On the Validity of Using CW Tones to Test the Linearity of Multichannel M-QAM Subcarrier Multiplexed Lightwave Systems

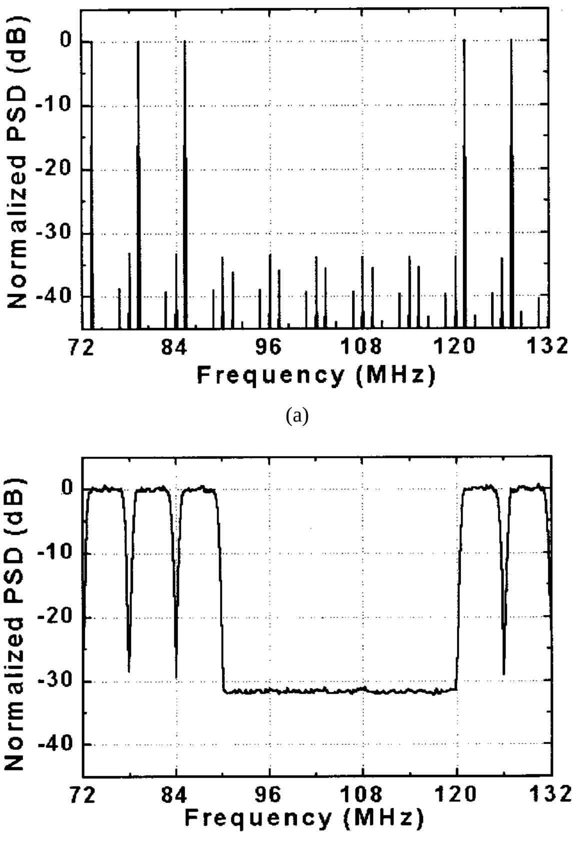
Ming-Chia Wu, Pi-Yang Chiang, and Winston I. Way, *Senior Member, IEEE*

***Abstract*—This paper investigates the validity of using multiple continuous-wave (CW) tones as the signal source to test the linearity of a multichannel M-ary quadrature-amplitude-modulation (M-QAM) subcarrier multiplexed lightwave system. We consider the following representative optical fiber system nonlinearities: 1) laser clipping and 2) the combined effect of laser frequency chirp and fiber dispersion. Our results show that if all orders of nonlinear distortions (NLD's) in a signal bandwidth are included in the total NLD power, the error caused by replacing M-QAM signals with CW tones can be within measurement uncertainty.**

***Index Terms*—AM-VSB, CATV, hybrid fiber coax, nonlinear distortion, quadrature amplitude modulation (QAM).**

I. INTRODUCTION

IT IS believed that subcarrier multiplexed (SCM) lightwave systems can be used to transport multichannel M-ary quadrature amplitude modulation (M-QAM) signals to provide broad-band digital services such as Internet access, digital video, IP telephony, etc. [1], [2]. In the past, the linearity characteristics of such systems were investigated by using multiple continuous-wave (CW) tones [3]–[5], mainly because of the practical difficulty in generating multiple distinct M-QAM channels. However, the spectral distributions of nonlinear distortions (NLD's) caused by multiple CW tones and multiple wide-band M-QAM signals are quite different. In the former case, NLD's consist of various distinct beats such as composite second orders (CSO's) and composite triple beats (CTB's). In the latter case, NLD's are spread over several channels and are like white noise. Fig. 1(a) and (b) illustrate the spectra of the two cases. To our knowledge, there is no report discussing the validity of using CW tones to replace the actual M-QAM signals. In this letter, we study this validity by performing spectral analysis, numerical simulation, and experimental verification. We chose two representative optical fiber nonlinearities in SCM lightwave systems to study: 1) laser clipping and 2) the combined effect of laser chirping and optical fiber dispersion.



(a)

(b)

Fig. 1. Illustrations of typical NLD's generated from: (a) CW tones and (b) QAM. Signal levels were normalized to 0 dB for comparison.

II. ANALYSIS AND NUMERICAL SIMULATION

Spectral analysis [2] has been used to calculate the NLD's induced by a general nonlinear transfer function. This analytical technique is based on the assumption that the input signal to the nonlinear device can be approximated as a Gaussian random process, and can be used to resolve all orders of NLD's by deriving from the output power spectral density (PSD).

Let us assume that all M-QAM signals are 64-QAM signals with a symbol rate of 5 Ms/s per channel and the rolloff factor α of the a receiver basebanc square-root-raised cosine (SRRC) filter is 0.2. We also assume that the root-mean-squared (rms) optical modulation index per channel (OMI/ch) and total channel number of 64-QAM and continuous-wave (CW) tone systems are equal. Besides, both 64-QAM's and CW tones use standard NTSC frequency plan, with a bandwidth of 6 MHz per

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M.-C.Wu and W. I. Way are with the Department of Communications Engineering, National Chiao-Tung University, Hsinchu, Taiwan, R.O.C. (e-mail: wiway@cc.nctu.edu.tw).

P.-Y. Chiang was with the Department of Communications Engineering, National Chiao-Tung University, Hsinchu, Taiwan, R.O.C. He is now with Askey International Corp., Fremont, CA 94538 USA.

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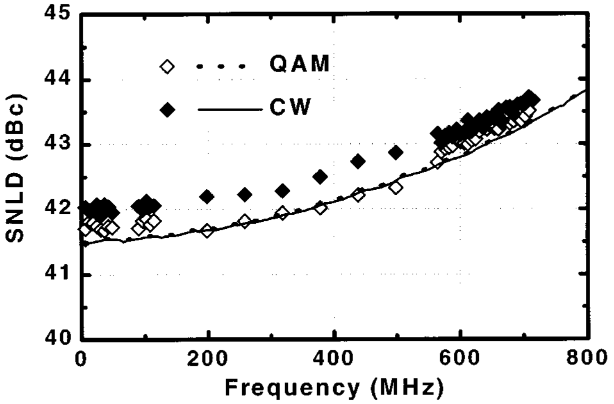

Fig. 2. Spectral analysis (solid and dotted lines) and numerical (solid and open symbols) results of LD clipping induced SNLD's. Seventy-four channels of CW tones or 64-QAM signals were used. Number of averages were 1000 and 150 for CW and QAM, respectively. RMS OMI/ch $= 3.9\%$

channel, center frequency of $6X+3$ MHz for 64-QAM's, and carrier frequency of $6X+1.25$ MHz for CW tones.

The first case study is on laser clipping with an ideal L–I curve. In this case, it is the higher order NLD's that dominate [2]. Therefore, in calculating the total NLD power in a signal band, we have included all NLD's up to the fifteenth order. Based on spectral analysis, the calculated results of using 74-channel CW tones or 64-QAM signals with rms OMI/ch $= 3.9\%$ are shown in Fig. 2. We can see that the resultant SNLD's in using the two different modulating signals are the same.

Numerical simulations were used to confirm the analytical results. In Fig. 2, each simulation data point is an average result of 1000 random phase combinations when using CW tones, or an average result of 150 random phase and symbol pattern combinations when using QAM signals. We can see in Fig. 2 that the simulation results match very well with those of spectral analysis, and the results of using either CW tones or QAM's differ by less than 0.5 dB. Note once again that in the case of CW tones, NLD's up to fifteenth order have been included.

For the case of a directly modulated 1550-nm laser passing through a span of conventional nondispersion-shifted fiber, NLD's (dominated by CSO's) generated from multichannel CW tones or QAM signals can also be compared. The solid and open squares in Fig. 3 are the numerically calculated SNLD caused by 74 channels of CW tones and 64-QAM signals, respectively. The directly modulated 1550-nm laser has a total frequency chirp parameter of 3.6 GHz, and the transmission distances were 20, 40, and 80 km. Each data point is an average result of 100 random phase combinations for CW tones, and 100 random phase and symbol pattern combinations for QAM. As shown in the figure, the results for CW tones or QAM signals are essentially equal. The numerically calculated results shown in Fig. 3 can be checked by using a closed-form formula of CSO generated from CW tones [6] propagating in a dispersive fiber. The solid line in Fig. 3 is based on that formula and matches well with the numerical simulation results.

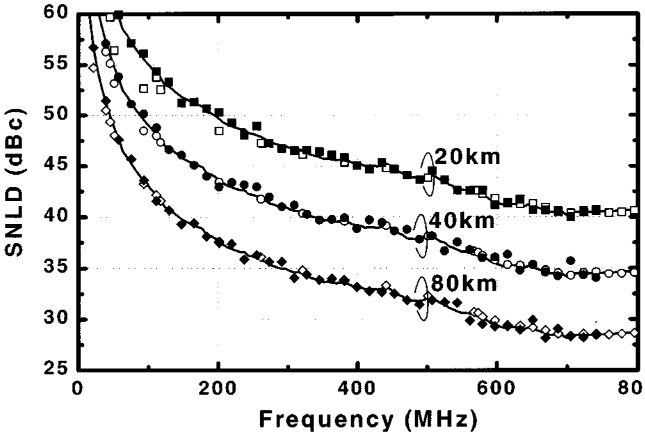

Fig. 3. Analytical (solid lines) and numerical results (open and solid symbols) of signal to second-order nonlinear distortions ratio due to laser frequency chirping and fiber dispersion. Three different fiber lengths were considered. Solid lines are calculated results based on [6]. Solid and open symbols resulted from 74-channel CW tones and 64-QAM, respectively.

III. EXPERIMENT

In our experimental setup, we used 16 uncorrelated channels of 64-QAM signals (in the frequency range 258–354 MHz) from a vector arbitrary waveform synthesizer [2] and used 16 channels of CW tones from a matrix generator. The measured 64-QAM signals were ensured to have a back-to-back signal-to-noise ratio of >40 dB. The total power of NLD's (either noise-like or discrete tones) in a 6-MHz channel was measured by using the band power measurement function of an HP89440 vector signal analyzer. When a tone-like intermodulation product occurs at the edge of a 6-MHz band, e.g., at a frequency of $6X$ MHz (where X is a positive integer), its power is included in the total NLD power of the signal band centered at either $6X+3$ or $6X-3$ MHz, but not both.

In the first part of our experiment, we compared the difference of strong laser clipping-induced NLD's due to the direct modulations of 16-channel CW tones and 16-channel 64-QAM signals, respectively. OMI per channel ranged from 18 to 29% per channel. The measurement results in Fig. 4 show good agreement between CW tones and 64-QAM's and agree well with the spectral analysis results. In the second part of our experiment, we verify the difference of fiber dispersion-induced second-order nonlinear distortions when using two different types of modulating signals. Sixteen CW tones or 64-QAM signals with the same total rms power were used to directly modulate a 1550-nm laser. The total frequency chirp under the modulation was 3.6 GHz. The measured results in Fig. 5 show that the difference of distortions for CW tones and 64-QAM's can be less than 1 dB. Also, the calculated results based on the analysis given in [6] show good agreement with our measurement.

IV. DISCUSSION

An SRRC pulse shaping filter with a rolloff factor $\alpha = 0.2$ at the transmitter and a 6-MHz rectangular filter at the receiver were used in all of our spectral analysis, numerical simulations,

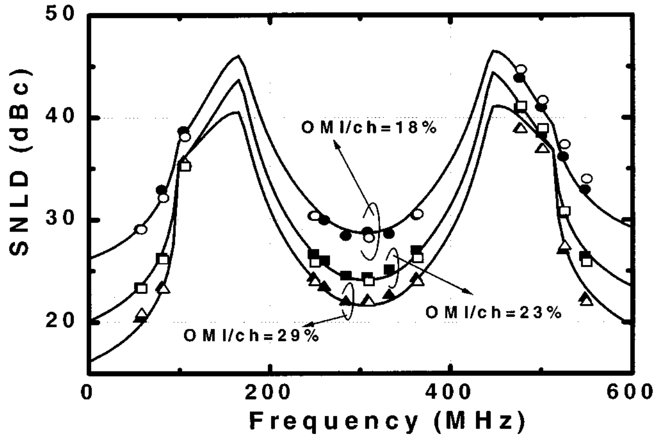

Fig. 4. Measured SNLD results for laser clipping. Results for 16 channels of CW tones (solid symbols) or 64-QAM's (open symbols) ranging from 258 to 354 MHz are shown. Solid lines are calculated results based on spectral analysis.

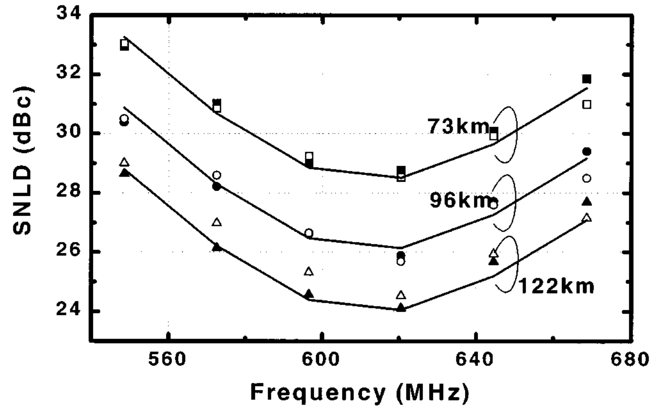

Fig. 5. Measured results of SNLD due to fiber dispersion and laser chirping for both 16-channel CW tones (solid symbols) and 64-QAM (open symbols). Solid lines are calculated results from [6]. Total laser frequency chirp is 3.6 GHz, and the fiber dispersion is 17 ps/nm/km.

and experiments. In practical M-QAM systems, however, SRRC filters are usually placed in both the transmitter and receiver ends. Therefore, the actual SNLD can be better than what we measured by about 0.33 dB.

Note that if we use CW tones as testing source, we should use a rectangular filter, rather than an SRRC filter, at the receiving end. This is because if an SRRC filter were used, it could filter out a NLD component located at a frequency equal to $6X$ MHz, while if a rectangular filter is used, that particular NLD component can still be counted in the total NLD. Therefore, we emphasize that all NLD components within the 6-MHz band must be included when using CW tones for testing.

Another measurement issue, which needs our attention, is that the carrier-to-noise ratio (CNR) of a signal generated from a practical M-QAM modulator is much lower than that from a practical CW-tone generator. The latter usually has a high CNR of >50 dB, while the former has low CNR of about 40 dB. Therefore, when CW tones are used as the signal source to characterize system linearity, the measured SNLD must be calibrated by adding the electrical noise contributions from the M-QAM modulator to reflect what would really be measured in a multichannel M-QAM system.

Although all experimental data in this paper were measured by the band power measurement function of HP89440, it is expected that regular spectrum analyzers can also be used. However, it should be cautioned that regular spectrum analyzers perform video average on log scale, and there is difference between log of average and average of log depending on the signal statistics [7]. For example, for Gaussian noise, there is a 2.51-dB underresponse by using the video average function. Since the statistics of the nonlinear distortions caused by CW tones and M-QAM's are quite different, the use of video average on a spectrum analyzer is not recommended.

V. CONCLUSION

Through spectral analysis, numerical simulations, and experiments, we found that the difference of resultant SNLD's in using multichannel CW tones and multichannel M-QAM signals is negligible, provided the following conditions can be met. The first is that both types of signal sources (having the same number of channels) have the same total rms OMI, channel bandwidth, and frequency plan. The second is that all orders of nonlinear distortions in a signal bandwidth must be included in the total NLD power when CW tones are used in the measurement. Other cautions, such as not using video average on spectrum analyzers, not double counting the CW tones-induced NLD's at the band edges, and not neglecting electrical noise contributions from M-QAM modulators, should also be carefully taken into consideration during the measurement.

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