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High-Capacity Data Transport via Large-Core Plastic Optical Fiber Links using Quadrature Amplitude Modulation

A.M.J. Koonen, J. Yang, M.S. Alfiad, X. Li, H.P.A. van den Boom
COBRA Institute, Dept. of Electrical Engineering, Eindhoven University of Technology,
Den Dolech 2, P. O. Box 513, NL 5600 MB Eindhoven, The Netherlands, e-mail: a.m.j.koonen@tue.nl

Abstract: Low-cost QAM chip sets enable high-capacity data transport over highly-dispersive POF links. The feasibility of QAM-64 and -256 system implementation options is shown. Wavelength-sliced QAM-64 performs the best regarding bandwidth consumption and link power budget.

OCIS codes: (060.4080) Modulation; (060.2330) Fiber optics communications

1. Introduction
Plastic Optical Fiber (POF) is attractive for realizing broadband in-building networks, such as in residential homes, hospitals, office buildings, airport departure lounges, etc. [1]. Its large core diameter and ductility ease installation considerably. In particular step-index PMMA POF with 1 mm core diameter facilitates cheap short-range data links, and may allow do-it-yourself network installation. Due to the heavy multimode dispersion, however, the bandwidth of such links is severely restricted, typically less than 30 MHz for 200 meters. The European 6th Framework IST joint research project POF-ALL, “Paving the Optical Future with Affordable Lightning-fast Links” aims to realize at least 100 Mbit/s over link lengths of 300 meters [2]. By means of multilevel amplitude modulation, the line rate can be reduced with respect to straight binary transmission; e.g. by a factor of 3 for 8-level coding [3]. However, also the link power budget is reduced because of the decreased eye openings. Quadrature Amplitude Modulation (QAM) offers an interesting alternative; it employs a two-dimensional coding space by modulating the data in multilevel format on two orthogonal carriers [4]. QAM techniques are already widely used in wireless LANs, in DVB-C, and in DOCSIS cable modems. With QAM-64 (a constellation of 64 signal points) or even QAM-256, the line rate is reduced with a factor of 6 or even 8, respectively. By combining them with orthogonal frequency division multiplexing (OFDM) or similar multi-tone techniques, the robustness against dispersion is improved even further. These QAM techniques are readily available in low-cost chip sets, thanks to the large market volume of wireless LAN and cable modem systems. Hence it is of interest to investigate whether QAM schemes can be applied for the realization of high data rates within the severely limited bandwidth of step-index POF links.

2. System implementation options for data transport using Quadrature Amplitude Modulation

QAM signalling involves transmission of data by means of two multilevel signals modulated on orthogonal carriers, commonly being the in-phase (I) and the quadrature-phase (Q) versions of a harmonic carrier. Commercially available QAM chip sets usually consist of a so-called Baseband Processor (BBP) that converts the binary input data stream into the I and Q multilevel signals, and a quadrature modulator/demodulator block. Next to this straightforward direct QAM approach, in the following a number of other approaches are proposed which also use parts of the chip set to implement QAM efficiently in a POF-based system.

The direct QAM approach is shown in Fig. 1a), using modulation of the I and Q signals on two electrical carriers at the same frequency which are \( \pi/2 \) out of phase. As sketched in Fig. 1b), when having a data rate of \( R \) bit/s and a QAM-2\( ^N \) scheme with double-sideband modulation, as a rule of thumb the bandwidth of the POF link needs to be at least \( 1.4 \cdot R/N \), and the carrier frequency \( f_c \) at least \( 0.7 \cdot R/N \). At the receiver site, careful recovery of the carrier and good phase matching of the I and Q signals are needed to avoid deformation of the QAM signal constellation.

A second option is depicted in Fig. 2a), and emulates QAM by putting the I and Q signals in two different frequency bands, e.g. the I signal in baseband and the Q signal in passband centred around the carrier frequency \( f_c \). Fig. 2b) illustrates that this option requires a POF link bandwidth of at least \( 2.1 \cdot R/N \).

A third option is shown in Fig. 3a). It establishes the two orthogonal carrier channels by creating two independent wavelength channels. This may be done cost-effectively by complementary spectrum slicing of two broadband light sources, such as super-luminescent LEDs (SLEDs). At the receiver, an extra crosstalk reduction stage may be applied to combat the overlap of the sliced spectra. The spectra of the electrical I and Q signals are
both positioned in baseband, as shown in Fig. 3b). Hence this option requires the least bandwidth of the POF link, only $0.7 \cdot \frac{R}{N}$.

3. Performance evaluation of the QAM system implementation options

Of the three options described, the direct QAM one and the wavelength-sliced emulated QAM one are considered the most interesting; the baseband/subcarrier emulated QAM one requires the largest POF link bandwidth without offering extra advantages.

3.1 Simulation results

Using VPI Transmission Maker, simulations have been made to assess the performance of the direct QAM system option and the wavelength-sliced QAM one, for QAM-64 and QAM-256 signals at a bitrate of 128 Mbit/s (so symbol rates of 21.3 and 16.0 MBaud, respectively). A link of 100 meters step-index POF with a core diameter of 1 mm and NA=0.5 was assumed, yielding a –3 dB bandwidth of 50 MHz, and a laser diode with 650 nm wavelength and 2.5 mW average output power.

In the direct QAM system, using a carrier frequency $f_c=40$ MHz, both for QAM-64 and QAM-256 nicely open signal constellation diagrams were obtained; see Fig. 4. The relative Error Vector Magnitude (EVM) was <5% in the QAM-64 system for >-18.4 dBm received power, and <2.5% in the QAM-256 system for >-19.5 dBm received power. These EVM performances meet the specifications for QAM-64 and -256 systems.

In the wavelength-sliced emulated QAM system, it was assumed that the I and Q channels each were launched with 2.5 mW average optical power, and that the wavelength slicing and demultiplexing caused negligible crosstalk between these channels. The received eye patterns of the I and Q signal showed clear eye openings both for the QAM-64 (8 amplitude levels) and –256 (16 levels) case, indicating a good error rate performance; see Fig. 5.

3.2 System analysis

A theoretical analysis has been made of the symbol error rate (SER) versus average received optical power for the direct QAM system and for the wavelength-sliced emulated QAM system (assuming ideal wavelength slicing, so negligible crosstalk between the I and Q channel). For comparison, also the SER for a multilevel amplitude-modulated (PAM) system has been analyzed. White Gaussian noise is assumed to be the dominant noise mechanism, making the noise power at the receiver proportional to the receiver’s bandwidth which is directly related to the QAM modulation scheme (see spectra in Fig. 1b) to Fig. 3b) ). The various SER curves calculated for a bitrate $R=100$ Mbit/s and an extinction ratio $\varepsilon=0.1$ (i.e. the ratio of the minimum received optical power and the average received optical power) are shown in Fig. 6. Clearly, the performance of a direct QAM-$M^2$ system is...
comparable to that of a PAM-\(M\) system. However, a wavelength-sliced emulated QAM-\(M^2\) system offers a 1.5 dB better receiver sensitivity and moreover relaxes significantly the bandwidth needed in the POF system link.

4. Experimental results

The EVM has been measured of a direct QAM system employing a link of 100 meters of step-index PMMA POF with a core diameter of 1 mm and an NA=0.51, and a 0.81 mm\(^2\) area silicon PIN photodiode. The sources used were a 658 nm FP laser diode emitting 5 mW average optical power, and a 520 nm LED of 2 mW. The measured EVM for QAM-16, -64, and –256 formats at a symbol rate of 7.0 MBaud is shown versus the carrier frequency in Fig. 7. The laser-based system clearly performs better than the LED system, due to a better linearity. The rapid increase of the EVM with carrier frequency for the LED system indicates the larger link bandwidth for the laser-based system, which may be caused by the larger fiber mode volume excited by the LED. Clearly, the EVM requirements for QAM-64 and –256 can be met by the laser-based system as well as by the LED system. In combination with comprehensive techniques employing 80 subcarrier tones, even 1 Gbit/s throughput has been achieved [5].

5. Conclusions

The feasibility has been shown of data transport using direct QAM and wavelength-sliced emulated QAM for data rates of Fast Ethernet and beyond on 1 mm core step-index POF networks. The wavelength-sliced QAM approach is the most promising one as it has the lowest link bandwidth requirements while offering the highest power budget.

6. References


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