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A Novel Configuration for Millimeter-Wave Radio-over-Fiber (ROF) Transmission Systems with Remote Local-Oscillator Delivery

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Abstract A novel configuration for millimeter-wave (mm-wave) radio-over-fiber transmission systems with remote local-oscillator (LO) delivery was proposed. The proposed technique provides a very simple solution to base-station access points for pico-cellular networks in order to distribute the future broadband wireless-access services. Both numerical and simulation results show that, 622 Mbit/s binary-phase-shift-keying (BPSK) data in the downlink can be successfully transmitted with a bit error rate $\leqslant 10^{-9}$ over 30 km of a conventional single-mode fiber, for a laser output power of -6.5 dBm, an optical gain of 6 dB, and laser linewidths (LLW's) of 1 MHz, 75 MHz, and 150 MHz, respectively. The variance of an additional phase error of the remotely delivered mm-wave LO due to laser phase noise and fiber dispersion is calculated to be only about 30.4 mrad (1.74°), in the case of the relatively large LLW of 150 MHz and a fiber length of 30 km.

Keywords Optical fiber communications; Radio-over-fiber; Millimeter-wave communications; Mach-Zehnder modulator; Remote local-oscillator delivery

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0 Introduction

With the development of next-generation wireless communication technologies, pico-cellular networks and millimeter-wave (mm-wave) carriers will be employed for distribution of future broadband wireless-access services[1]. In such systems, a pico-cell with radius of tens or hundreds of meters has the advantages of increased available bandwidth and frequency reuse efficiency. However, a disadvantage of this scheme is that a large number of base stations (BS's) must be installed to provide the full radio coverage, thus making the design of cost-effective BS's essential. Optical generation and transmission of mm-wave signals or called the "radio-over-fiber" (ROF) can have a potential of greatly simplifying the design of BS's by the use of remote optical heterodyne. This technology has attracted much interest recently.

It has been shown that, in a full-duplex ROF-access system, the BS structure for uplink transmission can be simplified if the mm-wave local-oscillator (LO) is remotely delivered from a central office (CO) in order to down-convert the received uplink mm-wave carrier to the intermediate-frequency (IF) band[2~5]. However, the schemes given in [2, 3] have relatively poor power spectral efficiency, while the method proposed in [4] needs the stabilization of central frequencies for two lasers, which is a rather difficult task to do.

The problems associated with remote delivery of mm-wave local-oscillator can be eliminated when the scheme proposed by the authors of this paper is used, and the better link performance has been achieved[5]. In this paper, a novel and even simpler configuration for ROF transmission systems with remote LO delivery was proposed. Both numerical and simulation results show that, 622 Mbit/s binary phase-shift keying (PSK) data in the downlink can be successfully transmitted at the BER$\leqslant 10^{-9}$ (without any repeater) over 30 km of a conventional single-mode fiber, for a laser output power of -6.5 dBm, an optical gain of 6 dB, and laser linewidths (LLW's) of 1 MHz, 75 MHz, and 150 MHz, respectively. After transmission over 30 km of a conventional fiber (with dispersion parameter of 17 ps/nm/km), even in the case of a large LLW of 150 MHz, the variance of an additional phase error of the remotely delivered mm-wave LO is calculated to be only about 30.3 mrad (1.74°), which is caused by the laser phase noise and fiber dispersion.

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1 Modulation scheme and system configuration

1.1 The proposed modulation scheme

A dual-electrode Mach-Zehnder modulator (MZM) can be modeled as two phase modulators in parallel. Then the lightwave signals from a common optical source can be separately modulated in two arms of a MZM by applying different radio-frequency (RF) driving signals to its two RF electrodes. Fig. 1 shows the proposed modulation

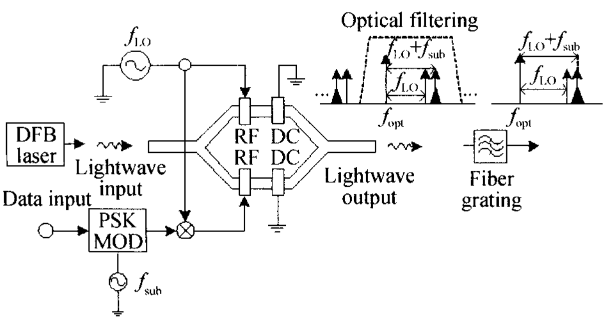


Fig. 1 Diagram of the proposed modulation scheme

scheme based on the principle of ROF transmission with remote mm-wave LO delivery. The two direct-current (DC) biasing electrodes are grounded; while one of the RF electrodes is applied a mm-wave LO at the frequency f_{LO} to be delivered and another RF electrode is used for a data carrier signal with binary PSK (BPSK) modulation (MOD) at the frequency of $f_{LO}+f_{sub}$, where f_{sub} is the sub-carrier frequency (see Fig. 1). If the output of a distributed feedback (DFB) laser is

$$E_{LD}=\sqrt{2P_o}\cos\left[\omega_o t+\phi(t)\right] \tag{1}$$

where P_o is the laser output power, ω_o is the optical angular frequency, $\phi(t)$ is the laser phase noise. Then the output of a dual-electrode MZM is given by[5]

$$E_M=\sqrt{P_o/2I_M}\cos\{\omega_o t+\beta\pi\cos\left[(\omega_{LO}+\omega_{sub})t+\varphi_s(t)\right]+\phi(t)\}+\sqrt{P_o/2I_M}\cdot\cos\{\omega_o t+\beta\pi\cos\omega_{LO}t+\phi(t)\} \tag{2}$$

where I_M is the MZM insertion loss, β is the normalized driving voltage of a MZM, $\omega_{LO}=2\pi f_{LO}$, ω_{sub} is the angular frequency of a sub-carrier, $\varphi_s(t)$ represents the BPSK data such that $\varphi_s(t)=0$ for a binary "1" and $\varphi_s(t)=\pi$ for a binary "0". Equation (2) can be expanded into the Bessel series

$$E_M=\sum_{n=-\infty}^{\infty}J_n(\beta\pi)\sqrt{P_o/2I_M}\cos\left[(\omega_o+n\omega_{LO}+n\omega_{sub})t+\frac{n\pi}{2}+n\varphi_s(t)+\phi(t)\right]+\sum_{n=-\infty}^{\infty}J_n(\beta\pi)\cdot\sqrt{P_o/2I_M}\cos\left[(\omega_o+n\omega_{LO})t+\frac{n\pi}{2}+\phi(t)\right] \tag{3}$$

where $J_n(\cdot)$ is the nth Bessel series of the first kind. It is clear that the MZM output contains the original optical carrier component at the frequency f_o, the sidebands at $f_o\pm f_{LO}$, other sidebands at $f_o\pm(f_{LO}+f_{sub})$, and higher-order harmonics.

To avoid the signal fading found in optical double sideband systems due to the fiber chromatic dispersion[6], a fiber grating (FG) is used to tailor the MZM output spectrum such that only the components at the frequencies of f_o, f_o+f_{LO} and $f_o+f_{LO}+f_{sub}$ are reserved, while all the other sidebands and higher-order harmonics are eliminated. Thus, the transmitted optical signal can be given by

$$E_T=\sqrt{2P_o/I_M I_{FG}}J_0(\beta\pi)\cos\left[\omega_o t+\phi(t)\right]+J_1(\beta\pi)\sqrt{P_o/2I_M I_{FG}}\cos\left[(\omega_o+\omega_{LO})t+\pi/2+\phi(t)\right]+J_1(\beta\pi)\sqrt{P_o/2I_M I_{FG}}\cos\left[(\omega_o+\omega_{LO}+\omega_{sub})t+\pi/2+\varphi_s(t)+\phi(t)\right] \tag{4}$$

where I_{FG} is the insertion loss of a FG.

After the square-law detection of a photodiode (PD) in the BS, the beats among the three spectral components in Eq. (4) yield the mm-wave LO at f_{LO} and the mm-wave carrier signal at $f_{LO}+f_{sub}$. In a general case, the deviation of fiber dispersion induced propagation delays for those three components are not significant. They can thus keep to be highly correlated after the fiber delivery when they are from a common optical source. Then the laser phase noise can be counteracted through the beating process, and the pure mm-wave signals can be obtained.

1.2 System configuration

Fig. 2 shows the proposed system configuration based on the modulation scheme discussed above. An erbium-doped fiber amplifier (EDFA) is used to compensate the loss of both the MZM and the FG. An optical bandpass filter (OBPF) removes the out-of-band amplified-spontaneous-emission (ASE) noise from the EDFA. After optical fiber transmission, a broadband PD is used to recover the mm-wave LO and the mm-wave BPSK carrier-modulated signal, respectively. They are separately filtered out by the use of two electrical bandpass filters. After the electronic amplification, the mm-wave BPSK signal is radiated out to the air, while the mm-wave LO is used to down-convert the received uplink mm-wave carrier (from a mobile terminal) into the IF band for uplink transmission. In a general case, an uplink data rate is low (≤tens of Mbit/s) and a fiber connecting distance is also short (≤tens of kilometers). Thus, a cheap source like Fabry-Perot

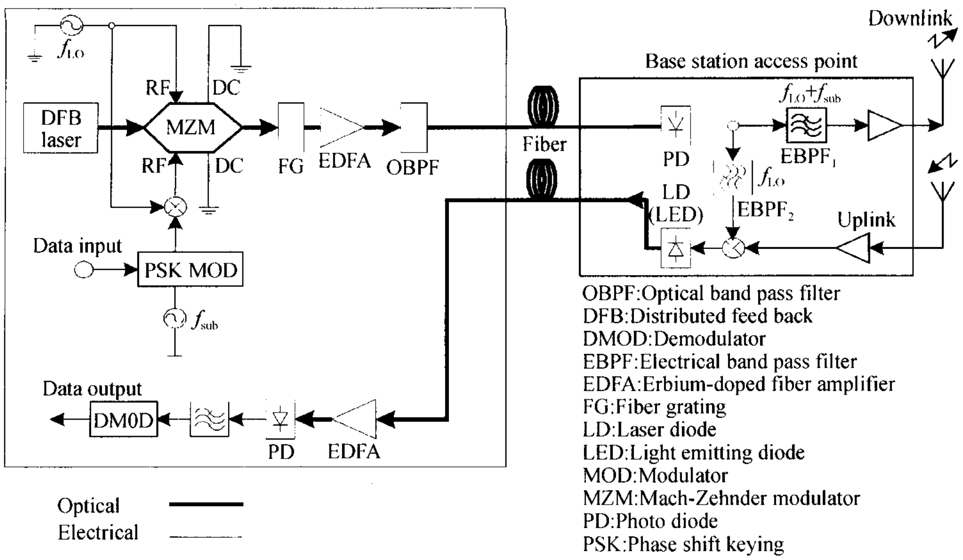


Fig. 2 The proposed system configuration for ROF transmission with remote mm-LO delivery

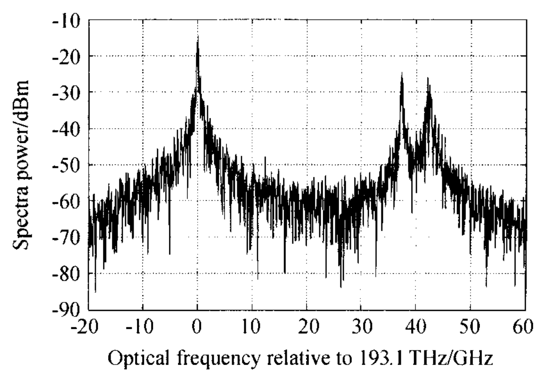
(FP) laser or even light emitting diode (LED) can be used in the uplink fiber transmission when the power budget is sufficient[2]. In doing so, the cost of a BS can be further reduced.

2 Numerical and simulation results

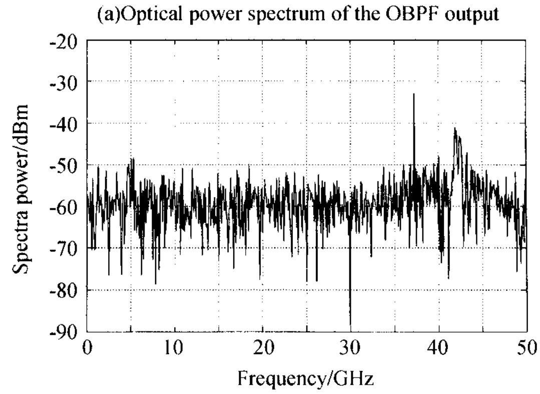
The performance of the proposed system is investigated by both numerical analysis and computer simulation based on our previous method presented in [5]. For the purpose of comparison, the same parameters listed in Table 1 are used in both computation cases. The wavelength is set to 1553.6 nm, which corresponds to a standard optical frequency of 193.1 THz. Fig. 3 shows the simulated optical power spectrum at the output of an OBPF and the electrical power spectrum of the detected photocurrent in the BS . In order to

Table 1 Main parameters used in the calculation and the simulation

Wavelength/ Optical Frequency	1553.6 nm/ 193.1 THz
Laser Output Power	−6.5 dBm
Laser Linewidth	1 MHz/75 MHz/150 MHz
Frequency of the MM-Wave LO	37.32 GHz
Frequency of the Sub-Carrier	4.976 GHz
Normalized Driving Voltage of the MZM	0.35
3 dB Linewidth of the FG	80 GHz
EDFA Gain	6 dB
Spontaneous Emission Factor of EDFA	2.75
Fiber Length	30 km ~ 39 km
Fiber Dispersion	17 ps/nm/km
Fiber Loss Parameter	0.25 dB/km
Efficiency of the PD	0.8 W/A
3 dB Bandwidth of the Electrical BPF	4.976 GHz
Noise Figure of the Receiver	6 dB
Transmitted Data Rate and Type	622 Mbit/s BPSK



(a)Optical power spectrum of the OBPF output



(b)Electrical power spectrum of the photo current

Fig. 3 Simulated power spectra for 622 Mbit/s BPSK data transmission over 30 km of a conventional fiber, with parameters: $f_o = 193.1$ THz, laser linewidth = 150 MHz, laser output power = −6.5 dBm, $f_{LO} = 37.32$ GHz, and $f_{sub} = 4.976$ GHz

demonstrate the counteraction of laser phase noise, a LLW of 150 MHz and a dispersion parameter of 17 ps/nm/km have been used in the simulation. As shown in Fig. 3(a), the frequency at 193.1 THz is the original spectral component, the one at 193.1 THz + 37.32 GHz is the upper sideband from the arm driven by the mm-wave LO, and the other frequency at 193.1 THz + 37.32 GHz + 4.976 GHz is the upper sideband from the arm driven by the mm-wave BPSK carrier-modulated signal. By this optical spectrum arrangement, the recovered mm-wave LO at 37.32 GHz and the mm-wave BPSK carrier at 42.296 GHz are clearly shown in Fig. 3 (b). The purity of the recovered mm-wave LO can not be directly observed because of the frequency-resolution limitation. However, it can be investigated by calculating the variance of its additional phase error caused by the laser phase noise and the fiber dispersion delay[6]. In the case of LLW = 150 MHz and fiber length = 30 km, the extra phase-error variance of a mm-wave LO is about 1.74°, a small value due to the optical beating components from a common source. From Fig. 3(b), a weaker carrier at 4.976 GHz is also seen. It is caused by the beat of two optical upper sidebands.

By using the method given in [5], the bit error rate (BER) is calculated and plotted against the transmission distance as a function of LLW shown in Fig. 4(a) where the simulated BER is also illustrated. Because of the speed limitation in the computer, the simulated BER is not directly from the bit-errors counting, but is obtained by analyzing the corresponding eye diagrams. For simplicity, the air transmission effect is not considered in the calculation and simulation, respectively. This assumption is reasonable since the BER performance of cellular wireless transmission is much lower than that of optical fiber transmission section. As shown in Fig. 4, the results obtained from both calculation and simulation tally with each other very well. This makes our confidence to both methods. It can be seen that, for 622 Mbit/s BPSK data transmission over 30 km of a conventional single-mode fiber, the BER less than 10^{-9} can be achieved with a laser output power of −6.5 dBm, an EDFA gain of 6 dB, and laser linewidths of 1 MHz, 75 MHz, and 150 MHz, respectively.

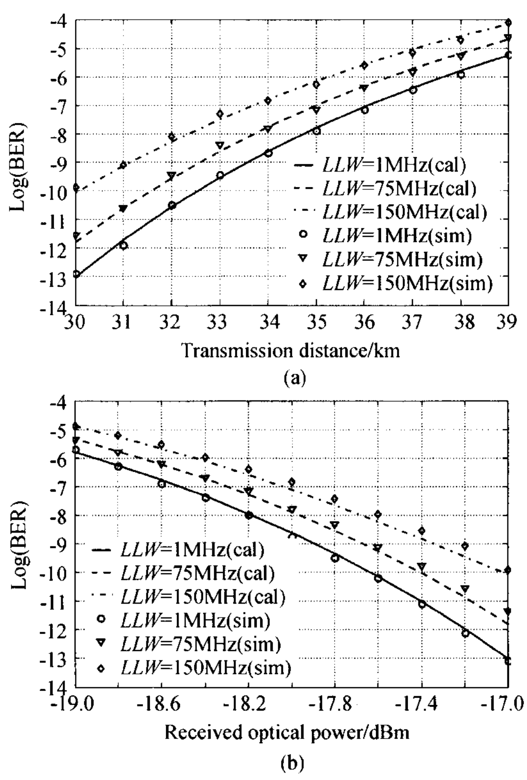


Fig. 4 Calculated and simulated BER versus (a) the transmission distance and (b) the received optical power as a function of LLW, for 622 Mbit/s BPSK data transmission over a conventional fiber. sim: simulated results. cal: calculated results

Fig. 4(b) shows the BER versus the received optical power as a function of LLW. In this case, a fiber length of 30 km is simulated, and an optical tunable attenuator is used before the photodetection to verify the received optical power. The results show that, for 622 Mbit/s BPSK data transmission over 30 km of a conventional fiber, the BER less than (or equal to) 10^{-9} can be obtained with a received optical power of −17.2 dBm.

3 Conclusion

This paper has proposed a novel configuration for ROF transmission systems with remote mm-wave LO delivery. By using the proposed modulation scheme, a very simple BS solution can be achieved. The simulated power spectra have verified the feasibility of our proposal. Moreover, both the calculated and simulation results have shown that, the 622 Mbit/s BPSK data can be transmitted over 30 km of a conventional single-mode fiber with the BER less than 10^{-9}, for a laser output power of −6.5 dBm, an optical gain of 6 dB, and laser linewidths of 1 MHz, 75 MHz, and 150 MHz, respectively. The variance of an additional phase error due to laser phase noise and fiber dispersion for the remotely delivered mm-wave LO is calculated to be only 1.74°, with a fiber length of 30 km and a laser linewidth of 150 MHz.

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一个新型的毫米波无线信号光纤传输系统及本振信号远程传送结构

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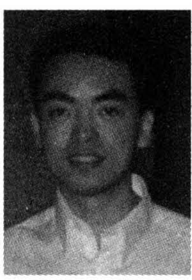
摘　要　提出一个新型的毫米波光纤传输系统及本振信号远程传送的结构．此技术能为将来使用皮蜂窝网络提供宽带无线接入服务给出一个简单的基站接入点解决方案．计算和仿真结果表明,在激光器输出功率为−6.5 dBm,光放大增益为 6 dB,激光线宽为 1 MHz,75 MHz 或 150 MHz,误码率不超过 10^{-9} 的情形下,622 Mbit/s 的下行相移键控信号能够在传统单模光纤上传输超过 30 km 的距离．在具有相对大的激光器线宽 150 MHz 和光纤距离为 30 km 时,由激光器相位噪音和光纤色散所引起的(通过远程传送的)毫米波本振信号的额外相位误差的方差仅为 1.74°.

关键词　光纤通信;无线信号的光纤传输;毫米波通信;马赫-曾德调制器;远程本振信号传送



Zhou Mingtuo　was born in March 1977, Sichuan, China. He received his bachelor, master and Ph. D. degree (all in EE) in 1997, 2000, and 2004, respectively. Since July 2004, he is with the Wireless Communications Laboratory, National Institute of Information and Communications Technology (NICT), as a researcher. His research interest includes optical communications, radio-over-fiber, radio channel modeling, and high-speed wireless communication technologies.