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Challenges to radio over fiber (RoF) technology and its mitigation schemes – A review

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ABSTRACT

For realization of future high performance integrated networks, broadband distribution and access networks and to meet the increasing demand of multimedia services with a guaranteed quality of service, RoF technology comes out as the most promising technology that combines the capacity of optical networks with the flexibility and mobility of wireless networks. Reduction in complexity at the antenna site, reduction in installation cost of access networks, possibility of dynamically allocation of radio carriers to different antenna sites, transparency and scalability are the few advantages of radio-over-fiber (RoF) technology. In this paper, we review the different challenges that limit the probable capabilities of RoF communication networks and different mitigation techniques to combat with these challenges to realize high-performance RoF links.

1. Introduction

Future broadband-wireless networks will probably use a radio over fiber (RoF) architecture to provide wireless connectivity to the users and to meet the increasing demand of multimedia services. The applications of RoF technology include cellular networks, satellite communication, Multipoint Video Distribution Services (MVDS), Mobile Broadband System (MBS) and Wireless LANs over optical networks [1]. As a matter of fact, the growing number of mobile subscribers coupled with the increasing demand of broadband services has kept sustained pressure on mobile networks to offer increased capacity. For example, from 2 G to 3 G mobile communications, a variety of wireless systems such as GPRS, Bluetooth, Ultra-Wideband, Wireless LAN and Hyper LAN, have been developed and more can be expected in 4 G mobile communications in which considerable difficulties must be faced by network operators in accommodating the increasing traffic to each user. RoF technology involves the use of optical components and techniques to allocate RF signals from the control stations (CS) to the base stations (BS). Thus, RoF makes it possible to centralize the RF signal processing function in one shared location (CS) with use of single mode optical fiber that has a very low signal loss to distribute the RF signals to the BSs [2]. The micro and pico-cellular architectures are installed with low power radio access points (RAPs) to increase the frequency reuse and capacity of a wireless network to provide wireless access and the best way to connect these RAPs to CS unit is RoF technology. Further, RoF technology allows a microcellular network system to be implemented by using a fiber-fed distributed antenna network. At each remote antenna, the received RF signals are transmitted over an analog optical fiber link to a CS unit where all the demultiplexing and signal processing functions are performed. Such architectures simply consist of a linear analog optical transmitter, an amplifier and a small low power transceiver of antenna that helps in reducing the cost of microcellular antenna site. Realization of such distributed antenna networks that can provide several advantages such as low RF power remote antenna units, frequency reuse, better coverage, high capacity, high quality signal as well as low fiber attenuation, RoF technology becomes an attractive, promising and potential technology in mobile communication. Even in the case that an RF interface is changed, no modification is necessary for RoF systems. With RoF technology, the antenna need not be within the control area but can be sited a lot of kms away for the purpose of improved satellite visibility or reduction in interference from other terrestrial communication systems.

This paper is divided into three sections. Some introductory application areas of RoF technology are presented in Section 1 followed by Section 2 that presents the previous research work on different schemes of optical millimeter-wave generation, challenges and their mitigation schemes in RoF technology and finally, the conclusion is reported in Section 3.

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2. Challenges and mitigation methods in ROF technology

Several methods have been reported for the generation of modulated RF optical carriers in fiber-wireless systems. These include optical heterodyne [3] and self-heterodyne techniques [4], and using pulsed lasers [5,6]. However, the simplest technique for the optical generation and distribution of the RF signal modulated with data is an intensity modulation scheme via direct or external modulation of a laser in which the RF signals are either externally or directly modulated onto the optical carrier. These optically modulated RF signals, then, are transported over an analog photonic link. This approach leads to a simple BS unit design which only requires optical-to-electrical conversion and RF amplification while enabling centralized control and management of the wireless signals. However, another schemes employed a single optoelectronic device, which is electroabsorption modulator that acts as a photodiode for the downlink and as a modulator for the uplink. It also replaces the laser, photodiode, circulator [7–10] and thus, known as electro-absorption transceiver. A new scheme is proposed [11] to generate double-sideband optical millimeter-wave with signal carried only by optical carrier that leads to the little influence of time shift of the sidebands on its transmission performance and suffered by fading effect only. The downlink 2.5-Gb/s data is successfully transmitted over 20-km single mode fiber with less than 0.15-dB power penalty by using four-wave-mixing effect in semiconductor optical amplifier for millimeter-wave generation in a millimeter wave radio-over-fiber system [12] and by using multiple-frequency Brillouin fiber-ring laser [14]. To increase the capacity and mobility of future-proof contents delivery and serve both fixed and mobile users, a new scheme to generate frequency-diversity binary phase shift keying (BPSK) signals for radio-over-fiber (RoF) system is proposed [13]. This duplex RoF system can generate 20 GHz and 40 GHz millimeter-wave (mm-wave) signals simultaneously with the data rate of 1.25 Gbps employing only one electrical optical phase modulator (EOPM) and one Mach–Zehnder modulator (MZM) at the central station and with one additional MZM at the base station. The OSSB signal generated by conventional modulation scheme experiences much distortion in the RF signal at the base station (BS) when the RF modulation index is large. The performance of such transmission links is largely improved in single-channel and dense wavelength-division multiplexing (DWDM) cases with suppression of undesired higher order harmonics by using a novel Mach–zehnder modulation technique [15] which employs a 1 × 4 multimode interference MMI coupler and four optical phase-modulator waveguides to generate optical single sideband (SSB) signals in radio-over-fiber (ROF) transmission link. The other schemes involve optical millimeter-wave generation and transmission for 1.25 Gbps downstream link using a gain switched laser [16], a 64 GHz optical millimeter-wave generation via a nested $LiNbO_3$ Mach–Zehnder modulator with an 8 GHz local oscillator [17], using one dual-parallel MZM with optical carrier suppression [18], without carrier suppression [20] and via frequency 12-Tupling [19]. The study has revealed that RF signals experience a number of inevitable signal impairments in RoF links such as non linear distortion consist of harmonic distortions (HDs) and intermodulation distortions (IMDs), both of which come from the nonlinear modulation characteristics of the optical modulators which leads to reduce dynamic range. In addition, the impact of fiber chromatic dispersion on the transported RF signals becomes more pronounced with increasing RF carrier frequency as shown in Fig. 1. A number of different strategies have been proposed and demonstrated to measure and overcome these impairments.

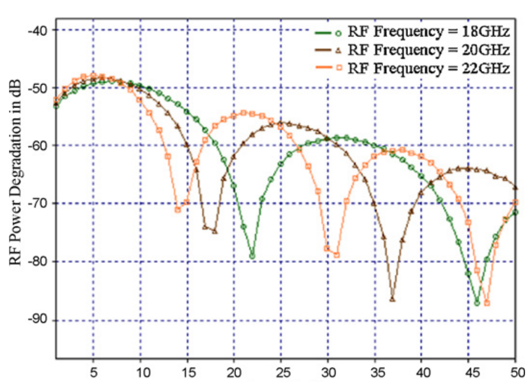

Fig. 1. Dispersion induced RF power degradation versus optical distances at different RF frequencies with $\alpha_{MZ} = -3$ using single-electrode MZM modulator.

2.1. Impact of chromatic dispersion and its mitigation

In conventional intensity modulation (IM), the optical carrier is modulated to generate an optical field with the carrier and two sidebands. At the optical receiver, each sideband beats with the optical carrier, thereby generating two beat signals which constructively interfere to produce a single component at the RF frequency. However, if the signal is transmitted over fiber, chromatic dispersion causes each spectral component to experience different phase shifts depending on the fiber-link distance, modulation frequency, and the fiber-dispersion parameter. These phase shifts result in relative phase differences between the carrier and each sideband, and produce a phase difference in the two beat signals at the RF frequency, which results in a power degradation of the composite RF signal. The phase changes in the optical sidebands change the resultant phase of the RF beat signals and the RF power, P_{rf} will vary [21–23] as

$$P_{rf} \propto \cos\left[\frac{\pi . L . D . \lambda^2 . f^2}{c}\right] \quad (1)$$

where D = fiber dispersion parameter in ps/nm/km, c is the velocity of light in a vacuum, L = fiber transmission length, f_{rf} = RF carrier frequency, and λ = carrier wavelength. From the results given by Eq. (1), it can be seen that the RF power varies in a periodic manner with complete power suppression occurring at specific modulating frequencies and at phase difference of π. Also, as RF frequency increases, the effect of dispersion becomes more pronounced and the fiber-link distance is severely limited [21–23].

Various techniques have been proposed and demonstrated to mitigate fiber dispersion effects in RoF system including Up/Down Conversion techniques [24–28] where the IF signals is transmitted over optical fiber instead of RF signal and deals with minimum fiber dispersion induced power degradations as the transmission of IF-band optical signal is almost free from the fiber dispersion effect. But, unfortunately, these techniques add an additional cost to the system because of addition devices are involved such as mm-wave oscillator along with a high conversion efficiency RF mixer designed with use of high bandwidth and fast mixing elements such as metal semiconductor metal photo-detector (MSM-PD), high electron mobility transistor (HEMT), hetero-junction bipolar phototransistor (HPT), and hetero-junction bipolar transistor (HBT). Incorporating of high speed external modulators such as electro-absorption modulator (EAM) in RoF system design [29–33] leads a simple configuration and can support high frequency RF signals. By varying the chirp parameter of a dual-electrode Mach–Zehnder external modulator (DEMZM) to give large negative chirp biased at quadrature, dispersion induced power degradations is reduced in fiber-wireless systems. The successful transmission of a 51.8 Mbps BPSK data at 12 GHz over 80 km of standard single-mode fiber is achieved with power penalty of less than 0.5 dB due to dispersion

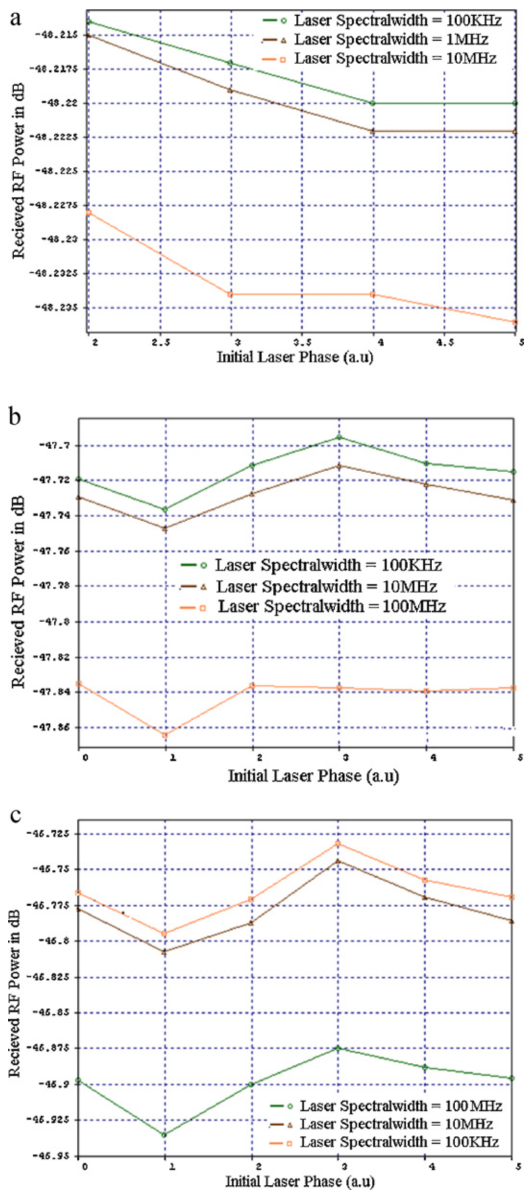

Fig. 2. Reduction and measurement of dispersion effect (a) using OSSB technique [27] and by minimizing laser spectral width [29] with (b) chirp = 0, (c) chirp = −1 and (d) chirp = −3.

for a BER equal to 10^{-9} by implementing a DEMZM to generate an optical carrier with single sideband (SSB) modulation [29,30]. With minimum laser spectrum widths of light sources in such systems, a BER power penalty due to fiber dispersion can be further reduced [32] as shown in Fig. 2. Together with tolerance to dispersion, these approaches potentially provide simple implementation and high linearity but are suffered from high insertion-, RF return-loss, frequency chirping, require high drive voltage and thus, have to pay a fixed 6 dB power penalty. To save this additional power requirement, the biasing of the electro-optical modulator is done at the minimum transmission point, instead of biasing at the quadrature point which results in an increased frequency-length product in millimeter-wave optical systems [34]. Using optical carrier suppression technique [34,35], a feasible solution for the future RoF based optical-wireless access networks can be realized, providing a successful transmission of 2.5 Gbps data for bidirectional transmission over 40 km with less than 2 dB power penalty due to dispersion. These schemes has very simple and cost-efficient configuration, high spectral efficiency due to using the same wavelength, and good performance on long-distance transmission. In addition to the above mentioned techniques, external filtering with use of fiber grating can be used to produce single-sideband optical modulation for the elimination of the fiber dispersion penalty on conventional external optical intensity modulation at millimeter-waves [36–39]. A filter designed with three dynamic Bragg gratings that is controlled by the input optical double sideband signal itself, which makes it independent of the modulated optical carrier wavelength and generate SSB signals may be used to mitigate the power degradation due to chromatic dispersion [38] and an Arrayed Waveguide Grating (AWG) device that act as a wavelength multiplexer of the different optical channels and SSB generator can also be used for very high frequencies (>20 GHz) to provide an elimination of the career suppression effects (CSE) [39]. The fiber nonlinearities such self phase modulation (SPM) and Four wave mixing (FWM) are also playing a vital role in reducing the dispersion penalties [40–43]. A significant reduction of chromatic dispersion effects is achieved by generating a chirp distortion effect by using SPM effect of fiber opposite to that induced by the chromatic dispersion [40] or by generating of a phase-conjugated wave by means of FWM in a DSF placed at the midspan of the fiber-optic link [41] or by using midspan optical-phase conjugation [43]. The Optical Heterodyne schemes [44,45] also offer minimum fiber dispersion effect with high intensity of modulation depth and provide high link gain with high carrier-to noise ratio (CNR) but add more complexity in system designing as it includes complicated light sources.

2.2. Nonlinear distortion and its mitigation

In RoF architecture, data signals are generated at CS unit, modulated onto an optical carrier, sent over optical fiber to many base stations (BSs), and then transmitted over the air to users. It is expected that these broadband hybrid radio/fiber systems will divide the available radio spectrum into a number of channels for broadcasting and the RF bands to be used will be higher than the 2.4 GHz RF band to be used for 3 G systems. Taking these two points into account, it is clear that a major problem that may be encountered in these networks will be nonlinearity problems of the various devices used. The systems that use direct modulation of the laser transmitter with the multi-channel RF signal, the dynamic nonlinearity of the laser diode may impose serious limitations on the system performance due to inter-modulation distortion (IMD) effects. A vast research work has been done to reduce this non linearity problem. One method of reducing the nonlinearity of laser diodes is the use of external injection into the directly modulated laser from a second laser source. Under external injection conditions, the relaxation frequency of the laser may be increased significantly and the modulation response at lower frequencies can be made significantly more linear than that without external injection [46–50]. This helps in reducing IMD problems. In this case, the greatly improved system performance is due to the enhanced modulation response of the laser at RF band employed in the hybrid system. However, the nonlinear response of the laser with external injection may still cause problems for multi-carrier radio-over-fiber systems. By linearization of the lasers-modulation response, an improvement of 2 dB is achieved of a multi-carrier radio-over-fiber system operating at a frequency of 6 GHz [50]. Further, a vector control theory (VCT) based circuit [51] provides the third-order inter modulation (IMD3) suppression for two-tones by maximum 38 dB even after 20 km regardless of distance or dispersion. To improve the link performance, the second- and third-harmonic generations of single- and two-tone RoF systems have been studied and minimized using external-laser modulation techniques with EDFA [52,53] as shown in Fig. 3. To minimize the nonlinear effects from optoelectronic conversion, the amplitude of the drive signals

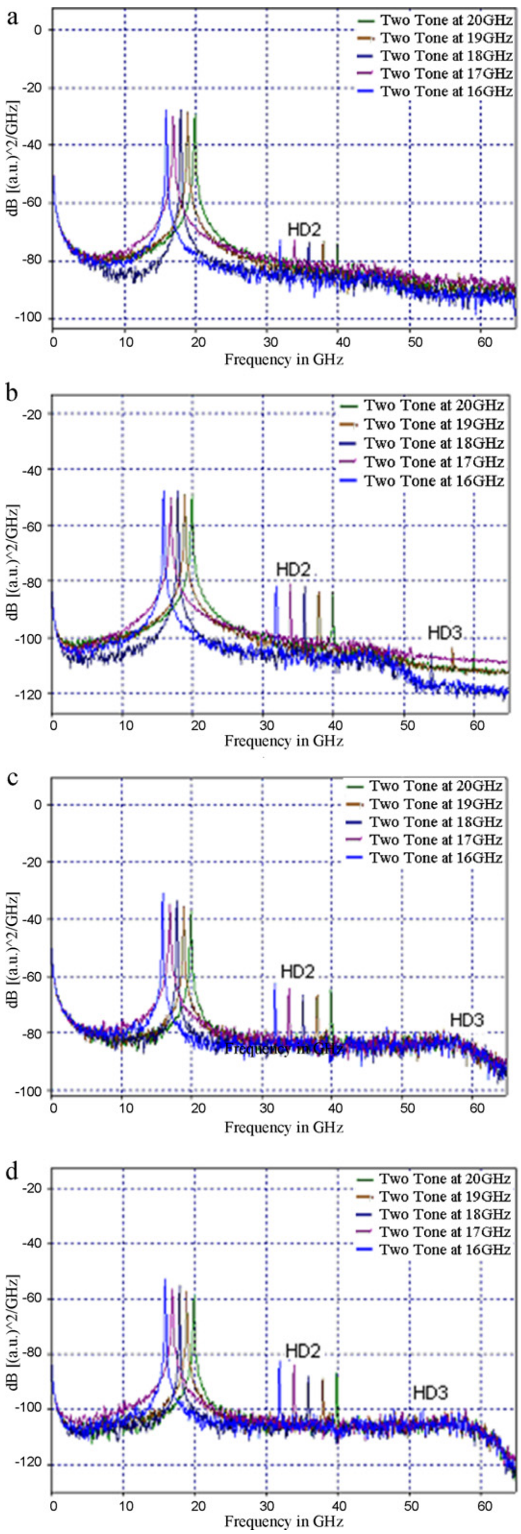

Fig. 3. Harmonic distortion (HD) measurement of two tone RoF system [52] at chirp = 0 with (a) EDFA with external modulation, (b) SOA with external modulation, (c) EDFA with direct modulation and (d) SOA with external modulation.

need to be kept low and RoF signals experiences a weak modulation due to the narrow linear region of intensity modulators which leads to low conversion efficiency and thus, reduced the carrier-to-side band ratio. To improve the link performance, the optical power of the signals can be increased by using a high power optical source or an optical amplifier; however, this may lead to increase the inter-modulation distortions at the receiver or even damage the receiver due to a large optical power incident on the optical detector. Due to the inherent low modulation efficiency at mm-wave frequencies, the mm-wave radio signals are typically weakly modulated onto the optical carrier which leads to a relatively large carrier to-sideband ratio. The modulation depth improvements of RoF system can be achieved to improve system dynamic range and to reduce carrier to-sideband ratio of the mm-wave modulated signal to be operated slightly above the SBS threshold to use SBS as a carrier filter to reject the carrier while allowing the modulation sidebands to pass with low loss [54,55]. Efficiency improvements can be achieved by employing an external delay line filter with MZM modulator biasing at quadrature [56] and by carrier subtraction method using a Fabry–Perot filter operating in the reflection mode [57]. Both of these techniques increase the fiber-optic link efficiencies by increasing the modulation depth. But, the second order distortion products increase rapidly as the bias is shifted towards the null, which restricts the usefulness to sub-octave applications. The optical power at the quadrature bias point is 13 mW, which exceeds the limitation of photodiode.

An alternative method of carrier filtering is used that uses a feedback loop to control the MZ biasing to produce the photocurrent of 1.5 mA. The idea is to bias the MZM away from quadrature towards the minimum transmission point. The bias shift method of carrier filtering introduces low loss, and fewer components involvement compared with using an external filter.

A number of techniques have been proposed for increasing the modulation of the mm-wave modulated signals including Brillouin scattering schemes and the use of external optical filters which adds not only the system complexity but also cannot be applied to a wide range of signal formats, modulation depths, and radio frequencies. Therefore, the simple and inexpensive passive techniques using narrowband fiber Bragg grating with different reflectivities for increasing the modulation depth to provide better transmission performance for radio over fiber systems are reported [59–61]. These techniques are applicable to a wide range of radio frequencies and modulation depths and thus, can be applied in a conventional downstream link and also for the upstream in a wavelength-reused scheme. Further, the performance of the fiber-wireless links can be significantly improved when the optical signal is transmitted at the optimum CSR of 0 dB [62].

3. Conclusion

A comprehensive review of research in the area of radio-over-fiber (RoF) systems on the challenges that exist within the RoF link and strategies to mitigate these various optical impairments to enhance the overall link performance is presented in this work. The main focus of this work is to put attention towards the realization of future high performance integrated networks, mobile broadband distribution and access networks by reviewing the past few year efforts in the area of impairments associated with RoF links and its mitigation techniques.

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