

Performance Evaluation of Radio-over-Fibre (RoF) System Using Mach-Zehnder Modulator (MZM) and On-Off Keying (OOK) Modulation Schemes

A. Bahrami, *Student member, IEEE*, T. Kanesan, W. P. Ng, *Senior member, IEEE*, Z. Ghassemlooy, *Senior member, IEEE*, A. Abd El Aziz, *Student member, IEEE*, S. Rajabhandari, *Member, IEEE*, *Optical Communications Research Group, NCRLab, Northumbria University, Newcastle upon Tyne, UK*
arash.bahrami@northumbria.ac.uk

Abstract— This paper investigates the bit error rate (BER) performance of a radio-over-fibre system utilizing binary phase shift keying (BPSK) at radio frequency (RF) of 5 GHz. The RF signal is externally modulated using the Mach-Zehnder modulator (MZM). The results have been obtained for RoF link over 8, 30, 60 90 and 120 km distance to study the effect of dispersion and attenuation on signal and compare the results with on-off keying (OOK) modulation. The paper proves the chromatic dispersion has no effect on MZM whereas it has distinct effect on OOK modulation scheme.

I. INTRODUCTION

Radio-over-fibre (RoF) refers to a technique where light is modulated by a radio signal and transmitted over an optical link to extend the wireless access. RoF system has been designed to improve the performance of radio system by providing higher bandwidth for mobile communications. These systems have several advantages including lower attenuation compared to the coaxial cable [1], higher bandwidth [2], immunity to the RF interference, and durability [3]. Among these advantages, lower signal attenuation and higher bandwidth which provides higher data rate are the most distinct characteristics of RoF systems compared to RF over coaxial cables. For instance a RG8 type coaxial cable has an attenuation of 10.6 dB at 5.80-5.85 Giga Hertz (GHz) which indicates the worst attenuation when higher frequency signal such as millimeter-wave (MMW) (> 40 GHz) applies in them [4]. It has been reported in [5] that an optical link which was set in the laboratory can deliver more than 12.5 Petabyte/s data rate for a distance of ~ 1 km (1 Petabyte = 10^{15} Bytes).

Modulation technique is one of the most significant processes in RoF system where the RF electrical signal is applied to modulate the optical carrier. RoF modulation methods can be categorized into two main groups: direct modulation and external modulation [6]. Direct modulation which is also known as intensity modulation, directly modulates the amplitude of the laser beam (OOK) [6]. On the other hand, in external modulation method devices such as MZM can be used to modulate the phase of the optical carrier. For

frequency range beyond 5 GHz which is used in worldwide interoperability for microwave access (WiMAX) and MMW, external modulation is preferred due to the fact that direct modulation is ideal for inexpensive transmitters, but it causes an undesirable wavelength chirp, which causes excessive chromatic dispersion at high speeds. In addition, lasers develop undesirable relaxation oscillations at frequencies of a few GHz. Therefore, external modulation is needed for higher speeds or when the light cannot be directly modulated [6].

In this paper the BER performance of a RoF system at a carrier frequency of 5 GHz with BPSK using MZM is investigated. The fibre channel used in this performance investigation will include chromatic dispersion and fibre attenuation over a distance of 8, 30 60 90 and 120 km of single mode fibre (SMF). The paper will compare the performance of the direct and external modulation techniques.

The rest of this paper is organized as follows. In section II we present the methodology and theoretical analysis. Section III, depicts the simulated results and discussion. Finally, section IV concludes the paper findings.

II. METHODOLOGY AND THEORETICAL ANALYSIS

A. Mach-Zehnder (MZ) Modulation and Methodology

MZM modulates the phase of the optical carrier using the electrical signal. Fig 1, illustrates the general block diagram of RoF system is being used in this paper. It consists of central office (CO) at the left hand side and base station (BS) on the right hand side separated by SMF. At the CO the modulating electrical signal, $x_{RF}(t)$, depicted in (1), is inserted into the MZM from the top and the bottom of the device in forms of in-phase and quadrature, $x_i(t)$ and $x_q(t)$, respectively. The inside structure of MZM has been illustrated in Fig. 2. The optical carrier in Fig.1, $x_{LD}(t)$ which has been described in (2), enters to the left hand side of MZM at the value of 1 mV. The output of MZM which is denoted as $y_R(t)$ is the modulated optical carrier. The details of $y_R(t)$ has

been illustrated in (1). The received data will be converted back into electrical form after being detected by photo detector (PD). After completing the electrical demodulation process at the BS the received data can be evaluated in terms of BER value.

Fig.2, illustrates the MZM modulator which consists of two electrical inputs denoted as $x_i(t)$ and $x_q(t)$ enters from the bottom of the device. The optical carrier enters from the left hand side of the device shown as $x_{LD}(t)$ and optical carrier, $E_R(t)$, leaves the device at the right hand side.

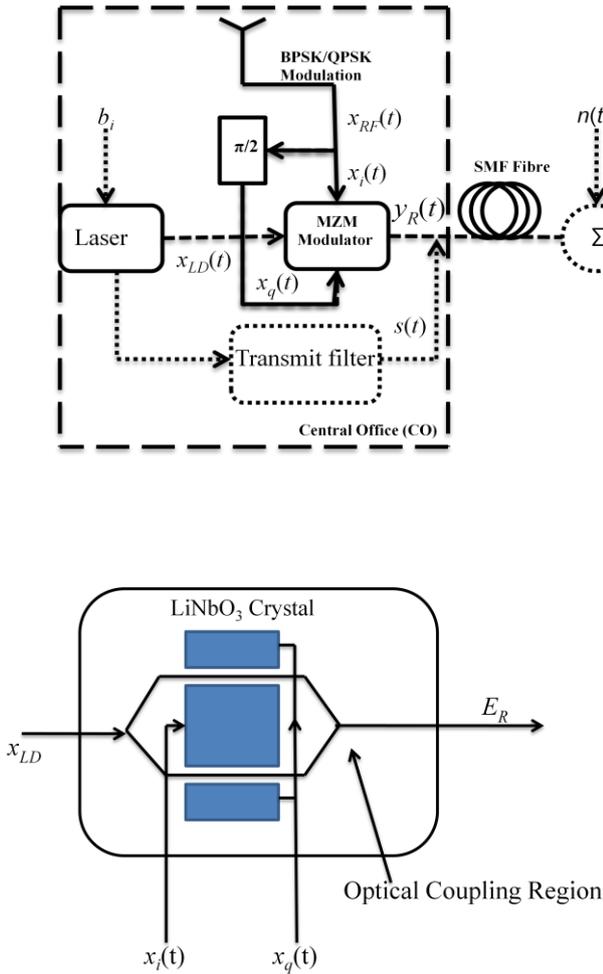


Fig. 2. MZM modulator

$$x_{RF}(t) = V_{RF} \cos[(\omega_{RF}(t) + \theta(t))], \quad (1)$$

RF signal amplitude is V_{RF} and is set to 1 mV in this paper. The electrical carrier frequency ω_{RF} is defined as $2\pi f_{RF}$ where $f_{RF} = 5$ GHz and is modulated by the pseudorandom binary sequence (PRBS). The optical carrier has been defined in (2) as following:

$$x_{LD}(t) = V_{LD} \exp[j(\omega_c t + \Phi_{LD}(t))], \quad (2)$$

where V_{LD} is the laser source voltage in mV, ω_c is optical carrier frequency and $\Phi_{LD}(t)$ representing phase change (radians/s). In this paper, the optical output power of CW laser is normalized to 1 mV. The applied RF signal is presented as [7].

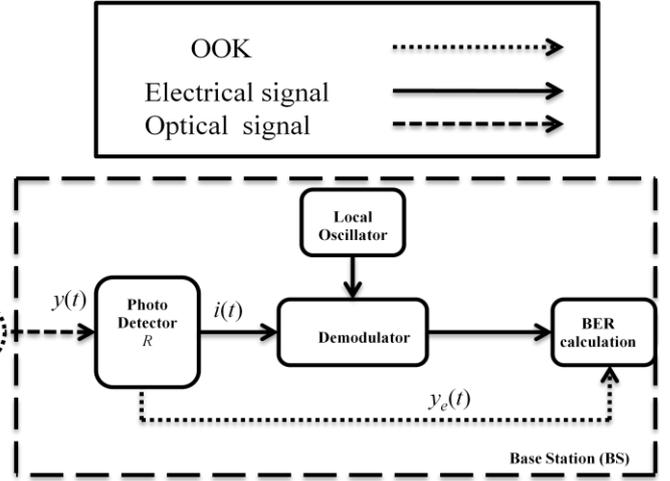


Fig. 1. BPSK modulation block diagram using MZM

The modulated optical carrier at the output of the MZM is given by [7] as presented in (3), where L_M is the insertion loss of MZM, $\gamma = V_{dc}/\sqrt{2} \times V_\pi$, is defined as the normalized dc voltage, V_{dc} is the threshold voltage for MZM device in volts and in order to obtain OSSB from the MZM output, $V_{dc} \sim 1.7677$ and V_π is the switching voltage of MZM and is 2.5 V. , In order to generate the OSSB signal, the value of γ is half. $x_{RF}(t)$ denotes the phase shifted $x_{RF}(t)$. Φ_{in} is the phase difference of optical carrier within MZM in radian.

Values of $x_i(t)$ and $x_q(t)$ are divided by $\sqrt{2}$ due to the 3 dB power splitter attenuation of RF input signals [7]. The receiver front-end consists of a photodetector (PD) and, the electrical signal at the receiver is then extracted from the optical carrier using direct detection as given by [7]

$$i(t) = R |y_R(t)|^2 + n_{th}(t), \quad (4)$$

where R is the photodetector responsivity and $n_{th}(t)$ is a random fluctuation which has unit of current due to thermal noise in the load resistance. The general block diagram of RoF system simulated is depicted in Fig. 1.

$$y_R(t) = \frac{V_{LD}}{\sqrt{2} \times 10^{L_M/20}} \times \left(\exp \left(j \left(\omega_c + \gamma \pi + \Phi_{in}(t) + \frac{x_i(t)}{\sqrt{2}} \right) \right) + \exp \left(j \left(\omega_c + \Phi_{in}(t) + \frac{x_q(t)}{\sqrt{2}} \right) \right) \right), \quad (3)$$

attenuation in optical fibre at 1550 nm is 0.2 dB/km [8]. If an exponential loss behaviour is expected, the input and output intensity of a channel waveguide can be described as [9].

$$P_{out} = P_{in} e^{-\alpha L}, \quad (5)$$

where P_{out} is the output optical power, P_{in} is the input optical power, α is the optical attenuation constant in m^{-1} [10], and L is the length of the channel waveguide. In SMF, chromatic dispersion is significantly higher than other dispersive and hence neglected. Chromatic dispersion in SMF can be described by:

$$P = \cos^2 \left(\frac{\pi D \lambda^2 L f_c^2}{c'} \right), \quad (6)$$

where D is the dispersion parameter ($D = 17$ ps/km-nm), $\lambda = 1550$ nm and f_c is the optical carrier wavelength and c' is the speed of light in the fibre ($c' = 2.04 \times 10^8$ m/s), P is the dispersion coefficient [11].

C. OOK Modulation and Methodology

The PRBS b_i where $i = 1, 2, \dots$ is generated using MatlabTM. The method of intensity modulation-direct detection (IM-DD) is used for unipolar non-return-to-zero (NRZ) format in order to modulate the laser source. The experiment is carried out over CW laser source at 1 mW. As it has been depicted in Fig. 3, the generated bits are transmitted through a transmitter filter, $p(t)$, with a unit amplitude impulse response to one slot duration T_b . The transmitter output signal $s(t)$ is [12]:

$$s(t) = A \sum_{-\infty}^{\infty} b_i p(t - iT_b), \quad (7)$$

where A is the amplitude of the signal and T_b is the bit period. When a bit '0' is generated then there is no signal transmitted through the optical channel in the time interval of T_b , while in the case of '1', a signal waveform $s(t)$ is generated. The generated signal will pass through the optical channel by taking (5) and (6) into consideration. Consequently, the received signal waveform with the absence of noise is given as $s(t)$.

Noise is inherent part of any communication system and at the received signal $y(t)$ can be represented as:

$$y(t) = \begin{cases} n(t) & \text{for } s(t) = '0'. \\ s(t) + n(t) & \text{for } s(t) = '1'. \end{cases} \quad (8)$$

where $n(t)$ is the additive white Gaussian noise (AWGN) and it is independent of $s(t)$. It has been outlined in [13], chirp and extinction ratio are neglected, but thermal and shot noise are accounted for an equal amount of AWGN at the optical receiver output. The signal $y(t)$ is converted to its electrical equivalent $y_e(t)$ by the photodetector of optical receiver which has a responsivity R of 1 A/W in

ideal case. In reality the value is 0.6 A/W. This electrical signal $y_e(t)$ is given as:

$$y_e(t) = R[s(t) + n(t)], \quad (9)$$

The received electrical signal will be fed into matched filter $z(t)$ which incorporates with the receiver, its impulse response is $z(t) = p(-t)$ when matched to the transmitter filter $p(t)$. The output of matched filter is set to '1' or '0' with reference to the fixed threshold level in order to estimate the output data. The estimated data stream is compared with the random transmitted data stream b_i to calculate the BER. The theoretical BER calculation is given by [14]:

$$Q(x) = \frac{1}{2} \operatorname{erfc} \left(\frac{x}{\sqrt{2}} \right), \quad (10)$$

where erfc is the complementary error function and x represents the signal to noise ratio (SNR).

III. RESULTS AND DISCUSSION

The simulation is implemented to investigate the effect of external modulation scheme on BER under the influence of fibre attenuation and dispersion independently. The results are compared with RF-OOK modulation technique.

OOK modulation scheme will be subjected to severe dispersion as it has been illustrated in Fig. 3. The reason relies on the fact that in OSSB modulation, the phase of the optical carrier will be modulated whereas in OOK scenario the amplitude of the carrier is modulated. Dispersion has direct effect on the amplitude of the signal. As a consequence the OOK modulation method suffers tremendously especially at distances of 60, 90 and 120 km.

In Fig. 4, the effect of dispersion of the SMF with distances of 8, 30, 60, 90 and 120 km at the dispersion value of 17 ps/km/nm with the pulse linewidth of 1 ns is illustrated. The simulated curve is compared with theoretical plot and proves the validity of the simulation.

The obtained results comply with the conclusion which has also been outlined in [14] and [15] indicate that theoretically if optical single sideband modulation is employed and the modulation index is small, dispersion does not affect the propagation of signal.

IV. CONCLUSION

This paper has examined the performance of RoF system using two different modulation techniques of OOK and MZM, under the attenuation and dispersion of a SMF.

The results illustrate that the performance of the system is degraded severely when the dispersion effect is taken into consideration in OOK case over the selected fibre range.

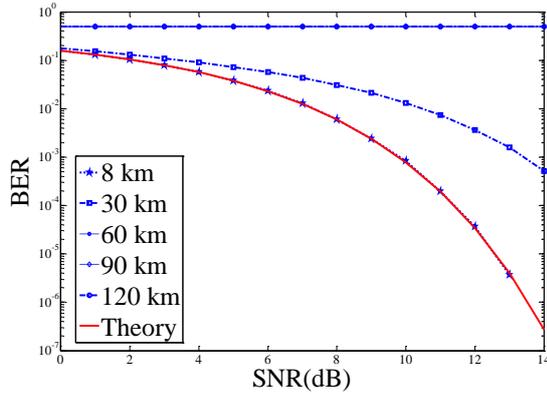


Fig. 3. OOK modulation.

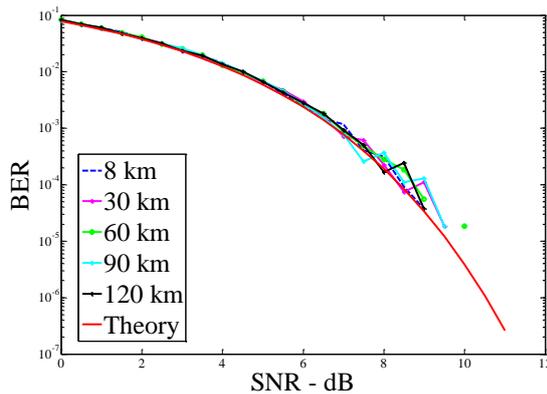


Fig. 4. MZM modulation at carrier frequency of 5 GHz.

However, dispersion has almost no effect on MZM technique which provides OSSB modulation and is immune to chromatic dispersion over different fibre length.

ACKNOWLEDGMENT

We would like to take the opportunity to thank the PGnet 2010 symposium to provide the opportunity for presenting papers.

REFERENCES

- [1] N. Uesugi, T. Horiguchi, M. Nakazawa, and Y. Murakami, "Optical Fiber Cable Measurements in the Field," *Selected Areas in Communications, IEEE Journal on*, vol. 4, pp. 732-736, 1986.
- [2] M. Sauer, A. Kobayakov, J. E. Hurley, and J. George, "Experimental Study of Radio Frequency Transmission over Standard and High-Bandwidth Multimode Optical Fibers," in *Microwave Photonics, 2005. MWP 2005. International Topical Meeting on*, pp. 99-102, 2005.
- [3] R. J. Green, "Secure communications: The infrared alternative," in *ICTON Mediterranean Winter Conference, 2007. ICTON-MW 2007*, pp. 1-4, 2007.
- [4] "Coaxial Cable Attenuation Chart." vol. 2007 Sydney: RFI.
- [5] S. Higginbotham, "Alcatel Boosts Fiber Speed to 100 Petabits in Lab," *GIGAom*, 2009.
- [6] J. Hecht, *Understanding Fiber Optics*, 4 ed.: Prentice Hall, 2002.

- [7] C. Tae-Sik, Y. Changho, S. Jong-In, and K. Kiseon, "Analysis of CNR penalty of radio-over-fiber systems including the effects of phase noise from laser and RF oscillator," *Lightwave Technology, Journal of*, vol. 23, pp. 4093-4100, 2005.
- [8] B. P.-C. Tsou, "Electrooptic Mach-Zehnder Modulators in Gallium Arsenide," in *The Department of Electrical Engineering* vol. Master of Applied Science British Columbia: The University of British Columbia., p. 143 1993,.
- [9] K. Y. Lau, "Fiber Chromatic Dispersion Effects on Broadband mm-Wave Subcarrier Optical Signals and Its Elimination," in *Ultra-High Frequency Linear Fiber Optic Systems*, Springer, Ed. California: Springer, pp. 115-123 2009.
- [10] L. C. Ong, C. S. Lim, B. Luo, Y. X. Guo, and A. Alphones, "Impulse response of a millimeter wave single mode radio-over-fiber," in *Antennas and Propagation Society International Symposium, 2007 IEEE*, pp. 4669-4672, 2007.
- [11] S. Rajbhandari, Z. Ghassemlooy, and M. Angelova, "Effective Denoising and Adaptive Equalization of Indoor Optical Wireless Channel With Artificial Light Using the Discrete Wavelet Transform and Artificial Neural Network," *Lightwave Technology, Journal of*, vol. 27, pp. 4493-4500, 2009.
- [12] G. J. Foschini, and Greenstein, L.J., "Spectral Efficiency of Optical FDM Systems Impaired by Phase Noise," *IEEE TRANSACTIONS ON COMMUNICATIONS*, vol. 41, pp. 125-131, 1993.
- [13] S. Elnoubi and A. Elshinnawy, "New closed form expressions for the bit error rate (BER) Of MC-CDMA systems in generalized Nakagami-m fading channels," in *Radio Science Conference, 2004. NRSC 2004. Proceedings of the Twenty-First National*, pp. C15-1-8, 2004.
- [14] P. L. Ricardo Avó, Maria C. R. Madeiros, "Transmission Performance of mm-Waves on Radio over Fiber Systems: Dispersion and Intermodulation Issues ". vol. 314/2010: Springer Boston, pp. 289-29, 2006.
- [15] P. L. Ricardo Avó and M. C. R. Medeiros, "Dynamic range of optical links employing optical single side-band modulation," *Photonics Technology Letters, IEEE*, vol. 15, pp. 748-750, 2003.