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3×2^N -QAM Constellation Formats for DMT Over 1-mm Core Diameter Plastic Optical Fiber

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Abstract—The family of 3×2^N quadrature amplitude modulation (QAM) constellations in combination with discrete multitone modulation is employed to maximize the throughput of 1-mm core diameter plastic optical fibers. Using this scheme together with a bit and power loading algorithm, a bit-rate improvement of 12% is achieved compared with using only 2^N -QAM scheme. A bit rate of 5.6 Gb/s is demonstrated over 50 m of 1-mm core diameter graded-index plastic optical fiber (POF).

Index Terms—Frequency-division multiplexing, optical fiber communication, plastic optical fiber, signal processing.

I. INTRODUCTION

IN THE last decade, optical communication have passed from the use of simple modulation schemes to more complex solutions [1]. This is possible not only due to the higher quality of available optical components, but mainly attributed to the introduction of electronic signal processing techniques. This is more evident in short-range optical communications where only simple intensity-modulation direct-detection (IM-DD) scheme is considered for real implementation because of the main concerns of simplicity and cost issue. Due to the “do-it-yourself” installation and the availability of low-cost transceivers, large core polymer methylmethacrylate (PMMA) POFs are a potential solution for short-range in-home communications [2]. Using simple binary modulation and complex electrical equalization techniques, 1 Gb/s systems using step-index (SI) POF have been demonstrated [3] and will soon be available on the market. However, to scale to higher

Fig. 1. The 3×2^N -QAM modulator.

bit-rates, spectrally efficient modulation formats should be employed [4].

Discrete multitone modulation (DMT) aided with bit and power loading algorithm has been proposed to achieve high spectral efficiency, overcoming the bandwidth bottleneck in order to realize multigigabit transmissions over POF links. The use of DMT has led to transmission records of Ø1 mm POF recently: 4.7 Gb/s transmissions over 50 m SI multicore [5], 10 Gb/s over 25 m SI single-core [6], and 5.3 Gb/s over 50 m graded-index (GI) single-core [7].

The conventional constellations are based on power of $2 (2^N)$ quadrature amplitude modulation (QAM). This corresponds to an integer number, N , of bits per subcarrier of the DMT signal.

For radio communication systems, novel adaptive constellation formats have been proposed in the recent years [8]. In particular, the family of 3×2^N -QAM constellations have been studied [9]. Fig. 1 shows the (de)modulator for 3×2^N -QAM constellations. $2N + 3$ bits are parallelized and then divided into three groups: one group of 3 bits and two groups of N bits. The 3 bits are then converted from binary to a ternary format. One of the ternary values and one group of N bits is selected for each symbol time to be mapped on the 3×2^N -QAM constellations. The mapping was described in detail in [8], [9]. Therefore, we obtain two symbols every $2N + 3$ bits, leading to $N + 1.5$ bits per symbol. These new constellation schemes allow a finer granularity in the bit allocation, hence more efficient in using the available bandwidth.

In this letter, we employ this novel constellation format to maximize the bit-rate in a graded-index POF link. The key consideration discussed in this letter is the comparison between 3×2^N and the conventional 2^N QAM constellation scheme. This letter is organized as follows: after evaluation of the water filling capacity in Section II, experimental results are presented in Section III and compared with the water filling capacity of Section II. Finally, conclusions are drawn.

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Fig. 2. Normalized noise level to the link gain of the POF link with water lines for different input power obtained through water filling algorithm.

Fig. 3. Comparison of the water-filling spectral efficiency of the POF link with a flat additive white Gaussian noise (AWGN) channel Shannon limit.

II. WATER FILLING CAPACITY

To establish the theoretical capacity of the POF system considered, we start from the evaluation of the water filling capacity of the channel [10].

In Fig. 2 we show the noise level $N(f)$ of the link normalized by the link gain $G(f)$ of the system. The principle of the water filling algorithm is to determine the water line, corresponding to a given fixed value of input power, which discriminates the frequencies with allocated power (below the line) from the ones without any power allocated for transmission (above the line) [10]. In Fig. 2 an example of three water lines corresponding to the three input power P_s values of -10 , 0 and $+10$ dBm are drawn. Starting from a water line, as represented in Fig. 2, we determine the Shannon limit for a single value of the signal-to-noise ratio (SNR). Fig. 3 shows the Shannon limit spectral efficiency of the POF link compared to the Shannon limit of a flat additive white Gaussian noise (AWGN) channel. The SNR corresponding to the three water lines of Fig. 2 are also shown in Fig. 3.

The model described here does not include clipping and thus represents an upper bound of the channel capacity. We believe that the results are still valid for clipping values which cause a decrease of the average signal power by a maximum of 0.2 dB and for SNR values less than 10 dB.

III. EXPERIMENTAL SETUP AND RESULTS

In Fig. 4 the experimental setup is depicted. The available 3 and 6 dB system bandwidth is 1.35 and 1.6 GHz, respectively. A Firecomms red VCSEL with a wavelength of 667 nm is directly modulated by the DMT signal generated from a Tektronix AWG7122B arbitrary waveform generator (AWG) operating at 3.2 GSamples/s. The modulated optical power is launched, without the use of a lens, into a 1 mm diameter

Fig. 4. Experimental setup.

Optimedia PMMA GI-POF with the power level of 0 dBm. The optical signal after 50 m link (-15.5 dBm) is coupled to a silicon avalanche photodetector (Si-APD) with a photosensitive diameter of 230 μm followed by a two-stage electrical amplifier with a gain of 40 dB. Finally, the electrical signal is captured by a Tektronix DPO72004 digital phosphore oscilloscope (DPO) with a sampling speed of 50 Gsample/s and an ADC resolution of 8 bits. This high receiver sampling speed is due to the absence of external synchronization between generator and receiver, thus the synchronization process is realized off-line. In real implementation a lower sampling speed can be used with a clock synchronization control.

For both 2^N and 3×2^N QAM constellations we employed 256 subcarriers distributed in 1.6 GHz, an electrically limited crest factor of 9 dB and a peak-to-peak voltage of 0.65 V. The corresponding transmitted power is 0.25 dBm. Due to this available power and the spectral response, no bits are allocated on the subcarriers above 1.6 GHz. The choice of these DMT parameters were obtained after an experimental optimization process, since they give the better results in term of achieved bit-rate with a bit error rate (BER) below 10^{-3} . To achieve optimal bit allocation, we used a rate-adaptive Chow's bit-loading algorithm [11].

Figs. 5 and 6 show the bit allocation distribution obtained when the bit-loading algorithm uses only 2^N -QAM constellations or 2^N and 3×2^N -QAM, respectively. Note that in Fig. 5(a) the constellations allocated to the subcarriers range from 2 -QAM to 16 -QAM, and the power allocated inside a group of subcarriers with the same constellation can vary of up to 3 dB, as in Fig. 5(b). On the opposite, the power allocated inside a group of subcarriers with the same constellation can vary up to 1.5 dB when also the 3×2^N -QAM are involved, as shown in Fig. 6(b). In fact, allowing a finer granularity in the bit allocation leads to a more uniform power distribution among the subcarriers.

Moreover, the total bit-rate achieved with only 2^N -QAM constellations is 5 Gb/s, while with 2^N and 3×2^N -QAM constellations becomes 5.6 Gb/s. Thus, a percentage gain of 12% in maximum achievable bit-rate is achieved.

Finally, in Fig. 7 we compared the achieved data rate of DMT with (w/) and without (w/o) employing 3×2^N -QAM constellations with the water filling capacity obtained in Section II. Note that the data rates of the two types of DMT signal have the same values when the SNR is below 10 dB, since none or few subcarriers are allocated with 3×2^N -QAM constellations. Then, for increasing values of SNR, 3×2^N -QAM constellation formats begin to be allocated to a larger number of subcarrier leading to an increasing distance between the two types of DMT signal.

Fig. 5. (a) Bits and (b) power allocation of the DMT signal with bit-loading algorithm and involving only 2^N -QAM constellation formats.

Fig. 6. (a) Bits and (b) power allocation of the DMT signal with bit-loading algorithm and involving both 2^N and 3×2^N -QAM constellation formats.

IV. DISCUSSION AND CONCLUSION

With the family of 3×2^N -QAM constellations discussed in this letter, finer granularity in the bit and power allocation scheme is allowed, hence enhancing the transmission capacity of IM-DD POF links.

Fig. 7. Comparison of the DMT achieved data rate with or without 3×2^N QAM and the theoretical water-filling capacity.

This technique requires two symbols for constellation coding and decoding [9]. Requiring an intermediate step for parallelization before symbol mapping and demapping, this additional step can be implemented in existing DSP chip set.

With this scheme, an improvement of 12% in the bit-rate compared to the case of only 2^N -QAM constellation formats has been achieved over a 50 m large core graded-index POF link.

These results show that with slight modifications of mapping and demapping the capacity improvement in bandwidth-limited channel is feasible proving DMT to be an upgradable solution for high-speed short-range POF communication systems.

REFERENCES

- [1] A. Gershtein and D. Sadot, "Advanced modulation formats and digital signal processing for fiber optic communication," in *Proc. Int. Conf. Transp. Opt. Netw. (ICTON)*, Munich, Jun. 27–Jul. 1, 2010.
- [2] A. M. J. Koonen, H. P. A. van den Boom, E. Tangdiongga, H.-D. Jung, and P. Guignard, "Designing in-building optical fiber networks," in *Proc. OFC/NFOEC*, 2010, Paper JThA46.
- [3] A. Nespoli, S. Straullu, P. Savio, D. Zeolla, S. Abrate, D. Cardenas, J. Ramirez, N. Campione, and R. Gaudino, "First demonstration of real-time LED-based Gigabit Ethernet transmission on 50 m of A4a.2 SI-POF with significant system margin," in *Proc. ECOC*, 2010, Paper PD3.1.
- [4] S. Randel, F. Breyer, S. C. J. Lee, and J. W. Walewski, "Advanced modulation schemes for short-range optical communications," *IEEE J. Sel. Topics Quantum Electron.*, vol. 16, no. 5, pp. 1280–1289, Sep./Oct. 2010.
- [5] H. Yang, E. Tangdiongga, S. C. J. Lee, C. M. Okonkwo, H. P. A. van den Boom, S. Randel, and A. M. J. Koonen, "4.7 Gbit/s transmission over 50 m long 1 mm diameter multi-core plastic optical fiber," in *Proc. OFC/NFOEC*, 2010, Paper OWA4.
- [6] S. Loquai, R. Kruglov, O. Ziemann, J. Vinogradov, and C. Bunge, "10 Gbit/s over 25 m plastic optical fiber as a way for extremely low-cost optical interconnection," in *Proc. OFC/NFOEC*, 2010, Paper OWA6.
- [7] D. Visani, C. M. Okonkwo, S. Loquai, H. Yang, Y. Shi, H. P. A. van den Boom, A. M. H. Ditewig, G. Tartarini, B. Schmauss, S. Randel, A. M. J. Koonen, and E. Tangdiongga, "Record 5.3 Gbit/s transmission over 50 m 1 mm core diameter graded-index plastic optical fiber," in *Proc. OFC/NFOEC*, 2010, Paper PDA3.
- [8] A. T. Le and K. Araki, "A group of modulation schemes for adaptive modulation," in *Proc. ICCS*, 2008, pp. 864–869.
- [9] S. Noda, Y. Saito, and T. Yoshida, "Configuration and error ratio performance of M -QAM whose number of signal points is not a power of 2," *Electron. Commun. Jpn.*, vol. 90, no. 2, pp. 46–57, Feb. 2007.
- [10] T. M. Cover and J. A. Thomas, *Elements of Information Theory*, 2nd ed. New York: Wiley, 2006.
- [11] P. S. Chow, J. M. Cioffi, and J. A. C. Bingham, "A practical discrete multitone transceiver loading algorithm for data transmission over spectrally shaped channels," *IEEE Trans. Commun.*, vol. 43, no. 2–4, pp. 773–775, Feb./Mar./Apr. 1995.