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Subcarrier multiplexed radio over fiber system with optical single sideband modulation

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Abstract: A subcarrier multiplexed radio over fiber (RoF) system using optical single sideband (OSSB) modulation is proposed. OSSB modulation reduces the bandwidth requirements and also combats the radio frequency (RF) power fading issue due to the dispersive effects in optical fiber. Subcarrier multiplexing (SCM) is a technique used to transmit multiple RF signals through the same optical fiber to utilize its large bandwidth. A theoretical analysis showed that OSSB generation with a number of subcarriers can be done by Hilbert transform method employing a single dual drive Mach–Zehnder Modulator (MZM). This technique is very relevant in the emerging 5G standards which require accesses of multiple standards simultaneously (5G, LTE, and Wi-Fi). This paper demonstrates a low cost solution of OSSB-RoF system and more effective utilization of the spectrum. Simulations results showing satisfactory reception of signals up to 50 km.

Keywords: Hilbert transform; Mach–Zehnder modulator; optical single sideband; radio over fiber; subcarrier multiplexing.

1 Introduction

The exponential growth and popularity of cell phones and widespread usage of wireless Internet services made a larger requirement of high-speed data [1]. The wireless spectrum is very congested and demands alternative solutions for high-speed data delivery. Radio over fiber (RoF) [2] is one among the promising solutions to cope with the huge data demand. In RoF system, radio signals modulated on to optical carrier and optical fibers used for the distribution such signals between the central point to radio

access points [3]. RoF system has the benefit of large bandwidth of fiber optical systems and flexibility of wireless systems. This innovative technology will encourage the concurrent transmission of different radio frequency (RF) signals having different modulation formats and information rates [4].

However, the bit rate is restricted to 10 Gbps in typical cases because of the limitations of dispersive and nonlinear media and also by the operating frequency constraints of electronic components [5]. The nonlinear nature of optical modulators introduces harmonics and intermodulation products to the optical signal. A double sideband modulated optical signal experiences RF power fading due to group velocity dispersion (GVD) of optical fibers. Single side band (SSB) transmission can effectively minimize the effect of RF power fading due to GVD in SMFs [6]. Simultaneous transmission or multiplexing of different RF signals over the same channel is a simple way for increasing the system capacity. It is more spectrum efficient and cost-effective method than deploying new optical fiber [7]. This paper proposes the subcarrier multiplexed RoF system with single sideband modulation for better performance.

2 Subcarrier multiplexing in RoF systems

A scheme in which microwave subcarriers are multiplexed and used to modulate the optical signal is referred to as subcarrier multiplexing (SCM) [8]. In SCM, multiple microwave carriers which are well separated in frequency are used for transmitting data. Each such channel is capable of carrying data of different applications at different rates. These RF carriers are combined together and modulated on to an optical carrier which is transmitted through optical fiber, as illustrated in Figure 1. Normal intensity modulation of the optical carrier is carried out, and the modulated optical signal is fed through a single mode fiber (SMF). SM fiber reduces the effect of time domain dispersion (intermodal) which is a limiting factor for high-speed communication. At the receiving side, by photo detection, these summed RF carriers are recovered. The combined RF signals are then passed through different bandpass filters

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Figure 1: Optical sub-carrier multiplexing.

tuned to respective channel frequencies to separate out individual channels for further wireless transmission. The SCM-RoF is a cost-effective technique as it largely avoids the use of high power RF transmitters and it also makes use of existing optical fibers.

3 Optical single sideband SCM system

The nonlinearity of the laser, modulator and propagation characteristics of fibers generate harmonics and inter-modulation products in the form of $x\omega_1 \pm y\omega_2 \mp z\omega_3$ where x, y, z are integers. Some of the intermodulation products which are in the passband of the transmission frequency will introduce distortion to the transmitted signal. Because of GVD, different frequency components experience different velocities or phase shifts. As a result, speed variations are converted into intensity fluctuations while propagating through optical fibers. This may cause the sidebands of the RF signal propagating through the fiber cancel each other at periodic intervals. A single sideband technique [9] together with balanced detection is suggested to minimize the RF power fading effect caused by group velocity dispersion of the optical fiber and harmonic distortion caused by modulator nonlinearity [6].

Different techniques of single sideband (SSB) modulation like filter method, phase shift method etc. are discussed in the literature. Hilbert transformer is an ideal phase shifter that changes the phase of every spectral component of the signal by $-\pi/2$ without changing its amplitude. The transfer function of Hilbert transform can be written as,

$$H(\omega) = -j\text{sgn}(\omega) = \begin{cases} -j & \omega \geq 0 \\ j & \omega < 0 \end{cases} \quad (1)$$

A typical phase-shift arrangement of SSB generation is shown in Figure 2.

The output signal can be expressed as,

$$S_{SSB}(t) = \frac{1}{2}m(t)\cos\omega_c t \pm \frac{1}{2}\hat{m}(t)\sin(\omega_c t) \quad (2)$$

where $\hat{m}(t)$ is the Hilbert transform (HB) for $m(t)$.

Here, we explore the possibility of using a single dual drive Mach-Zehnder modulator to obtain single sideband modulation by incorporating Hilbert transform technique [10]. The RF signal is Hilbert transformed and both direct and phase-shifted signals fed to the arms of a dual drive MZM. The phase shift of optical carrier inside the wave guide is obtained by adjusting the bias voltages. The setup and analysis for such an arrangement is shown in Figure 3.

For a double electrode MZM, the output optical electric field can be expressed as,

$$E_{odual}(t) = E_{in}e^{j\omega_c t} [e^{j\frac{\pi}{V_\pi}(V_{b1}+V_1(t))} + e^{j\frac{\pi}{V_\pi}(V_{b2}+V_2(t))}] \quad (3)$$

Figure 2: Single sideband (SSB) generation using Hilbert transform.

Figure 3: Mach-Zehnder modulator (MZM) configured to produce SSB modulation.

Figure 4: Optical single sideband subcarrier multiplexing (SCM).

where E_{in} is the average electric field applied to the electrodes of MZM, V_1 and V_2 are the amplitudes of the modulating signal fed to the two electrodes, respectively. The resulting output optical power is expressed as,

$$P_o = E_o^* E_o = P_{in} \cos^2 \left[\frac{\pi}{2V_\pi} (V_1(t) - V_2(t) + v_{b1} - v_{b2}) \right] \quad (4)$$

The biasing voltages to both the arms of MZM can be acclimated to such an extent that only single sideband modulation is created. Same RF modulating signal but at 90° out of phase is fed to both the arms of MZM. If $V_1(t) = V_0 \sin(\Omega t)$ and $V_2(t) = V_0 \cos(\Omega t)$ and the dc biasing voltages $v_{b1} = 0$ and $v_{b2} = -\frac{V_\pi}{2}$ then the optical field of the out coming light can be expressed as,

$$E_{out}(t) = E_{in} e^{j\omega_c t} \left[e^{j\frac{\pi}{V_\pi} V_0 \sin(\Omega t)} + e^{j\frac{\pi}{V_\pi} (V_0 \cos(\Omega t) - \frac{V_\pi}{2})} \right] \quad (5)$$

Let us define the modulation index as $m = \frac{\pi V_0}{V_\pi}$ then the output in normalized form can be written as

$$E_{out}(t) = \frac{1}{\sqrt{2}} E_{in} e^{j\omega_c t} \left[e^{jm \sin(\Omega t)} + e^{jm \cos(\Omega t) - \frac{\pi}{2}} \right] \quad (6)$$

where E_{in} is the input electric field, Ω is the RF signal angular frequency and ω is the optical carrier angular frequency, respectively.

This equation can be elaborated using Bessel function of the first kind as,

$$\begin{aligned} E_{out}(t) &\approx \frac{E_{in}}{2} (2J_0(m) + [J_1(m) + J_1(m)]e^{j\Omega t} \\ &\quad + [-J_1(m) + J_1(m)]e^{-j\Omega t} + \dots)e^{j\omega_c t} \\ &= \frac{E_{in}}{2} (2J_0(m) + 2J_1(m)e^{j\Omega t} + \dots)e^{j\omega_c t} \end{aligned} \quad (7)$$

In the above equation, the first term represents the optical carrier of the exiting electric field and the sideband (upper) is shown as the second term. The other sideband gets canceled, and optical single sideband (OSSB) modulation is achieved. By modifying the bias either upper or lower sideband can be suppressed. Hence, in this method, OSSB

can be obtained with a single device while other methods require more components and thus higher cost.

For generating SCM in RoF systems, rather than a solitary RF signal, an aggregate of various RF signals is utilized. We assume that each of these RF signals conveys distinctive data planned for various applications or users. The combined RF signal is fed to the MZM modulator which is configured to perform single sideband modulation as shown in Figures 4 and 5

Thus, the output optical field of the above dual drive MZM configured to generate OSSB can be expressed as

$$E_{out}(t) = \frac{1}{\sqrt{2}} E_{in} e^{j\omega_c t} \left[e^{jm \sin(\Omega t)} + e^{jm \cos(\Omega t) - \frac{\pi}{2}} \right] \quad (8)$$

where E_{in} is the input optical field, $m = \frac{\pi V_0}{V_\pi}$ is the modulation index, V_π is the MZM switching voltage, ω_c is the lightwave carrier frequency, Ω is the RF. So in the proposed SCM system with n number of channels, the output electrical field from the modulator is

Figure 5: Compensation of radio frequency (RF) power fading using SSB modulation.

$$E_{out}(t) = \frac{1}{\sqrt{2}} E_{in} e^{j\omega_c t} \left[e^{j \sum_{k=1}^N u_k(t) m_k \sin(\Omega_k t)} + e^{j \sum_{k=1}^N u_k(t) m_k \cos(\Omega_k t) - \frac{\pi}{2}} \right] \quad (9)$$

where $u_k(t)$ is the normalized digital signal of the k th subcarrier. For binary “zero” and “one”, $u_k(t) = \pm 1$ and $u_k(t) = 0, 1$ respectively, for phase shift keying (PSK) and amplitude shift keying (ASK) modulation. The k th RF subcarrier frequency is denoted by Ω_k .

$$E_{out}(t) = \frac{E_{in}}{2} \left\{ \cos \left[\omega_c t - \sum_{k=1}^N u_k(t) m_k \sin \Omega_k t \right] - \sin \left[\omega_c t + \sum_{k=1}^N u_k(t) m_k \cos(\Omega_k t) \right] \right\} \quad (10)$$

The modulation index is kept small to operate modulator in the linear region thereby minimizing harmonic components. Assuming small signal modulation, Equation (10) can be written in a linear form as [11],

$$E_{out}(t) = \frac{E_{in}}{\sqrt{2}} \left\{ \sin \left(\omega_c t - \frac{\pi}{4} \right) - \frac{1}{\sqrt{2}} \sum_{k=1}^N u_k(t) m_k \cos(\omega_c + \Omega_k)t \right\} \quad (11)$$

In the above expression, the first term indicates the carrier and the second term is the signal. The out-coming SSB modulated optical signal is then coupled to single mode fiber for onward transmission. At the photo detector, the optical carrier beats with the subcarriers thus down converting the optical subcarriers to the RF domain. The resulting photocurrent is,

$$I_{out}(t) = I_0 \left\{ 1 + \sum_{k=1}^N u_k(t) m_k \cos(\Omega_k t) \right\}, \text{ and} \quad (12)$$

$$I_0 = \eta G \mathcal{R} P_{in} \quad (13)$$

where η is the system losses, G is the preamplifier gain, $\mathcal{R}$ is the responsivity of the photodiode and $P_{in} = E_{out}^2/2$ is input optical power to the detector. The detected RF signal is then passed through power splitter and individual channels are separated using filters.

4 Simulation results and analysis

The proposed system is designed and simulations are carried out using optisystem[®] v14 software with different simulation parameters are set, as shown in Table 1.

To show RF power fading compensation, optical signal is modulated with a 10 GHz RF carrier in both double sideband and single sideband modes. The received RF

signal power is measured for different lengths of a lossless fiber.

For simulating SCM, RF carriers of 7, 10, and 15 GHz are chosen arbitrarily. These RF carriers are summed using an ideal RF combiner (having zero insertion loss and zero phase shift). The combined signal is used to modulate the light carrier at 193.1 THz. The dual drive MZM produces SSB-modulated optical signal. Each of the individual RF signals generates corresponding sidebands. As single sideband modulation is employed, the sidebands appear only in one side. This technique effectively suppresses the RF fading that occurs in DSB modulation as the optical

Table 1: Parameters values for simulation.

Parameter	Value	Parameter	Value
Opt Txr	Continuous wave (CW) laser	Photo Det	PIN
Opt pow	1 mW	Responsivity	1 A/W
Wavelength	1552.5 nm	Dark current	10 nA
Linewidth	10 MHz	Shot noise	Gaussian
		Thermal noise	15e(-24) W/Hz
Opt fiber	Silica	Opt mod	Mach-Zehnder
Type	Single mode	Type	Double electrode
Dispersion (GVD)	16.25 ps/nm.km	Ext ratio	30 dB
Attn	0.2 dB/km	Ins loss	0 dB

Figure 6: Optical spectrum of the SSB SCM system.

signal propagates through the dispersive medium. The optical spectrum of the OSSB SCM signal is shown in Figure 6.

At the receiving end, the RF carriers are retrieved from the optical signal by a PIN photo detector. RF spectrum of the detected signal is shown in Figure 7. Respective channels are separated using bandpass filters. The harmonics and other intermodulation products are filtered out for proper reception.

The OSSB system has got a satisfactory reception up to 50–55 km. The bit error rate is 10^{-10} at a distance of 50 km and the eye pattern at this distance showing reasonably good opening. The corresponding BER versus fiber length

and eye pattern of 10 GHz carrier at a data rate of 1 Gbps are shown in Figure 8.

5 Conclusion

This paper proposes a low cost solution of OSSB-RoF system by using a single dual drive MZM for SSB generation and more effective utilization of the spectrum by incorporating subcarrier multiplexing. Single sideband technique reduces the bandwidth requirements and helps in combating the RF fading problem encountered in dispersive channels. SCM aids in simultaneously transmitting different RF carriers intended for different purposes. This technique has got high relevance in the emerging 5G systems which require co-existent accesses of multiple standards (5G, LTE, and Wi-Fi). At the detector side, the microwave or RF signals are recovered and transmitted to respective users/applications. For demonstration purpose, 7, 10, and 15 GHz RF carriers are chosen and satisfactory reception obtained up to 50 km. This can be modified to the real-world operating frequencies like 2.4, 5 and 26 GHz etc. Other performance affecting factors like harmonic distortion, intermodulation distortion, etc. are not addressed here.

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References

1. Ohmori S, Yamao Y, Nakajima N. The future generations of mobile communications based on broadband Access technologies. *IEEE Commun Mag* 2000;38:134–42.

Figure 7: Radio frequency (RF) spectrum of the received SCM System.

Figure 8: BER curve and eye pattern of the proposed system.

2. Fernando XN, Anpalagan A. On the design of optical fiber based wireless access systems. In: 2004 IEEE International Conference on Communications. (IEEE Cat. No.04CH37577), Paris, France; 2004, pp. 3550–3555, Vol. 6.
3. Wake D, Nkansah A, Gomes NJ. Radio over fiber link design for next generation wireless systems. *J Lightwave Technol* Aug 2010; 28:2456–64.
4. Novak D, Waterhouse RB, Nirmalathas A, Lim C, Gamage PA, Clark TR, et al. Radio-over-fiber technologies for emerging wireless systems. *IEEE J Quant Electron* Jan 2016;52:1–11.
5. Thomas VA, El-Hajjar M, Hanzo L. Performance improvement and cost reduction techniques for radio over fiber communications. *IEEE Commun Surv Tutor* Second quarter 2015;17:627–70.
6. Pradeep R, Vijayakumar N. A novel single wavelength balanced technique to suppress second order distortion in RoF system. In: IEEE International Conference on Computational Systems. ICCS, Trivandrum; 2015.
7. Maier M. WDM passive optical networks and beyond: the road ahead [Invited]. *IEEE/OSA J Opt Commun Netw*;1.4: C1–16.
8. Arsat M, Idrus SM, Nawawi NM. Performance analysis of Sub carrier multiplexed system for radio over fiber technology. In: 2008 6th National Conference on Telecommunication Technologies and 2008 2nd Malaysia Conference on Photonics, 2008, pp. 226–9.
9. Fu H, Zhu K. Radio-over-fiber system with multiple-optical-source-based microwave photonic filter performing as a subcarrier demultiplexer. *IEEE Photonics J* 2011;3.2:152–7.
10. Holdenried CD, Haslett JW, Davies B. A fully integrated 10 Gb/s tapped delay Hilbert transformer for optical single sideband. *IEEE Microw Wireless Compon Lett* 2005;15.5:303–5.
11. Olshansky R. Microwave subcarrier multiplexing: new approach to wideband lightwave systems. *IEEE Circ Dev Mag* 1988;4.6: 8–14.