



**[www.RedMountainRadio.com](http://www.RedMountainRadio.com)**

Thanks for your interest in my technical paper. If you find this work to be interesting, or have additional questions, please contact me at the address below. Red Mountain Radio LLC offers professional RF, optical, and microwave design services, and problem solving.

Regards,  
Eric Funk, Ph. D.  
Partner, Red Mountain Radio LLC  
[eric@redmountainradio.com](mailto:eric@redmountainradio.com)  
970-325-2158 x12

The following IEEE paper is subject to copyright as noted below.

This material is presented to ensure timely dissemination of scholarly and technical work. Copyright and all rights therein are retained by authors or by other copyright holders. All persons copying this information are expected to adhere to the terms and constraints invoked by each author's copyright. In most cases, these works may not be reposted without the explicit permission of the copyright holder.

©2001 IEEE. Personal use of this material is permitted. However, permission to reprint/republish this material for advertising or promotional purposes or for creating new collective works for resale or redistribution to servers or lists, or to reuse any copyrighted component of this work in other works must be obtained from IEEE."

## Hybrid Fiber/Millimeter-wave Wireless for Broadband Last Mile Access

Eric E. Funk  
Naval Research  
Laboratory  
Washington, DC

W. D. Jemison  
Lafayette College  
Easton, PA

P. R. Herczfeld  
Drexel University  
Philadelphia, PA

Demand for broadband last-mile wireless connectivity is leading to the development of millimeter-wave fixed cellular wireless services such as the Local Multipoint Distribution Service (LMDS) at 28 GHz in the U.S. At these frequencies, practical propagation limits lead to cell sizes that are as small as 1 mile in diameter. The small cell size promotes both efficient frequency reuse for commercial applications and signal security for military applications.

In a fixed wireless system, such as LMDS, each subscriber is assigned customer premise equipment (CPE) consisting of a fixed high-gain antenna, a block down-converter and a broadband digital modem. The CPE communicates with a nearby base-station via a fixed wireless link. Each base-station is then connected to a central office (CO) via either fiber or a point-to-point millimeter-wave link. Fiber backhaul is more advantageous, allowing the allocated wireless bandwidth to be dedicated to multipoint service.

A variety of architectures have been developed for the distribution of modulated millimeter-wave wireless radio signals over fiber [1] using either intensity modulation at millimeter wave frequencies or heterodyne techniques. Each of these approaches involves a cost/performance tradeoff.

As an example of a typical performance analysis, we treat the downlink of a mode-locked chip laser [2] fiber radio architecture as shown in Fig. 1. For the purpose of demonstration, this link operates at a 22 GHz RF/wireless frequency.

As shown in Fig. 1, the laser is actively mode-locked with an external reference, producing an optical comb spectrum with optical modes spaced at  $f_L = 20$  GHz. A broadband modem [3] generates a 6 MHz bandwidth, QPSK modulated signal with Reed-Solomon (204, 188) coding at an IF frequency of  $f_{IF} = 2$  GHz. The modem drives a Mach-Zehnder modulator at the IF frequency, adding upper and lower modulation sidebands to each of the mode-locked optical frequencies. At the base-station photodiode, the optical frequencies mix with each other to generate microwave signals of interest at,  $f_{RF} = f_L \pm f_{IF}$  and  $f_L$ . The sum frequency (at  $f_{RF} = 22$  GHz) is retained and amplified for transmission, while the other frequencies are filtered out. This self-heterodyne approach is resistant to the carrier suppression effect [4]; the first null does not occur until a fiber length of 580 km.

The energy per bit to noise ratio,  $E_b/N_0$ , required to achieve a fixed bit error rate (BER) is a key system performance parameter. The impairment due to the fiber link can be isolated from other system impairments by noting the increase in required  $E_b$  when the optical link is added into the system. Assuming an additive white Gaussian noise wireless channel, the error corrected BER is bounded below  $<10^{-10}$  with a carrier to noise ratio (CNR) of 11 dB [5]. Adding in measured sources of optical layer impairment yields a required CNR of 11.5 dB on the wireless link as shown in Table 1. This implies an acceptable power penalty of only 0.5 dB. The optical link impairment results from amplitude and phase noise appearing on the self-heterodyned signals as well as thermal noise in the receiver. Both error vector magnitude (EVM) [6] measurements of the modulated QPSK signal (Fig. 2) and independent measurement of integrated amplitude, phase, and thermal noise of the un-modulated carrier yield identical amplitude and phase noise levels.

While the measurements discussed above qualify the system for single-channel operation, two-tone measurements are used for multi-channel qualification. The measured two-tone spur free dynamic range of the optical link was 79 dB-Hz<sup>2/3</sup>. By permitting up to 1 dB of power penalty, we predict that we can operate up to 68 equal power incoherent subcarrier multiplexed channels with an acceptable level of composite triple beat (CTB) [7]. We note that the distortion performance with QPSK modulation will likely be better than the predicted un-modulated CTB.

In summary we have analyzed many of the technical issues involved in the development of a base-station to central office fiber link for last-mile wireless service. A power penalty due to the insertion of the fiber link has been determined for a chip laser based fiber radio downlink. Measurements have been performed to predict system performance, both for single channel and multi-channel operation.

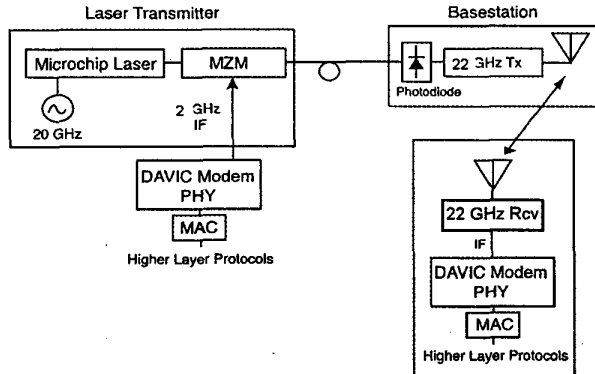


Fig. 1. Layout of fiber radio link with microchip laser.

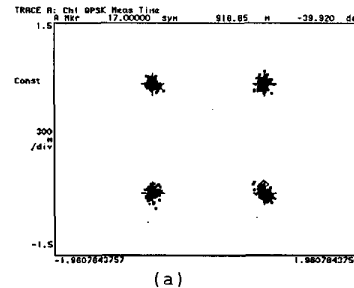


Fig. 2. Measured 5 MBaud QPSK Constellation: EVM= 7% rms, 6% rms magnitude

TABLE I  
SINGLE CHANNEL OPTICAL LINK POWER PENALTY

Noise Source	Level
Integrated Amplitude Noise (laser)	-27 dBc
Laser Relaxation Oscillation (tone)	-35 dBc
Integrated Absolute Phase Noise (laser)	-38 dBc
Integrated Thermal Noise (photoreceiver)	-26 dBc
SUM OPTICAL LINK NOISE	-23 dBc
Wireless Link Noise (budgeted)	-11.5 dBc
TOTAL NOISE LEVEL ( $<10^{-10}$ BER)	-11 dBc
Power Penalty (Wireless Link Noise less Total Noise)	0.5 dB

#### REFERENCES

- [1] R. P. Braun, and G. Grosskopf, "Optical Millimeter-wave systems for broadband mobile communications, devices and techniques," *Proceedings 1998 International Zurich Seminar on Broadband Communications*, pp. 51-58, 1998.
- [2] A. J. C. Vieira and P. R. Herczfeld, "Nd:LiNbO<sub>3</sub> Microchip laser with 20GHz subcarrier", *Digest of the 1997 IEEE MTT-S International Microwave Symposium*, pp. 229-232, June, 1997.
- [3] Digital Audio Visual Council, "DAVIC 1.4.1 Part 8," 1999.
- [4] Zaheer Ahmed, Dalma Novak, Rod B. Waterhouse, and Hai-Feng Liu, "37 GHz fiber-wireless system for distribution of broad-band signals," *IEEE Trans. Microwave Theory Tech.*, vol. 45, pp.1431-14-1435, 1997.
- [5] Eric E. Funk, P. R. Herczfeld, W. D. Jemison, and Maja Bystrom, "Performance Limits of Hybrid Fiber/Millimeter-Wave Wireless System," *International Microwave and Optoelectronics Conference*, Brazil, August 6-10, 2001.
- [6] "Using vector modulation analysis in the integration, troubleshooting, and design of digital RF communications systems," HP Product Note HP89400-8.
- [7] Makoto Shibutani, Toshihito Kanai, Watani Domom, Katsumi Emura, and Junji Namiki, "Optical fiber feeder for microcellular mobile communications systems," *IEEE J. Select. Areas Commun.*, vol. 7, pp.1118-1126, 1993.