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DAPSK – OFDMA PON Based Heterogeneous Optical Network

Priyadharshini R.*
Department of Electronics and Communication Engineering, Sri Venkateswara College of Engineering, Sriperumbudur-602117, Tamil Nadu, India
E-mail: ripriyadharshini@gmail.com
ORCID iD: https://orcid.org/0000-0001-7726-2322
*Corresponding author

Geetha G.
College of Engineering Guindy/Department of Electronics and Communication Engineering, Chennai-600 025, India
E-mail: geetha@annauniv.edu
ORCID iD: https://orcid.org/0000-0002-6440-8406

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Abstract: The broadband access networks require suitable differential modulation techniques that can provide better performance in real-time fading channels. A heterogeneous optical access network adopting spectrally efficient DAPSK – Orthogonal Frequency Division Multiple (OFDMA) - Passive Optical Network (PON) is proposed and simulated. The performance of the proposed heterogeneous network is analyzed in terms of received Bit Error Rate (BER) and spectral efficiency. The results show that 64 DAPSK – OFDMA over the proposed architecture achieves a better spectral efficiency of about 1.062 bps/Hz than 64 QAM – OFDMA with less degradation in error performance.

Index Terms: DAPSK, Ring Ratio, OFDMA PON, Spectral Efficiency, RoF.

1. Introduction

The ever-increasing demand for capacity needs an improved version of the heterogeneous access network. More efficient innovative technologies are needed for backhaul and fronthaul that should be scalable and cost-effective to address the technical challenges provided by recent access network. Different options available for the implementation are dark fibers, small cells, and Radio Access Networks. Radio over Fiber (RoF) uses an analog link to transmit Radio Frequency (RF) signal modulated using an optical signal. Next-Generation Passive Optical networks combined with Radio over Fiber (RoF) can act as one solution for heterogeneous access network. For efficient implementation of this architecture, several technical challenges like seamless integration of both networks, reducing cost, resiliency, integrated routing, fair and dynamic bandwidth allocation are to be addressed. The heterogeneous access networks provide wired and wireless services over the same infrastructure and thus lead to considerable cost savings.

The state-of-the-art candidate architectures proposed for NGPONs, such as TDM PON, WDM PON, Hybrid TDM/WDM PON, Fi-Wi PON, LR-PON, OFDMA PON, OCDMA PON, should provide high capacity for long reach with efficient power consumption. The integrated architecture that can operate on the existing infrastructure can support future broadband access networks. OFDMA PON is most recently used in broadband access networks because of its flexible bandwidth allocation and efficient use of limited frequency resources.

A heterogeneous network integrating DAPSK-OFDMA PON using RoF technology is proposed, and the performance is analyzed in terms of BER, Error Vector Magnitude (EVM), Signal to Noise ratio (SNR), and Spectral efficiency. DAPSK modulation is an evaluated version of the Differential Phase Shift Keying (DPSK) modulation technique. First amplitude shift is introduced to DPSK modulation, and then differential amplitude shift is introduced. It is proposed to reduce the redundant data, thus improving spectral efficiency. The DAPSK- OFDMA-PON-based access network achieves a spectral efficiency of about 1.06 bps/Hz.

2. State of the Art

A survey report on current progress in backhaul networks suggests OFDMA-PON as one solution for recent broadband access networks. OFDMA –PON is a technical candidate architecture for Next-generation PON because of high spectral efficiency and better resilience to dispersion [1]. High-speed access for point to multipoint optical access networks can be supported by OFDMA-enabled multi-level modulation. Appropriate modulation techniques should be selected that are supported by OFDM –PON to provide high-speed transmission to various services [2].

OFDMA-PON employing QAM has been widely used in access networks that use RoF technology. The OFDM-RoF converged network can provide a high capacity with a reduced error rate [3]. The OFDM-PON-RoF link showed better performance for up to 500km with a 10 Gbps bitrate [4]. For a 100 GHz OFDM-RoF system, the transmission distance can be increased by Decision-aided Phase Noise suppression and Pilot-aided Phase Noise suppression [5]. The 32-QAM-OFDM system employing Discrete Multi-Tone modulation and demodulation simplifies the system configuration and reduces the overall cost [6]. The nonlinear distortions caused by Inter Symbol Interference (ISI) which could be a problem in optical systems, may be overcome by using Artificial Neural Network scheme [7]. These works show better error performance and improved capacity compared to other PONs. OFDMA PON can also be employed to support 5G services [8-9]. The PAPR of the OFDM system should be reduced for efficient transmission [10].

Despite being widely used in conventional OFDM, the QAM techniques suffer certain limitations. One such constraint is the need for redundant data for channel estimation. The use of pilot tones for synchronization affects the spectral efficiency of the network, which is a prime concern in access networks. The redundant data in OFDMA PON, required for noise reduction and synchronization, reduces spectral efficiency.

Recent progress shows the use of some differential modulation techniques in OFDM, namely DAPSK, that are advantageous in dispersive environments. The differential detection process employed here itself cancels the noise introduced by the dispersive nature of the channel [11]. This method avoids pilot tones, thereby reducing system complexity and improving the spectrum efficiency [12]. DAPSK-OFDMA PON is used in access networks to improve spectral efficiency by reducing the redundant data needed for channel noise and phase noise compensation [13,14].

A heterogeneous network integrating DAPSK-OFDMA PON using RoF technology is proposed, and the performance is analyzed in terms of BER, Error Vector Magnitude (EVM), Signal to Noise ratio (SNR), and Spectral efficiency. DAPSK modulation is an evaluated version of the Differential Phase Shift Keying (DPSK) modulation technique. First amplitude shift is introduced to DPSK modulation, and then differential amplitude shift is introduced. It is proposed to reduce the redundant data, thus improving spectral efficiency. For DAPSK- OFDMA-PON-based access network, the spectral efficiency of about 1.06 bps/Hz is achieved.

3. Proposed Heterogeneous Access Network

3.1. Simulation Block Diagram

DAPSK, a differential modulation technique, is an enhanced version of DPSK. Only phase shift is applied to represent the change in the symbol in DPSK. But in DAPSK, both phase difference and amplitude difference is applied to indicate a change in the symbol. As higher-order modulation provides an improvement in spectral efficiency, 64 DAPSK modulation is preferred. The ring ratio is the foremost consideration in the DAPSK modulation, and it is selected as 1.4 that corresponds to the minimum SNR. The DAPSK-OFDMA PON architecture integrated with RoF forms a heterogeneous network suitable for the broadband access network. The simulation block diagram of the proposed downlink architecture is shown in Fig. 1. The Central Office (CO) acts as the interface between the server network and the users. The CO consists of the Optical Line Terminal (OLT) responsible for the transmission of the optical signal. The Pseudo Random Bit Sequence (PRBS) generator provides the input bit sequence, and the DAPSK OFDMA coder performs the modulation. The modulated in-phase and quadrature components are up-converted and then applied to the two electrodes of the Dual Electrode Mach Zehnder Modulator (DEMZM) to generate the modulated optical signal.

The Optical Distribution Network (ODN) consists of a single-mode fiber (SMF), and the optical signal is transmitted through that SMF to reach the ONU.

The Optical Network Terminal (ONT) performs the reception of optical signal and decoding. At the receiver side of the Optical Network Unit (ONU), balanced photodetection is performed using a 900 hybrid and four photodiodes. The in-phase and the quadrature components are then downconverted and transmitted through a wireless channel to the User Equipment (UE). The UE performs the DAPSK OFDMA demodulation and recovers the original data bit-stream. The BER estimation involves comparing the input and the output bit-streams, and the EVM value is obtained by estimating the difference between the ideal and the received constellation plots.

3.2. Analytical Evaluation

The electrical representation of DAPSK-OFDMA modulated signal at the transmitter side is given by,

$$E_s(t) = [I_0 + \delta S_{OFDM}(t)] \cos(\omega t + \phi_0) \tag{1}$$

where S_{OFDM} (t) is the DAPSK-OFDM modulated signal, I_0 is the DC bias, δ is the optical modulation index, $\omega=2\pi f$, f is the carrier frequency of the optical signal, and ϕ_0 is the phase fluctuations.

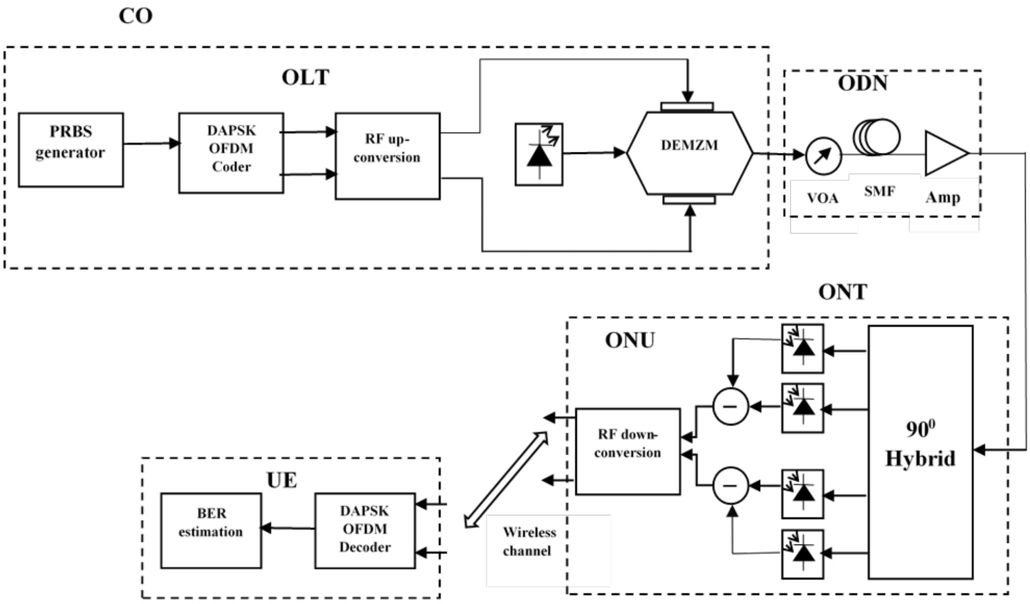


Fig.1. Simulation block diagram of proposed heterogeneous network architecture - Downlink

The input electrical signals given to the two electrodes of DEMZM $E_1(t)$ and $E_2(t)$ are given by,

$$E_1(t) = E_s(t) - V_{bias1} \tag{2}$$

$$E_2(t) = E_s(t) + V_{bias2} \tag{3}$$

where V_{bias1} and V_{bias2} are the biasing voltages of the two electrodes of DEMZM. The biasing point of DEMZM is determined by the DC bias voltage given by,

$$V_{bias} = V_{bias1} - V_{bias2} \tag{4}$$

The resultant electric signal of DEMZM is given by [4],

$$E_{out}(t) = \frac{E_{in}}{2}\left\{e^{j\phi_1(t)} + \gamma e^{j\phi_2(t)}\right\} \tag{5}$$

In this equation, the ϕ_1 (t) and ϕ_2 (t) is given by,

$$\phi_1(t) = \frac{\pi E_1(t)}{V_\pi},\ and\ \phi_2(t) = \frac{\pi E_2(t)}{V_\pi}$$

$$\gamma = \frac{\sqrt{\varepsilon}-1}{\sqrt{\varepsilon}+1}$$

where V_π corresponds to the half-wave voltage of DEMZM, and ε is the Extinction Ratio of the DEMZM.

If α=0, γ=1, it represents the push-pull operation of the DEMZM which results in E_1 (t) = -E_2 (t).

From this relation, the transfer function is given by,

$$\frac{E_{out}(t)}{E_{in}(t)} = \cos\left(\frac{\pi S_{OFDM}(t)}{2V_\pi}\right) \tag{6}$$

Power is given by,

$$\frac{P_{out}(t)}{P_{in}(t)} = \frac{1}{2} + \frac{1}{2}\cos\left(\frac{\pi S_{OFDM}(t)}{V_\pi}\right) \tag{7}$$

The optical signal generated at the output of DEMZM is given by,

$$E_{opt\_sig} = \sqrt{2P_{opt\_sig}}\, exp[j\{\omega_s t + \phi_s(t)\}] \tag{8}$$

Where P_{opt_sig} is the Power of the optical signal, ω_s is the frequency of the optical signal, ϕ_s is the phase of the optical signal.

The signal generated at the local oscillator is given by,

$$E_{lo\_sig} = \sqrt{2P_{lo\_sig}}\, exp[j\{\omega_l t + \phi_l(t)\}] \tag{9}$$

Where P_{lo_sig} is the Power of the local oscillator signal, ω_l is the frequency of the local oscillator signal, and ϕ_l is the phase of the local oscillator signal.

The output of the 90^0 hybrid is given by,

$$E_{01} = \frac{E_{opt\_sig} + E_{lo\_sig}}{2} \tag{10}$$

$$E_{02} = \frac{E_{opt\_sig} - E_{lo\_sig}}{2} \tag{11}$$

$$E_{03} = \frac{E_{opt_{sig}} + jE_{lo_{sig}}}{2} \tag{12}$$

$$E_{04} = \frac{E_{opt\_sig} - jE_{lo\_sig}}{2} \tag{13}$$

The resultant in-phase and Quadrature components after balanced photodetection are,

$$E_1 = E_{01} - E_{02} \tag{14}$$

$$E_2 = E_{03} - E_{04} \tag{15}$$

The photocurrents after photodetection [15],

$$I_{p,1} \propto \left|\frac{E_{opt\_sig} + E_{lo\_sig}}{2}\right|^2 - \left|\frac{E_{opt\_sig} - E_{lo\_sig}}{2}\right|^2 \tag{16}$$

$$I_{p,2} \propto \left|\frac{E_{opt\_sig} + jE_{lo\_sig}}{2}\right|^2 - \left|\frac{E_{opt\_sig} - jE_{lo\_sig}}{2}\right|^2 \tag{17}$$

The resultant photocurrent is given by,

$$I_p(t) = I_{p1}(t) - I_{p2}(t) \tag{18}$$

$$I_{p1}(t) = \frac{1}{2}\mathcal{R}\left\{P_{opt\_sig} + P_{lo\_sig} + 2\sqrt{P_{opt\_sig}P_{lo\_sig}}exp[j\{\omega_{IF}t + \phi_s(t) - \phi_l(t)\}]\right\} \tag{19}$$

$$I_{p2}(t) = \frac{1}{2}\mathcal{R}\left\{P_{opt\_sig} + P_{lo\_sig} - 2\sqrt{P_{opt\_sig}P_{lo\_sig}}exp[j\{\omega_{IF}t + \phi_s(t) - \phi_l(t)\}]\right\} \tag{20}$$

Where ω_{IF} is the intermediate frequency of the transmitted optical signal and is given by,

$$\omega_{IF} = \omega_s - \omega_l$$

Substituting Equation (19) and Equation (20) in Equation (18), the $I_p(t)$ is given by,

$$I_p(t) = 2\mathcal{R}\sqrt{P_{opt_{sig}}P_{lo_{sig}}}exp[j\{\omega_{IF}t + \phi_s(t) - \phi_l(t)\}] \tag{21}$$

The phase of the optical signal is given by,

$$\phi_s(t) = \phi_{sig}(t) + \phi_{PN}(t) \tag{22}$$

Where ϕ_{sig} is the phase due to the modulation of the signal, ϕ_{PN} is the phase noise of the signal.

$$I_p(t) = 2\mathcal{R}\sqrt{P_{opt_{sig}}P_{lo_{sig}}}exp\left[j\{\omega_{IF}t + \phi_{sig}(t) + \phi_{PN}(t) - \phi_l(t)\}\right] \tag{23}$$

The total phase noise is given by,

$$\phi_N(t) = \phi_{PN}(t) - \phi_l(t) \tag{24}$$

$$I_p(t) = 2\mathcal{R}\sqrt{P_{opt_{sig}} P_{lo_{sig}}} exp\left[j\{\omega_{IF} t + \phi_{sig}(t) + \phi_N(t)\}\right] \tag{25}$$

This term is the resultant photocurrent of the signal. The SNR can be calculated from,

$$SNR = \frac{I_p{}^2}{\sigma_{total}{}^2} \tag{26}$$

Where I_p^2 is the average signal power, σ_{total} is the average noise power of the signal.
The average noise power is given by,

$$\sigma_{total}{}^2 = \sigma_{shot}{}^2 + \sigma_{thermal}{}^2 \tag{27}$$

Where σ_{shot} is the average shot noise power, $\sigma_{thermal}$ is the thermal noise power.
The average shot noise power is given by,

$$\sigma_{shot}{}^2 = 2q\left(I_p + I_d\right).\Delta f \tag{28}$$

Where I_d is the dark current, q is the charge of an electron, Δf is the noise bandwidth.

$$\sigma_{thermal}{}^2 = \frac{4k_B T}{R_L}.\Delta f \tag{29}$$

Where k_B is the Boltzman constant, T is the Temperature, R_L is the load resistor.
The error performance parameters like EVM can be calculated from the SNR using the equation [16],

$$SNR = -\left(3.7 + 20 * \log_{10}\left({}^{EVM\ (\%)}/_{100\%}\right)\right) \tag{30}$$

Where the value 3.7 corresponds to the Peak to Average Power (PAPR) of the system.
Rewriting Equation (30) with the RMS value of EVM,

$$EVM_{RMS} = -(SNR + 3.7) \tag{31}$$

The penalty for differential detection is given by,

$$F = 1 + \frac{\log_2 \mathrm{M}}{2(\sqrt{\mathrm{M}} - 1)} \tag{32}$$

Where M is the order of modulation.

F=1.43 for M=64

Substituting this,

$$EVM_{RMS} = -(SNR + 2.27)$$

Also, PAPR of the DAPSK-OFDMA system = 2.5
The EVM of the 64 DAPSK technique is given by,

$$EVM_{RMS} \cong -(SNR + 2.5) \tag{33}$$

The Capacity of the overall link is estimated using Shannon's capacity theorem.

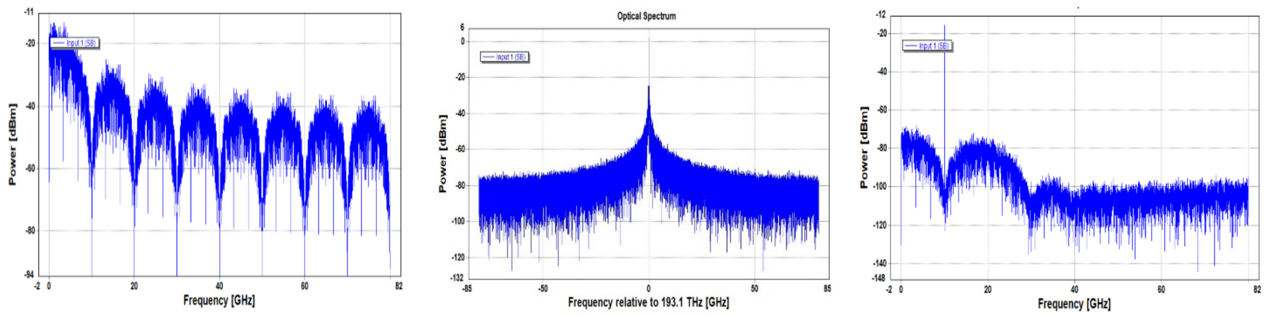
$$C = B\log_2(1 + SNR) \tag{34}$$

Where C is the maximum capacity of the link (bps), and B is the bandwidth of the considered channel (Hz).
Spectral efficiency is the prime concern of a broadband access network that quantifies the efficient utilization of the available spectrum that is expressed in bps/Hz.

$$Spectral\ Efficiency\ (\eta_{spec}) = \frac{C}{B} \quad (35)$$

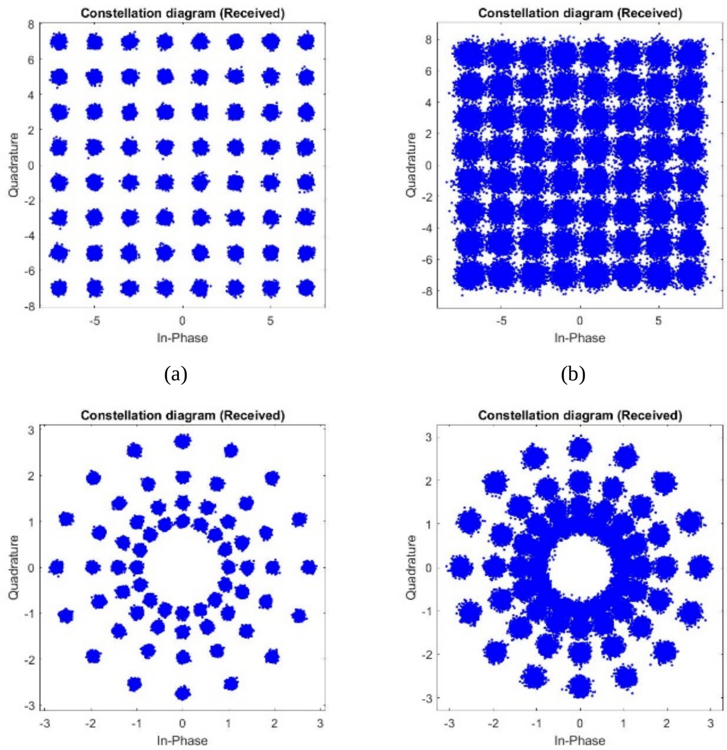
4. Simulation Results

The simulation tools used for the study are MATLAB R 2018a, VPI Transmission Maker 9.7, and VPI Photonics Analyzer. The spectrum of the DAPSK-OFDMA modulated signal with a bandwidth of 10 GHz is shown in Fig. 2 a). Fig. 2 b) represents the spectrum of the modulated optical signal at 193.1 THz. Fig. 2 c) presents the spectrum of the received RF signal. Considering RF carrier frequency of 10 GHz, optical carrier frequency of 193.1 THz, and a wireless link distance of 1 km, the performance of the proposed architecture is analyzed.



(a) (b) (c)

Fig.2. The spectrum of (a) Transmitted RF signal (b) Transmitted optical signal (c) Received RF signal



(a) (b)

(c) (d)

Fig.3. Constellation diagram of the received OFDMA signal of (a) 64 QAM with 25km fiber length (b) 64 QAM with 50km fiber length (c) 64 DAPSK with 25km fiber length (d) 64 DAPSK with 50km fiber length

The conventional QAM-OFDMA modulation is realized over the proposed architecture, and a performance comparison is made. Fig. 3 a) and 3 b) show the received constellation plots of 64 QAM for at 25km and 50 km fiber length, respectively. Fig. 3 c) and 3 d) show the same for 64 DAPSK. It is evident that as the fiber length increases, the constellation plot becomes more scattered, making the error performance deteriorating.

5. Performance Evaluation

5.1. Error Performance Analysis

A. Effect of Laser Power

In the 64-QAM/64-DAPSK-OFDMA PON, single-user and multiple users cases are compared. Due to simulation constraints, three users are considered for the simulation study of 64-QAM/64-DAPSK-OFDMA PON, and the number of users can be increased in multiples of three.

The BER vs. transmitted optical power of 64 QAM-OFDMA and 64-DAPSK-OFDMA considering single-user and three users are shown in Fig. 4.

A comparison is made between QAM-OFDMA PON and DAPSK-OFDMA PON, considering one user and three users. From Fig. 4, it is evident that the BER decreases as the transmitted optical power increases. From the figure, it is evident that increasing the number of users has a negligible impact on the error performance. DAPSK-OFDMA has a slight degradation in performance than QAM, but this has less impact considering the spectral efficiency achieved. The desirable BER is considered as 10^{-6}, and the proposed scheme achieves this BER for transmitted powers of above 0 dBm.

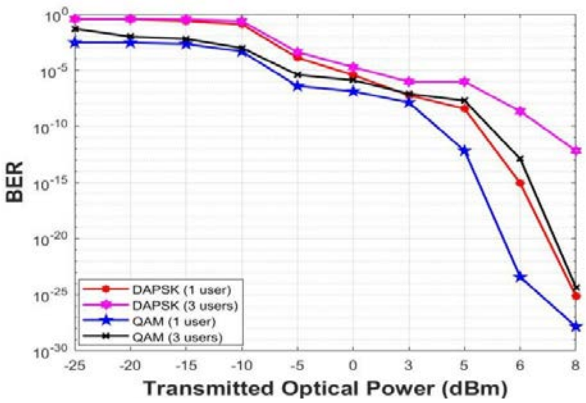
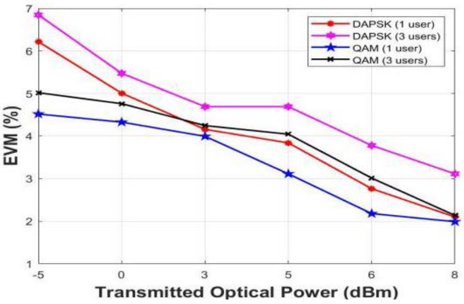
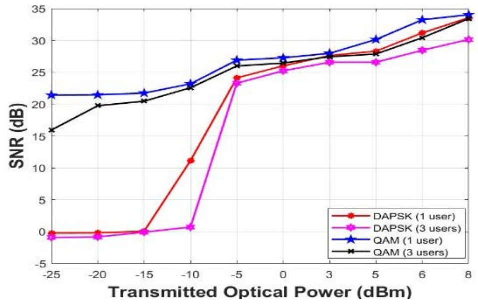


Fig.4. BER vs. Transmitted optical power (dBm) for QAM and DAPSK for fiber length of 25 km

The EVM and SNR values obtained are plotted for 64 QAM-OFDMA and 64 DAPSK-OFDMA considering single-user and three users in Figs. 5 a) and 5 b).



(a)



(b)

Fig.5. (a) EVM vs. transmitted optical power for QAM and DAPSK (b) SNR vs. transmitted optical power for QAM and DAPSK

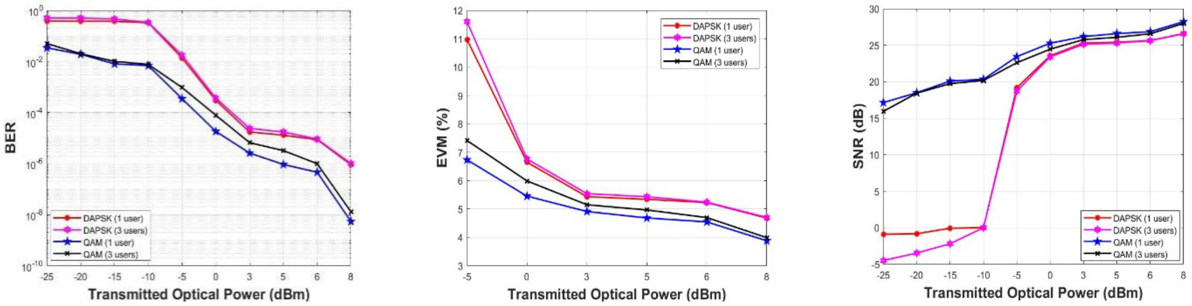
From Fig. 5 a), it is evident that the EVM decreases as the transmitted power increases as expected. The EVM value of 64 QAM should be better than 8% [17]. For 64 DAPSK, the EVM requirement is estimated, including the penalty for differential modulation, and it is about 6%. From Fig. 5 a), both 64 QAM-OFDMA and 64 DAPSK-OFDMA systems can achieve an EVM well below their respective requirement values for a fiber length of 25 km. From Fig. 5 b), it is evident that higher SNR values are achieved for transmitted powers above -5 dBm.

B. Effect of Fiber Length

The effect of fiber length on the error performance of 64 QAM-OFDMA and 64 DAPSK-OFDMA are studied. The BER, EVM, and SNR for different transmitted optical power of 64 QAM-OFDMA and 64-DAPSK-OFDMA for 50 km fiber length are shown in Fig. 6.

Fig. 6 a) shows a similar behavior as Fig. 4, but BER reduces due to the increase in fiber length. However, desired error performance can be achieved with a slight increase in input power supporting long backhaul fibers. For 50 km fiber, the required EVM levels are achieved with an increase in laser power as shown in Fig. 5 b). From Fig. 6 c), it is observed that for transmitted power of above 0 dBm, better SNR values of about 20 dB are obtained.

The effect of varying the fiber length is studied by observing the error performance for different fiber lengths and is shown in Fig. 7. The transmitter power is set as 0 dBm, and as the fiber length is increased, the BER value increases. But desirable error performance is achieved for fiber lengths up to 30 km. However, for longer fiber lengths of up to 100 km, the BER value obtained satisfies the FEC limit (10^{-3}). Thus, the proposed architecture can be implemented over long backhaul fibers for access systems.



(a) (b) (c)

Fig.6. (a) BER vs. transmitted optical power for QAM and DAPSK (b) EVM vs. transmitted optical power for QAM and DAPSK (c) SNR vs. transmitted optical power for QAM and DAPSK

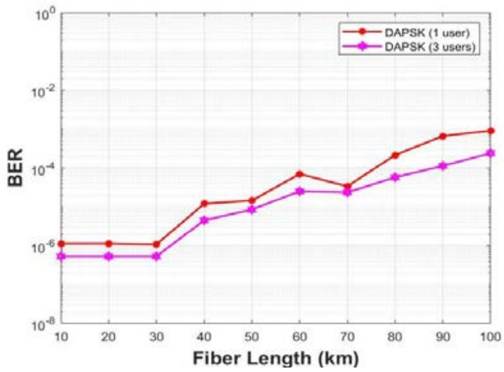


Fig.7. BER vs. fiber length (km) for DAPSK

C. Effect of OSNR

The effect of Optical Signal to Noise Ratio (OSNR) on the error performance of the proposed 64-DAPSK OFDMA based heterogeneous network is studied. OSNR quantifies how the optical noise interferes with the optical signal. The input signal is considered as noise-free, and an Amplified Spontaneous Emission (ASE) noise is added, and the effect is analyzed to study the effect of noise on the optical signal. The OSNR value is calculated using Eqn. (36)

$$OSNR = 10\ \log_{10}\left(\frac{P_{opt}}{B_{ASE}*W_{ASE}}\right) \tag{36}$$

Where Popt is the power of the optical signal, BASE is the bandwidth of ASE Noise, and WASE is the Power Spectral Density (PSD) of ASE noise.

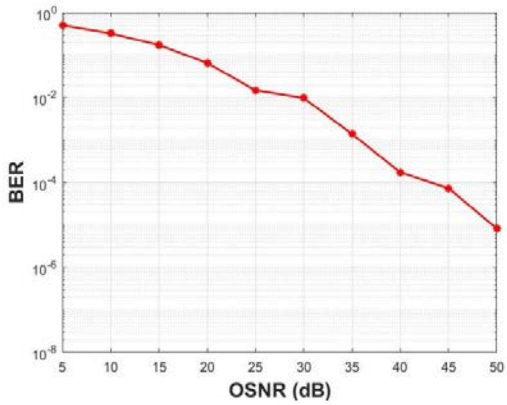


Fig.8. BER vs. OSNR (dB) for DAPSK

The BER values for different OSNR values are shown in Fig. 8. A lesser reference BER of 10^{-3} (FEC limit) is considered here, as ASE noise is added. From the figure, it is clear that an OSNR of about 30 dB is required to achieve the required BER of 10^{-3}.

5.2. Spectral Efficiency Analysis

For the proposed link, Table 1 lists the obtained SNR, BER, and calculated Spectral efficiency values.

Table 1. Comparison of BER, SNR, and spectral efficiency for the proposed link

Scenario	CW Laser power (dBm)	BER	SNR (dB)	Spectral efficiency (bps/Hz)
QAM-OFDMA PON				
1 user	-5	1.32×10^{-7}	23.20	4.59
3 users	-5	3.97×10^{-7}	22.29	4.54
DAPSK-OFDMA PON				
1 user	0	5.92×10^{-7}	22.31	4.54
3 users	0	9.53×10^{-7}	21.53	4.49

The reference BER considered is 10^{-6} for effective transmission. The results obtained show that QAM-OFDMA PON requires 5 dB lesser laser power than that of DAPSK-OFDMA PON to achieve the desired error performance. This 5 dB power penalty is insignificant compared to the spectral efficiency improvement achieved. For the proposed downlink, the capacity is 45 Gbps/user, and the total capacity is 135 Gbps considering three users. The Peak to Average Power Ratio (PAPR) of the link is about 2.5 dB. Since the PAPR of the system is low, the same link can be modified for uplink.

Table 2. Spectral efficiency comparison of QAM-OFDMA PON and DAPSK- OFDMA PON

Modulation Technique	Spectral efficiency (η_{spec}) (bps/Hz)		
	η_{spec} due to channel	η_{spec} due to reduction of redundant data	Total η_{spec}
QAM-OFDMA PON	4.54	-	4.54
DAPSK-OFDMA PON	4.49	1.062	5.552

Table 2 shows the spectral efficiency (η_{spec}) due to the channel condition and spectral efficiency due to the reduction of redundant bits. It is evident that both QAM-OFDMA and DAPSK-OFDMA achieve a spectral efficiency of about 4.5 bps/Hz due to the channel condition. QAM-OFDMA requires 16% of the total transmitted bits for channel and phase noise cancellation, which is not required in the case of DAPSK-OFDMA. Due to the reduction in the number of redundant bits required, DAPSK-OFDMA achieves an additional spectral efficiency of about 1.062 bps/Hz.

The link power analysis is an efficient method of calculating the power requirements of the transmission link, and the link power budget for the downlink of the proposed architecture is carried out and presented in Fig. 9.

For efficient transmission, the received power at the UE should be higher than the receiver sensitivity, and the minimum value of transmitter power that satisfies the above condition has to be selected at the Central Office itself. The total loss experienced by the signal traversing the overall link is 122.8 dB, including an overall optical link loss of 23.04 dB and an RF wireless link loss of 99.76 dB. The FSPL specified for the wireless fronthaul is estimated using Equation (37).

$$\text{Free Space Path Loss (FSPL)} = 10 * \log_{10}\left({4\pi d}/{\lambda}\right)^{n} \tag{37}$$

where distance ‘d’, $\lambda = c/f$, $c = 3 \times 108$ m/s, f =frequency in (Hz), and ‘n’ is the path loss exponent of 2.

The total fiber link loss of the signal at ONU-eNB is 23.04 dB, including the loss due to attenuation, connector loss, splice loss, and dispersion margin. The receiver sensitivity of the photodetector at ONU-eNB is -28 dBm. For the link, the transmitted optical power requirement is estimated using Equation (38).

$$\text{Transmitted Power} = \text{Receiver Sensitivity} + \text{Total Loss} + \text{System Margin} - \text{Gain} \tag{38}$$

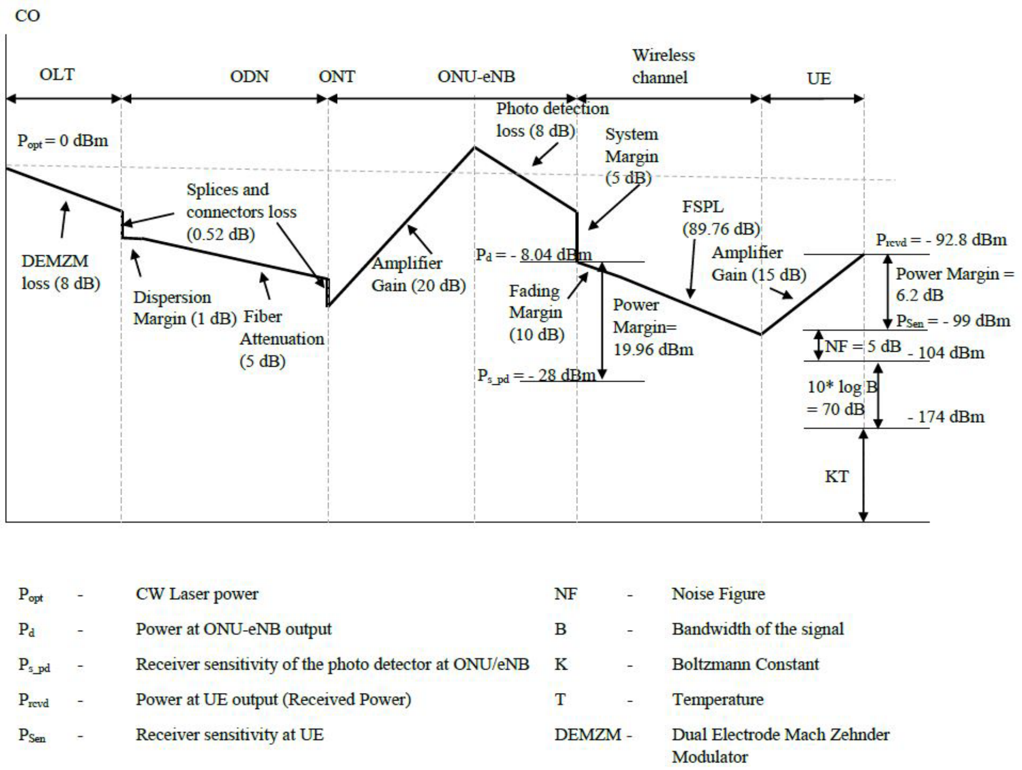


Fig.9. Link budget analysis

For the proposed downlink, amplifier gain of 20 dB and the system margin of 5 dB are considered for the calculation. Hence, the minimum optical power requirement using Equation (38) is found to be -20 dBm. For the optimum transmitted power of 0 dBm, a power margin of about 20 dBm is obtained.

The wireless link loss includes a fading margin of 10 dB and the Free Space Path Loss (FSPL). For the LTE – Pedestrian Channel considered, the FSPL is found to be 89.76 dB (Equation 37). The receiver sensitivity of the User Equipment is calculated using Equation (39).

$$P_{sen} = -174 + 10 * \log B + NF \tag{39}$$

The Noise Figure is 5 dB, and the receiver sensitivity estimated using the above equation is -99 dBm. An amplifier of gain 15 dB is used at the UE, and the minimum power required is estimated to be -6 dBm from the Equation (38). For the transmitted power of 0 dBm, a power margin of 6 dBm is obtained. The power margin reduces, and hence the power requirement of the link is very high if the wireless link loss is included. Therefore, RF power amplifiers have to be used at the ONU-eNB for efficient transmission.

6. Conclusion

The spectrally efficient DAPSK-OFDMA is implemented in PON over RoF as proposed for the heterogeneous access network. The downlink in the proposed network is simulated, and the performance is analyzed in terms of BER, EVM, SNR, Capacity, and spectral efficiency. The PAPR of the link is found to be 2.5 dB. Since the PAPR of the system is low, the same link could be modified for uplink. A high capacity of about 135 Gbps is achieved for three users DAPSK-OFDMA PON-based heterogeneous network with an average capacity of 45 Gbps/user. The results indicate that the QAM-OFDMA and the DAPSK-OFDMA systems could achieve a spectral efficiency of about 4.5 bps/Hz due to the channel condition. QAM-OFDMA requires 16% of the total transmitted bits for channel and phase noise cancellation, which is not in the case of DAPSK-OFDMA. Due to the reduced number of redundant bits required for phase noise cancellation and synchronization, DAPSK-OFDMA achieves an additional spectral efficiency of about 1.062 bps/Hz. Further improvement in spectral efficiency can be achieved by increasing the number of ONUs.

The proposed DAPSK-OFDMA PON heterogeneous network can interoperate with the current 4G and 5G wireless technologies, and it can also support other services like Bluetooth, Wi-Fi, Wi-Max.

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Authors’ Profiles

Priyadharshini R. has received a B.E. (ECE) degree from Panimalar Engineering College and an M.E. degree in Communication Systems from College of Engineering Guindy, Anna University, Chennai. She is currently a Research Scholar in the Department of Electronics and Communication Engineering, College of Engineering Guindy, Anna University. Her research interests are Optical access networks, Radio over Fiber, Fiber wireless networks, RF system design.

Geetha G. has completed her Ph.D. degree in Optical Communication from the Department of Electronics and Communication Engineering, College of Engineering Guindy, Anna University, Chennai. She is currently a Professor in the Department of Electronics and Communication Engineering, Anna University, Chennai. Her research interests are satellite communications, Radio Frequency, microwave engineering, optical technology and planar antennas.

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