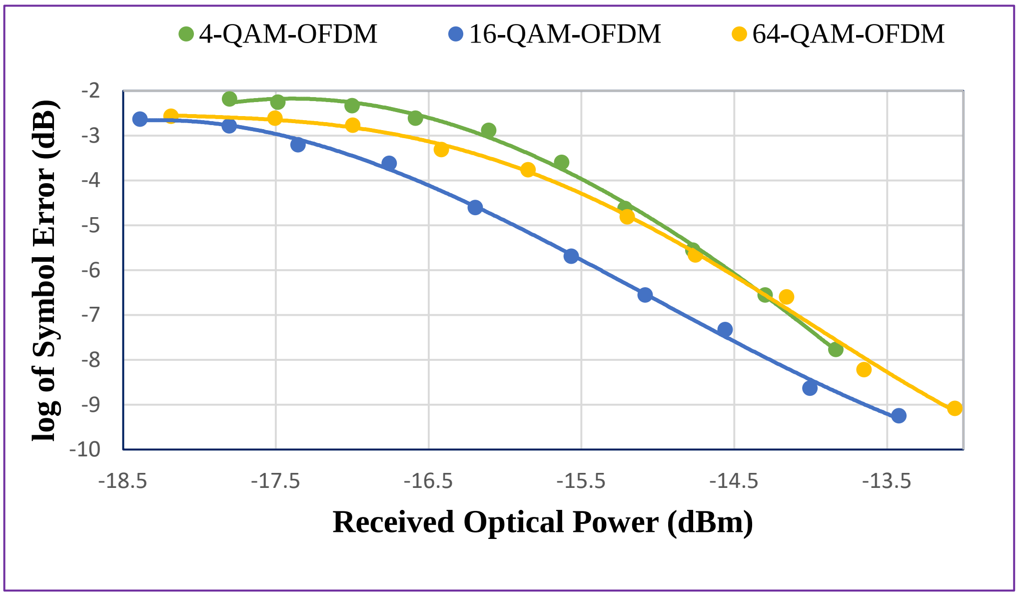


Figure (10): Symbol error versus received optical power for SCM/WDM RoF link after 50 km of fiber length

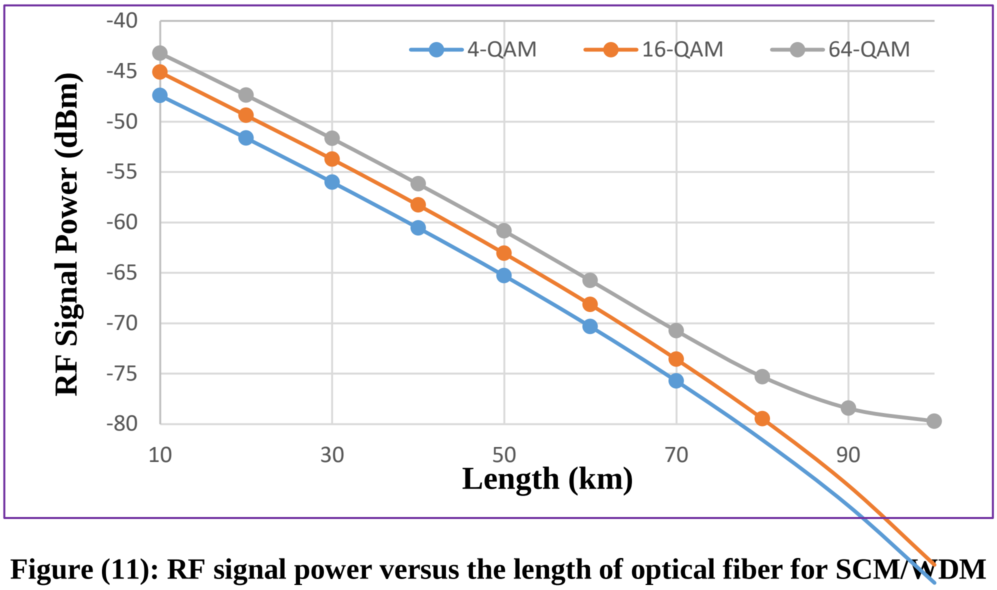


Figure (11): RF signal power versus the length of optical fiber for SCM/WDM RoF link

Conclusion

In this paper, the capacity of the system performance is improved by combining the properties of WDM and SCM techniques to obtain high data rate capacity of 160 Gb/s with 32 RF channel carried by 8 optical channels. Three modulation schemes with OFDM technique were used in this system such as 4-QAM, 16-QAM, and 64-QAM. The simulation results show that the system with 64-QAM-OFDM gave the highest value of RF signal power, but it has little difference of RF signal power with 16-QAM-OFDM. It can be concluded that this system of 16-QAM with OFDM technique gives the acceptable performance as well as reduces power consumption and the system complexity using high level of modulation formats.

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