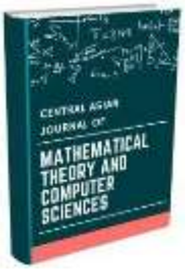

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Article

Design and Simulation of Fiber Wireless Communication Network

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Abstract: The exponential growth of mobile data demand and the need for high-capacity backhaul networks have led to the integration of optical and wireless technologies. Existing passive optical networks (PONs) offer high-speed connectivity, yet limitations remain in addressing increased data rates and dense small-cell deployments in 4G, 4.5G, and emerging 5G networks. Despite advancements in radio-over-fiber (RoF) and WDM-PON architectures, comprehensive simulation-based evaluations of their joint performance for large-scale deployments are limited. This study aims to design and simulate a WDM-PON based Radio and Fiber (R&F) communication system using 16 wavelengths to assess its feasibility in supporting dense cell site architectures and reliable transmission. Simulation results reveal that a 10 Gbps per wavelength configuration over 20 km can support 32,768 base stations with a cell radius of ~110 m, while 40 Gbps configurations over 1 km achieve a 1:65536 splitting ratio. The RoF system optimized at 24 dBm RF input provides maximum Q-factor (26) and highest receiver sensitivity (–30 dBm) over 5 km fiber. The integration of R&F and RoF architectures using WDM-PON is simulated with varying input RF power, frequency bands, and fiber lengths to determine optimal configurations for reliable, scalable communication. The findings demonstrate the viability of WDM-PON based R&F networks for next-generation mobile backhaul, offering a scalable solution with high data rates, extended reach, and optimized performance suitable for dense, low-latency wireless access environments.

Keywords: Optical fiber, wireless networks, R&F design, Radio and Fiber (R&F), MZM (Mach Zehnder Modulator)

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1. Introduction

Mobile network backbone is being upgraded from conventional coaxial cable to optical fiber due to many advantages offered by optical fiber technology. The prominent one is huge bandwidth which can support high data rates. In the initial stages of mobile backhaul network, the nature of signal transmission was analog which in later stages was upgraded to digital signal transmission. The digital signal transmission has transformed the world in each and every leading sector and today it is a billion dollar economy globally. Currently, the mobile network utilizes optical fiber in backhaul i.e. from mobile switching station to antenna base station. The digital optical signals are used to transmit the information from mobile switching station to the base station in terms of Ethernet frames in the ITU-T as well as IEEE standards [1].

This information is then converted into standard wireless frames at base station and radiated through antenna subsystem. This is called R&F network since optical to wireless protocol conversion happens at the base station. When native wireless signal is optically transmitted from Mobile Switching Center to the Base Station or BS to the Remote Radio

Head it is called RoF network. In general, network between MSC to BS is called backhaul-network and BS to RRH is called front haul-network [2].

For 2G and 3G, GSM cell sites, a data transmission link of 100Mbpsis sufficient per cell. For 10 such cell sites, 1Gbps dedicated link is sufficient. 4G standard guarantees 1Gbps per cell sites hence for 10 such cell sites, 10Gbps dedicated link is required. Moreover, it is observed that as new generation of mobile network is evolved, the data rate increases and coverage radius decreases. Thus to fulfill the coverage area and data rate requirements, eight to sixteen wavelengths are used. Each wavelength is modulated at a rate of 10 Giga bytes per second, multiplexed using WDM-MUX and transmitted downstream [3].

2. Materials and Methods

The optical access network is mainly focused to deliver 10's of a gigabit of data per second to the ONUs or users. Optical access network data transmission is majorly dominated by the digital information or bits and in recent years analog radio signal is also transmitted over optical fiber infrastructure to gain advantages like low loss, wide bandwidth and immune to electromagnetic interference. When laser light is modulated by an analog electrical signal and transmitted through passive fiber infrastructure it is called a RoF system. Thus far, the RoF system is considered as a part of microwave photonics and explored in the same area [4].

Recently, efforts are initiated by ITU-T to standardize RoF technology and the task is assigned to question 2 of study group 15 whereas, on the other side, digital information transmission based PON is booming with different standards, fulfilling the demand. PON has enabled high-speed broadband connectivity over the years and it has become popular by providing high data rates at economical cost. The popularity of PON started with a BPON, EPON, and GPON in 2000, 2004 and 2008 respectively. The EPON was proposed by IEEE in 2004 as standard 802.3ah with a peak data rate of 1.25 Gbps. The BPON and GPON both are proposed by ITU-T as standard ITU-T G.983 in 2005 and ITU-T G.984 in 2008 respectively. BPON provides a data rate of 1.20 Gbps and GPON provides data rates of 2.5Gbps. Over time these standards got updated in terms of data rates, reach and number of simultaneous users based on the demand as 10G-EPON and XG-PON also referred to as NG-PON to transmit 10Gbps of information [5].

In 2011, the Full-Service Access Network (FSAN) started an investigation on upcoming technologies that had the potential to deliver a data rate of 10 Gbps and beyond under the name NG-PON2. Many PON technologies were reviewed and one of them was 40 Gbps Time Division Multiplexed Passive Optical Network, another approach was WDM-PON where each user was provided with a separate wavelength and promised 1Gbps of data rate. In one of the proposal digital Orthogonal Frequency Division Multiplexing signal was quadrature amplitude modulated and transmitted which is called OFDM-PON [6].

Finally, TWDM-PON was selected for NG-PON2. Wong, Elaine et al reviewed the future direction in which the NGPON2 can be standardized and with this 10Gbps PON system is presented. It reviews the multiple access technology like TDMA-PON, WDM-PON, and a combination of both, hybrid TDMA/WDM PON. Results provided a data rate of 10Gbps and beyond, enhanced the capacity of the system, and deepened the fiber reach of PON [8]. Advantages of complex technologies like Orthogonal Frequency Division Multiple Access, Optical Code Division Multiple Access and digital coherent detection are discussed to improve the tolerance against system impairments and enhanced spectrum efficiency [9].

In April 2012, FSAN has carefully chosen the WDM-PON as an upcoming NG-PON2 solution. The world's first 40Gbps downstream and 10Gbps upstream NG-PON2 system with the ODN of 1:512 split and 20 km reach was demonstrated by Luo, Yuanqiu et al. The results of TWDM-PON architecture are endorsed by an operator-vendor joint test using available components and reusing existing devices. It also specifies the wavelength options available and further confirms the full backward compatibility. Many researchers and optics foundries accepted the challenges in deploying full working TWDM-PON and provided with particular working solutions for a given problem [10].

3. Results

Architecture of Wavelength Division Multiplexed-Multiplexer Passive Optical Network (WDM-PON) based R&F Network

This radio and fiber-based network is designed and simulated to use the dark fiber of the deployed WDM-PON. The architecture below is R&F based which is shown below in figure1. By using an optical distributed network, the digital information from the optical line terminal or Central Office or Mobile Switching Center will be sent to the home optical network unit at the base transceiver station. In this work, sixteen downstream wavelengths are used and sixteen upstream wavelengths are employed to set up a reliable bidirectional communication link (Figure 1).

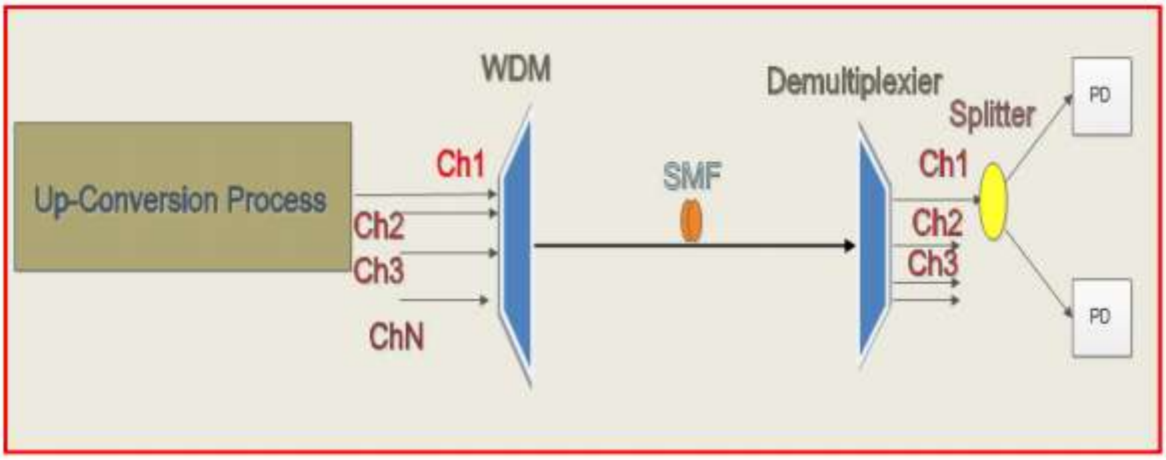

Figure 1 R&F network over WDM-PON architecture

PON-OLT consists of a digital optical transmitter module as shown in Figure 1. The optical transmitter module consists of a CW laser, MZM, and digital information generator. Each of the downstream wavelengths can be modulated at standard data rates [17]. Downstream sixteen wavelengths are multiplexed using WDM-M UX and amplified using EDFA to pre-compensate for the fiber attenuation and other losses. The multiplexed downstream wavelengths are transmitted towards ONU and ONU- BTS. ONU and ONU-BTS consist of an optical filter followed by a PIN photodiode and Gaussian electrical filter. O NU-BTS receives the digital information and converts it into native transmission format and then radiate s from the respective transmitter tower. Received signals at O NU and O NU-BTS are analyzed and compared for different data rates and reach [11].

Result and Discussion on WDM-PON based R&F Network

The performance of the R&F system is evaluated in terms of Q-factor for different data rates and fiber reach of the network. Furthermore, the transmitted optical spectrum is observed at the input and output of the optic al fiber. The Q-factor for various fiber reach of WDM-PO N based R&F system (Table 1).

Table 1: Receiver Sensitivity at Varying Data Rates and Fiber Reaches in WDM-PON Systems

Data rates per Wavelength (Gbps)	Re ach (k m)	Receiver sensitivity (dB m)
40	1	-2 9.5
	2	-2 8.5
20	5	-2 9.5
	10	- 28
10	20	- 30

	40	- 29

It is observed that as data rate increases the reach of the network for acceptable performance decreases for WDM-PON. Receiver sensitivity degradation with respect to reach of the network is observed in Table 1. In mobile backhaul network as the generation of mobile network is upgraded, data rate an increase which in turn increases the data rate requirement at BTS and cell size at the BTS decreases. These conditions are perfect fit for the WDM-PON to support mobile backhaul through R&F network. Since the receiver sensitivity at fixed reach and optical power at output of fiber are known, the power budget and number of simultaneous users can be estimated. The power budget and number of simultaneous users of WDM-PON based R&F network are tabulated in Table 2 [12].

Table 2 Power estimation and number of simultaneous users of WDM-PON based R&F network for fixed reach and data rates

Data rate per wavelength (GBPS)	Reach (KM)	Power at poutput of optical fiber (dBm)	Receiver Sensitivity (dBm)	Loss budget (dB)	Max splitter loss (dB)	Splitter value
40	1	20.110	-29.5	49.61	48	1:65536
	2	19.91	-28.5	48.41	48	1:65536
20	5	19.31	-29.5	48.81	48	1:65536
	10	18.31	-28	46.31	45	1:32768
10	20	16.31	-30	46.31	45	1:32768
	40	12.31	-29	41.31	39	1:8192

The chart presents comparative metrics for WDM-PON based R&F networks, illustrating variations in data rate, fiber reach, optical power, receiver sensitivity, and loss budgets. Notably, higher data rates correlate with reduced reach and tighter receiver sensitivity requirements, while maximum splitter loss remains consistently high, confirming efficient scalability across multiple deployment configurations (Figure 2).

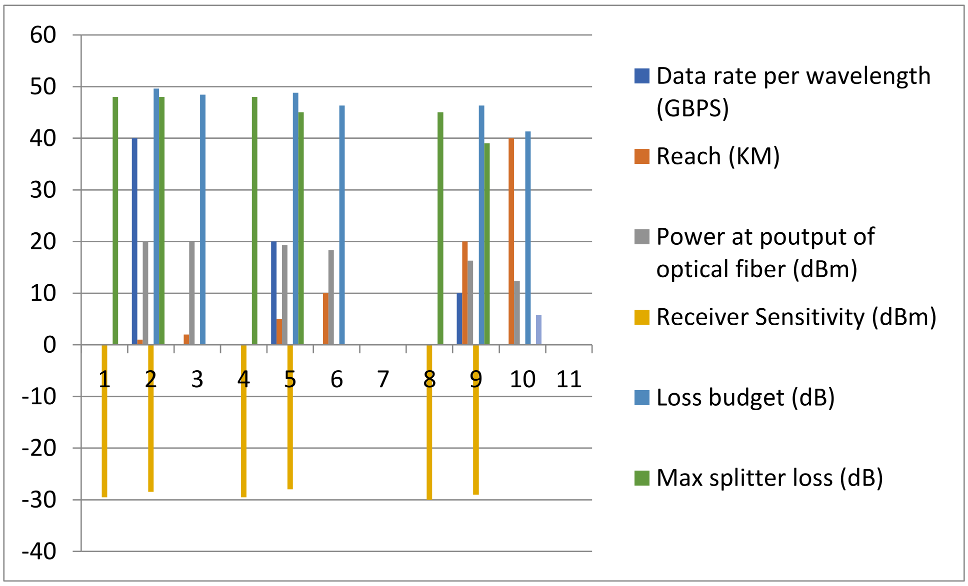

Figure 2: WDM-PON based R&F network for fixed reach and data rates

It is observed from the Table 6.2 that for a 40Gbps system, receiver sensitivity is -29.5 dBm at 1km of fiber reach. Optical power at the output of 1km fiber is 20.110dBm. The designed 40Gbps per λ, WDM-PON based R&F network can allow loss of 49.61dB which means it can support 1:65536 splitter theoretically. Considering a 10Gbps per λ, WDM-PON based R&F network of 20km reach, the receiver sensitivity is –30 dBm. The optical power at output of 20km fiber is 16.31 dBm. Thus the allowable loss for 10Gbps per λ is 46.31dB. Hence, it can support total 32,768 numbers of splitting points or in other words 45dB of splitter loss. Considering the hexagonal geometry of the area covered by the optical network, the radius of the ONU-BTS cell is given by the following equation [13].

Considering a 10Gbps per λ, WDM-PON with reach of 20 km, the total splitting points where reliable communication is achieved are calculated to be 32768 from Table 2. Therefore, 10Gbps per λ based R&F architecture can support 32768 cell sites where the radius of each cell site is ~110m. Similarly, if WDM-PON with reach of 40 km is considered for 10Gbps per λ,8192 numbers of splitting points are supported which can serve 8192 cell sites and the radius of each ONU-BTS cell site in this case is ~440m calculated. This 10Gbps configuration is suitable for meeting the data rate demands of 4G and 4.5G specifications [14].

5. RADIO OVER FIBER NETWORK

The RoF system are mainly designed to transmit analog RF signal over fiber infrastructure by using sophisticated opto-electronic devices to gain advantage of enormous bandwidth of fiber and low loss transmission characteristic. It is a part of microwave photonics which deals with the transmission and processing of Radio Frequency signal. Data rate demand of connected devices is increasing day by day and numbers of connected devices are also increasing exponentially due to Internet of Things. To provide uninterrupted high speed connectivity, the microcellular system and the Distributed Antenna Systems are developed. DA S is considered a s more beneficial as far as deployment of RoF is concerned due to reduction in complexity and cost [15].

In DAS, Radio Antenna Units is geographically distributed over microcell and all the distributed RA Us are connected to BS or Central Unit. The mode of communication between RAU and CU is purely analog optical communication. CU transmits an R F signal over light, which is then distributed via existing fiber infrastructure and then received b y an RAU. RAU converts optical signal into electrical, amplifies the electrical signal suitably and then radiates the signal through an antenna subsystem [16].

6. ROF COMMUNICATION SYSTEM BLOCK

RoF communicating is beneficial at areas at which a bodily base station can't be placed because of infrastructure limitations for instance, within a tube, cross global boundary places, etc. The block structure of this RoF process is displayed at Figure 2 Gbps of electronic data is Amplitude-Shift Keying regulated on 10GHz of both RF carriers. This ASK controlled 10GHz signal today functions as a regulating sign to get an optical carrier that's regulated with dual-drive MZM (Figure 2).

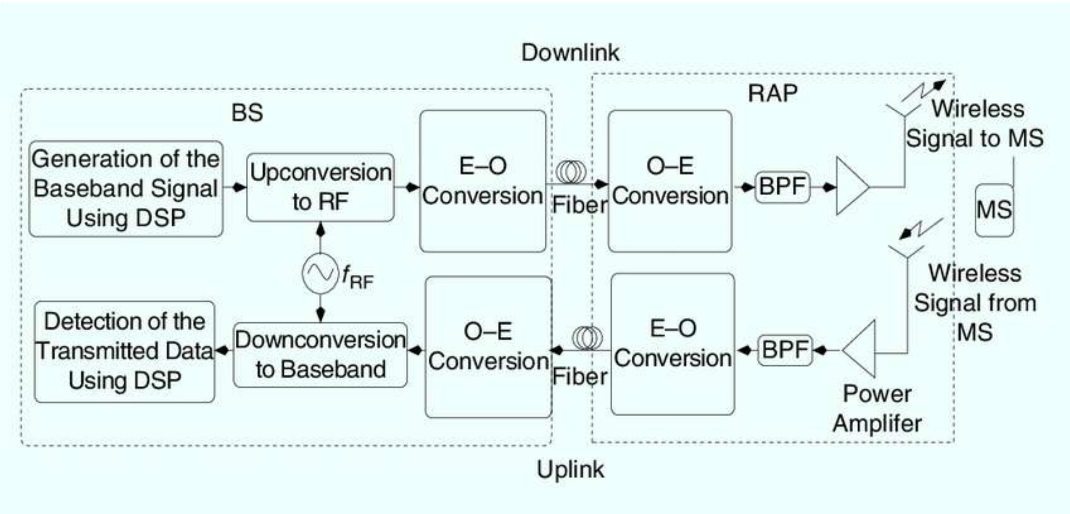

Figure 2: RoF block diagram

The DSB modulated optical sign al is transmitted through optical fiber infrastructure and detected at the receiver using PD unit. Detected sign al is demodulated and received 1Gbps of digital information is analyzed using eye pattern analyzer [17].

7. ROF POWER OPTIMIZATION

RoF system is designed and simulated based on Figure 3, to find the maximum input RF power which provides superior performance so that RoF communication link is considered to be reliable. Two parameters are observed with respect to the input RF power, firs t is output optical power of MZ M and second is Q -factor of the receive d optical signal. Input RF power is varied and the output optical power at MZM is plotted in Figure 3(a) and Q-factor of the received optical signal is plotted in Figure 3.(b).

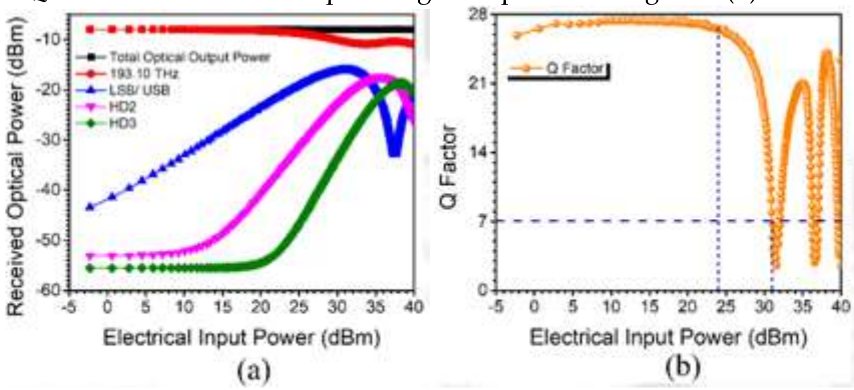

Figure 3: Plot of input RF power vs (a) optical power at MZM and (b) Q-factor

The harmonics interact nonlinearly with the transmitted signal whilst dispersing the fiber that distorts s the input. To examine the effects of harmonics independently, receiver and transmitter are attached to back along with also the Q-factor of the received optical signal plotted in Figure 4 in 5km of fiber back and reach to back (B2B) transmitter-receiver arrangement is detected. From Figure 3 (b) it can be observed that the highest Q- variable is observed while the input RF power ranges between 1 0dBm into 24 dBm. The highest input RF power is 24 dBm using Q-factor≈26 and then Q-factor reduces hence 24dB m is chosen as the best input RF power. It's also noted for input RF power that range from 5dBm to 24dBm that the Q-factor of the obtained signal is practically horizontal and the Q-factor is minimal at 30dBm of input RF power. The Q-factor researches at different input RF energy is plotted in Figure 4 in 5km of fiber back and reach into your rear transmitter -receiver setup (Figure 4) [18].

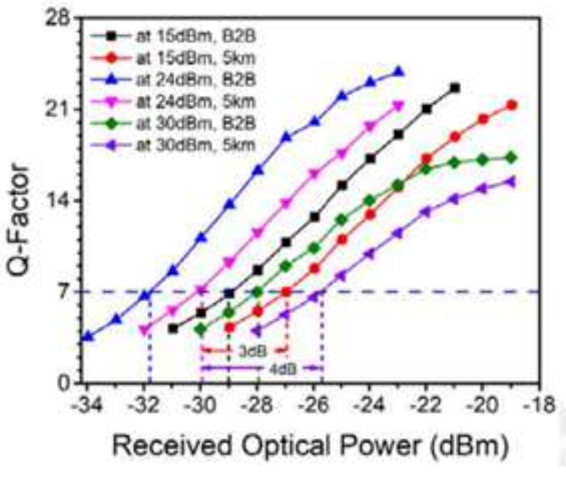

Figure 4 Q-fact or analysis of RoF network at various input RF power

It's seen from Figure 4 which receiver sensitivity in B2B that the setup is highest (~ -32 dBm) in 24dBm of input RF power (optimal RF power) compared to receiver sensitivity with an input RF power of 15 dBm and 30 dBm. Likewise the receiver sensitivity in the event of 5km of fiber hit for an optimal input RF energy of 24dBm can also be greatest i.e. ~-30dBm. This 24dB m of RF input capacity provides 3 dB and 4 dB receiver sensitivity benefit compared to receiver sensitivity at 15 dB m and 30 dBm of RF input power at 5km of fiber achieve respectively. The fiber station isn't level for a specific RF frequency regarding the reach and also vice-versa. The subsequent subsection investigates the selection of frequency bands in predetermined achieve that offers dependable performance [19].

8. FIBER CHANNEL AT DYNAMIC REACH AND FIXED FREQUENCY OF OPTICAL D SB-WC

Although the Link between BTS and RAU is mostly restricted within 3km, the simulation analysis is carried out b y varying the fiber reach up to 10km. The selected electrical carrier frequencies in the simulation belong to UHF band (2.5GHz) and SHF band (10GHz). The total received powers of these electrical carriers are analyzed with respect to reach of the RoF system as shown in Figure 5 [20].

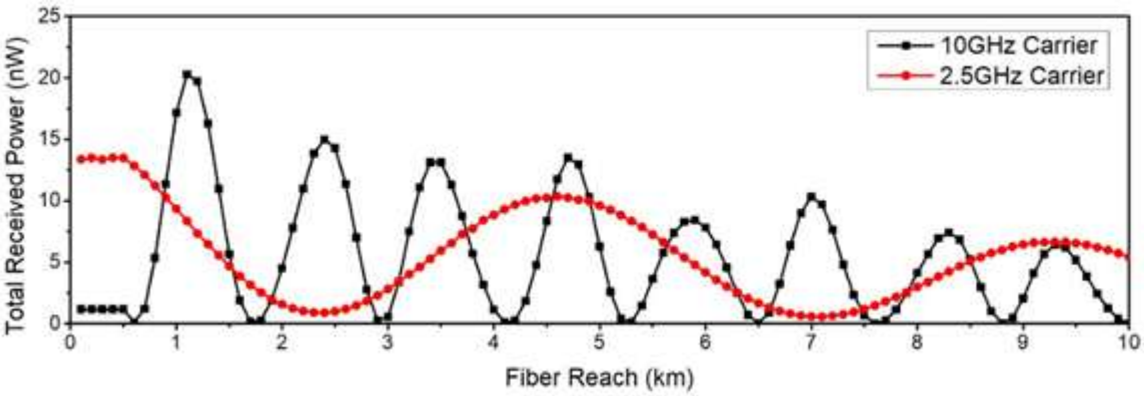

Figure 5: Fiber reach versus total received optical power for optical DSB-WC

It is observed from Figure 5 that as the length of the fiber increases the side-bands of Amplitude-Shift Keying and the side-bands of transmitted analog optical signal interact nonlinearly with each other while traversing through an optical fiber. Due to fiber dispersion, both sidebands go out of phase and start interfering destructively over a length of fiber which results in the oscillatory nature of the signal as shown in Figure 5. It is also observed that as the electrical carrier frequency increases the frequency of nonlinear interaction increases due to the inverse relation between operating frequency and fiber reach as described.

4. Discussion

The WDM-PON based R&F link is designed and simulated for sixteen wavelengths. It is concluded that designed WDM-PON based R&F network covers 20km radius of hexagonal cell and delivers aggregated 160Gbps downstream (10Gbps per λ) to total 32,768 base stations with each base station coverage of ~110m radius of the hexagonal small cell [21].

THE proposed R&F design can be used in the backhaul network of 4G, 4.5G, and 5G mobile networks. The optical DSB-WC and SSB-WC are simulated at a modulating frequency of 10 GHz for front-haul application. The transfer function of optical fiber is analyzed and the relationship between operating RF frequency and the length of the optical fiber is observed. Since MZM is the primary nonlinear device at the RoF transmitter, the effects of harmonic distortion are observed and input RF power is optimized to establish a reliable communication link. The length of optical fiber is fixed and range of carrier frequencies which provides reliable communication for optical DSB-WC is identified and their respective FDD and TDD band number is noted. The operating frequency is fixed, one from the UHF band and another from the SHF band, and power profile in terms of nano-watt is observed concerning the reach of the fiber.

5. Conclusion

The optical TWDM-PON was created with postponed amplitude modulation and the outcomes are contrasted with the traditional TWDM-PON. It's also noted that because of optical TDM, the amount of 20 dB gain, supplies 6 dB and 3 dB of receiver sensitivity benefit over, higher power amplifier and laser of 10 dB profits respectively. The operation of NG-PON2 is enhanced concerning the Q-factor by maximizing the laser power from the computer system. In contrast, BER performance at laser launch energy supplies ~3 dB of receiver sensitivity benefit within the greater launching power significance for both NRZ outside modulation and RZ outside modulation. RZ-EM stipulates an extra ~2 dB of receiver sensitivity benefit over traditional NRZ-EM during its best laser power for all the contrasted functional fibers. The best laser power of engineered NG-PON2 is available for adjusted reach and mended splitter/AWG established ODN setup, lively reach and adjusted splitter/AWG established ODN setup, and mended reach and lively fixed splitter/AWG established ODN configuration. The energy budget is calculated to get its designed NG optimal -PON2 for the two ODN forms at optimal laser power and an energy allowance of 2 dB is accomplished. The WDM-PON established R&F connection was created and modeled for three dimensional wavelengths. It's confirmed in the results that made WDM-PON established R&F system offers reliable communication around 20 kilometers fiber reach 10 Gbps per wavelength together with 1:32768 dividing ratio. Thus, the R&F system can pay for a 20 km radius of their hexagonal region and provides 160 Gbps into a total of 32,768 base channels with every base station protection of 110 m radius of this small cell.

FUTURE ENHANCEMENT

The given OTWDM-PON can be extended to provide higher-order modulation to achieve spectrally efficient data transmission. PAM-4 and a higher version will be the best choice. Instead of using simple and dispersion tolerant RZ external modulation, the duo-binary or Manchester coding based external modulation must be explored to improve the dispersion tolerance of the designed network. Coherence optical communication-based UDWDM-PON must be explored to further reduce the channel spacing below 25 GHz and gain the advantage of high data transmission point to point PON system. Laser power optimization can be configured for multi-data rate, multi-wavelength and multi-standard network. Since in near future, multiple standards are going to share a common ODN. For that case, nonlinear wavelength integration and especially Raman cross talk need to be explored Energy-efficient framing and convergence framing protocols are also widely under research to provide connectivity to all devices and access to the web through all available optical access networks. The given OTWDM-PON can be extended to provide higher-order modulation to achieve spectrally efficient data transmission. PAM-4 and a higher version will be the best choice. Instead of using simple and dispersion tolerant RZ external modulation, the duo-binary or Manchester coding based external modulation must be explored to improve the dispersion tolerance of the designed network. Coherence optical communication-based UDWDM-PON must be explored to further reduce the channel spacing below 25 GHz and gain the advantage of high data transmission point to point PON system. Laser power optimization can be configured for multi-data rate, multi-wavelength, and multi-standard network. Since in future multiple standards are going to share a common more to gain the advantage of Raman amplification. The on-chip electro-optical circuit must be preferred for A RoF system design. For quick deployment of the WDM-PON network, alternative fiber infrastructure needs to be explored for strengthening disaster relief network or improve the resiliency of the deployed optical networks.

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