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Design of A Chaos-based Digital Radio over Fiber Transmission Link using ASK Modulation for Wireless Communication Systems

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Abstract

Secured broadband radio communications are becoming increasingly pivotal for high-speed connectivity in radio access networks, playing a crucial role in both mobile information systems and wireless IoT connections. This paper introduces a chaos-based two-channel digital radio communication system utilizing fiber optic radio transmission technology. The system comprises two radio channels operating at up to 1 Gbps using amplitude shift keying (ASK) modulation, followed by modulation with a chaotic sequence before conversion to the optical domain using the MZM modulator. To compensate for fiber loss, the system utilizes an Erbium-Doped Fiber Amplifier (EDFA) and employs the optical links through standard ITU-G.655 optical fibers. Numerical simulation of the designed system is performed using the commercialized simulation software Optisystem V.15 to assess and characterize transmission performance. The results demonstrate the system's effective operation on two channels with a fiber transmission distance of up to 110 km, maintaining a bit error ratio of less than 10^{-9}. This feature ensures reliable performance for high-speed radio connections, particularly in applications such as fronthaul networks in cloud radio access and wireless sensor network connections.

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1. Introduction

Radio over fiber (RoF) has been becoming a very favored technology for broadband communication systems where light is modulated with radio frequency signals and transmitted over the optical fiber to facilitate wireless access and transmission [1]-[4]. The merge of wired and wireless networks on an optical platform is a promising solution for rapid bandwidth growth demands in current communication systems, such as next-generation mobile communication systems or broadband wireless Internet of Things connection networks, due to its broad bandwidth and low attenuation characteristics [5]-[6]. The RoF system enables the modulated radio frequency (RF) signals to be deployed on an optical link to provide many wireless communication applications. For example, RoF is used to construct a transmission platform for the fronthaul subsystem of cloud-radio access networks, as illustrated in Figure 1, where RF signals can be connected between a baseband unit (BBU) with remote radio heads (RRHs) or a central unit with a base station (BS) [7]. The main requirements of a RoF link architecture are duplex operation (downlink-uplink), reasonable length, and high-performance optical components. RoF systems have enhanced cellular coverage, lower attenuation losses, higher bit-rate, broader bandwidth, and immunity to radio frequency interference [8].

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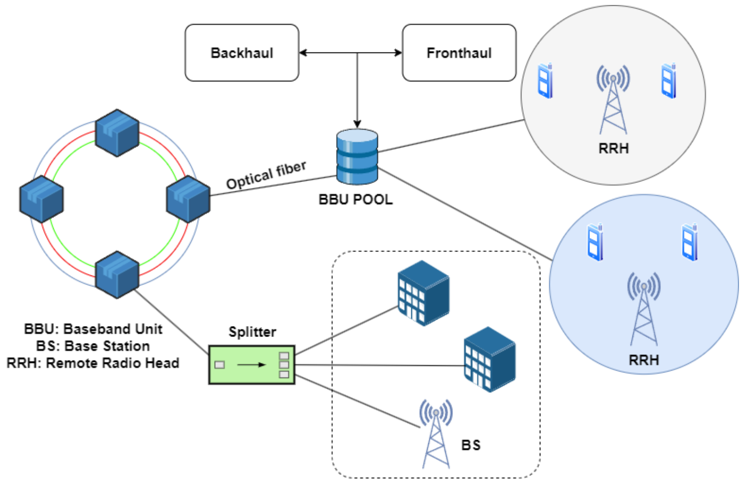

Figure 1. A radio over fiber model for the fronthaul subsystem of a wireless communication system

The access network is the final node in the telecommunications network that communicates with people in delivering services to the end user, and it is an essential part of the network. At present, the access network is constantly developing with many different types such as copper cable access networks, fiber optic access networks, and radio access networks. Each type of network has its characteristics. However, wireless access networks are getting the most attention and growing rapidly, such as 3G, 4G, and 5G mobile communication networks, wireless LAN for connections; WiFi, and WiMax wireless access networks in homes. This is because of the outstanding advantages of wireless technology and its high mobility characteristics that wired access technologies cannot achieve. Radio communication has become an indispensable part of today's telecommunications network. On the other hand, with the development of broadband access networks, near radio access networks began to encounter disadvantages such as low speed and narrow coverage area. The continued proliferation of mobile and wireless devices coupled with the demand for broadband services has put pressure on increasing the capacity of wireless systems. Therefore, more and more technologies and techniques are being researched and developed to overcome this drawback, providing users with a secured high-speed access network [9]-[10].

Recognizing that the outstanding advantage of the optical communication system is to provide high speed and stability, the technique of transmitting radio waves over optical fibers is focused on research. Radio over Fiber (RoF) technology is expected to play an important role in current and future access networks as it provides end users with high-access true broadband network service while ensuring the increasing mobility requirements of access [11]. To improve capacity, speed, and the ability to transmit over long distances, the use of modulation methods is necessary. There are three different modulation methods: analog modulation, pulse modulation, and digital modulation. In the radio part, because of its simplicity in design as well as in implementation, digital amplitude shift keying modulation (ASK) is widely used in communication systems. ASK signals are oscillating waveforms at a dedicated frequency, and each bit is characterized by a different amplitude of the signal. Moreover, amplitude modulation also helps increase speed by incorporating quadrature multilevel schemes. For example, 4-QAM modulation increases the speed by 2 times compared to without modulation. Although the higher the modulation level, the higher the speed, the bit error rate also increases because the closer the levels are together, the better the reception of the signal is increasingly difficult. Therefore, depending on the purpose of use, the designer can choose a modulation level suitable for the information system. In the field of communications, the necessity for high security is paramount, particularly in military information systems and banking transactions. Developers in information security have devised numerous encryption methods, including DES, 3DES, AES, etc. However, these methods are progressively being compromised by the development of typical lock-breaking algorithms such as brute force algorithms [12].

Recently, chaotic signals and systems have been gaining widespread usage in digital information systems due to their security advantages. Chaotic sequences in radio communications can enhance information security owing to their unpredictable nature. In chaotic signals, large bandwidths can be generated across any frequency range. The power

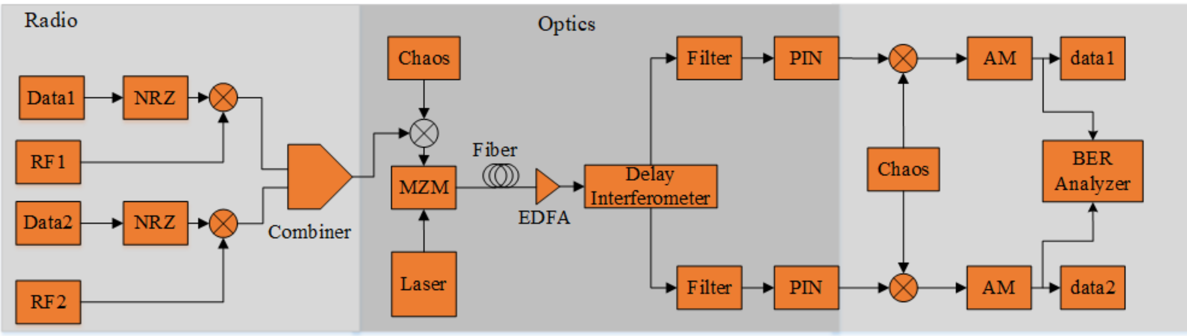

Figure 2. The proposed model for two-channel chaos-secured RoF transmission system

spectral density has a low magnitude because the signal power is dispersed over a broad frequency band. The direct chaotic communication (DCC) method is implemented when transmitted digital information is directly mapped onto a continuously changing broadband chaotic carrier [13]. Numerous works on coherent and non-coherent modulation based on chaos have been researched and published. Chaos engineering is applied in many studies related to cognitive radio communications, broadband radio, security in wireless and optical communication systems, and IoT systems [14]-[19]. However, implementing coherent receivers is challenging because the basis function cannot be reproduced identically at the receiver end unless the initial conditions of the chaotic signal generator used at the transmitter are provided [20]. Therefore, using chaos to enhance security and ensure information performance strongly depends on the knowledge and implementation of creators. Nevertheless, chaotic systems remain a significant approach to improving communication security. Employing the chaos function makes it nearly impossible for eavesdroppers to steal information because only a legitimate recipient with the decryption chaos function can recover the information [21]. The receiver parameters are well-matched with the transmitter parameters to achieve chaotic synchronization [22]. The message is decoded by subtracting the chaos signal synchronized with the transmitter from the incoming signal. Eavesdroppers cannot decode messages without understanding the structure and parameters of the transmitter because they only receive random signals from the channel. Optical turbulence produces lasers of larger size and wider bandwidth. However, generating optical chaos is difficult and expensive, as it requires high-speed optical circuitry to match today's high-speed systems. Therefore, electrical chaos is a superior solution, easy to create chaos laws, and easy to integrate into electronic circuits. In this paper, we present a model of a wireless information system transmitted via optical fiber. The proposed system is intended for two wireless channels modulated with the ASK modulation scheme and then mixed with a chaotic sequence to enhance the security of the transmission channel before converting to the optical domain for fiber transmission. Numerical simulation and performance analysis demonstrate that the system satisfies all quality requirements for a secure wideband chaotic wireless information connection, given appropriate design parameters and suitable dispersion compensation solutions.

2. Model description of the proposed communication system

The diagram proposal for the RoF transmission system is schematically shown in Figure 2. Information data from two independently different sources are encoded in the form of the non-return to zero format (NRZ) to create a spectrum of the digital signal that is more suitable for the digital transmission channel. Besides, a channel carrying the chaotic synchronization signal is dedicated to another channel for detection and recovery processes at the receiver side. From two independent channels at the transmitter side, the signals of the two sources are ASK amplitude modulated to the radio frequencies f_1 and f_2. The signals of the two radio channels are combined before being multiplied by the chaotic signal generated from the mixer. The chaotic sequence rule is followed by a logistic map diagram, which is a sequence of numbers followed by the recurrence rules as [23]:

$$x_{n+1} = a.x_n(1 - x_n) \quad (1)$$

where n==1,2,3... is a positive integer. If the driving coefficient $a = 3.9$ the system will fall into chaos. Then, the output value wildly varies between 0 and 1. The chaos function has the form of probability distribution density as follows:

$$p(x) = \frac{1}{\Pi\sqrt{x(1-x)}} \text{with} 0 < x < 1 \quad (2)$$

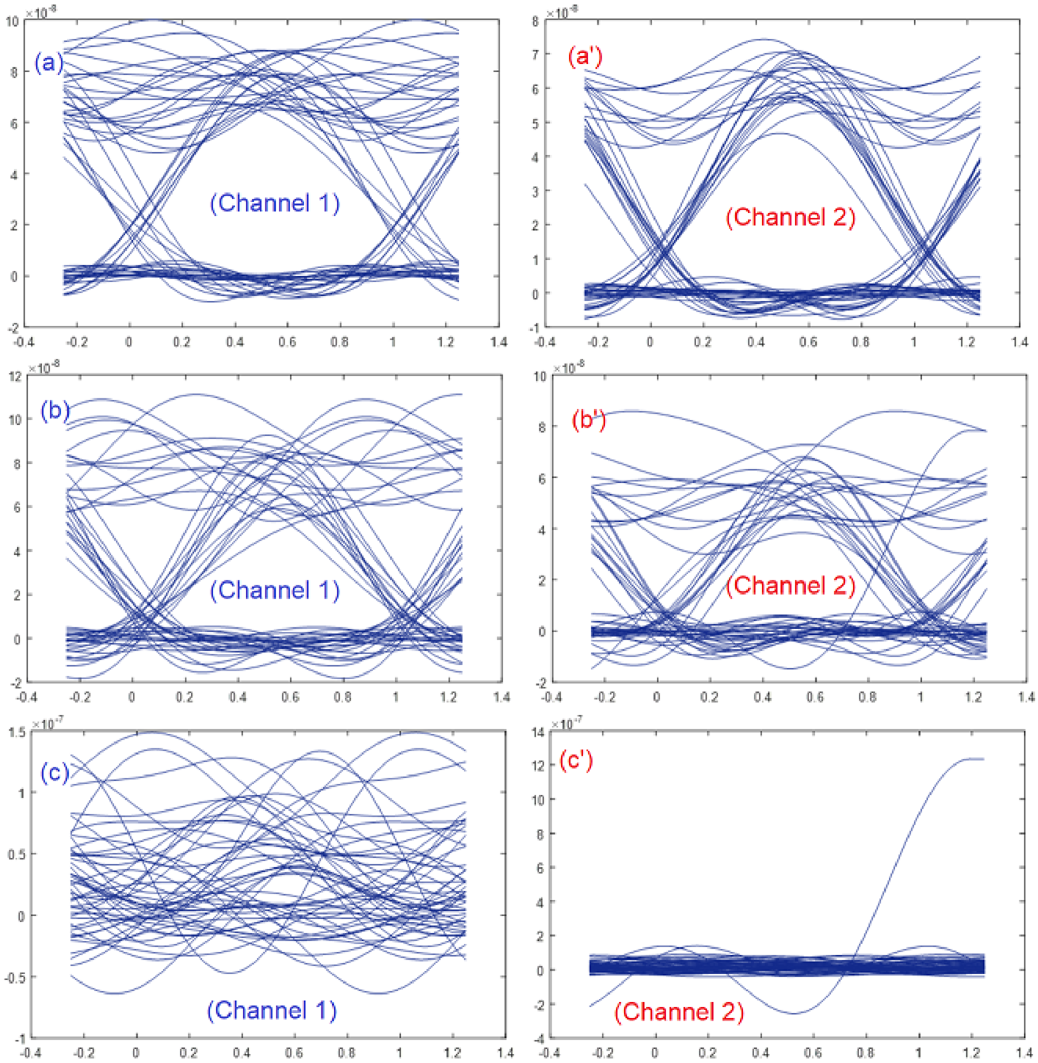

Figure 3. Eye diagrams for two radio frequency channels (channel 1 denoted by the blue character, channel 2 denoted by the red character) at some transmission distances corresponding to 70km (a, a'), 120km (b,b'), and 170km (c,c')

Next, the signals are passed through the NZ-DSF fiber after passed to the optical domain by external modulation using the MZM modulator. To compensate for the loss caused when information is transmitted through the optical fiber, we use an erbium-doped fiber amplifier (EDFA - erbium-doped fiber amplifier) with a gain factor G (as shown in Table 1) for fiber loss compensation is calculated by the formula as follows:

$$G = L.\alpha(\text{dB}) \tag{3}$$

where α is the fiber loss factor NZ-DSF, and L is the total non-zero dispersion-shifted fiber path length NZ-DSF. When reaching the receiver side, separate the two radio channels using a delay interferometer with a time delay of as much as a bit to separate a combined channel to become two individually independent channels. All required parameters for this communication system are listed in Table 1. After that, the signals are divided into two paths corresponding to the two radio channels and filtered with a bandpass filter. The signals are directly detected by using a PIN photodetector for converting the optical signals to the electric signals. Next, the electric signals are demodulated at radio frequencies. Finally, two information channels are restored and characterized for the performance analysis process.

3. Numerical simulation results and performance characterizations

The waveform of the chaotic carriers can be changed through the fiber transmission link under the influence of the transmission environment. Therefore, the chaotic synchronization issue between the transmitter and the

Table 1. System Parameters

Parameters	Value
Bit Rate R_b	1 Gbps
Frequency	193.1 THz
Power	0 dBm
Length L	100 km
Attenuation α	0.2 dB/km
Dispersion D	17 ps/nm/km
Gain G	20 dB
Radio frequency f_1	10 GHz
Radio frequency f_2	15 GHz

receiver needs to be considered. On the transmitter side, both radio channels are multiplied by the chaotic signal for transmission. On the receiver side, the received signals are once again multiplied by the chaotic signals to get the original information. In this study, we assume that synchronization information between the transmitter and receiver sides is dedicated to an individual channel so that the receiver can understand the generation rule of chaotic sequence for the detection process. The proposed communication system model manipulates the amplitude shift keying modulation scheme (ASK). In this investigation, the numerical simulation process and performance characteristics are based on the commercial software Optisystem V.15 for optical communication systems and the source code of the chaotic signal from the Matlab simulation tool.

Firstly, the proposed chaos-secured RoF system operates at a central frequency of 193.1 THz, corresponding to the laser's operation wavelength of as much as 1550.52 nm. Figure 3 shows the eye diagram at the receiver side of the two radio channels of the system at transmission distances of 70 km, 120 km, and 170 km, respectively. Eye-opening qualitatively represents the bit error rate; the wider the eye, the lower the bit error rate, and vice versa. Therefore, at a distance of less than 120 km, the eyes are wide open, proving that the system can distinguish bit 0 and bit 1 relatively well. At a distance of 170 km, the eyes of two radio channels are almost absent; bit 1 and bit 0 are interleaved, resulting in indistinguishable identifiable data. The bit error rate is almost equal to 1, for instance, thus leading to the system error completely. In addition to the qualitative assessment through the eye diagram, the parameter BER bit error rate, which is an important measurement characterizing the impact on the quality and performance of the constructed communication system, On the aspect of communication, BER in the proposed system is theoretically calculated as follows:

$$\mathrm{BER} = P_e = \frac{M}{N+M}P_{e0} + \frac{N}{N+M}P_{e1} \tag{4}$$

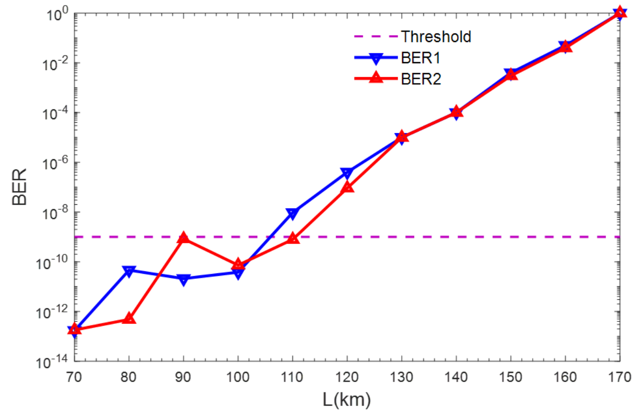

Figure 4. BER as a function of the transmission distance L

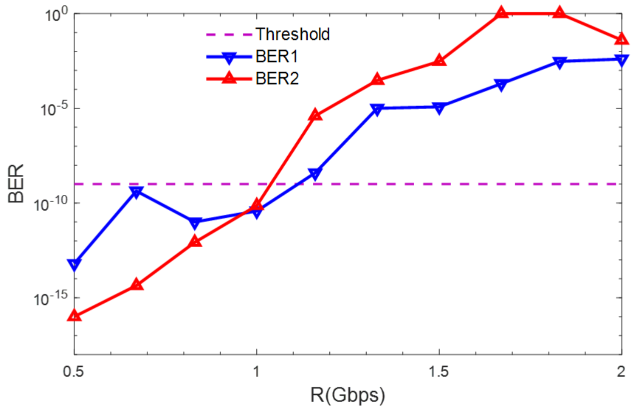

Figure 5. BER as a function of the transmission bit rate R

where P_{e0} and P_{e1} are the error probability of symbols 0 and 1, respectively, and they are calculated as formula (4); M is the number of samples for a logic level of 0, and N is the number of samples for a logic level of 1.

$$P_{e0} = \frac{1}{2}erfc\left(\frac{S-\mu_0}{\sqrt{2}\sigma_0}\right); P_{e1} = \frac{1}{2}erfc\left(\frac{\mu_1 - S}{\sqrt{2}\sigma_1}\right) \tag{5}$$

where μ_0, μ_1 are the mean and σ_0, σ_1 are the standard deviation of 0 and 1 bits, respectively, and S is the threshold value.

Environmental transmission elements always have a significant impact on communication systems. For instance, fiber nonlinearities, modal polarization dispersion in the fiber, and monochromatic dispersion will all have an impact on an optical transmission system. In addition, one crucial consideration when configuring an information system is how the system will respond when the pace of the signal transmission rises since this will impact the system's power margin and guarantee BER quality. Firstly, Figure 4 evaluates the BER according to the fiber distance of the two radio channels when the distance is less than 110 km, the system works well with BER<10^{-9} assuring the required BER level for the high-quality optical fiber transmission system. The best system is at a distance of 70 km and the bit error rates of radio channels 1 and 2 are 1.7×10^{-13} and 1.8×10^{-13}, respectively. This is clear because the transmission distance is small, the gain of the EDFA amplifier always preserves at the full compensation level for the fiber loss of 100 km, thus leading to a redundant margin. At a distance of 100 km, the BER of radio channels 1 and 2 is 3.8×10^{-11} and 7.3×10^{-11}, respectively. When the transmission distance exceeds 110 km, the system does not preserve the quality standard required for an optical fiber transmission link due to high fiber loss, especially when the distance is up to 170 km, the bit error rate is 1, which shows that the system is completely faulty. Secondly, Figure 5 shows the influence of BER according to the data rate of the communication channel. It can be seen from Figure 5 that when the speed is below 1 Gbps, the system guarantees a significant quality of BER less than for both channels; however, if the speed is greater than 1.5 Gbps, both two channels will have a very poor BER quality. In addition, it is seen that, when the bitrate is smaller than 1 Gbps, the BER level of channel 1 associated with the lower radio frequency of 10 GHz is worse than the BER level of channel 2 associated with the higher radio frequency of 15 GHz. On the contrary, when the bitrate is larger than 15 GHz. Generally, for digital communication modulated by the ASK modulation technique, the higher radio frequency is more effective than the lower radio frequency in the chaos-modulated RoF system. Next, not only do transmission distance and data rate impact the performance of communication systems, but the dispersion parameter also affects the quality of BER performance in an optical fiber communication system. Dispersion is the reason that causes the optical pulse to broaden when propagating through the optical fiber environment, especially at high bit-stream rates. Figure 6 shows the functional dependence of the bit error rate on the dispersion coefficient. As we can see, dispersion strongly fluctuates to affect the BER quality of ASK-modulated channels mixed with a chaotic sequence after propagating through the optical fiber environment with an unpredictably irregular pattern. However, at D=16.75 (ps/nm/km), the system exhibits its best performance by fully compensating for dispersion, corresponding to BER levels of 3.8×10^{-11} and 7.3×10^{-11} for channel 1 and channel 2, respectively. As a result, the proposed communication model needs to compensate for dispersion to avoid its negative impact. Finally, we consider the important parameter influencing the transmission quality is the optical signal-to-noise ratio (OSNR). Figure 7 shows the dependence of BER on OSNR as a function. It is seen that, the larger the OSNR, the smaller the port BER, the better the system quality. When OSNR is more than

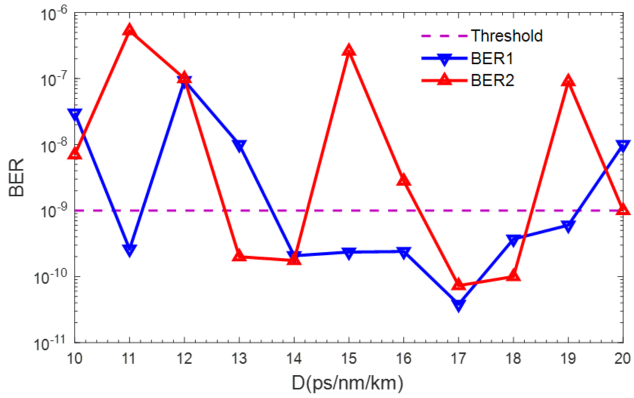

Figure 6. BER as a function of the dispersion coefficient D

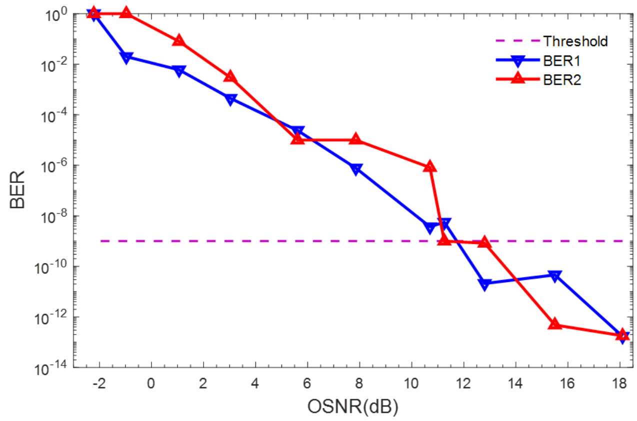

Figure 7. BER as a function of the OSNR

12dB, the system quality is satisfied in an acceptable criterion of BER as much as 10^{-9}.

4. Conclusion

In conclusion, this study has designed and numerically simulated a two-channel chaos-secured radio-over-fiber transmission system employing the ASK modulation technique. Utilizing the Optisystem V.15 software tool, the simulations demonstrated significant improvements in communication performance, meeting quality requirements for high-speed wireless communication at a rate of 1 Gbps and a long-haul transmission link of 100 km. The numerical simulations also provided valuable insights into the dependence of bit error rate (BER) on various parameters, including bitrate, transmission distance, dispersion coefficient, and optical signal-to-noise ratio (OSNR). Notably, the survey results indicated that to maintain a BER under a specified level of as much as 10^{-9}, the transmission distance should not exceed 110 km when operating at a high bitrate of up to 1 Gbps. Furthermore, the study highlighted the importance of dedicated synchronization and effective fiber loss compensation in ensuring the security of the communication system through chaotic modulation. This insight facilitates the seamless connection of broadband and high-speed radio channels transmitted over optical fibers, meeting the demands for secure high-speed radio transmission, particularly in fronthaul subsystems of the C-RAN network. In essence, this research contributes to the advancement of secure and efficient optical communication systems for high-speed wireless applications.

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