Coherent-Detection of Narrow-Linewidth Millimeter-wave and Microwave Subcarrier Signals for Future Mobile/Personal Communications

Wing C. Kwong, Paul R. Prucnal†, and Malvin C. Teich‡

Department of Engineering, Hofstra University, Hempstead, NY 11550
†Department of Electrical Engineering, Princeton University, Princeton, NJ 08544
‡Department of Electrical Engineering, Columbia University, New York, NY 10027

ABSTRACT Optical wireless offers broadband telecommunication services in confined and densely populated environments. It also avoids the utilization of the scarce and already-congested radio spectrum. However, the optical transmission power in optical wireless systems is restricted to a level that may severely degrade the system performance because of human-safety reasons. A coherent-detection technique for very narrow linewidth millimeter-wave and microwave subcarrier signals is investigated and demonstrated. This technique is particularly suitable for power-limited optical wireless systems. In addition, wide channel-tunability and improved receiver-sensitivity are supported even with cheap, wide-linewidth semiconductor lasers, without using expensive optical amplifiers.

1. Introduction

Wireless local-area networks (LAN's) have been proposed to provide telecommunication services, such as digital HDTV, personal communication services, video phone, data transfer, and multi-media, within confined or densely populated environments (e.g., offices and metropolises) because they provide easy hardware reconfiguration, flexible access, and connectivity in an easy-to-use way to the widest possible community of users [1]. Traditionally, wireless communication uses radio and/or microwave (i.e., subcarrier) technologies. However, the radio spectrum (of about 20-30 MHz) is a very limited resource and will get congested easily as the traffic demand rises; thus limiting the broadband capability of wireless transmission for densely populated environments. Therefore, "optical" wireless, offering much wider bandwidth, is a good alternative. In addition, optical radiation is highly containable and does not interfere with other electronic systems in the same service area.

As a result, the issues facing the development of optical wireless systems, such as optical safety and involved technology, have recently been studied. To ensure that the optical radiation posses no harm to human, especially eyes and skin, various national and international standards on laser safety, such as IEC825, has been published to specify the safe optical emission levels from lasers [2]. In addition, to reduce particularly the danger of eye damage, diffusely scattering transmission has been proposed, where optical signals, usually in the form of millimeter-wave or microwave "subcarriers", generated from various locations in an office are directed to a hologram at the ceiling. The signals are then distributed uniformly and finally downward-broadcasted to the whole area [3]. For distributing signals among offices (i.e., within a building), an optical equivalence of a leaky feeder (i.e., a special type of optical fibers) can be used [3]. Furthermore, for communications between two buildings, which are in the line-of-sight, atmospheric optical transmission using a similar subcarrier technique can be employed [4]. Fig. 1 summarizes the application of optical wireless within and between two buildings.

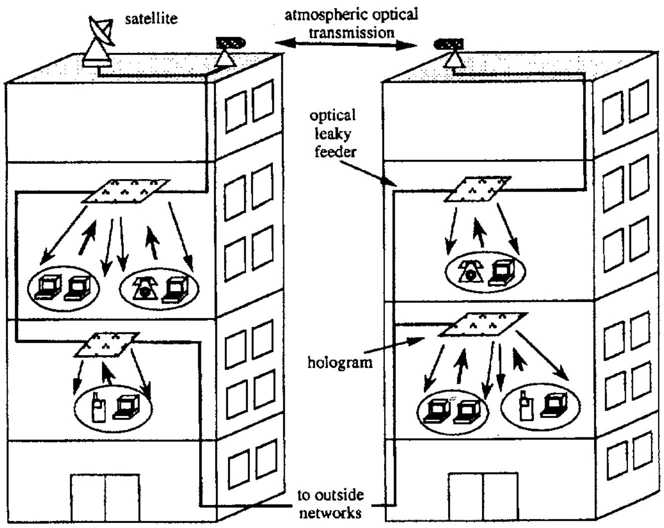

Figure 1: An application of optical wireless

As in the technological aspect, a simple and potentially low-cost method for the optical generation of very narrow linewidth millimeter-wave and microwave subcarrier signals for optical wireless LAN's and mobile/personal communications was demonstrated [5]. This technique uses a properly biased Mach-Zehnder waveguide modulator to introduce a millimeter-wave or microwave subcarrier onto the intensity of an arbitrary-linewidth continuous-wave (CW) semiconductor laser. A frequency-modulated (FM) optical signal with two strong components (i.e., sidebands) separated by twice the subcarrier frequency are generated. Coherently mixing of these two sidebands at a photodiode results in an electrical millimeter-wave or microwave signal with linewidth depending only on the electrical source that drives the modulator.

However, the conversion efficiency from the electrical domain to the optical domain at the modulator is relatively low. Together with the restriction on the maximum permissible laser exposure, the transmission power of the optical subcarriers is very limited and the system performance may be severely degraded. Using a typical office with a floor area of 100 m^2 as an example [2], the maximum optical transmission power is assumed, say at 1300 nm, to be 10 mW. Using a photodetector with a collection area of 1 cm^2, the receiving power after diffuse-scattering is only 10 nW, which is well below the acceptable receiver sensitivity for any useful application. Although the degradation can be overcome by the deployment of high-gain optical amplifiers at the front-end of receivers, it may not be justified in some situations because of the high cost or some pre-existing physical constraints. In addition, channel tunability may also be an important factor to consider in some applications.

Therefore, a "coherent-detection" technique may serve as a good alternative in such systems, since it provides improved sensitivity (i.e., theoretically, by at least 10 dB) and also supports a wide channel-tuning range [6]. In the proposed technique, photodiodes are used solely for converting the FM optical signals into intermediate-frequency (IF) electrical signals. Coherent-mixing of two strong IF components through a nonlinear (e.g., square-law) operation results in a phase-noise-cancelled signal at the receiver. As a result, the final signals is only a weak function of the laser linewidth, while conventional coherent-detection systems degrade severely even in the presence of small amount of phase noise (i.e., a few percentage of the data bit rate) [6]. Therefore, cheap, wide-linewidth semiconductor lasers can still be used to keep the system cost down.

2. Operation Principle

The set-up of the transmitter and receiver are shown in Fig. 2 [6]. The laser source generates an optical continu-

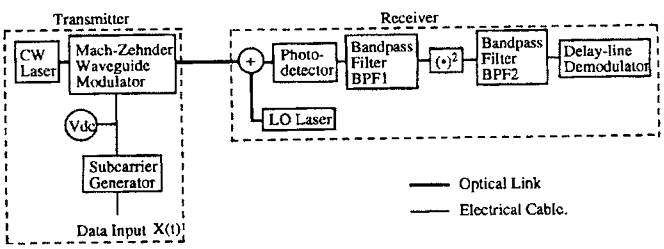

Figure 2: Block diagram of the transmitter and receiver

ous wave (CW) at a given center frequency f_c with phase noise $\theta_c(t)$. The electrodes of the Mach-Zehnder waveguide modulator are driven by a DC bias voltage V_{dc} added to a sinusoidal drive signal $V_{drvie}(t) = V\cos(2\pi x(t))$ generated by the subcarrier generator, where V is the amplitude and

$$x(t) = \tfrac{1}{2}(f_s t + f_d \int_0^t X(t')dt') \qquad (1)$$

is the microwave subcarrier with continuous-phase frequency-shifted keying (CPFSK) modulated information. f_s is the microwave carrier frequency of the CPFSK signal after phase-noise cancellation at the receiver. $X(t) \in \{-1, +1\}$ is a binary data sequence with a bit period T. f_d is the frequency deviation, defined by the modulation index $m \overset{\text{def}}{=} 2f_dT$.

The optical CW signal is split in the two waveguides of the modulator and then phase-modulated by the drive signal $V_{drive}(t)$. Because of the push-pull design of the electrode structure, two optical fields with the same optical parameters (i.e., f_c and $\theta_c(t)$), but opposite phase components are generated and later recombined at the output. The resulting optical field $E(t)$ can then be written as

$$\begin{aligned} E(t) \;\propto\; & e^{j(2\pi f_c t + \theta_c(t) + \Theta + \Phi\cos(2\pi x(t)))} \\ & + e^{j(2\pi f_c t + \theta_c(t) - \Theta - \Phi\cos(2\pi x(t)))}, \end{aligned} \qquad (2)$$

where $\Theta \propto V_{dc}$ is the phase difference between the fields imparted by the two waveguides and Φ, controlled by the subcarrier amplitude V, is the phase modulation depth. (2) simply represents a frequency-modulated (FM) optical signal with harmonic frequencies related to the subcarrier $x(t)$. The harmonics are used effectively by setting $\Theta = \frac{1}{2}\pi$ to generate a *double-sideband suppressed-carrier* signal, where

$$E(t) \propto \sum_{\substack{n=-\infty \\ n=\text{odd}}}^{\infty} 2J_n(\Phi) e^{j(2\pi f_c t + \theta_c(t) + 2\pi n x(t) + \frac{1}{2}n\pi)}. \qquad (3)$$

$J_n(\Phi)$ is the Bessel function of the first kind with integer order n. For Φ within the range of interest (i.e., $\Phi = [1.0, 1.5]$ rad), terms with $|n| > 3$ are negligible. Only those terms with $J_{\pm 1}(\Phi)$, which are the two sidebands (i.e., strong components), and $J_{\pm 3}(\Phi)$ contribute appreciably. Actually, the adverse effects caused by terms with $J_{\pm 3}(\Phi)$ can be minimized by carefully adjusting the system parameters.

As also shown in Fig. 2, the receiver consists of a local oscillator (LO) laser, a photodiode, a bandpass filter BPF1, a square-law device, a narrow-bandpass filter BPF2, and a delay-line demodulator. Here, polarization fluctuations and intensity noise of the optical signal and LO laser signal are ignored for simplicity; otherwise, the standard polarization-diversity and dual-balanced detector configurations can be added to the receiver with some minor modifications [7], [8].

The desired intermediate-frequency (IF) signal (i.e., channel tuning) is selected by tuning the center frequency of the LO laser. The bandpass filter BPF1, which is used as a noise suppressor, is assumed to be ideal with a bandwidth $B_1 = (1 + 0.25m)R_b + f_s + 12\Delta\nu_{IF}$ that is large enough to retain most of the energy in the information carrying signals with total IF linewidth $\Delta\nu_{\mathrm{IF}}$ taken into consideration [9], where R_b is the data bit rate. Therefore, the photocurrent $i(t)$ at the input of the square-law detector can be written as

$$i(t) \approx i \sum_{\substack{n=-3 \\ n=\mathrm{odd}}}^{3} 2J_n(\Phi)\cos(2\pi f_{\mathrm{IF}}t + \theta_{\mathrm{IF}}(t) + 2\pi n x(t) + \tfrac{1}{2}n\pi), \tag{4}$$

where i is the photocurrent converted from the received optical signal and LO power, f_{IF} is the IF carrier frequency, and $\theta_{\mathrm{IF}}(t)$ is the total IF phase noise process. The square-law device allows the strong components of the IF signal being coherently mixed together and results in a photocurrent $a(t)$ with a DC term, double IF (i.e., $2f_{\mathrm{IF}}$) terms with phase noise $\theta_{\mathrm{IF}}(t)$, and frequency-difference terms without phase noise, where

$$\begin{aligned} a(t) \;&\approx \text{a DC term} + 2f_{\mathrm{IF}} \text{ terms} \\ &+2i^2[(J_1^2(\Phi) - 2J_1(\Phi)J_3(\Phi))\cos(2\pi\cdot 2x(t)) \\ &-2J_1(\Phi)J_3(\Phi)\cos(2\pi\cdot 4x(t)) + J_3^2(\Phi)\cos(2\pi\cdot 6x(t))]. \end{aligned} \tag{5}$$

The $2x(t)$ term represents the desired phase-noise-cancelled subcarrier signal, while other undesired terms can be filtered out by BPF2 with a bandwidth $B_2 = (1 + 0.5m)R_b$ [9]. Finally, the filtered phase-noise-cancelled signal $b(t)$ can be written as

$$\begin{aligned} b(t) \;&\approx\; 2i^2(J_1^2(\Phi) - 2J_1(\Phi)J_3(\Phi)) \\ &\cdot\cos(2\pi f_s t + 2\pi f_d \textstyle\int_0^t X(t')dt'), \end{aligned} \tag{6}$$

which simply represents a conventional binary orthogonal CPFSK modulation signal with the microwave/millimeter-wave carrier f_s and the frequency deviation f_d. Data are then recovered by the delay-line demodulator.

3. Experimental Demonstration

In the experiment, the coherent-detection technique is demonstrated at the subcarrier frequency $f_s = 600$ MHz with total IF linewidth $\Delta\nu_{\mathrm{IF}} = 200$ MHz. Although a higher subcarrier frequency, such as 36 GHz demonstrated in [5], can be used, 600 MHz is chosen with an eye toward demonstrating the phase-noise-cancelling capability of this technique.

Using the set-up in Fig. 2, a 10 Mbit/s data bit sequence $X(t)$ is applied to the subcarrier generator, which is made of a voltage-controlled oscillator (VCO) circuit. The VCO circuit, in turn, generates a microwave signal $x(t)$ containing a subcarrier $\frac{1}{2}f_s = 300$ MHz and a CPFSK signal with $\frac{1}{2}f_d = \pm 1.4$ MHz. As described in Section 2, these correspond to a CPFSK signal centered at 600 MHz with a modulation index $m = 0.56$ at the receiver. A DC bias voltage of about 4 V is applied to the modulator to obtain the double-sideband suppressed-carrier optical signal. In addition, the subcarrier amplitude V is adjusted to give a phase modulation depth Φ of approximately 1.36 rad to optimize the signal-to-noise ratio (SNR) at the receiver output. The detail about the SNR calculation is given in [6]. Two single-mode DFB semiconductor lasers, each with a center wavelength in the vicinity of 1.321 μm and a linewidth of about 100 MHz, are used as the laser source and LO lasers, which also have CW optical powers of about 0.7 mW and 1.0 mW, respectively. In the actual measurement, the IF is tunned to 10.76 GHz and a laser IF linewidth of 200 MHz (or, equivalently, a normalized IF linewidth $\zeta = \Delta\nu_{\mathrm{IF}}T \approx 2000$ %) is measured by a microwave spectrum analyzer. The square-law device is made of a microwave coaxial detector. A delay-line demodulator with the delay paths made up of two coaxial cables and a phase shifter, which provides a variable delay of $0 - 1$ ns, are used for demodulating the phase-noise-cancelled CPFSK signal.

Shown in Fig. 3 is the spectrum of the IF signal with-

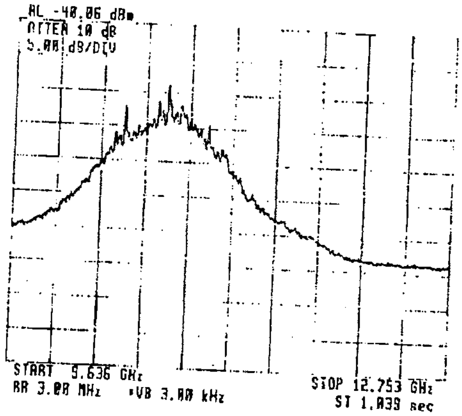

Figure 3: Spectrum of the IF signal without a proper DC bias

out a proper DC bias V_{dc}, where the IF carrier and the two sidebands are overlapped because of the wide IF phase-noise sidebands. Fig. 4 shows the case where a proper V_{dc} (i.e.,

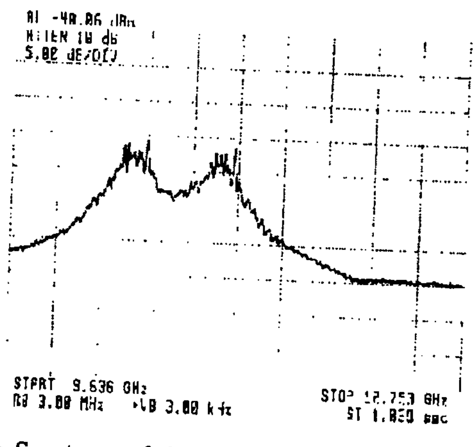

Figure 4: Spectrum of the IF signal with a proper DC bias

≈ 4 V) is applied; the IF carrier is suppressed and the two strong (i.e., first-harmonic) sidebands are left behind with a 600 MHz separation. Note that the high spectral power level between the two sidebands is caused by the wide phase-noise side-slope, not by incomplete carrier suppression. Other harmonic components are, however, too weak and can not be seen in the figure.

This double-sideband suppressed-carrier signal then passes through the coaxial detector (i.e., the square-law device), resulting in the phase-noise-cancelled signal, as shown in Fig. 5. The desired signal, whose linewidth is now limited by

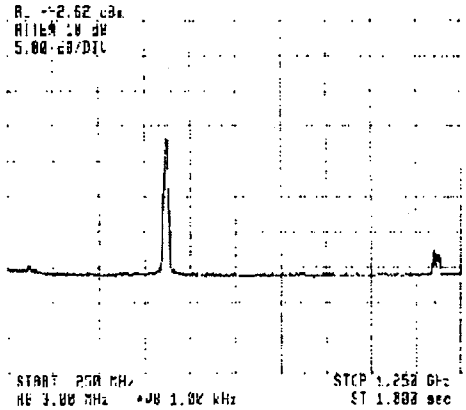

Figure 5: Spectrum of the phase-noise-cancelled signal after the square-law device

the bandwidth resolution of the spectrum analyzer, is found at 600 MHz and free of laser phase noise. The almost flat spectra in the vicinity of 300 MHz and 900 MHz, caused by the 23 dB extinction ratio of the Mach-Zehnder modulator, confirm that the double-sideband suppressed-carrier signal is successfully generated. The weak harmonic signal at 1.2 GHz, corresponding to the term with $4x(t)$ in (5), is found about 20 dB below the peak power of the desired signal, which agrees with the theoretical calculation [6]. In addition, the IF spectrum in the vicinity of 600 MHz is expanded and shown in Fig. 6, where the spectrum resembles closely to a

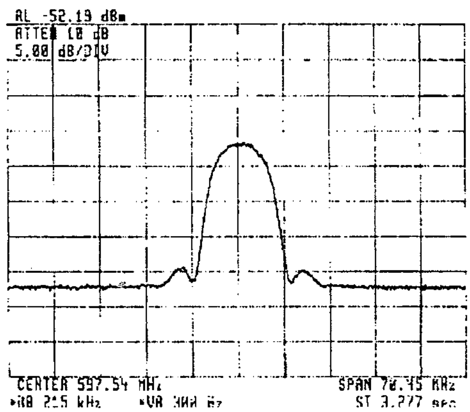

Figure 6: Expanded spectrum of the phase-noise-cancelled signal

CPFSK signal with a modulation index of 0.56. In addition, Fig. 7 shows that the original data bits (upper trace) at the input of the transmitter and the recovered bits (lower trace) at the output of the receiver.

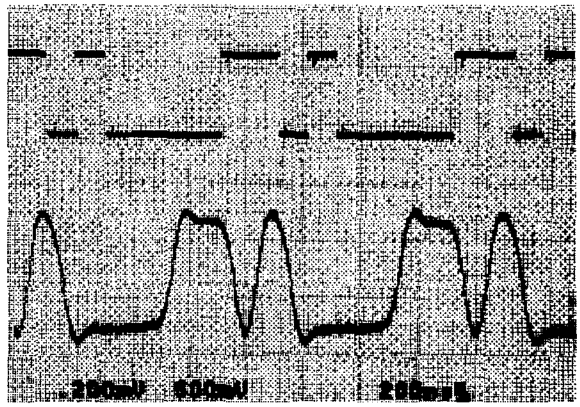

Figure 7: Original data bits (upper trace) at the input of the transmitter and the recovered bits (lower trace) at the output of the delay-line demodulator

Finally, the result of the bit-error-rate (BER) measurement is shown in Fig. 8 (dots), where the theoretical BER

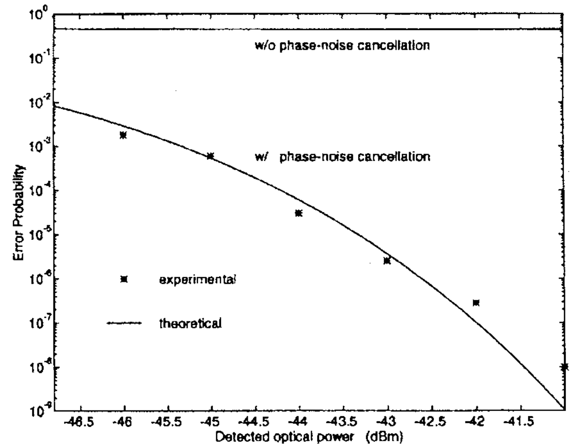

Figure 8: Bit-error-rate (BER) curves of the proposed system, obtained from the experiment (dots) and theoretical calculation (solid), with and without phase-noise cancellation, where $R_b = 10$ Mbit/s, $\zeta = 2000$ %, and $m = 0.56$

(solid) curves for the cases of with and without phase-noise cancellation are also shown. The solid curve on the top of the figure reveals the fact that phase noise is an important factor affecting the performance of coherent-detection systems. In short, the experimental result agrees with the theoretical calculation [6]. The deviation of the experimental result from the theoretical curve is caused by the degradation of the square-law performance of the coaxial detector as the signal power increases. Furthermore, the system performance can be improved by properly designing a better square-law circuitry and including dual-detector and polarization-diversity structures in the receiver.

4. Summary

A coherent-detection technique of very narrow linewidth millimeter-wave and microwave subcarrier signals has been studied. An experiment demonstrating the feasibility of such a system at 10 Mbit/s with a normalized IF linewidth of 2000 % and a modulation index of 0.56 has been reported. A BER measurement has been performed and agreed with the theoretical calculation. Wide channel-tunability and improved receiver sensitivity (i.e., theoretically, at least 10 dB better than that of using direct detection) can be provided with cheap, wide-linewidth semiconductor lasers, without using expensive optical amplifiers. Therefore, this technique is particularly suitable for low-cost, power-limited optical wireless (subcarrier) LAN's.

5. Acknowledgements

This research was supported by the N.J. Commission on Science and Technology under its Innovative Partnership Program in Telematics, the Focal Project through the Advanced Technology Center for Photonics and Optpelectronic Materials (ATC/POEM) at Princeton University, the Joint Services Electronics Program through the Columbia Radiation Laboratory, and the National Science Foundation through the Center for Telecommunications Research at Columbia University.

Reference

[1] T.S. Rappaport, "The wireless revolution," *IEEE Commun. Mag.*, vol. 29, no. 11, pp. 52-71, 1991

[2] IEC825: Radiation safety of laser products, equipment classification, requirements, and user's guide, 1984; Amendment 1, 1990

[3] P. Smyth, D. Wood, S. Ritchie, and S. Cassidy, "Optical wireless: New enabling transmitter technologies," *in Proc.*, ICC '93, pp. 562-566, Geneva, Switzerland, 1993

[4] W. Huang, J. Takayanagi, T. Sakanaka, M. Nakagawa, "Atmospheric optical communication system using subcarrier PSK modulation," *in Proc.*, ICC '93, pp. 1597-1601, Geneva, Switzerland, 1993

[5] J. O'Reilly, P. Lane, R. Heidemann, and R. Hofstetter, "Optical generation of very narrow linewidth millimetre wave signals," *Electron. Lett.*, **28**, No. 25, pp. 2309-2310, 1992

[6] W. Kwong, P. Prucnal, and M. Teich, "Coherent subcarrier fiber-optic communication systems with phase-noise cancellation," *Trans. Commun.*, vol. 42, June 1994

[7] M. Kavehrad and B.S. Glance, "Polarization-insensitive frequency shift keying optical heterodyne receiver using discriminator demodulation," J. Lightwave Technol., vol. LT-6, pp. 1386-1394, Sept. 1988.

[8] G.L. Abbas, V.W.S. Chan, and T.K. Yee, "A dual-detector optical heterodyne receiver for local oscillator noise suppression," J. Lightwave Technol., vol. LT-3, pp. 1110-1122, Oct. 1985

[9] I. Garrett and G. Jacobsen, "Statistics of laser frequency fluctuations in coherent optical receivers," *Electron. Lett.*, **22**, pp. 168-170, Jan. 1986 Oct. 1985