Terabit Optical Wireless-Fiber Communication with Kramer-Kronig Receiver (Part II)

Iman Tavakkolnia, *Member, IEEE,* Cheng Chen, Yinzhou Tan, and Harald Haas, *Fellow, IEEE.*

(Invited Paper)

***Abstract*—A high speed optical wireless-fiber solution was proposed in part I of this research with applications such as network backhaul and data center links. The proposed system is based on the utilization of state-of-the-art modulation and multiplexing techniques in optical fiber and optical wireless communications, including multicore fibers (MCFs) and coherent detection based on Kramer-Kronig (KK) receivers. In this paper, we analyze the performance of the proposed system and compare it with an intensity modulation and direct detection (IM/DD) system. Superior performance of the KK receiver is shown for various modulation formats and optical amplification schemes. We also consider the eye-safety constraint for the optical power as a practical design factor. It is demonstrated that the position of optical amplifiers affects the multiplexing gain and achievable data rate when eye-safety constraint is imposed. Further important challenges for the practical deployment of the system are discussed.**

***Index Terms*—Optical wireless communication, Optical fiber communication, Multicore fibre, Kramer-Kronig, data center, eye safety.**

I. Introduction

The global Internet connection is based on an immeasurable network of high speed point-to-point connections. In order to continuously improve the user experience, along with the ever-increasing number of connected devices and services, the core network must also evolve to support growing demands. High speed optical wireless communication is a solution that can be used in applications where scalability and reconfigurability are desired, such as data centers and back-haul point-to-point links. Reduced physical footprints of communication systems is another benefit of optical wireless communication. The proposed link in part I combined optical fiber and wireless techniques and provided a system structure that can be adopted for high speed point-to-point data transmission.

The proposed fiber-wireless link is based on coherent optical communication. Due to recent advances in signal processing techniques, Kramer-Kronig (KK) receivers have become popular. They can replace conventional local oscillator-based coherent receivers and achieve high data rates while having comparable physical footprint and component cost to direct detection (DD) receivers [1]. The signal-signal beat interference, originated from the direct detection receiver nonlinearity, is effectively mitigated when the KK scheme is utilized. The other feature of the proposed architecture is the integration of mulicore fibers (MCFs) and an optical lens system, which enables spatial division multiplexing in both fiber and wireless links. All noise sources and the signal-to-noise ratio (SNR) were analyzed, and a tera-bit-per-second achievable data rate was estimated in part I [2].

In the second part of this work, we first review an intensity modulation and direct detection (IM/DD) system that uses the same components as the proposed link architecture in part I. Direct-current orthogonal frequency division multiplexing (DC-OFDM) is selected because of its simplicity and a potential wide deployment in the optical wireless communication standards [3]. Moreover, frequency domain modulation makes it possible to mitigate effects of the chromatic dispersion of the optical fiber and the low-pass frequency response of the optical wireless channel. The bit-error ratios (BERs) of the two systems are compared, and a better performance of the KK receiver is observed for various modulation depths and optical amplification scenarios.

This paper also investigates the eye safety constraint. Coherent optical communication is based on the modulation of light from a laser source. Also for the IM/DD case, laser is the only possible light source because of its compatibility with high bandwidth external modulators. As a consequence, the safety of people working around these systems is an important design factor. This is subject to existing standards for fiber and wireless systems [4]. The optical power that reaches the eyes and skin is limited to a level that cannot cause any health concerns. Therefore, a power constraint for the most hazardous points should be considered which effectively is translated to a power constraint for the system. In this paper, potential most hazardous points of the optical link are identified, and the maximum input power is determined for two possible amplification scenarios. Then, achievable data rates are calculated according to the corresponding optical power constraints. The results show that only the optical amplification at the receiver side guarantees tera-bit-per-second data rates when eye safety is considered. By optical amplification at the receiver, independent parallel channels in the space and wavelength domains are fully realized, and the multiplexing gains in both domains are utilized effectively.

A few challenges are discussed which need to be addressed for practical deployment of the proposed link. For instance, long-term reliability is critical for the data center application. Therefore, wireless optical alignment as well as the temperature sensitivity of the system are of vital importance. Moreover, reconfigurable routing and high speed switching within a data center requires accurate design and novel techniques and

Authors are with the LiFi Research & Development Centre, Department of Electronic & Electrical Engineering, The University of Strathclyde, Glasgow, UK. e-mail: { i.tavakkolnia, c.chen, yinzhou.tan, harald.haas}@strath.ac.uk.
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components such as co-packaged optical interfaces [5] and semiconductor optical amplifier-based wavelength selectors [6]. Some of the challenges and a number of directions for further research are discussed at the end of this paper.

The rest of the paper is structured as follows: In section II, the IM/DD system model is presented, and compared with the KK-based detection. The impact of the eye-safety constraint and the corresponding achievable data rates are discussed in section III, followed by a review of potential challenges and conclusions of the paper in sections IV and V.

II. Comparison between IM/DD and KK

In this section, the proposed coherent system is compared with an IM/DD system. While KK detection is used for the coherent system, DC-OFDM is selected for the IM/DD because of its simplicity and the possibility of using a quadrature amplitude modulation (QAM) format similar to the KK scheme. Key differences are highlighted including available modulation bandwidth and receiver sensitivity.

A. Intensity modulation

By intensity modulation, the information-carrying signal is modulated on the intensity of the optical wave, and consequently, negative and imaginary samples cannot be realized in the time domain. Although the data samples are complex in the frequency domain (*i.e.*, QAM modulated), the time domain signal should be modified to comply with the aforementioned physical constraint. Therefore, Hermitian symmetry is imposed on the OFDM frame in the frequency domain which guarantees a real signal in the time domain. The signal is then biased and the remaining negative values are clipped to zero to ensure a positive time domain signal. The same block diagram presented in part I of the paper [2, Fig. 1] can be considered where the Mach-Zehnder modulator (MZM) unit is used as an intensity modulator. However, assuming a fixed bandwidth of the electrical units, *e.g.*, digital-to-analog converter (DAC) and MZM, the usable modulation bandwidth is halved in comparison to coherent transmission due to the Hermitian symmetry of the input frame.

The biased signal is expressed as $x(t) = x_{\mathrm{DC}} + s(t)$, where $s(t)$ is a baseband signal with power P_{s}, and x_{DC} is the DC bias. The unbiased OFDM signal follows a zero mean real Gaussian distribution for a sufficiently large number of subcarriers [7]. Therefore, usually a bias of $x_{\mathrm{DC}} = 3P_{\mathrm{s}}$ is used which guarantees that 99.7 % of the signal is above zero, and therefore, the resulting distortion, which is caused by clipping the negative samples to zero, is negligible. As a result, the modulated optical field envelope after amplification and at the input of the corresponding core of the MCF is expressed as

$$y(t) = \sqrt{G_1 \alpha_{\mathrm{Tx}}} x(t) + n_{\mathrm{ASE}}^{(1)}(t), \tag{1}$$

where G_1 is the amplifier power gain and all power losses at the transmitter are included in the parameter α_{Tx}. The amplified spontaneous emission (ASE) noise, added by the amplifier, is shown by $n_{\mathrm{ASE}}^{(1)}(t)$. As seen in part I of this work, the impact of the inter-core crosstalk and the relative intensity noise (RIN) are negligible for short fiber length scenarios. Therefore, we discard these terms for simplicity.

The optical signal is transmitted through the channel including the MCF, optical lens systems, and the wireless link. The loss term α_{l} accounts for losses in the fiber, wireless link, fiber-space coupling, and optical alignment. At the receiver side, another optical amplifier, with a G_2 power gain, can be used to amplify the signal to the required level. Therefore, the received signal can be described as

$$\begin{aligned} \hat{I}(t) &= R\alpha_{\mathrm{Rx}} |\sqrt{G_2 \alpha_{\mathrm{l}}} y(t) + n_{\mathrm{ASE}}^{(2)}(t)|^2 \\ &= R\alpha_{\mathrm{Rx}} |\sqrt{G_2 G_1 \alpha_{\mathrm{Tx}} \alpha_{\mathrm{l}}} x(t) + \sqrt{G_2 \alpha_{\mathrm{l}}} n_{\mathrm{ASE}}^{(1)}(t) + n_{\mathrm{ASE}}^{(2)}(t)|^2 \end{aligned} \tag{2}$$

where α_{Rx} accounts for all the optical losses at the receiver side and R is the photodiode (PD) responsivity.

In an intensity modulation system, the dominant noise sources are thermal and shot noises and the contribution from the amplifier noise. In (2), the beating of spontaneous emission with the signal produces a noise current of

$$\Delta I = 2R\alpha_{\mathrm{Rx}} \sqrt{G_2 G_1 \alpha_{\mathrm{Tx}} \alpha_{\mathrm{l}}} |E_x||E_n| cos\theta_{\mathrm{P}}, \tag{3}$$

where $|E_x|$ and $|E_n|$ are respectively the envelope of the signal and noise optical fields oscillating at different frequencies with a random phase difference [8]. θ_{P} is a rapidly varying random phase which will be canceled out by averaging. Therefore, the effective noise photocurrent variance, which originated from the mixing of the spontaneously emitted radiation and the amplified signal is given as $4H\bar{P}R\alpha_{\mathrm{Rx}}S_{\mathrm{ASE}}B_{\mathrm{IM}}$ for the average power of $\bar{P} = x_{\mathrm{DC}} = 3P_{\mathrm{s}}$ and the total link gain $H = RG^2\alpha_{\mathrm{Tx}}\alpha_{\mathrm{l}}\alpha_{\mathrm{Rx}}$, where the equivalent noise power spectral density is expressed as

$$S_{\mathrm{ASE}} = [(G_2 - 1) + G_2 \alpha_o (G_1 - 1)] n_{\mathrm{sp}} h\nu. \tag{4}$$

The effective bandwidth of the system is B_{IM}, h is the Planck constant, ν is the frequency (photon energy $h\nu$), and n_{sp} is the spontaneous emission factor. The SNR is therefore derived as

$$\mathrm{SNR} = \frac{H^2 P_{\mathrm{s}}^2}{(N_0 + 2qH\bar{P} + 4H\bar{P}R\alpha_{\mathrm{Rx}}S_{\mathrm{ASE}})B_{\mathrm{IM}}}, \tag{5}$$

where N_0 is the thermal noise power spectral density.

B. Coherent modulation

The SNR for the coherent system based on the KK receiver is derived in part I of the paper [2]. In the following simulation results, we remove the negligible terms of RIN noise and inter-core crosstalk. Other receiver noises are included in the analysis, but it is worth recalling that the main contributing noises are the phase noise and phase-to-amplitude noise in addition to thermal noise, shot noise, and ASE noise which exist for IM/DD as well [2]. The critical point in the following analysis is that the available modulation bandwidth for the coherent system is twice the available bandwidth of the direct detection. This adds extra noise to the link, but the eventual sensitivity and achievable SNR is still expected to be higher compared to the direct detection.

C. Bit error ratio (BER)

We consider a QAM modulation format for both IM/DD and KK systems. A tight approximation of the BER for an M-ary square QAM constellation in an AWGN channel is derived in [9]. It has been shown in many simulation and experimental analysis that this is a reliable performance indicator. As a result, we use the analytical expression for the BER performance of a Gray-coded M-QAM system as [9]

$$\mathrm{BER} = \frac{4(\sqrt{M}-1)}{\sqrt{M}\log_2 M} Q\left(\sqrt{\frac{3}{M-1}\mathrm{SNR}}\right) + \frac{4(\sqrt{M}-2)}{\sqrt{M}\log_2 M} Q\left(3\sqrt{\frac{3}{M-1}\mathrm{SNR}}\right), \quad (6)$$

where $Q(u) = \int_u^\infty \exp(-v^2/2)/\sqrt{2\pi}dv$ is the Guassian Q-funtion.

D. Simulation results

The receiver sensitivity has been used as a performance indicator for conventional systems, defined as the minimum received optical power necessary to achieve a target BER. This was a valuable indicator for systems with no amplifications. However, multiplexing and switching components are lossy, and therefore, amplification is necessary for the state-of-the-art systems with high data rates, usually using an Erbium-doped fiber amplifier (EDFA). Our proposed system also fits in the latter category. Therefore, in order to quantify the system performance, SNR and BER are studied, respectively for different values of link loss and transmitted power, instead of the receiver sensitivity.

The system parameters are the same as in part I of the paper [2, Table I]. The achievable SNR values are depicted in Fig. 1. The optical signal power is fixed at $P_s = -10$ dBm. The carrier-to-signal power ration (CSPR) is 10 dB for the KK system. It can be observed that higher SNR values are achieved using the KK system, when an amplifier is used on either the transmitter side or the receiver side. For both IM/DD and KK systems, a very high link loss leads to the domination of thermal noise and consequently no difference between amplification at the transmitter or receiver.

The BER is calculated based on (6) for different modulation formats and $\alpha_l = 10$ dB for the IM/DD and KK system. The results are shown in Fig. 2. It is observed that KK requires approximately 6 dB smaller input optical power compared to the IM/DD system to achieve the same BER levels. Therefore, based on Figs. 1 and 2, it can be concluded that the proposed KK system can be a potential solution for future data centers due to better performance while requiring less power.

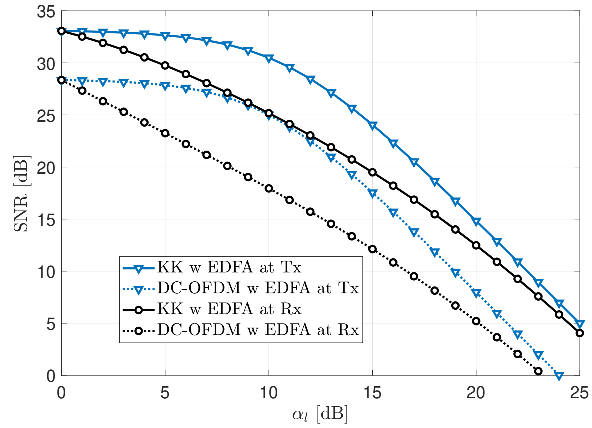

Fig. 1: The SNR values for IM/DD and KK systems for different values of link loss and optical amplification at the transmitter (Tx) or receiver (Rx) sides.

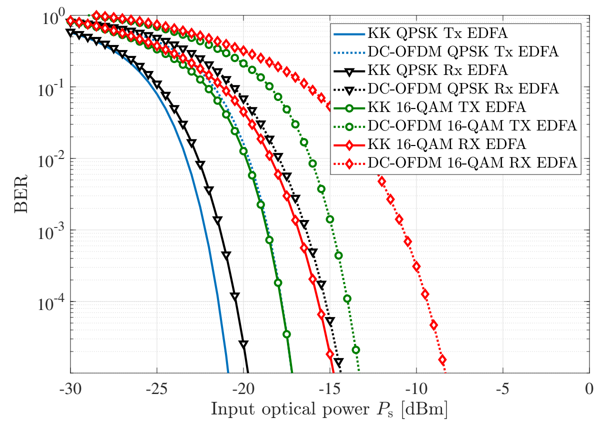

Fig. 2: The BER values for IM/DD and KK systems for different values of input signal power, modulation format, and optical amplification at the transmitter or receiver sides. Quadrature Phase Shift Keying (QPSK).

III. Eye-safety

The proposed system is based on using a laser that is the light source in fiber-based systems as well. Since the link is designed for a hybrid fiber-wireless environment, it is sometimes necessary to include the eye and skin-safety regulations in the design process when a total shielding is not possible. As a result, in a real-world scenario, such as data centers, the overall optical power will be limited to guarantee the safety of technician working closely with the system.

The damage that a laser light beam may cause depends on several factors. The wavelength of the incident light dictates which part of the body may be at a higher risk. For instance, in the visible range, the retina is most at risk because the light is focused on a very small spot on the retina through the eye lens. However, at the 1550 nm wavelength considered in this work, the eye-safety limit is generally not as strict as lower wavelengths, because most of the radiation is absorbed by the water on the cornea. Therefore, general skin-safety should be considered as opposed to the more strict limits due to retinal exposure. Moreover, the duration of the exposure as well as the area that is exposed determine the maximum permissible exposure (MPE), defined as the maximum irradiance level of the light that does not cause an injury to the body. The MPE values, reported in $\mathrm{W/m^2}$, are determined by standardization bodies such as the American national standards institute (ANSI) [10] and the international electrotechnical commission (IEC) [11] for various wavelengths and exposure durations.

In an optical system, the eye-safety condition is satisfied only if the irradiance level is lower than the MPE at all hazardous positions. Therefore, it is sufficient to limit the optical power at the most hazardous location of the optical link, where the optical irradiance is at its maximum value. This ensures safe levels of irradiance elsewhere in the optical link. The most hazardous position for eye or skin safety in 1550 nm is at the narrowest beam radius along the propagation direction of the beam, which is called beam waist. Based on our system design, three critical positions in the optical link may impose the maximum permissible power due to the eye-safety limit. The optical power should be smaller than the maximum allowed power according to the MPE at these points. Two locations are within the fiber link, at the output of the optical amplifier units at the transmitter and receiver at a beam waist radius equal to the core radius of the standard single mode fiber (SSMF). The third hazardous point is located within the wireless path, at the narrowest equivalent beam waist after the lens system at the transmitter side, where the optical power per unit area is at its highest due to the accumulation of beams from all cores of the MCF. Since the optical lens is placed at a distance equal to its focal length from the MCF aperture, the maximum hazardous point for the wireless link is at the focal length after the transmitter lens. At the receiver side, the beams are widened and separated in the free-space, and therefore, the output of the receiver amplifier is the only hazardous point. We assume that the space between the fiber and the lenses are shield at both transmitter and receiver (*e.g.*, similar to commercial free-space to fiber coupling systems).

The maximum possible transmit power for an ideal Gaussian beam for a small diameter is given as [12]

$$P_{\max} = \frac{1}{\eta}\pi r^2 \mathrm{MPE}, \tag{7}$$

where η is the coupling efficiency defined as the ratio of the emitted power to the power that passes through a measurement aperture with a radius of r. The coupling efficiency η can be expressed as

$$\eta = 1 - e^{\frac{-2r^2}{W^2(z)}}, \tag{8}$$

where $W(z)$ is the beam radius at a distance of z from the beam waist expressed as $W(z) = \omega_0\sqrt{1 + (z/z_0)^2}$, where $z_0 = \pi\omega_0^2/\lambda$ is the Rayleigh range for beam waist radius ω_0 and wavelength λ [13]. For wavelengths above 1400 nm and for exposure duration longer than 10 s (*i.e.*, most hazardous scenario) the MPE is equal to 1000 $\mathrm{W/m^2}$ [10]. Thus, based on (7), the maximum optical power for a SSMF, with $\omega_0 = 4$ μm, $\lambda = 1550$ nm, $z = 5$ cm, and $r = 1.75$ mm can be calculated as $P_{\max}^{\text{fiber}} = 64.7$ mW. For the wireless link hazardous point, it should be noted that beams from all cores focus on roughly the same position at the focal length of the lens, based on the thin lens assumption, and therefore, the total power from all cores together would be limited. The beam radius is 4.95 mm as calculated in part I of the paper. Thus, the maximum allowed power at the same location ($z = 0$) is $P_{\max}^{\text{wireless}} = 43.5$ mW, based on parameters and calculations mentioned earlier. Note that $P_{\max}^{\text{wireless}}$ is for all core and the maximum allowed power for each core is $P_{\max}^{\text{wireless}}/N_{\mathrm{c}}$. This means that the eye-safety constraint is stricter for the wireless link hazardous point. To understand the effect of the eye-safety constraint, simulations are performed for a number of scenarios.

Depending on the use of amplifiers at the transmitter or receiver, the maximum allowed power is determined by the minimum of admissible optical powers at the discussed hazardous points. A 16-QAM format and a 4-core MCF are assumed, and the rest of the parameters are the same as part I of the paper [2, Table I]. For each scenario, the required input power is calculated that results in a BER less than the forward error correction (FEC) threshold of 0.0046 for a single core and single wavelength [14]. Then, the number of allowed wavelengths, N_λ, which can be multiplexed with a total power less than the eye-safety limit, is derived. Finally, the total data rate is found when data streams are multiplexed in wavelength and spatial domains. The results are shown in Figs. 3 and 4.

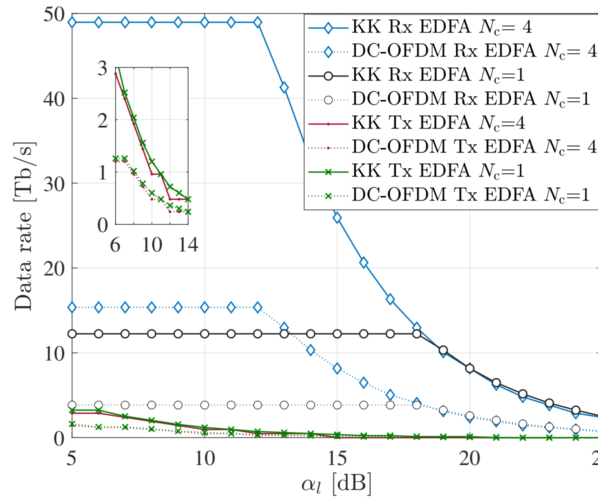

Fig. 3: The achievable data rate with a total power less than the eye-safety limit and the BER less than the FEC threshold using 16-QAM modulation format. Values for DC-OFDM and KK systems are presented for various link losses, fiber cores, and optical amplification at the transmitter or receiver sides.

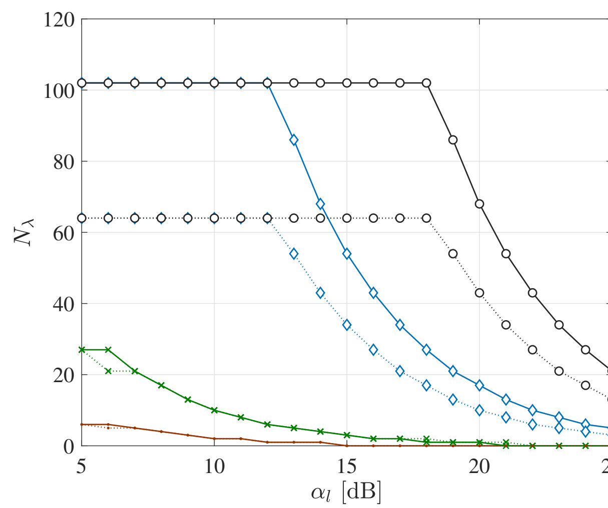

Fig. 4: The maximum number of wavelength channels, N_λ, with a total power less than the eye-safety limit and the BER less than the FEC threshold using 16-QAM modulation format. Values for DC-OFDM and KK systems are presented for various link losses, fiber cores, and optical amplification at the transmitter or receiver sides.

When the optical amplification is performed at the transmitter side, the wireless link hazardous point imposes the power limitation, which means that the total optical power from all cores and wavelengths are limited. Therefore, only a few wavelengths can be multiplexed. In other words, there is no meaningful difference between the spatial or wavelength domain channels, and single-core and 4-core fiber data rates are similar. On the other hand, when the amplifier is used at the receiver side, the receiver fiber hazardous point is the limiting point up to a certain link loss. After that, again the wireless link hazardous point limits the power. In either case, a larger number of wavelengths can be multiplexed, and effectively, parallel channels in space and wavelength are not bound to the same constraint. Therefore, around 100 and 60 wavelengths can be multiplexed, respectively for KK and DC-OFDM. Note that a system without spatial multiplexing (*i.e.*, single-core fiber) may require a different lens system, which results in a slightly different eye-safety constraint. However, we consider the same optics for the two detection methods to have a fair comparison highlighting the fundamental differences.

IV. Discussion and challenges

An optical wireless-fiber link was proposed in this research, and advantages of space division multiplexing and coherent communication were highlighted. However, several issues should be addressed for a complete deployment of the system in future communication networks. In this section, important challenges and next steps are discussed.

The higher data rate and lower required power of the proposed system compared to the IM/DD are gained by increasing the signal processing complexity. The KK detection requires a high digital signal processing (DSP) complexity and umpsamling to perform logarithm and square root computations [15]. The additional complexity is translated to higher cost and power consumption by the analog/digital converters and DSP units. Various techniques are introduced to reduce the complexity [16] . However, a rigorous power efficiency analysis is needed that accounts for both signal transmission power as well as processing power.

A high speed optical wireless system requires a high bandwidth photodetector, which have a very small detection area (*e.g.*, tens of micro-meters in diameter) or a fiber-coupled optical detector. Precise optical alignment is essential for these systems. Moreover, some kind of misalignment compensation is needed to mitigate effects such as building vibration in indoor scenarios. Various alignment systems can be used [17], [18]. However, a new technique is still needed for applications such as data centers, where reliability over time and no need for frequent calibrations is of the utmost importance.

The link architecture in this research is a general structure that can be modified for specific purposes in the network. For instance, the number of cores and wavelengths can be adjusted based on the location of the system, *e.g.*, top-of-rack (TOR) or spine switches. However, nanosecond optical switching is required for data center applications. The authors of [6], have proposed a semiconductor optical amplifier-based wavelength selectors for this purpose. Moreover, designing photonic-integrated circuits (PIC) as well as co-packaging of optical and electronic circuit for the proposed system would be beneficial by reducing the power consumption and component footprint [19]. A complete analysis and experimental validation is required for the complete system while considering issues such as temperature fluctuations and multi-core functionality of the components.

V. Conclusion

It is demonstrated that the optical wireless-fiber system with KK detection significantly outperforms its IM/DD counterpart. It is observed that the signal multiplexing gains, in space or wavelength domains, depend on the total admissible input power which is determined by the eye-safety constraint in this work. The total number of parallel channels may be limited according to the design of the link (*i.e.,* position of EDFAs) and the most hazardous points. We showed that parallel independent channels in the wavelength and spatial domains can be realized by a careful link design and, a tera-bit-per-second data rate can be achieved.

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