Influence of Fibre Chromatic Dispersion on the Performance of Analogue Optical Links for an Opto-electronic Oscillator within a 5G Network Structure

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Abstract*. Analogue optical links are widely used in radio-frequency, micro-wave and millimetre-wave signal range applications. One of parameters that affect the performance of an analogue optical link is the chromatic dispersion. Chromatic dispersion affects the signal transmission over the fibre-optic line and in some cases it can destroy the signal shape on the link.*

In this paper we will give a brief introduction to the opto-electronic oscillator, the analogue optical links and the modulation techniques. Then we will describe the chromatic dispersion and its effect on the analogue optical links. The next step shows the measurements that were made up to 13 GHz for analogue optical links of a length up to 70 km. The final part is composed of the summary and a brief discussion of the results.

Index terms- Fibre-optic line, chromatic dispersion, external modulation, opto-electronic oscillator.

1 Introduction

The opto-electronic oscillator (OEO), which was invented by Yao and Maleki [1-2], is a new type of oscillator that can be used to produce a high-frequency signal in the radio-frequency (RF), micro-wave (μW) and millimetre-wave (mm-W) ranges. Due to its many advantages we intend to use an OEO in a 5G network structure with the help of radio-over-fibre (RoF) technology. Figure 1 shows how we can implement the idea of an OEO to distribute the signals between the central station and the base station.

As shown in Figure 1, our idea for using the OEO in 5G has two analogue optical links. One of them is internal, located in the oscillator itself to complete the opto-electronic feedback given as L1. The second analogue optical link is external for the optical connection between the laser in the central station and the photodiode in the base station given as L2 in Figure 1. Both of these analogue links must be sufficiently long to satisfy the system requirements. The external optical link must be long enough to overcome the physical distance between the central station and the base stations, which can be in different ranges. The internal optical link must be long enough to bring enough delay and oscillator quality to generate a low-phase-noise signal.

The OEO consists of the electrical and optical parts [3], which provides an electrical and an optical output signal at the same time [4]. The optical output is connected to the electrical part by analogue optical links. The opto-electrical conversion is, in both cases, made with a photodetector.

This signal generated by the OEO is transmitted via a separate optical fibre link (known as an oscillator link) to the base station, as shown in Figure 1. At the base station, the optical signal is converted to the electrical domain on the photodiode, creating a RF signal that is suitable for the frequency up- and down-conversion of the data signal in the mixers.

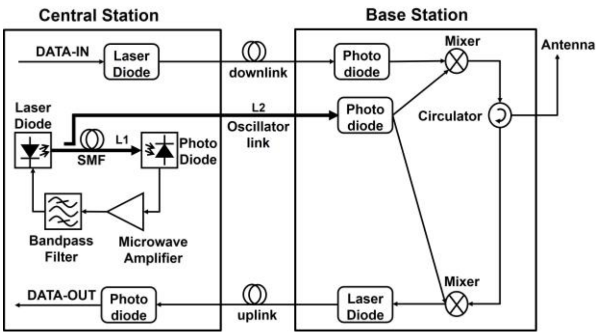

Figure 1. OEO implemented in the central station and connected to the base station with an analogue optical link.

2 Basics of Analogue Optical Links

In today's fibre-optics technology, analogue optical links are used for a variety of applications in the RF, μW and mm-W range signals. It is widely used in different areas such as cable television signal distribution [5], RoF technology [6-7], OEO [8-9], local area networks, remote antenna beam steering [10] etc. In [11], the advantages of optical fibre are described over coaxial cables in GSM applications such as cellular remote antenna feeding.

The analogue optical link can be summarized as a combination of components, such as a semiconductor laser diode, optical modulator, fibre-optic line and photodiode, which are linked together. Generally, a distributed feedback (DFB) laser or a Fabry-Perot laser can be used in the optical link. In general, the DFB laser is integrated with an external modulator due to its advantages [12]. In the literature, there have been a number of methods to generate RF, μW and mm-W range signals in the optical domain with analogue optical links. Some examples can be given, such as optical heterodyning [13], fundamental and harmonic signal generation using a pulsed laser [14] and optical phase-locked lasers [15]. In general, intensity modulation can be used as a simple technique to produce a RF, μW or mm-W signal from an optical signal. With this technique, the laser can be directly or externally modulated. In the literature there have been many applications for direct [16-18] and external modulation of the laser. The Mach-Zehnder Modulator (MZM) [19-21] and the electro-absorption modulator [22] are widely used as an external modulator for analogue optical links. Due to having problems with direct modulation, such as laser frequency chirps, and because external modulation allows higher modulation speeds than direct modulation [23], external modulation is widely used in analogue optical links [19-22]. Figure 2 shows a typical implementation of analogue optical links with an externally modulated laser.

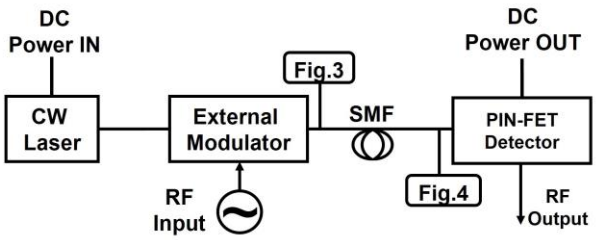

Figure 2. Analogue Optical Link with external modulator.

In the Mach-Zehnder modulator (MZM) the phase of the light in the optical waveguides is modulated and converted to an intensity modulation in the second part of a Mach-Zehnder interferometer. The optical spectrum of the output optical signal consists of an optical carrier and two side bands (Fig. 3). At the output of the MZM all three components are ideally in-phase.

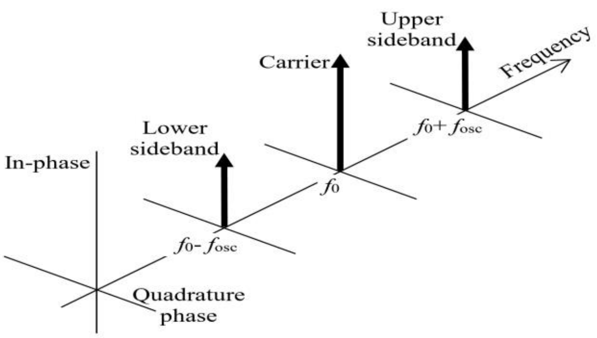

Figure 3. Spectrum of intensity-modulated optical signal at the modulator output at the fibre input.

As described before, analogue optical links are also used in the opto-electronic oscillator. One of the problems of the opto-electronic oscillator is the phase noise [3]. In order to overcome this problem, the fibre length of the optical links is increased to 15 km or even more to reduce the phase-noise effect [3].

3 General Information about the CD on the Analogue Optical Links

In optical communications, chromatic dispersion (CD) can limit the transmission of the signal transmitted by a single-mode optical fibre. As the modulated optical signal is transmitted via fibre-optic link, the chromatic dispersion causes a different phase shift on each of the optical spectral components (the carrier and double sidebands), as shown in Figure 4. In other words, chromatic dispersion can be defined as an attenuation effect that degrades the signal over the optical fibre's length [24].

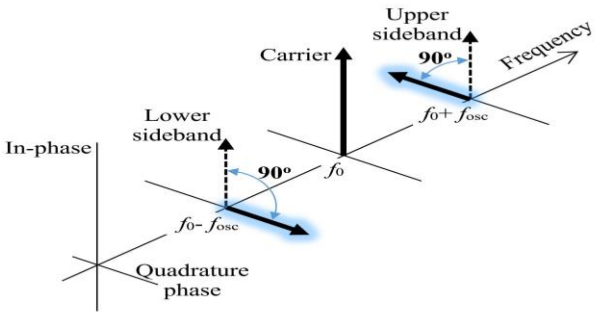

Figure 4. Worst-case situation for the spectrum of the intensity-modulated optical signal at the fibre output. Chromatic dispersion changes the phase relationship between the optical carrier and upper and lower sidebands to be of opposite phase.

The phase shift of each spectral component depends on the fibre length, the oscillator frequency and the dispersion coefficient. Consequently, the power of the detected signal is length dependent [7].

$$P_{osc}(L, f_{osc}) \propto 20\log\left(\cos\left(\frac{\pi L D_{oc}}{c_0}(\lambda_{oc} f_{osc})^2\right)\right) - 2\alpha L \quad (1)$$

where L is the fibre length, c_0 is the speed of light in free space, D_{oc} is the fibre-dispersion coefficient at the wavelength of the optical carrier, λ_{oc} is the optical carrier wavelength, f_{osc} is the oscillator frequency and α is the optical loss. In the case when the phase delay between the sidebands at the end of the fibre line is 180°, the destructive mixing on the PD will negate the entire oscillator signal, as shown in Figure 5.

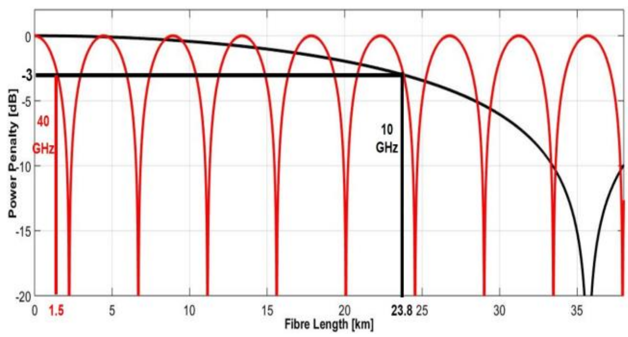

Figure 5. Power penalty of the oscillator signal depends on the optical fibre length.

For example, when a 10-GHz oscillation frequency is transmitted over the fibre-optic link at 1550 nm, where the standard single-mode fibre has a 17.5 ps/(nm.km) dispersion, a 3-dB degradation in the oscillator signal occurs at a distance of 23.8 km. For a 40-GHz oscillator frequency a 3-dB degradation occurs after just 1.5 km.

4 Analogue Optical Link Setup and Measurements

The experiment setup of the optical link is composed of several components. These include a signal generator, DFB laser with external MZM, fibre-optic lines, photodiode and electrical spectrum analyser (ESA). Figure 5 shows the block diagram of the experiment. The DFB laser, which defined the optical carrier signal, has a wavelength of 1552 nm.

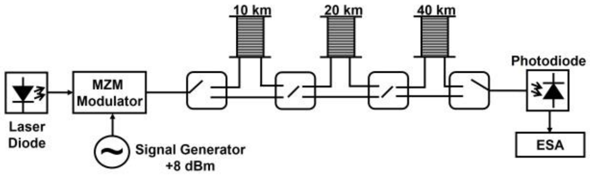

Figure 6. Experimental setup for the measurement on the analogue optical links.

With this paper, as shown in the Figure 5, we focus on the performance of analogue optical links with a DFB laser to measure the power of the signal with different frequencies starting from 2 GHz to 13 GHz in a combination of three different optical lengths (10 km, 20 km and 40 km). Therefore, we have a chance to measure the optical length starting from a 10-km to a 70-km fibre-optic line.

The value of the chromatic dispersion at the optical carrier wavelength D_{oc} is defined using the Sellmeier equation;

$$D(\lambda_{OC}) = \frac{\lambda_{OC} S_0}{4}\left(1-\left(\frac{\lambda_0}{\lambda_{OC}}\right)^4\right) \quad (2)$$

where λ_{oc} is the optical carrier wavelength of 1552 nm, λ_0 is the wavelength at which chromatic dispersion is equal to zero (1314 nm for the fibre used in this particular experiment) and S_0 is the dispersion slope with a value of 0.0862 ps/(nm^2·km). The calculated value of the dispersion at the optical carrier wavelength is 16.15 ps/(nm·km).

Figures 7 to 10 show the simulation and experimental results of the power penalty with different frequencies and optical lengths.

From the results it is clear that we should consider the optical length and the frequency that can be used in the OEO. We should design the length and the frequency of the OEO to avoid any power penalty. In the literature there is another way to avoid the power penalty, i.e., using a single sideband modulation [19] with an optical filtration or specially controlled MZM.

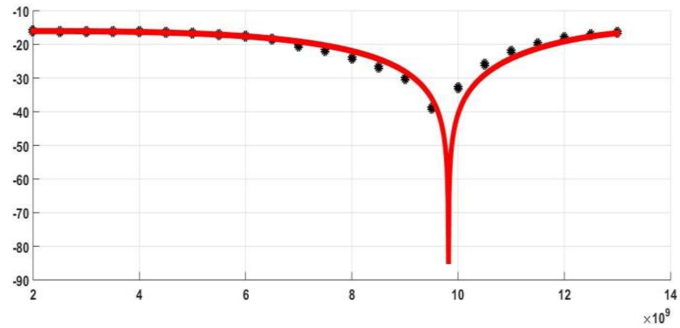

Figure 7. Simulated (line) and experimental results (dots) of power penalty depend on the frequency range between 2 and 13 GHz for the 40-km fibre length.

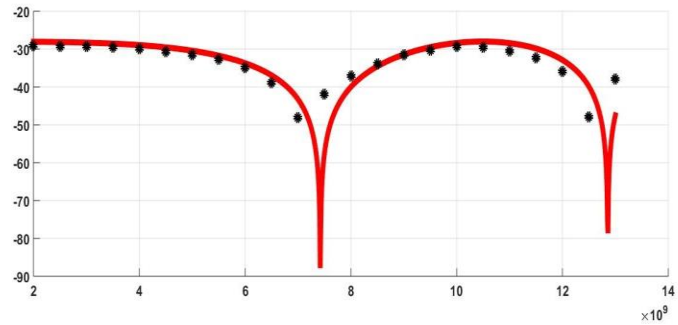

Figure 8. Simulated (line) and experimental results (dots) of power penalty depend on the frequency range between 2 and 13 GHz for the 70-km fibre length.

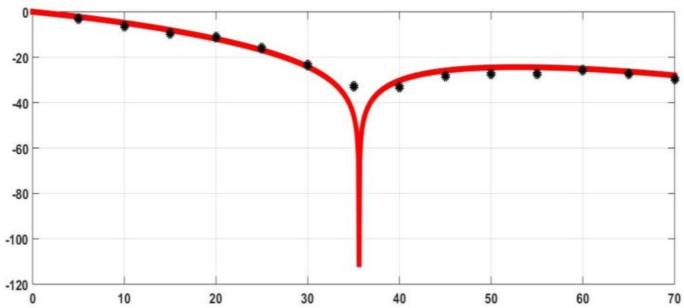

Figure 9. Simulated (line) and experimental results (dots) of power penalty depend on the optical length between 10 and 70 km for the 10-GHz frequency.

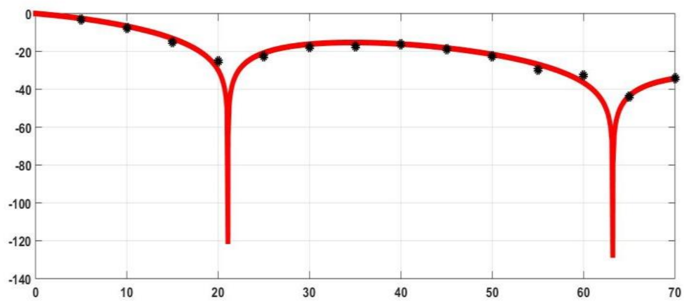

Figure 10. Simulated (line) and experimental results (dots) of power penalty depend on the optical length between 10 and 70 km for the 13-GHz frequency.

5 Conclusion

With this paper we explained the basic structure of the OEO and the structure and behaviour of the chromatic dispersion over analogue optical links. The OEO and analogue optical links are widely used to generate and distribute the RF, μW and mm-W signals. In addition, we describe one idea that analogue optical links can be used to generate mm-W range signals with the help of the OEO for 5G network technology thanks to RoF.

The laser can be modulated directly or externally. Due to its own advantages, external modulation is widely used in integrated optics and photonics applications.

Chromatic dispersion effects on the fibre are crucial criteria that we should take into consideration. Chromatic dispersion causes a different phase shift on each of the spectral components (the carrier and double sidebands). This means that chromatic dispersion is one of the undesired effects that limit the signal transmission over the fibre-optic line.

It seems that the transmission of the oscillator signal by an intensity-modulated optical signal is only applicable for frequencies up to 10 GHz. For higher oscillator frequencies the limiting dispersion occurrence can be reduced by using an OEO where a single sideband modulation [19] with an optical filtration or specially controlled MZM is used. In our further research we want to test these two methods.

Besides chromatic dispersion, the polarization mode dispersion (PMD) of a fibre-optic link can also cause a degradation in the quality of the transmitted oscillator signal. Consequently, a low-PMD fibre-optic link is required. However, attention must be paid to the Rayleigh scattering of the fibre-optic link and its contribution to the phase noise.

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References

[1] R. T. Logan, L. Maleki, M. Shadaram: Stabilization of oscillator phase using a fiber-optic delay-line, 45th Annual Symposium on Frequency Control, pp. 508-512, May 1991.

[2] X. S. Yao, L. Maleki: High frequency optical subcarrier generator, El. Lett., vol. 30, no. 18, pp. 1525-1526, Sept. 1994.

[3] B. Batagelj, L. Bogataj, M. Vidmar: Key properties and design issues for an opto-electronic oscillator, ICTON, 5.-9. July 2015, Budapest, Hungary.

[4] A. Madjar, T. Berceli: Microwave generation by optical techniques - a review, EUMC, 10.-15. September 2006 Manchester, UK.

[5] N. Hamilton-Piercy: Role of fiber optics in HDTV, Broadband Analog Optoelectronics: Devices and Systems, 1990. Conference Digest, LEOS Summer Topical on, 23.-25. July 1990.Monterey, USA.

[6] John E. Mitchell: Radio-over-Fiber (RoF) Networks, in Broadband Access Networks: Technologies and Deployments, Springer, 2009.

[7] B. Batagelj, Leon Pavlovič, Luka Naglič, Sašo Tomažič.: Convergence of fixed and mobile networks by radio over fibre technology, Inf. MIDEM, vol. 41, pp. 144-149, Jun. 2011.

[8] X. S. Yao, L. Maleki: Optoelectronic microwave oscillator, J. Opt. Soc. Am. B, vol. 13, no. 8, pp. 1725-1735, Aug. 1996.

[9] X.S. Yao, L. Maleki, D. Eliyahu: Progress in the opto-electronic oscillator – A ten-year anniversary review, IEEE MTT-S International Microwave Symposium Digest, vol. 1, pp. 287-290, Jun. 2004.

[10] P. Ritosa, B. Batagelj, M. Vidmar: Optically steerable antenna array for radio over fibre transmission, El. Lett., vol. 41, no. 16, str. 917-918, Aug. 2005.

[11] S. Hunziker, W. Baechtold: Cellular remote antenna feeding: optical fibre or coaxial cable?, El. Lett, vol.34, no.11, pp.1038-1040, May 1998.

[12] J. Hong, W.-P. Huang, T. Makino: Simulation of frequency chirps in MQW DFB lasers under external modulation, IEE Proceedings - Optoelectronics, vol. 142, no. 1, pp. 44-50, 1995.

[13] J. Yao: Microwave photonics, J. Lightw. Technol., vol. 27, no. 3, pp. 314-333, Feb. 1, 2009.

[14] D. Novak, Z. Ahmed, R. B. Waterhouse, and R. S. Tucker: Signal generation using pulsed semiconductor lasers for application in millimeter-wave wireless links, IEEE Trans. Microwave Theory Tech., vol. 43, pp. 733–734, Sept. 1995.

[15] L. Naglič, L. Pavlovič, B. Batagelj, M. Vidmar: Improved phase detector for electro-optical phase-locked loops, Electron. Lett., vol. 44, no. 12, pp. 758-760, June 5, 2008.

[16] E. Ackerman, D. Kasemset, S. Wanuga, D. Hogue, J. Komiak: A high-gain directly modulated L-band microwave optical link, IEEE MTT-S International, 8.-10. May 1990,

[17] E. Ackerman, D. Kasemset, S. Wanuga, R. Boudreau, J. Schlafer, R. Lauer: A low-loss Ku-band directly modulated fibre-optic link, IEEE PTL, vol. 3, no. 2, pp. 185-187, 1991.

[18] Jun-Hyung Cho, Hyuk-Kee Sung: Simple Optoelectronic Oscillators Using Direct Modulation of Dual-Section Distributed-Feedback Lasers, IEEE PTL, vol. 24, no. 23, pp. 2172 – 2174, 2012.

[19] G. H. Smith, D. Novak and Z. Ahmed: Overcoming Chromatic Dispersion Effects in Fiber-Wireless Systems Incorporating External Modulator, IEEE Trans. on Mic. Theory and Techn., vol. 45, no. 8, pp.1410-1415, 1997.

[20] G. E. Betts, F. J. O’Donnell: Optical Analog Link Using a Linearized Modulator, Lasers and Electro-Optics Society Annual Meeting, LEOS '94, 31. October-3 November 1994, Boston, USA.

[21] A. Garcia, S. Fedderwitz, A. Stöhr: Optical generation of low-phase noise microwave signals using nonlinear MZM and ultra-long SOA, SBMO/IEEE MTT-S Int. Microwave &Optoelectronics Conference, 29. October-1. November 2011, Natal, Brazil

[22] M. Shin, P. S. Devgan, V. S. Grigoryan, and P. Kumar: Low Phase-Noise 40GHz Optical Pulses from a Self-Starting Electroabsorption-Modulator-Based Optoelectronic Oscillator, OFC, 5.-10. March 2006 Anaheim, USA.

[23] D. Marcuse: DFB laser with attached external intensity modulator, IEEE Journal of Quantum Electronics, vol. 26, no.2, pp. 262-269, Feb. 1990.

[24] T. Berceli, E. Udvary, A. Hilt: A new equalization method for dispersion effects in optical links, ICTON, 22.-26. June 2008, Athens, Greece.