Regards,
Eric Funk, Ph. D.
Partner, Red Mountain Radio LLC
eric@redmountainradio.com
970-325-2158 ×12

110 KM 256-QAM DIGITAL MICROWAVE OVER FIBER LINK

Eric E. Funk, Vincent J. Urick, Shane J. Strutz, James L. Dexter, and Keith J. Williams

Naval Research Laboratory, Washington, DC 20375

Abstract – **A 110 km digital microwave fiber-optic link has been designed and demonstrated with 256 QAM at 20 GHz. The design approach, involving the management of loss, dispersion, and Brillouin threshold throughout the link is discussed.**

I. INTRODUCTION

Analog fiber-optic links have proven extremely useful for the distribution of microwave and millimeter wave signals in military and commercial applications. However, long range (>100 km) microwave fiber-optic links have always posed many challenges. With the prevalence of digital microwave radios, one particularly relevant problem is the potential impairment caused to *m*-ary quadrature amplitude modulated signals (*m*-QAM).

QAM [1] requires a higher signal to noise ratio than the more common bipolar phase shift keyed (BPSK) or quadrature phase shift keyed (QPSK) formats. It also requires a high degree of linearity in order to preserve the amplitude mapping of the signal constellation. However, the high spectral efficiency of QAM, up to 8 b/s/Hz for 256 QAM, is advantageous for use in wireless systems where the allocated spectrum and/or the channel coherence bandwidth are limited.

In this work, the design and demonstration of a unique 110 km 1550 nm 20 GHz fiber radio link is reported. The link was designed with sufficient dynamic range to transport 256-QAM and dispersion was dispersion managed to mitigate carrier suppression [2].

Although long-range QAM fiber radio links have been reported at CATV frequencies [3], it is to the authors' belief that this is the first report of a long range (> 100 km) 256 QAM link at microwave frequencies above 10 GHz.

At link lengths of greater than 100 km, link loss, fiber dispersion, and fiber non-linearities such as stimulated Brillouin scattering (SBS) can potentially cause significant signal impairment. The presented design considers each of these potential impairments, with a particular emphasis on achieving the high dynamic range that QAM requires.

Previous work has addressed spur free dynamic range (SFDR) in short links. For instance, Williams et al [4] have demonstrated greater than 119 dB/Hz$^{2/3}$ SFDR in a short analog link by launching over 20 dBm of optical power. In a short link, the optical launch power is typically limited only by the linearity of the detection photodiode, while in links with more than ten kilometers of fiber, SBS limits the launch power to the order of 10 dBm. Hence, in extending the research to long links, SBS management is a major concern.

To achieve a SFDR greater than 100 dB/Hz$^{2/3}$, long links require optical amplifiers to overcome propagation losses, which in turn introduce a cascaded optical noise figure and gain. The dispersion along a lengthy span of fiber likewise affects the link performance. An optimized link is presented that mitigates the limitations of long analog fiber-optic links by managing the optical noise figure-gain sum, dispersion, and SBS threshold. These techniques are applied to a 110 km analog link externally modulated with a Mach Zehnder modulator (MZM) biased at quadrature. Pre-distortion and offset biasing techniques, which may result in an additional improvement, have not yet been explored. The procedure will enable fiber links to reach lengths greater than 100 km with large SFDR in excess of 100 dB/Hz$^{2/3}$.

II. SFDR CALCULATION

In designing a high spurious-free dynamic range system, the key is to minimize noise figure and maximize output intercept points. For a fiber link with an MZM biased at quadrature, the third order intercept, limited primarily by the MZM's sinusoidal transfer function, is the dominant non-linearity. The output referenced third order intercept point (*OIP*3) at quadrature bias can be expressed as a function of detected photocurrent [5].

$$OIP3 = 4 I_{DC}^{\,2} R \qquad (1)$$

where I_{DC} is the detected DC photocurrent, R is the electrical load resistance, and photodiode nonlinearities have been neglected. It is therefore necessary to maximize received photocurrent for a high SFDR.

In a link containing optical amplifiers, the noise performance has a strong dependence on amplifier noise figure, gain, and position along the span. In most cases, noise power resulting from amplified spontaneous emission (ASE) is the largest source of noise for a long haul link. Following from Phillips [6], the noise power originating from the beat between signal and spontaneous emission, $N_{sig\text{-}sp}$, will given by

$$N_{sig-sp} = 2\eta F G I_{DC} ReB \tag{2}$$

where η is the detector quantum efficiency, F is the cascaded optical noise factor, G is the cascaded gain, e is the elementary charge constant, and B is the electrical detection bandwidth. Note that when the product, ηFG, is greater than unity, the ASE noise, $N_{sig\text{-}sp}$, is larger than the shot noise. In this ASE limit, the SFDR of the link will be given by:

$$SFDR_{ASE}\left(\frac{\text{dBm}}{\text{Hz}^{2/3}}\right) = \frac{2}{3}\left[OIP3(\text{dBm}) - N_{sig-sp}\left(\frac{\text{dBm}}{\text{Hz}}\right)\right]$$

$$= \frac{2}{3}\left[161\text{dBm} + 10\log\left(I_{DC}(\text{mA})\right) - NF(dB) - G(dB)\right] \tag{3}$$

This simple expression does not account for thermal or relative intensity noise (RIN) and assumes the availability of a low RIN laser source. However, as shown in Fig. 1, these additional contributions are comparatively small and justifiably neglected for photocurrents between 1 and 10 mA.

The salient features of the approach are highlighted by (3). Given a dispersion managed link design, the detected optical power is maximized and the cascaded optical noise figure-gain sum is minimized. Since the cascaded noise figure-gain sum must be low, the implication is that the optical power launched into the link should be as large as possible. In practice, the launch power is limited by the SBS threshold of the fiber. Likewise, the repeater spacing should be small to keep the amplified noise low.

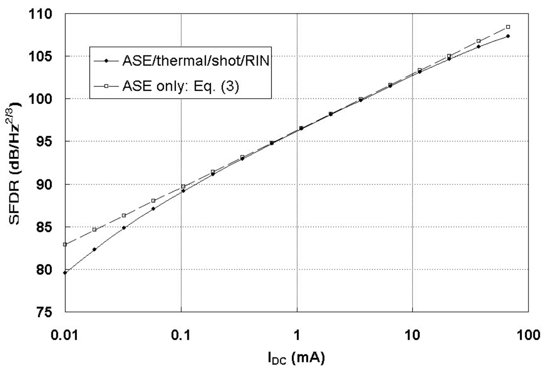


Fig. 1. Calculated spur free dynamic range as a function of detected DC current in an amplified fiber link. Cascaded optical noise figure-gain sum = 16.6 dB, RIN = -160 dB/Hz.

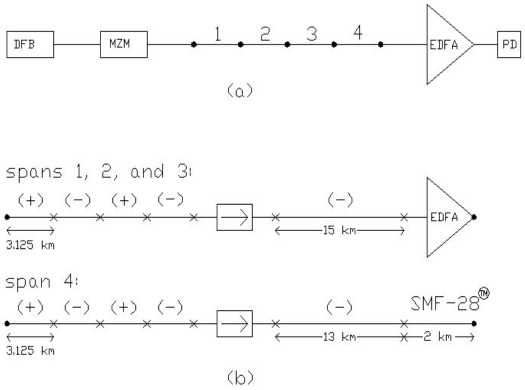


Fig. 2. (a) Architecture of 110-km high dynamic range link. DFB: Distributed Feedback Laser, MZM: Mach Zehnder Modulator, EDFA: Erbium doped fiber amplifier, PD: Photodiode. (b) Detail of hybrid span construction, (+): Lucent True-wave Positive fiber, (–): Lucent True-wave Negative fiber.

III. EXPERIMENTAL RESULTS

A 110 km link was constructed as shown in Fig. 2. The link consisted of a low RIN distributed feedback laser and an MZM followed by four 27.5 km spans of fiber. An erbium doped fiber amplifier (EDFA) followed each span. The output power of each EDFA was adjusted to yield the same launch power into each fiber span with the exception of the final amplifier. The final EDFA was designed with slightly different gain in order to provide the desired current in the detection diode.

The power launched at the input to each 27.5 km span of fiber was maintained at 11.2 dBm, just below the fiber span's SBS power threshold. In order to maximize the threshold, the front end of every span was assembled as a hybrid combination of fiber types, each with different SBS resonance frequencies. These SBS management sections consisted of alternating 3.125 km spans of Lucent Truewave positive dispersion and negative dispersion fiber. The detail of each hybrid span is shown in Fig. 2(b). The mismatch between these two fiber types results in an observed increase in SBS threshold of up to 6 dB when compared to a 27.5 km span of one fiber type. By mixing positive and negative dispersion fibers, a low net dispersion was maintained throughout the system. A section of SMF-28™ fiber in the final span offsets an otherwise negative net dispersion. Using the modulation phase shift method [7], the zero dispersion wavelength of the link was determined to be at 1550.2 nm. The SFDR measurements were made at 1551 nm where the measured dispersion at the output of the link was 8 ps/nm. As shown in Fig. 3, there are no adverse effects due to dispersion in the frequency response of the entire link.

The $SFDR_{ASE}$ was measured by plotting RF input and output powers, thus obtaining a value for $OIP3$ (see Fig. 4). The noise figure-gain sum was determined by spectrum analyzer noise measurements and $SFDR_{ASE}$ then given by (3). The $SFDR_{ASE}$ was measured for 1 and 10 mA detection currents and had values of 102 and 103 dBm/Hz$^{2/3}$ at 10.4 GHz, respectively. The measured third order intercept level was identical at both 10.4 GHz and 18 GHz. The 10 mA measurement corresponds to the conditions assumed in the theoretical model (Fig. 1) with an optical noise figure-gain sum of 16.6 dB. The optical noise figure and gain at I_{DC} = 1 mA were measured as NF = 16.4 and G = -9 dB, while those at I_{DC} = 10 mA were NF = 15.6 and G = 1 dB.

The practical performance of the link was then evaluated by transmitting 16-, 64-, and 256-QAM signals across the link. The QAM signal was generated with a vector signal source at a 2 GHz intermediate frequency. A symbol rate of 5 MBaud was chosen, and a raised root cosine (RRC) filter ($\alpha = 0.2$) was employed. This lead to an aggregate bit rate of 40 Mb/s within a 6 MHz channel with 256-QAM. A pseudo-random bit stream of length $2^{23}-1$ served as the message data. The vector-modulated signal was then up-converted to 20 GHz with an 18 Hz local oscillator. The 20 GHz signal was amplified and sent through the 110 km fiber link. The input RF power level at the MZM was fixed at 5 dBm.

The 20 GHz signal was received in the photodiode at the end of the 110 km link. The received signal was down-converted to a 500 MHz intermediate frequency with a 19.5 GHz local oscillator. The down-converted signal was then sent to a vector signal analyzer (VSA). The VSA used a matched RRC filter for reception, but no additional filtering or channel equalization was used.

The 16-QAM and 256-QAM constellations that were received by the VSA are shown in Fig. 5. The measured error vector magnitude (EVM) and modulation error ratio (MER) are shown in Table 1. The MER is analogous to carrier to noise ratio (CNR); it is the ratio of the error power in the received signal to the average power in the ideal QAM signal. Hence, the MER can be used to estimate the bit error rate. With the assumption that the noise is primarily additive white Gaussian, the estimated [8] un-coded BER is shown in Table 1.

The measured parameters for a back-to-back link are also shown in Table 1. In the back-to-back link, the fiber link was removed and replaced by a 20 dB attenuator. Hence, the measured error is due exclusively to the remaining components including the up and down conversion mixers and amplifiers. Note that the MER of the back-to-back link is only 0.6 dB better than that of the 100 km fiber link, indicating that the fiber link is almost transparent.

It must be emphasized that non-encoded BERs as high as 10^{-4} are satisfactory in a microwave QAM link, since these links are typically operated with strong forward error correction codes [9] that work quite well at this level.

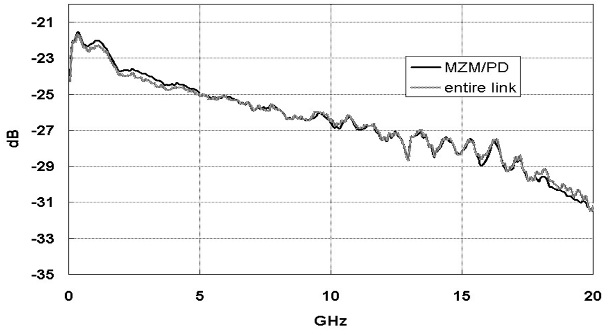


Fig. 3. The RF frequency response of the MZM and photodiode as compared to that for the entire link.

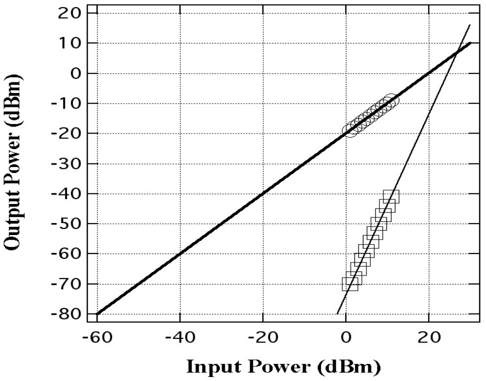
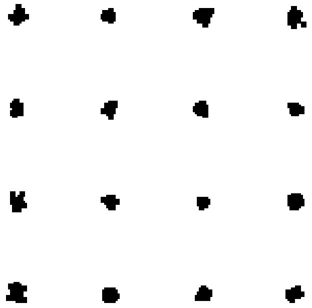
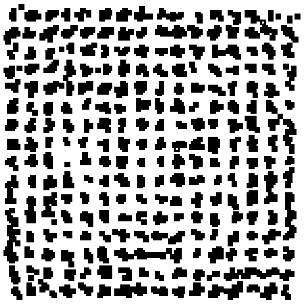


Fig. 4. Linear extrapolation of fundamental (circles) and third order distortion (boxes) output RF power as a function of input RF power. Data displayed yield $OIP3$ = 7 dBm for I_{DC} = 10 mA at 10.4 GHz. The noise floor is at –148 dBm for a 1 Hz bandwidth.



(a)



(b)

Fig. 5. Measured (a) 16- and (b) 64-QAM constellations following propagation through the 110 km link on a 20 GHz carrier.

Modulation	**EVM (%)**	**MER (dB)**	**BER (Est.)**
16 QAM	2.2	30.5	$<10^{-12}$
64 QAM	2.3	29.3	10^{-10}
256 QAM	2.2	28.9	10^{-4}
256 QAM (BTB)	2.1	29.5	10^{-4}

Table 1. Measured performance of 110 km link with different levels of QAM. BER estimated from measured MER. BTB indicates back to back measurement without fiber link.

IV. CONCLUSIONS

To the authors' knowledge, the first analog link with a length of greater than 100 km managed in terms of optical noise figure-gain sum, fiber dispersion, and SBS has been demonstrated. These management techniques have resulted in a high SFDR for the link, enabling operation with *m*-ary QAM with *m* as high as 256.

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