International Journal of Infrared and Millimeter Waves, Vol. 24, No. 7, July 2003 (© 2003)

MILLIMETER-WAVE OVER FIBER SYSTEMS USING HYBRID OCDM/WDM TRANSMISSION

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Received April 1 2003

Abstract

In this paper, we propose and simulate 2 OCDM $\times$ 4 WDM transmission system for a millimeter-wave (60 GHz) over fiber system to be used in broadband wireless access networks (BWANs). The general system setup is devised and the necessary building blocks identified. Results gathered (for a 155 Mbit/s per user system) under worst case parameter specifications and settings suggest indicate that system performance is severely limited by optical multiuser interference (OMUI) penalties. Several methods to reduce the OMUI limitations are described. These methods should ensure that this transmission scheme possible wavelength-reuse option for future MMW BWANs.

Keyword: 60 GHz millimeter-wave networks, optical access networks, wavelength-division multiplexing, optical code-division multiplexing

1 Introduction

Wavelength-division multiplexing (WDM) is expected to be the dominant optical transmission scheme for the emerging fiber-distributed 60 GHz millimeter-wave (MMW) band broadband wireless access networks (BWAN) [1]. In such networks, the expansion of the customer base or launch of new services can be accommodated by the addition of wavelength channels in the fiber distribution part of the network. Unfortunately, due to the physical limitation of optical devices and fiber waveguides, only a finite number of wavelengths can be utilized in a WDM network [2]. This reduces the competitiveness and revenue earning potential of the network operators and service providers. Therefore, it is necessary to devise methods

0195-9271/03/0700-1113/0

that increase the efficiency of the utilization of the existing wavelength channels so as to reduce (or eliminate) the need for new wavelength channels. Optical code-division multiplexing (OCDM) has been identified as way of enabling the sharing of existing wavelength channels by using different signature codes on the same wavelength [3]. In this paper we describe an implementation of a OCDM/WDM 60 GHz BWAN and present results of simulations of the configuration.

2 Optical Broadband Wireless Access

The license-free 60 GHz band (oxygen absorption band) has been identified as a band of choice for BWANs [4]. The contiguous 5 GHz bandwidth (typically 57 to 62 GHz) available in that band should support some very competitive data rates (>100 Mbit/s) for distances of up to 2 km. Active 60 GHz standardization efforts include the MMAC (Multimedia Mobile Access Consortium) standards for an ATM-based WLAN (100 Mbit/s) [5] and IEEE (Institute of Electrical and Electronics Engineers) standards (IEEE 802.16) for fixed BWANs that fall within 10-66 GHz frequency range [6]. In Europe, among the leading 60 GHz band initiatives is the MEDIAN project (ACTS AC 006) which has carried out demonstrations for WLANs and wireless CPNs with rates of up to 150 Mbit/s [7].

The high data rates supported by the 60 GHz MMW band communications have meant that only fiber-optics can provide the sufficient bandwidth and transmission range for the inter-connection of the central station, MMW base stations and/or MMW antennas [1]. Moreover, this MMW-over-fiber system enables the centralization of most systems functions (e.g. MMW signal generation) thus enabling compact (cheap) base station designs and simplifies network upgrade procedures [8]. The optical infrastructure serving the fixed part of he MMW system is usually known as the feeder or backhaul network. MMW-over-fiber transmission is achieved by transmitting data on a MMW carrier with frequency f_m (in this case, 60 GHz) over a fiber link using an optical carrier at frequency f_o(in the 185-250 THz range). In a conventional externally modulated MMW-over-fiber system, the transmitted signal is an optical double sideband signal composed of the optical carrier at ω_o and two sidebands at $\omega_o - \omega_m$ and $\omega_o + \omega_m$ where and $\omega_o = 2\pi f_o$ and $\omega_m = 2\pi f_m$ respectively.

Unfortunately, the RF signal fading occurs at the MMW base station (BS) due to the fiber-dispersion-induced phase-mismatched beating between the two sidebands. The normalized power P_{ω_m} of the MMW signal after fiber transmission varies according to [9]

$$P_{\omega_m} \propto \cos^2\left(\pi LDc\left(\frac{\omega_m}{\omega_o}\right)^2 + \arctan\alpha_c\right) \tag{1}$$

where L is the fiber length, D is the fiber's chromatic dispersion coefficient, c is the velocity of light in vacuum and α_c is the optical modulator's chirp parameter. Therefore, the signal is expected to fade to zero whenever $cos(*) = 0$ as shown in the example of Figure 1a. Fading can be suppressed by using non-zero dispersion shifter fibers (ITU G.655) instead of the more commonly used standard singlemode fibers (ITU G.652). However, this merely reduces the period of signal fading across the length of the fiber (see Figure 1b). A more effective solution would be ensure that the transmitted signal has only two components instead of three, by either suppressing one of the sidebands or the carrier. This can be achieved by performing optical heterodying using either two lasers with a f_m difference in emitted frequencies or a dual electrode differential Mach-Zehdner modulator at the transmitter [1].

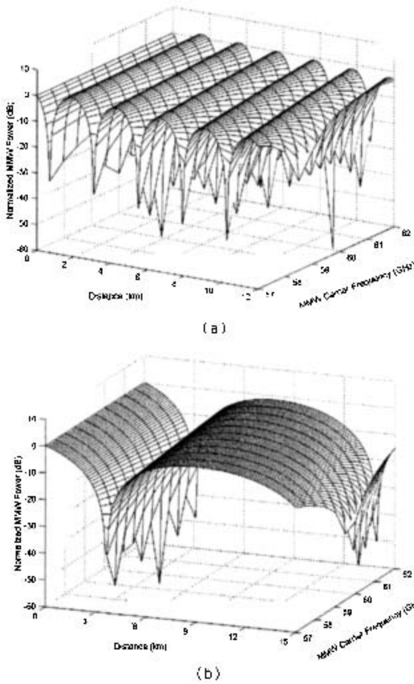

Figure 1: The normalized MMW signal power after the optical receiver as a function of the fiber length for the case of (a) ITU G.652 fibers [$D = 16.0$ ps/nm-km] (b) ITU G.652 fibers [$D = 3.0$ ps/nm-km]. In both cases, $\alpha_c = 0.8$.

3 OCDM Background

In OCDM different users share the same fiber by being assigned unique signature codes $(C_m : m = 1, 2, \ldots, M)$ where M is the number of available codes or cardinality [3], [10]. The idea behind OCDM is similar to conventional wireless spread spectrum systems. The obvious differences are that, in OCDM the signal is encoded/decoded optically and the transmission medium is fiber. OCDM offers several advantages that includes improved security, gradual performance degradation, ability to increment user numbers (or capacity), asynchronous operation, flexibility and low latency. Furthermore, OCDM is flexible as it is independent of bit rate, signal format, network topology etc. and can be implemented using existing optical technologies.

Direct-spreading (DS) spread spectrum techniques are the most prominent OCDM technique and have been widely studied [10], [3], [2, Chapt. 5]. Consider a data signal stream $x^{(j)}$ produced by a source j and is represented by a binary sequence $a_l^{(j)} \in \{0,1\}$ made of rectangular pulses $r(t)$ of duration T, that is

$$x^{(j)}(t) = \sum_l a_l^{(j)} r(t - lT). \qquad (2)$$

This signal stream is passed through an OCDM encoder so as to imprint a signature code $C_j = \left\{c_n^{(j)} | n = 0, 1, 2, \ldots, L_c - 1\right\}$, where $c_n^{(j)}$ is the nth chip and L_c is the code length or processing gain. The encoded stream $y^{(j)}(t)$ from the encoder jth is

$$y^{(j)}(t) = \sum_l \sum_{n=0}^{L_c-1} a_l^{(j)} c_n^{(j)} r(t - nT_c - lT) \qquad (3)$$

where $T_c \leq T/L_c$ is the duration of each chip. In amplitude (unipolar) encoded OCDM, the amplitude level of the chips takes on values of 0 or 1, with the codes being distinguished by the time location of nonzero chips in the code. For phase encoding all the chips have maintain levels of 1 but are distinguishable by the phase of each chip. These techniques are further illustrated in Figure 2. Matched filtering is implemented by decoders (time reversed version of the encoders) to recover the data signal at the receiver. For an encoded signal (3), the corresponding output of the kth decoder is

$$d_k^{(j)}(t) = \sum_l a_l^{(j)} \psi_n^{(j,k)} [t - (l+1)T] \qquad \forall k, \qquad (4)$$

where

$$\psi_n^{(j,k)}(t) = \sum_{n=0}^{L_c-1} \sum_p c_p^{(k)} c_{p+n}^{(j)} r(t - nT_c). \qquad (5)$$

In practical systems

$$\psi_n^{(j,k)}(t) > 0 \qquad \forall n, \qquad (6)$$

$$\psi_n^{(k,k)}(t) > 0 \qquad n \neq 0, \qquad (7)$$

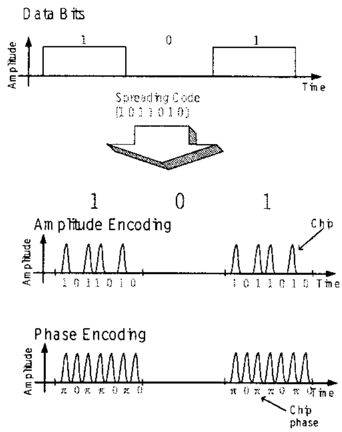

Figure 2: Example of seven chip [1011010] amplitude and bipolar phase coding schemes for a 3 bit data stream.

represent crosscorrelation and time-shifted autocorrelations peaks respectively. These nonzero peaks create optical multiuser interference (OMUI) that limits the performance of OCDM systems. Therefore, codes have to be carefully selected so as to minimize OMUI and maximize the autocorrelation $\psi_0^{(k,k)}(t)$. For the same code length, phase encoding can support a larger number of users to due lower optical OMUI and larger possible combinations of codewords since the chips have more possible levels (e.g. 4 phase levels [11]) compared to the two (0 and 1) levels of amplitude unipolar codes.

4 Hybrid OCDM/WDM Transmission

The efficiency of fiber utilization in MMW-over-fiber systems can be improved by using optical carriers with different frequencies and WDM transmission [12]. Moreover, the same could done for MMW carriers (subcarrier multiplexing [SCM]), to obtain even more efficient SCM/WDM systems [13]. In practice, due to the physical limitations of optical devices and fiber waveguides, the number of wavelengths can be utilized in a WDM network may not meet the demand for channels [2]. SCM/WDM implementations offer more channels, but SCM channel number is limited by the modulation bandwidth of optical transmitters and highly linear transmitters are required. The hybridization of OCDM and WDM (OCDM/WDM) has been identified as possible way of increasing channel numbers [14]. OCDM is easy to deploy (plug-and-play) in WDM systems with minimal disruptions to the existing setup. A possible downlink configuration of a OCDM/WDM MMW-over-fiber BWAN is depicted in Figure 3. The MMW is imposed only on the optical

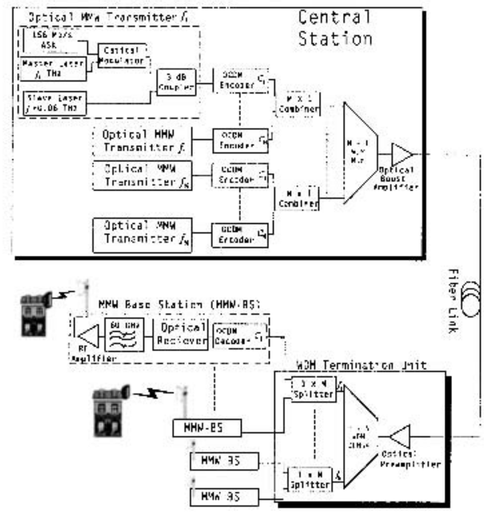

Figure 3: The general architecture of the downlink of a OCDM/WDM MMW-over-fiber system.

carrier produced by the master laser using an external modulator. Optical heterodyning at the central station (CS) is then achieved coupling the externally modulated signal and with the slave laser output with a 60 GHz difference in frequency. This approach could be considered to be more expensive than the use a 60 GHz externally modulated laser [9]. However, it eliminates the need for MMW local oscillators and automatically produces an optical single sideband (OSSB) signal.

The OCDM encoding and decoding (time reversed version of the encoders) is performed before WDM multiplexing and after WDM demultiplexing respectively. The encoders can be currently implemented by planar lightwave circuits [3] or custom tailored fiber Bragg gratings [15]. Our simulation setup closely resembles the configuration of Figure 3.

4.1 System Simulations

The simulations were carried out using the VPItransmissionMaker version 3.01 (by VPIsystems^{TM}) tool [16]. The parameters and settings of the modules used in the simulations are as follows:

- Lasers: average power 1.0 mW, linewidth 10 MHz.
- Modulator: Mach-Zehnder (MZM) modulator, extinction ratio 30 dB.

- Encoders (Decoders): splitters/combiners insertion loss (worst case) $10 \cdot log(L_c)$ where L_c is the code length, optical delay lines (914 ns).
- Fiber: Length 20 km, attenuation 0.2 dB/km, dispersion 16 ps/nm-km, nonlinearity coefficient $2.6 \times 10^{-20} m^2/W$.
- Optical Amplifier (used between OCDM decoder and optical receiver): semiconductor optical amplifier, injection current 0.15 A, dimensions 0.5 nm×3.0 μm×80 nm, differential modal gain 2.78×10^{-20} m^2, Optical confinement factor 0.15.
- Receiver: PIN photodiode, 1 A/W responsivity, thermal noise $10^{-12} A/\sqrt{Hz}$.
- RF Amplifier: gain 20 dB, noise spectral density $3 \times 10^{-12} A/\sqrt{Hz}$.

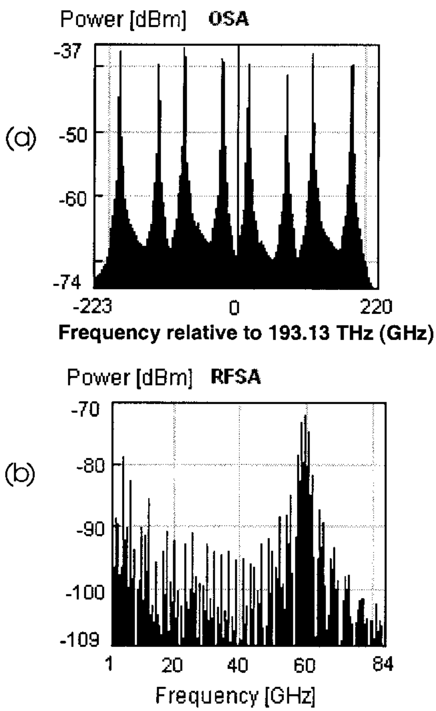

Figure 4: (a) The transmitted OCDM/WDM signal spectrum with each channel having two components separated by 60 GHz (b) received unfiltered MMW signal spectrum.

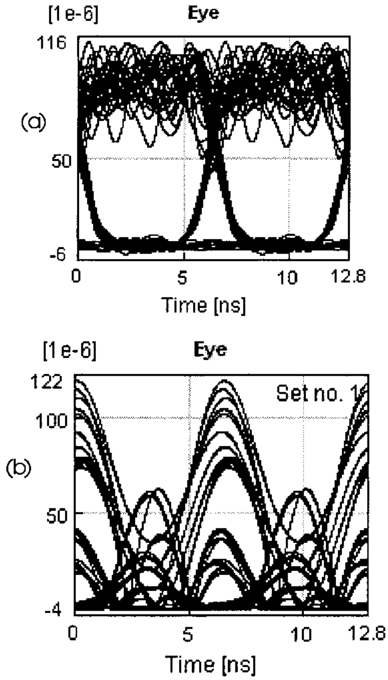

Figure 5: Received eye diagrams for the (a) 8 WDM and (b) 2 OCDM × 4 WDM cases.

Four transmission (156 Mb/s MMW signal per user) scenarios are considered; 2 users with unique codes (2 OCDM), 2 users with unique wavelengths (2 WDM), 8 users with unique wavelengths (8 WDM), and 8 users with both unique codes *and* wavelengths (2 OCDM × 4 WDM). A channel spacing of 100 GHz is assumed throughout and all the wavelengths (optical frequencies $f_1 - f_N$) are confined in the C-band (1530 to 1565 nm). Two 7-chip bipolar phase codes $C_1 = (0\pi00\pi\pi\pi)$ and $C_2 = (\pi\pi\pi00\pi0)$ are used for OCDM, where π is basically a 1 chip with 180° phase. The optical transmitted and received MMW signal spectra for the case 2 OCDM × 4 WDM are shown in Figure 4. The 400 GHz occupied by the WDM channels 1 to 4 (each bearing 2 OCDM signals) is half of that for the 8 WDM case. Unfortunately, unlike WDM, the received signal in the 2 OCDM × 4 WDM case is tainted by significant levels OMUI as depicted in the eye diagrams of Figure 5 (non-return-to-zero format used for WDM). The interference is further depicted by the decoder output of Figure 6.

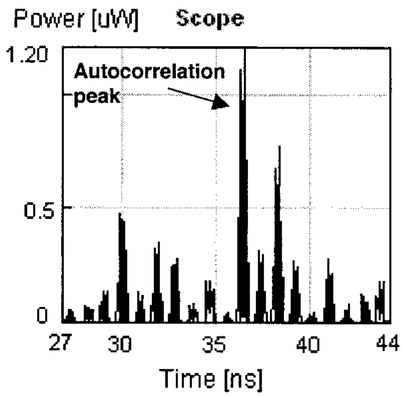

Figure 6: A decoded pulse (auto-correlation) with significant interfering sidelobes.

Figure 7 shows the simulated bit error rate (BER) at the end of the optical part of the system. It is observed that there is little difference in performance between 2 WDM and 8 WDM, where both there receiver sensitivities are within 1 dB of the baseline (back-to-back). By contrast, the difference between the 2 OCDM and 2 OCDM $\times$ 4 WDM is more significant. This implies that the power penalties due WDM interferences (attributed to imperfect component designs and fiber nonlinearities) are more significant when optical encoded MMW signals are multiplexed in wavelength domain. Moreover, both the OCDM systems have BER floors (see Figure 7) as a result of OMUI. Furthermore, the differences in performance between the OCDM-based transmission compared to basic WDM transmission (as shown in Figure 7) are due to the fact that in the former case signals are transmitted at a higher rate ($L_c \cdot 156$ Mchips/s) which implies that penalties due to chromatic dispersion are significantly higher. Moreover, the high losses of the worst-case OCDM encoders/decoders and 3-dB couplers deplete the power budget excessively (see Figure 4a where all signals launched on to the fiber are below -35 dBm).

4.2 Recommended Measures

The performance of 2 OCDM transmission was satisfactorily given unfavorable parameter specifications adopted in the simulations. In the case of 2 OCDM $\times$ 4 WDM, some remedies are necessary to improve the BER by at least 3 to 4 orders of magnitude. Straightforward measures include replacing the ubiquitous standard singlemode fibers (ITU Rec. G.652) with non-zero dispersion shifted fibers (ITU Rec. G.655), performing dispersion compensation and deploying erbium-doped fiber amplifiers as optical boost or preamplifiers. Unfortunately, these remedies are

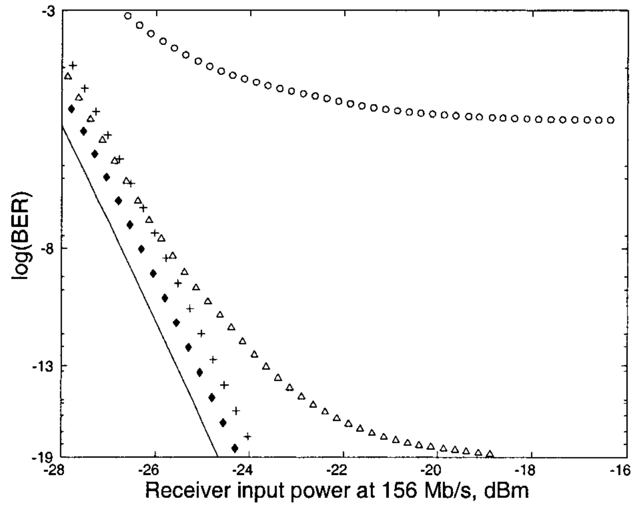

Figure 7: Simulated bit error rates (BER) for the 2 WDM (solid diamond), 8 WDM (plus sign), 2 OCDM (triangles) and 2 OCDM × 4 WDM (open circles) cases. The back-to-back case (solid line) is used a benchmark.

not cost-effective, complicate network operation and may not completely eliminate the OMUI induced BER floors. Simpler and more effective alternatives would be to improve the OCDM decoding process and/or implement error-correction coding.

4.2.1 Improved OCDM Decoding and Detection

Decoders made of passive optical tapped delay lines (fiber or integrated) are the most common used in most OCDM proposals [3]. Superstructured fiber Bragg grating decoders offer an alternative with lower insertion loss but still retain the OMUI limitations [15]. However, the OMUI can be subtracted from the received signal by using multiuser detection (MUD) in more than a single stage [17]. This of course requires some prior knowledge of the properties of the signals of the desired and interfering users, and gets very complicated with increased user number. Blind detection can reduce the amount of required knowledge and simplify MUD in OCDM systems [18]. An alternative to MUD would be chip-level detection whereby the sampling time after the photodetector corresponds to the chip rate [19].

Unfortunately, all those methods depend on electrical processing using integrated circuits made of expensive III-V compound semiconductor materials whose cost scales with the chip rate. Alternatively, the elimination or suppression of OMUI could be achieved using relatively faster optical devices at a potentially lower cost. The devices could perform optical time-gating [3] or optical thresholding [20] after the OCDM decoder. For improved performance optical thresholding devices could be used before and after the decoder [21] or in conjunction with optical time-gating [11]. Unfortunately, most of these optical devices are still at the experimental level.

4.2.2 Error-Correction Coding

Error-correction coding is fast gaining a reputation in optical systems as it has electrical systems. In this scheme, redundant bits or symbols are transmitted with the data and used by the receiver to correct most of the errors. These redundant bits/symbols are inserted electrically on the data signal before the optical transmitter and error-correction decoding is performed after the photodetector. These coding schemes can be used to reduce, not only OMUI, but also effects of WDM crosstalk and dispersion. Moreover, error-correction coding can be implemented using mature electrical chipsets that are readily available. The ITU (Rec. G.709) currently defines (255, 239) and (255, 223) Reed-Solomon (RS) codes for long distance 10 Gbit/s optical systems. Similar proposals for RS coding have been made for OCDM but are yet to be standardized [22]. Furthermore, the BER OMUI floors OCDM systems can be lowered even further using the more complex but effective convolutional [22] and Turbo coding schemes [23]. As before the speed of electronics devices set a limit on the chip rate. Moreover, the redundancy also reduces the possible transmitted data rates.

4.2.3 Alternative Modulation

In standard DS-OCDM, the chip duration $T_c = T/L_c$. Feng *et al* [24] have proposed a return-to-zero (RZ) modulation scheme (whereby $T_c = T/2L_c$), that increases the system tolerance to OMUI interference. Moreover, the use of RZ modulation improves the system immunity to fiber dispersion and nonlinear effects (e.g., four-wave mixing, self-phase modulation) [25]. Depending on the link length (necessary launch power), user number or chip rate, various variations of the RZ format exist (carrier-suppressed RZ, single-sideband RZ etc). The alternative formats have better spectral efficiency and provide even better transmission performance [26]. However, these RZ formats require complex transmitter structures with two stage external modulators whose cost restricts their use to long haul links.

5 Conclusions

We have analyzed and simulated hybrid OCDM/WDM transmission of MMW signals over fiber. The performance was compared to similar systems using OCDM and WDM transmission schemes. Worst case conditions were assumed for OCDM encoder/decoder designs and fiber links. The performance of 2 OCDM $\times$ 4 WDM was limited by OMUI with BER floors at 10^{-5}. Several measures that could increase the BER by over 4 orders of magnitude have been mentioned briefly. The viability of any those measures has to also be considered in terms of various factors such as cost, bandwidth efficiency and maturity of the technologies. Most of the proposed measures rely on mature electronic devices that have lower processing speeds than optical devices. However, the achievable speeds would suffice for the sub-10 Gb/s line rates demanded by a majority of current metropolitan access networks. The indications obtained from the analysis suggest that OCDM/WDM could offer a cost-effective solution for scaling MMW over fiber systems.

Acknowledgement: This work was supported by Academy of Finland through Grant 298850 and the Academic Frontiers Student Exchange Promotion Program Scholarship of the Ministry of Education of Japan.

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