



Research Article,

Design and Analysis of a Self-Healing High-Capacity Optical Communication Network for 5G Applications

Muhammad Umar Khan¹, Asia Zaman^{2,*}

¹ Department of Electrical Engineering, University of Engineering and Technology, Peshawar, 25000, Pakistan

² AHEAD, Chicago, Illinois, 60606, USA

*Corresponding Author: Asia Zaman. Email: asia.zaman@ahead.com

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Abstract: With the rising number of applications for 5G, the demand has surged for optical access networks that are high in capacity and are reliable. In this paper, a high capacity and resilient optical communication system based on double weight zero cross-correlation (DW-ZCC) optical code division multiple access (OCDMA) and hybrid fiber/free-space optical (FSO) protection architecture is proposed. The essence of the transmission is the combination of high-capacity DW-ZCC transmission and a dual-path fiber/FSO protection scheme and optical switching in the optical network terminal (ONT). The proposed architecture is assessed with the help of OptiSystem simulations and reliability analysis. The results of the simulations also demonstrate the effect of the FSO link length on the received power and quality factor (QF), achieving 99.999% connection availability for the proposed architecture and 99.9954% for the conventional architecture, while the QF remains higher than 43 over the range of FSO distances investigated. Reliability analysis also reveals that the proposed architecture reaches a five-nines connection availability whilst the conventional architecture achieves 0.999954. The outcome results show the potential of the proposed integrated architecture to transmit high capacity and to be more resilient for optical access of the 5G network.

Keywords: DW-ZCC; OCDMA; Hybrid Fiber/FSO; Passive Optical Networks; 5G Optical Access Networks; Self-Healing Networks;

1. Introduction

Past decades have witnessed an exponential growth in network capacity due to the penetration of artificial intelligence (AI) based services, integration of Internet of things (IoT) with the existing systems, and utilization of bandwidth intensive applications [1-3]. This growth is further fueled by the widespread adaptation of wireless communication devices across the globe [4, 5]. This exponential growth of network capacity has created a significant bottleneck at the fronthaul section of the network as service providers are experiencing several challenges in providing the required capacity at 99.999 % connection availability and acceptable costs [6].

One of the most promising solutions to the high-capacity bottleneck problem is provided through the implementation of optical fiber medium across the access network. Optical communication networks like passive optical network (PON) are widely adapted at the access domain to provide high-capacity

connectivity for both wired and wireless medium [7]. However, migration of wireless communication networks from the conventional D-RANs to centralized radio access networks (C-RANs) has hindered the adaptability of PONs owing to its dense deployment in the urban areas [8-10].

C-RANs for 5G and the upcoming 6G networks require dense deployment of remote radio heads (RRHs) at the subscribers' premises to ensure high capacity at low latency and desirable connection availability. However, deployment of PONs through such a dense network is difficult owing to the required cost of implementation and provision of redundant paths for enhanced connection availability. To address the said issue, this paper provides a detailed network architecture that is not only able to provide desirable network capacity but also enhance connection availability through the employment of a hybrid fiber/ free space optical (FSO) communication path [9, 10].

The network capacity required for the next generation of communication systems is provided through the implementation of optical code division multiple access (OCDMA) code called double weight zero cross-correlation (DW-ZCC) code [10, 11]. This code provides asynchronous connection availability along with minimum cross-correlation and maximum auto correlation to provide the required network capacity. 99.999% connection availability is ensured through a hybrid optical/ FSO path between the base band unit (BBU) remote node (RN) and RRHs. Optical fiber serves as a primary path to provide the required network capacity, whereas FSO based channel is implemented as a secondary path to provide connection availability in case of fiber failure or cuts.

This work highlights the combination of DW-ZCC based OCDMA transmission and high-capacity, robust, FSO protection architecture for optical access systems in 5G applications. While much of the research on existing protected PON architectures is based on implementing redundant fiber or FSO protection [12, 13], the proposed architecture is a guaranteed capacity increase of DW-ZCC spectral-amplitude-coded OCDMA in conjunction with a fiber/FSO dual-path protection mechanism and ONT-side optical switching. The proposed scheme is to use the optical fibre medium for high-capacity communication and the FSO link as an alternative when the fibre fails. The contribution is not FSO protection, but rather the integration of high-capacity coding via DW-ZCC, FSO/hybrid path protection, and optical switching in a common architecture. Both the communication-performance and the network-availability aspects of the proposed design are analyzed in both simulation and reliability OptiSystem-based analysis.

Thus, this research brings about the following contributions:

- A high-capacity optical access architecture based on DW-ZCC OCDMA is developed to support multiple subscribers through spectral-amplitude coding.
- A hybrid FSO/fiber protection is also incorporated into the architecture: FSO is used as a redundant protection link when fiber is failed.
- To allow for both selection of the communication path and continuity of service after a failure in the primary-path, an ONT-side optical switching mechanism is used.
- Performance and reliability analysis of the joint is done to check the proposed architecture through Q factor, Eye opening, distance of FSO transmission and received power, connection availability.

The self-healing and protection based on FSO have been studied for PONs [11, 12] previously. The studies mentioned above, however, deal mainly with network protection and availability; the present work, however, also considers DW-ZCC with OCDMA systems for meeting the high capacity demand of dense 5G optical access. So, the proposed architecture solutions solve both capacity and resilience issues together – not separately as design goals.

Analysis of the proposed system is performed through OptiSystem and mathematical formalism. OptiSystem is used to check the support of the proposed setup for the required network capacity in terms of reach, data, and the number of subscribers. Performance of the proposed system is evaluated for different lengths of the FSO channel by observing QF at the receiving end. Connection availability of the proposed setup is performed through mathematical analysis by using reliability block diagram (RBD).

2. Proposed Architecture

Figure 1 shows basic architecture of the proposed setup. The entire network is divided into three parts namely the optical line terminal (OLT) modules, the optical distribution network (ODN) and the ONT/RRH modules. OLT module is used to represent the base band unit (BBU) employed in the C-RAN architecture. Multiple OLT modules form a BBU pool that are then connected to their respective RRH through the ODN.

Each OLT module employs two laser diode (LDs) that are centered around the wavelength λ_1 and λ_2 , where 1 and 2 represents position of the binary 1 in the DW-ZCC code. End-face of the LDs are connected to the optical encoder, which houses a power combiner to combine the wavelengths λ_1 and λ_2 into a single pulse. The optical encoder is essentially employed to convert the binary placement of binary 1's in the DW-ZCC to their respective spectral presentation.

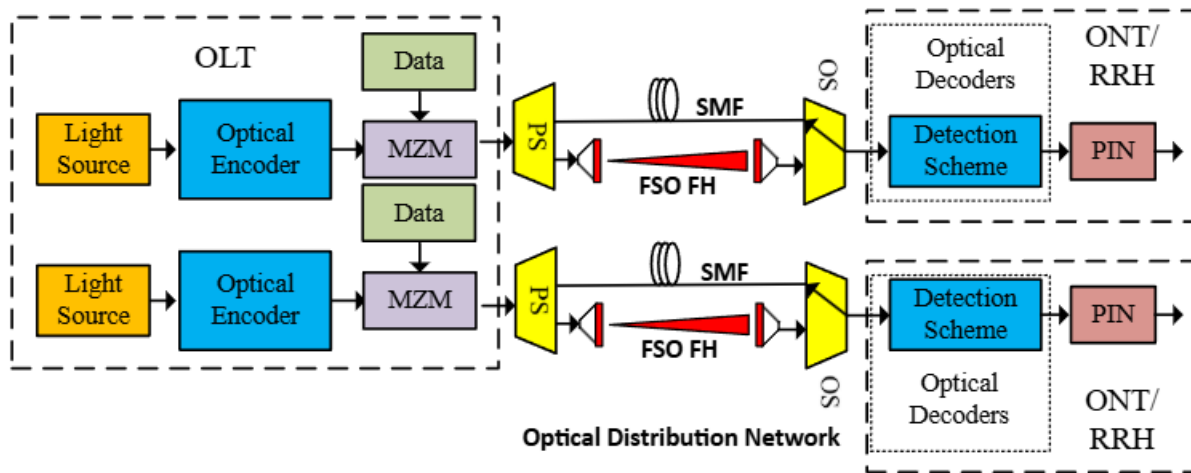


Figure 1: Proposed system architecture

DW-ZCC is an optical code division multiple access (OCDMA) code that is employed to ensure desired network capacity at relatively simple architecture. The DW-ZCC is formed from the combination of binary 1's that are placed in a pair of two. Furthermore, cardinality of the DW-ZCC matrix is increased by binary pair placement across a diagonal such that the final code maintains a zero-cross correlation property between adjacent codes and w auto-correlation property, where w represents weight of the DW-ZCC code [10, 11]. The basic DW-ZCC matrix with 3 users can be written as

$$DW - ZCC_3 = \begin{bmatrix} 1 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 1 \end{bmatrix}_{3 \times 6}$$

For clarity, the principal parameters and notation of the DW-ZCC code are defined as follows. The code weight w represents the number of binary ones assigned to each code, while N denotes the total number of supported users or subscribers. The code length is determined by the adopted DW-ZCC construction and can be expressed as $L = w \times N$. For the three-user DW-ZCC matrix shown above, $w = 2$, $N = 3$, and therefore $L = 6$. The positions of the binary ones in each row of the code matrix determine the wavelengths assigned to the corresponding user. For example, for the first user, the two wavelengths corresponding to the positions of the binary ones in the first row are selected for transmission. Similarly, the wavelength assignments for the remaining users are determined by the positions of the binary ones in their respective code rows. The DW-ZCC construction provides zero cross-correlation between distinct user codes while maintaining the required autocorrelation property for the intended user's code, thereby reducing multiple-access interference at the receiver.

It can be observed that each X^{th} code maintains a zero cross-correlation with the adjacent code. Furthermore, each code has a length (L) that can be determined through $w \times N$. Here w represents the weight of the code and N represents the total number of subscribers. Allocation of wavelengths to each X^{th} code is determined by the placement of 1 across the code matrix. For instance, for user 1 with the $X_1 = [1\ 1\ 0\ 0\ 0\ 0]$, wavelength of λ_1 and λ_2 are utilized. Similarly, for user 2 with $X_2 = [0\ 0\ 1\ 1\ 0\ 0]$, wavelength of λ_3 and λ_4 can be employed to perform the required binary to spectral conversion [11].

Output of the optical encoder is connected to Mach-Zehnder Modulator (MZM) that is used to modulate the message signal coming from a data source with the optical encoded spectrum. MZM employs on-off keying (OOK) to perform the required modulation and convert the signal from electrical-to-optical domain. End-face of the MZM is connected to a 1:2 power splitter (PS) as shown in Fig. 1.

The power splitter is employed to split the path into two communication channels. One channel is provided by the optical fiber media that is used as a primary path, whereas the other channel is implemented using FSO link that serves as a secondary path. It is pertinent to mention that the maximum allowable length of the ODN is set to 2 km to ensure the attainment of desirable signal quality via both paths.

The receiving module at ONT/ RRH employs an optical switch (OS) with two ports at the receiving end. Port 1 of the switch is connected primarily to the optical fiber link serving as a primary path. The switch can be moved to port 2 if the path fails to provide the required signal strength over a given period as shown in Fig. 2. End-face of the optical switch is connected to a decoding arrangement that employs a combination of bandpass filters centered across the wavelengths in accordance with the transmitter modules. For instance, for user 1, the bandpass filters at the receiver are centered across the wavelength λ_1 and λ_2 to receive the desired spectrum at maximum auto correlation and minimum cross-correlation. Output of the decoding arrangement is connected to the PIN photodiode that is used to convert the signal from optical-to-electrical domain for the required processing.

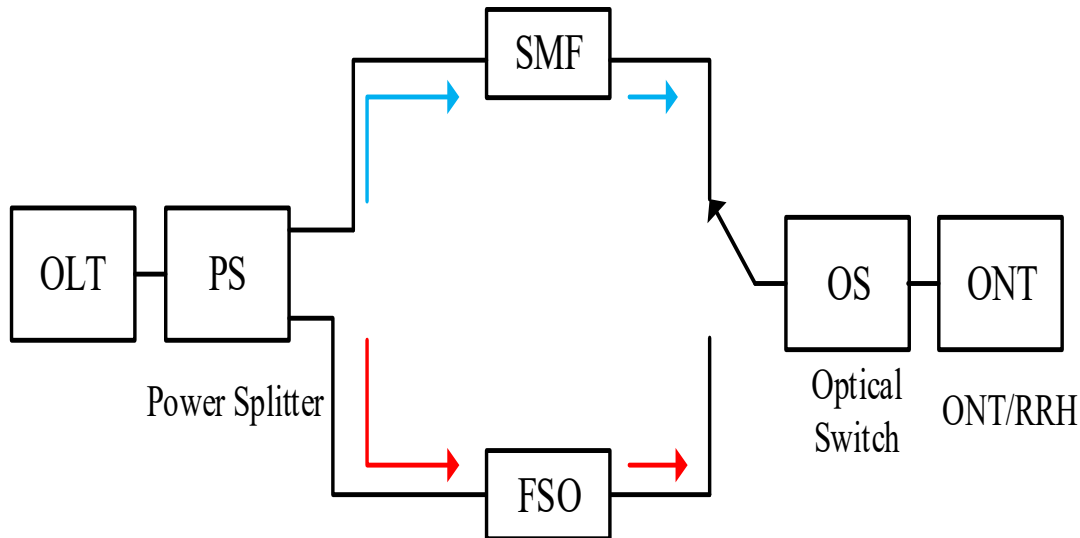


Figure 2: Protection mechanism for the proposed architecture

3. Performance Analysis

The proposed system is analyzed in OptiSystem using the system architecture presented as Fig. 1. Figure 3 represents the simulation setup that is configured to simulate the best possible scenario as per the practical conditions. Moreover, to test the proposed system's resilience, extensive simulations are carried out under varying operating conditions as shown in Table 1 and 2. During each simulation scenario, key performance indicators such as Quality Factor (QF), and eye diagram are observed to assess performance of the proposed system.

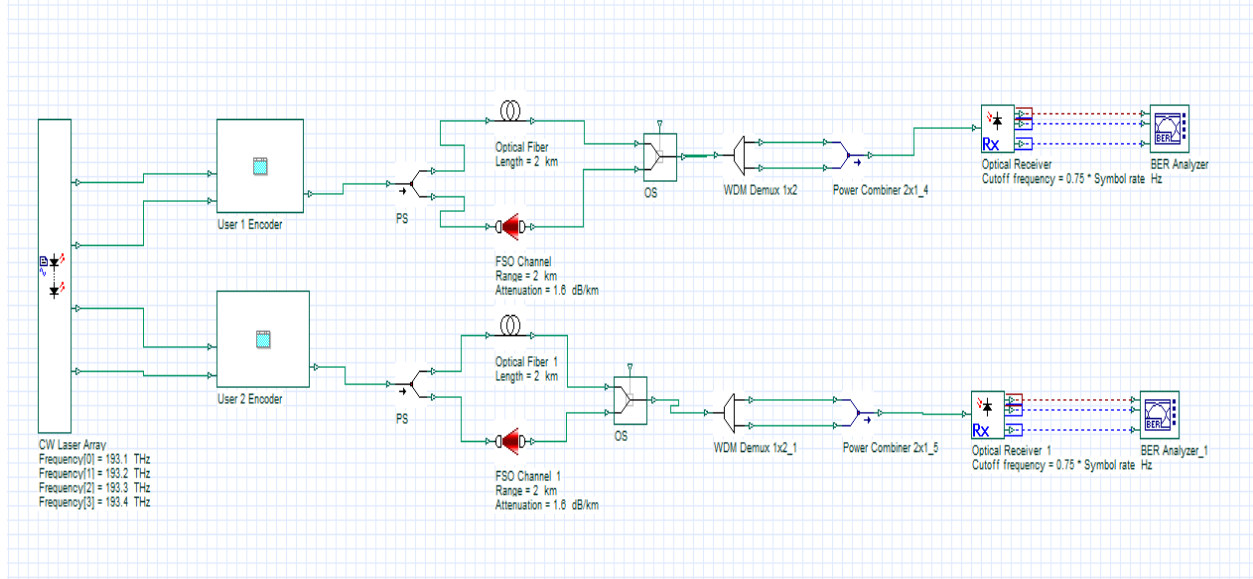


Figure 3: Simulation setup for performance analysis

Table 1: . FSO Channel Attenuation Parameters Under Different Weather

Atmospheric Condition	FSO Link Attenuation (dB/km)
Clear atmospheric conditions	0.43–0.6
Mild haze	1–1.2
Hazy conditions	3.1–4.6
Low-intensity rainfall	6.27
Moderate rainfall	9.64
Low-density fog	6.6–18.3

Table 2: System Simulation Parameters

Simulation Parameter	Specified Value
Data rate per wavelength	10 Gbps
Number of transmitter nodes	16, 32, 48, 64
EDFA in feeder fiber	25 dB
Photodiode responsivity	0.8 A/W
Modulation/signal format	NRZ
Noise model	Gaussian
Low-pass filter (LPF) cutoff	$0.75 \times \text{data rate}$
FSO channel model	Gamma–Gamma
FSO transmission range	Variable
Beam divergence angle	2 mrad
FSO transmitter aperture diameter	5 cm
FSO receiver aperture diameter	20 cm

The simulation parameters were selected to represent the operating conditions of the proposed optical access architecture. The FSO channel was evaluated under different atmospheric conditions and transmission distances, while the system-level parameters, including data rate, transmitter power, receiver characteristics, signal format, and optical aperture dimensions, were kept consistent with the configuration implemented in OptiSystem. The units of all physical parameters are explicitly provided in Tables 1 and 2 to improve reproducibility.

Table 3 presents the Q-factor performance of the proposed system when the optical switch selects the FSO path. The results show that the Q-factor decreases slightly as the FSO link length increases from 0.5 km to 2 km, decreasing from 43.7 to 43.0. This behavior is consistent with the corresponding reduction in received power, which decreases from 22 dBm at 0.5 km to -2.1 dBm at 2 km. The reduction in received power is associated with the increasing propagation loss experienced over the longer FSO path, which reduces the signal-to-noise ratio (SNR) at the receiver and consequently affects the Q-factor. The relatively small reduction in Q-factor across the investigated distance range indicates that the proposed configuration maintains a high-quality received signal despite the reduction in received optical power.

The FSO attenuation shown in Table 3 is kept constant for the reported distance-sweep simulations; therefore, the observed reduction in received power is primarily associated with the increase in propagation distance. The results also demonstrate the trade-off between FSO link distance and signal quality: longer protection paths provide greater deployment flexibility but result in increased propagation loss and lower received power. Nevertheless, the Q-factor remains around 43 throughout the investigated range, indicating that the protection path can maintain the required signal quality under the simulated conditions.

The corresponding eye diagrams in Table 4 provide a visual representation of this behavior. As the FSO distance increases, the eye opening becomes progressively smaller, reflecting the reduction in received signal quality associated with increased propagation loss. However, the eye remains clearly open at the investigated distances, which is consistent with the Q-factor results and indicates that the received signal remains distinguishable from the noise under the simulated conditions.

Table 3: Q-Factor Performance for Different FSO Link Lengths

Users	Data Rate (Gbps)	Data Rate (Gbps)	Data Rate (Gbps)	Data Rate (Gbps)	Rate	Data Rate (Gbps)	Data Rate (Gbps)
2	10	0	0.5	0.4		22	43.7
2	10	0	1	0.4		7.5	43.7
2	10	0	1.5	0.4		1.5	43.5
2	10	0	2	0.4		-2.1	43

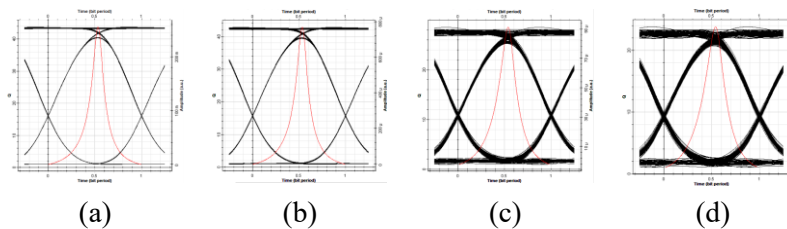


Figure 4: Eye diagrams illustrating system performance channel lengths of (a) 0.5 km (b) 1 km (c) 1.5 km and (d) 2 km

4. Reliability and Availability Analysis

In addition to transmission capacity and signal quality, connection availability is an important consideration in the design of resilient optical communication networks. Therefore, the proposed architecture is evaluated in terms of network availability using a reliability-block-based analysis and compared with the conventional architecture [12, 13]. **Availability** represents the probability that the network remains operational and capable of providing the required service, whereas **unavailability** represents the probability that the network is unable to provide the required service. The proposed protection architecture is analyzed by representing its constituent network components and communication paths through their corresponding unavailability values.

The reliability analysis assumes that failures of individual network components are statistically independent and that their unavailability values remain constant over the period considered. The primary optical-fiber path and the FSO path are modeled as alternative paths within the protection configuration, such that the FSO path can provide service when the primary fiber path becomes unavailable. The analysis assumes that the optical switch successfully transfers the connection to the available protection path following a primary-path failure. Simultaneous or common-cause failures affecting both the primary fiber and FSO paths are not explicitly considered in the analysis. These assumptions provide a simplified reliability model for evaluating the availability improvement provided by the proposed hybrid fiber/FSO protection architecture.

The overall connection availability of the proposed setup can be expressed as:

$$A_{VB} = 1 - \sum_{i=1}^j UA_{VB_i} \quad (1)$$

where A_{VB} represents the overall availability of the proposed network, UA_{VB_i} represents the unavailability of the i -th network component or block, and j denotes the total number of components or blocks considered in the availability analysis. The overall availability is obtained from the complementary relationship between system availability and the aggregate component unavailability.

The overall network unavailability can be further represented in terms of the major network blocks as:

$$UA_{VB_i} = UA_{VB_{CO}} + UA_{VB_{PF}} + UA_{VB_{ONTS}} \quad (2)$$

where $UA_{VB_{OLT}}$ represents the unavailability of the optical line terminal (OLT), and $UA_{VB_{1:2PS}}$ represents the unavailability of the 1:2 power splitter.

Similarly, the unavailability associated with the primary fiber path can be expressed as:

$$UA_{VB_{CO}} = UA_{VB_{OLT}} + UA_{VB_{1:2PS}} \quad (3)$$

where OF_{PR} represents the overall optical-fiber span between the BBU pool and the ONT module, while $UA_{VB_{OF}}$ represents the unavailability factor of the optical-fiber medium. The protection configuration incorporates the FSO path as an alternative communication path to maintain service availability when the primary fiber path becomes unavailable.

$$UA_{VB_{PF}} = (OF_{PR} UA_{VB_{OF}})^2 \quad (4)$$

Here OF_{PR} is used to represent the overall span of the OF medium deployed between the BBU pool and ONT module. where as $UA_{VB_{OF}}$ is used to employ the unavailability factor of the OF medium. Superscript 2 is utilized in the equation to incorporate the redundant feature of the as FSO link is applied in parallel with the primary fiber to operate in case of failure at the primary fiber.

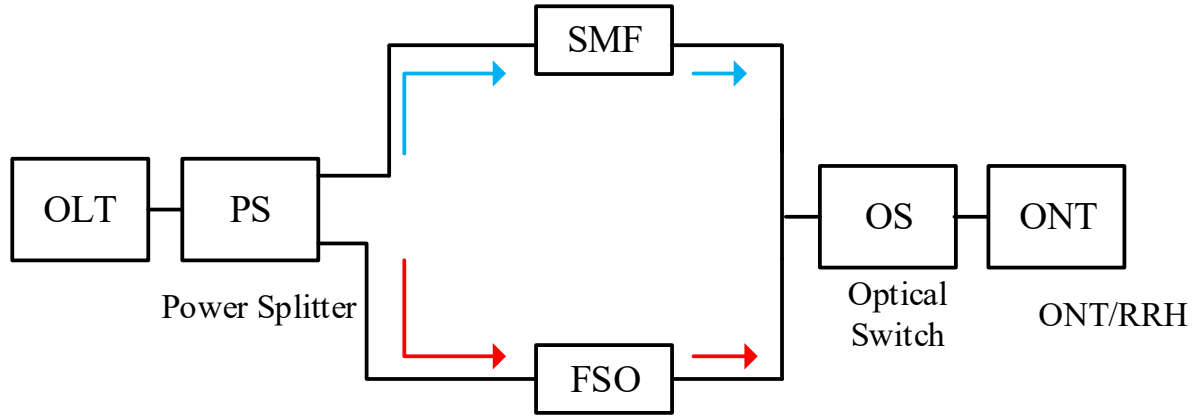


Figure 5: Reliability block diagram for the proposed architecture

Similarly, unavailability of the ONT module employed at the RRH can be written as

$$UA_{VB_{ONT_{Total}}} = UA_{VB_{OS}} + UA_{ONT} \quad (7)$$

Table 4 shows the unavailability values ($\frac{Failure}{10^9h}$) of the major system components used in the proposed architecture, as reported in [12].

Table 4: Unavailability Values of the Components in the Proposed Architecture

Component	Unviability
Optical line terminal (OLT)	5.12×10^{-7}
Power splitter (1:2, 2:2)	3×10^{-7}
Power combiner (1:2, 2:2)	3×10^{-7}
Optical switch	1.2×10^{-6}
Optical network terminal (ONT)	5.12×10^{-7}
OF/km	2.8×10^{-6}

Table 4 presents the eye diagrams for FSO channel lengths of 0.5 km, 1 km, 1.5 km, and 2 km. The eye diagrams further support the Q-factor observations reported in Table 3. At shorter FSO distances, the larger eye opening indicates better separation between the logical signal levels and lower signal distortion. As the FSO distance increases, the eye opening gradually decreases because the increased propagation loss reduces the received signal power. This behavior is consistent with the reduction in Q-factor from 43.7 at 0.5 km to 43.0 at 2 km. Nevertheless, the eye remains clearly open at the investigated distances, indicating that the FSO protection path maintains distinguishable signal levels under the simulated conditions, although the available signal margin decreases with increasing transmission distance.

The use of DW-ZCC coding also contributes to the observed signal quality by providing zero cross-correlation between distinct user codes and the required autocorrelation for the intended code. Consequently, the encoded users can be separated at the receiver with reduced multiple-access interference (MAI). The resulting reduction in MAI supports the maintenance of a relatively high Q-factor under the investigated FSO transmission conditions. However, the present results should be interpreted as evidence of the combined performance of the DW-ZCC coding and hybrid optical architecture rather than as an isolated quantitative comparison between DW-ZCC and alternative OCDMA codes, since such a comparative experiment was not conducted in this study.

Figure 6 shows connection availability of the conventional and proposed networks that is performed as per system parameters in Table 4. It can be observed that the proposed architecture provides the required connection availability of 5 nines in comparison to the conventional architecture whose availability is 0.999954. This can be attributed to the fact that the proposed architecture utilizes a parallel combination of optical and FSO paths at the ODN level which significantly elevates the overall connection availability by mitigating connection outages due to fiber cuts or failures.

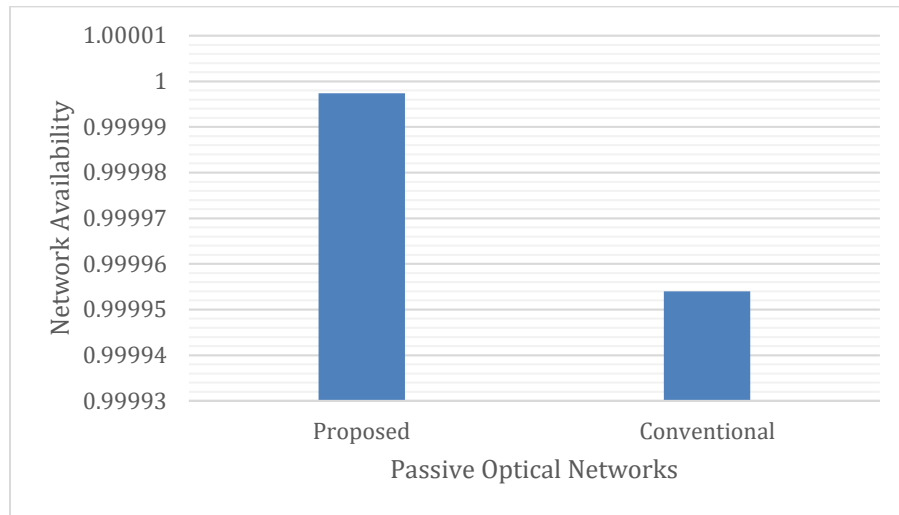


Figure 6: Connection Availability Comparison of the Conventional and Proposed Architectures

5. Conclusion

The exponential growth in Internet traffic demands innovative optical communication solutions that can provide high transmission capacity and reliable connectivity for next-generation wireless communication systems. To address these requirements, this paper proposes a DW-ZCC code-based hybrid PON architecture integrating fiber and FSO links with optical switching for protected communication. OptiSystem-based simulations demonstrate the communication performance of the proposed architecture under the investigated system parameters and FSO transmission distances. The Q-factor remains above 43 for FSO link lengths ranging from 0.5 km to 2 km, while the received power decreases with increasing FSO distance, demonstrating the trade-off between transmission distance and signal quality. The DW-ZCC coding provides a basis for high-capacity multi-user transmission, while the hybrid fiber/FSO configuration provides an alternative communication path in the event of primary fiber-path failure. Furthermore, the availability analysis indicates five-nines connection availability for the proposed architecture, compared with 0.999954 for the conventional architecture. These results demonstrate the potential of the proposed integrated architecture to provide high-capacity transmission with improved resilience for 5G optical access networks.

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Conflicts of Interest: The author declares no conflicts of interest regarding this study.

Data Availability: The data generated and analyzed during this study are available within the article. The simulation parameters, performance results, and reliability analysis presented in the paper provide the basis for reproducing the reported findings.

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