# Multiple Access in the Presence of Optical-Beat and Co-Channel Interference Using Walsh-Code-Based Synchronized CDMA Technique

C. C. Hsiao, B. H. Wang, and W. I. Way, *Senior Member, IEEE*

***Abstract*— We experimentally demonstrated the feasibility of using Walsh-code-based synchronized code-division-multiple access (S-CDMA) technique to achieve multiple access in the presence of optical-beat interference (OBI). This multiple access technique can, thus, be applied to WDMA networks using subcarrier-based common wavelength signaling, or PON's which generally do not have wavelength control on uplink laser diodes.**

***Index Terms*— Optical beat interference, passive optical network, synchronized code-division multiple access.**

## I. Introduction

THE performance of subcarrier-multiplexed (SCM) based optical wavelength-division-multiple-access (WDMA) and passive optical networks (PON's) can be severely degraded due to the presence of optical beat interference (OBI) [1]–[6]. OBI occurs when two or more of laser transmitters with nearly the same wavelength are received simultaneously by a photodetector. Several techniques had been proposed to reduce OBI in these SCM-based systems, including 1) over-modulating the laser [5], [6]; 2) adding out-of-band clipping tones [4], [7]; and 3) combining forward-error-correction (FEC) codes with out-of-band clipping tones [3]. Technique 1) has its limitation when there are multiple SCM channels driving the same laser, because additional nonlinear distortions due to over-modulation may fall into the signal band. Techniques 2) and 3) have their limitation when the number of SCM channels is large and spread over a wide frequency range, because it becomes difficult to select appropriate clipping-tone frequencies to avoid clipping-tone-induced in-band nonlinear distortions. In this paper, we propose and demonstrate using Walsh-code-based [8] synchronized code-division-multiple-access (S-CDMA) technique to achieve multiple access in the presence of OBI. Multiple access is achieved due to a) the suppression of OBI by over-modulating the laser with a large CDMA signal and b) the application of orthogonal Walsh codes which use different row vector of the Hadamard matrix for each user [8].

## II. Experiment

Our experimental setup is shown in Fig. 1. A 1.3-$\mu$m DFB laser (laser A) was modulated by a direct-sequence CDMA signal centered at 672 MHz. The CDMA signal was generated by spreading a 1.5625 Mb/s, $2^{20}-1$ pseudorandom data with a 200-Mb/s Walsh code (using Walsh code generator #1) which had a code length of 128. A second 1.3-$\mu$m DFB laser (laser B), was used to generate OBI by using a delayed self-homodyne interferometer (DSI). In other words, the setup including laser B and DSI was used to generate a calibrated OBI and to simulate the beating of two lasers. When laser B was left unmodulated, the DSI produced an OBI centered and peaked at zero frequency. To simulate the real conditions when OBI can wander anywhere in the RF spectrum (due to the drifting wavelengths of the beating lasers), the baseband OBI was further up-converted by using a tunable frequency synthesizer. Fig. 2(a) shows three up-converted OBI measured at point B′ in Fig. 1, when the received optical power at photodetector B ($P_{\mathrm{rec,\,B}}$) was −19 dBm. The OBI peaked at 672 MHz falls right into the center of the CDMA signal band, and the other two OBI's peaked at 472 and 872 MHz correspond to the two edges of the CDMA signal band, respectively. Note that the small Lorentzian-shaped spike at 944 MHz [Fig. 2(a)] was due to the nonlinearity of the up-conversion mixer. When laser B was modulated by a strong Walsh-code based CDMA signal with an optical modulation index (OMI) of 135%, the OBI was suppressed significantly, as shown in Fig. 2(b). It was observed that the OBI level was insensitive (with a variation $<$2.5 dB) to the selection of center carrier frequency due to the averaging effect of multiple PN-code-modulated Walsh code tones. The large OMI was necessary not only to suppress OBI level but also to increase the transmission system power budget (laser A which carried the other CDMA signal was also modulated at an OMI of 135%). It can be seen that the spectrum of the suppressed OBI becomes flat, and that the power levels at 672 and 672 $\pm$ 500 MHz were 24.4 dB lower and 6.6 $\pm$ 2.2 dB higher than those of the original OBI spectrum. Note also that a number of spiky narrow-band signal components, due to the short Hadamard code length of 128, was also observed. Since OBI and signal are in reality received by the same photodetector, the OBI at point B′ was carefully adjusted to simulate what should be obtained at point A′ when the DSI output at a certain power level is directly connected to the photodetector A. The combination of the received signal and the simulated OBI was down-converted simultaneously by a perfectly-phase-locked 672-MHz carrier, and subsequently

Manuscript received January 17, 1997; revised April 28, 1997. This work was supported by the National Science Council, R.O.C., under Contract NSC86-2215-E009-011.

The authors are with the Department of Communication Engineering, National Chiao-Tung University, Hsin-Chu 30050, Taiwan, R.O.C.

Publisher Item Identifier S 1041-1135(97)05660-7.

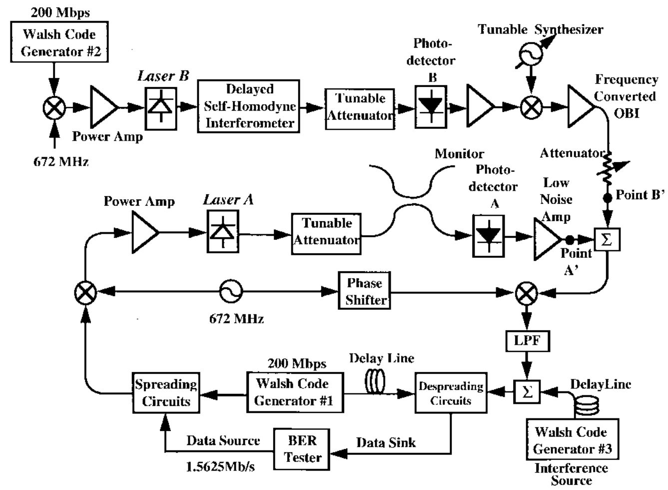


Fig. 1. Experimental setup.

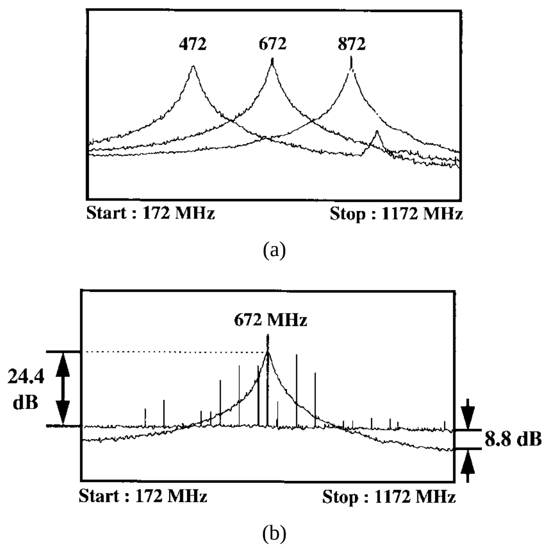


Fig. 2. Spectra of OBI's. (a) "Unchirped" OBI peaked at three different frequencies and (b) comparison between the spectra of "unchirped" and "chirped" OBI. The latter has a flat spectrum due to the large Walsh-code-based CDMA signal modulation. The output from the delayed self-homodyne interferometer was −19 dBm.

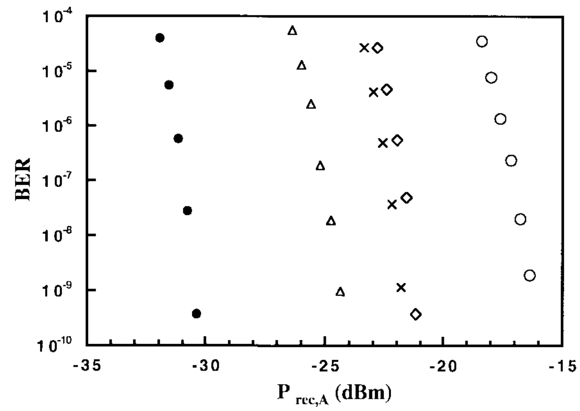


Fig. 3. BER of the Walsh-code-based CDMA signal as a function of the received optical power at photodetector A ($P_{rec,\,A}$). •: without OBI; $\Delta$: with Walsh-code-chirped OBI ($RIN_{OBI} = -93.4$ dB/Hz); **x**: OBI peaked at 472 MHz; ◇: OBI peaked at 872 MHz; **O**: OBI peaked at 672 MHz.

despread by a perfectly-synchronized Walsh code. As shown in Fig. 1, the synchronized conditions were carried out by carefully adjusting the 672-MHz carrier phase and the code delay at the receiving end. Walsh code generator #3 with its power and delay properly adjusted was used to simulate the total interference generated by other synchronized users in a multiple access environment.

When laser A was modulated at an OMI of 135%, its bit-error-rate (BER) test results for several different OBI conditions are shown in Fig. 3. It is clear that when the "unchirped" OBI falls right into the center of the CDMA signal band, i.e., OBI peaked at 672 MHz, there is a power penalty of about 14 dB @ BER $= 10^{-9}$, comparing with the case of no OBI. This large power penalty was reduced to about 9 dB when the un-chirped OBI drifted to either edge of the CDMA signal band, i.e., OBI peaked at 472 or 872 MHz. The power penalty was further reduced to 6 dB when the OBI is "chirped" and suppressed due to a large modulating CDMA signal (OMI $=$ 135%) applied to laser B.

The multiple access capability of Walsh-code-based CDMA signals in the presence of OBI (which was generated from DSI in Fig. 1) and CDMA co-channel interference (which was generated from Walsh code generator #3 in Fig. 1) was tested and the results are shown in Fig. 4. When there was no OBI, the CDMA signal can be received with a BER of $10^{-9}$ at a signal-to-co-channel interference ratio ($S/I_{co}$) of −25 dB, where the co-channel interference power from Walsh code generator #3 was carefully calibrated against the received power of a single user. Although from the $S/I_{co}$, the system can accommodate an estimated 317 ($10^{2.5}+$ 1) users simultaneously, the actual user number is limited by the code length, i.e., the maximum system capacity is 128 users. Next, to test the BER degradation in the presence of OBI, three different levels of chirped OBI with a flat spectrum were added to the signal. The relative intensity noise associated with each OBI level is expressed in terms of $RIN_{OBI} = \langle i^2_{OBI}\rangle / I^2_{dc}$, where $\langle i^2_{OBI}\rangle$ is the spectral density of the OBI noise current and $I_{dc}$ is the received photocurrent from laser A. Note that we used $RIN_{OBI}$ instead of ROBIN ($= \langle i^2_{OBI}\rangle / I_{signal}I_{interferer}$) [4] because the OBI in our experiment was artificially generated from the DSI setup, and was not due to the actual beating between signal and interference lasers. Therefore, the net effect of the separately generated OBI on the signal laser BER performance is due to the OBI-induced intensity noise relative to the received signal power. When the added $RIN_{OBI}$ was −95.4 dB/Hz (the received power at photodetector A, $P_{oA}$, is −24 dBm, and the received power at photo-detector B, $P_{oB}$, is −20 dBm), which was a very strong intensity noise, the required $S/I_{co}$ @ BER $= 10^{-9}$ was forced to increase from −25 to about −22 dB which corresponds an estimated 159 interferers. Again, due to the codelength limit, we can only have a maximum of 128 users. When the added $RIN_{OBI}$ was further increased to −93.4 and −91.4 dB/Hz (by decreasing the optical attenuation before photo-detector B by 1 and 2 dB, respectively), error floors occurred as can be observed in Fig. 4. Nevertheless, 128 users in the presence of a high $RIN_{OBI}$ of −95.4 dB/Hz are quite sufficient

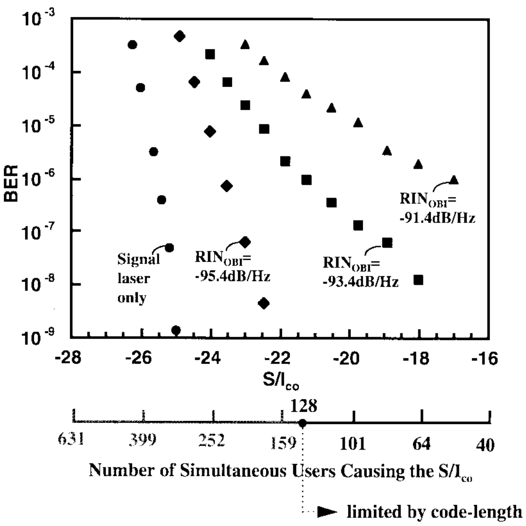


Fig. 4. BER versus signal-to-co-channel interference ratio (S/$I_{CO}$) for different levels of added OBI. The corresponding numbers of simultaneous users which cause the S/$I_{CO}$'s are also shown in the second horizontal axis.

for a PON, or a WDMA network using common-wavelength SCM signaling. Note that if we assume that each laser has an intrinsic RIN of $-140$ dB/Hz, the total added RIN noise from 128 users is $-140 + 10 \cdot \log(128) \approx -119$ dB/Hz, which is insignificant compared to the OBI RIN noise. We must also emphasize that the maximum 128 users do not have to use 128 lasers because a single laser can be shared by multiple S-CDMA users, and during a short period of time, only a few lasers may run into the same wavelength and generate optical beats.

Generally speaking, networks using CDMA must have a tight power control on all transmitters (as in wireless networks). However, in our experimental conditions, the received signal laser power was $-24.5$ dBm @ BER $= 10^{-9}$ when the total received optical power from the DSI setup was as high as $-19$ dBm, which means that each of the interfering lasers can be 2.5 dB $[= (-19 - 3) - (24.5)]$ stronger than the signal laser. This implies that the tight power control could be slightly relaxed. We have also investigated the requirement on code phase accuracy by measuring several different code patterns, and found that the $1010\cdots$ code was the most vulnerable to phase offset. When using this code with a phase offset of about 1/6 chip (or 0.8 ns in our experiment), 2- and 3-dB power penalties in signal-to-noise ratio (S/N) and S/$I_{CO}$ were incurred, respectively, in the BER performances of the CDMA signal (when compared to those of a perfect code-phase condition).

## III. Conclusion

By taking advantage of the excellent orthogonality among Walsh codes, we have demonstrated that S-CDMA technique can be successfully used in lightwave networks where strong OBI and co-channel interference are present. We have shown that, if each laser is modulated by a large CDMA signal, multiple access and significant OBI suppression can be simultaneously achieved. Since no out-of-band clipping tones were used to suppress OBI, not only additional nonlinear distortions can be avoided, but also significant modulating power can be saved to maximize the system power budget. Since it is easy to share a single laser by multiple S-CDMA signals within the same signal band, the number of lasers in a network and the probability of optical beating can both be reduced. We have also shown that, with a data rate of 1.5625 Mb/s and a chip rate of 200 Mb/s, the S-CDMA network can accommodate as many as 128 users simultaneously (limited by the code length), even in the presence of a very strong DSI-generated OBI level of $RIN_{OBI} = -95.4$ dB/Hz.

## References

[1] C. Desem, "Optical interference in subcarrier multiplexed systems with multiple optical carriers," *IEEE J. Select. Areas Commun.*, vol. 8, pp. 1290–1295, 1990.

[2] B. H. Wang, K. Y. Yen, and W. I. Way, "Demonstration of gigabit WDMA networks using parallelly processed subcarrier hopping pilot-tone ($P^3$) signaling technique," *IEEE Photon. Technol. Lett.*, vol. 8, pp. 933–934, 1996.

[3] N. Hayashi, H. Yoshinaga, and K.-I. Suto, "Eight channel upstream transmission demonstration for subcarrier multiple access networks," in *IOOC'95 Tech. Dig.*, 1995, pp. 66–67.

[4] S. L. Woodward, X. Lu, T. E. Darcie, and G. E. Bodeep, "Reduction of optical-beat interference in subcarrier networks," *IEEE Photon. Technol. Lett.*, vol. 8, pp. 694–696, 1996.

[5] T. H. Wood and N. K. Shankaranarayanan, "Operation of a passive optical network with subcarrier multiplexing in the presence of optical beat interference," *J. Lightwave Technol.*, vol. 11, pp. 1632–1640, Oct. 1993.

[6] R. D. Feldman, T. H. Wood, G. Raybon, and R. F. Austin, "Effect of optical beat interference on the dynamic range of a subcarrier multiple access passive optical network using Fabry–Perot lasers," *J. Lightwave Technol.*, vol. 14, pp. 711–715, May 1996.

[7] H. Sasai, H. Yamamoto, K. Utsumi, and K. Fujito, "Optical access links suppressing optical beat interference with FP-LD's for microwave transmission," in *Int. Topical Meet. Microwave Photonics, Tech. Dig.*, Kyoto, Japan, Dec. 1996, pp. 237–240, paper WE4-6.

[8] TIA/EIA/IS-95 Interim Standard, "Mobile station-base station compatibility standard for dual-mode wide-band spread-spectrum cellular system," Telecommunications Industry Association, July 1993.