

Real-Time Experimental Demonstration of Multi-band CAP Modulation in a VLC System with Off-the-Shelf LEDs

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Abstract—We demonstrate, for the first time, m -CAP modulation using off-the-shelf LEDs in a VLC in real time experimental setup using field programmable gate arrays based in universal software radio peripherals (USRPs). We demonstrate transmission speeds up to ~ 30 Mb/s can be achieved, which supports high definition television streaming.

Index Terms—Digital signal processing, field programmable gate array, modulation, real time, visible light communications

I. INTRODUCTION

Advanced modulation formats are commonly used to increase transmission speeds in visible light communications (VLC), where modulation bandwidths are typically limited to several MHz [1–4]. They allow, in principle, additional spectral efficiency and hence, higher data rates [3]. One of the most popular formats is carrier-less amplitude and phase (CAP) modulation, which, in 2013 [1], was shown to outperform experimentally orthogonal frequency division multiplexing (OFDM) in terms of bit-error rate (BER). Since the report in [1], several variations of CAP have been proposed, the most significant of which is the multi-band system (m -CAP) that protects against chromatic dispersion in fibres [5]. Subsequently, m -CAP was adopted in VLC [2], it was shown that reducing subcarrier bandwidths led to tolerance of out-of-band attenuation caused by the low LED modulation bandwidths, and thus, higher spectral efficiencies.

In recent years, there have been only a limited number of studies of real-time VLC systems, where the two most recent examples are reported in [6, 7]. Both reports utilise OFDM modulation rather than CAP due to the ease of deploying an (inverse) fast Fourier transform ((I)FFT) pair. The computational complexity of the (I)FFT pair increases with $2\log_2(N)$, where N is the number of subcarriers, while m -CAP requires finite impulse response (FIR) pulse-shaping filters whose complexity increases with $4Lm$, where L is the number of taps and m is the number of subcarriers [8]. Clearly, m -CAP has a higher computational requirement than OFDM, however recent reports have shown that look-up tables at the transmitter can reduce this by 50%, and when used together with new receiver architectures and pulse shapes, the computational load can be reduced by a up to $\sim 90\%$ [9], meaning straightforward implementation.

Here, we experimentally demonstrate a real-time m -CAP system for the first time over a VLC system using white LEDs. Two field programmable gate arrays (FPGAs) are used in this real-time demonstration to ensure fair synchronisation and BER measurement across two independent clocks. We show that transmission speeds up to ~ 30 Mb/s can be supported with a 20% forward error correction (FEC) code, and ~ 20 Mb/s with a 7% FEC code. These rates are sufficient to support full high-definition television (HDTV) transfer, as will be demonstrated, across real VLC links using off-the-shelf LEDs.

II. EXPERIMENTAL REAL TIME DEMONSTRATOR SETUP

The system block diagram is shown in Fig. 1. Details of the generation of m -CAP signals may be referred to in the literature, due to space considerations, in [2, 5]. We tested m -CAP signals, varying from $m = 1$ to $m = 10$, using the 4-, 16- and 64-QAM constellations for each subcarrier, with a fixed bandwidth of 6.5 MHz and roll-off factor of 0.15 as used in [2]. The incoming information is modulated into the m -CAP signal format inside the transmitter FPGA, which is a Xilinx Kintex 7 (410T) contained within a National Instruments universal software radio peripheral reconfigurable input/output (USRPRIO) 2953. The FPGA outputs the signal to an Ettus Research LFTX digital-to-analogue converter (DAC) daughtercard, which has an analogue bandwidth up to 30 MHz. The signal is then passed through a Texas Instruments THS3202 amplifier with 4 times gain, before superimposing on a 250 mA bias current.

The biased signal that intensity modulates the Osram Golden Dragon LED (optoelectronic characteristics can be referred to in [10]) for transmission over a 0.5 m link, which is fixed to maintain a compact demonstrator, however operation can also be supported at 1 m distances. No bulk optics, such as lenses, are used and a Thorlabs PDA100A2 packaged receiver is used, which consists of a silicon p - i - n photodiode and an in-built transimpedance amplifier. The amplifier output is further amplified ($10\times$) by a Texas Instruments THS3202 amplifier to maximize symmetrical swing at the receiver input. The receiver is a National Instruments USRPRIO 2943 with the same Xilinx Kintex 7 FPGA on-board, but running independently from the transmitter. An Ettus Research LFRX analogue-to-digital converter (ADC) daughtercard (0-30 MHz) is used to digitise the data and direct it to the FPGA, for demodulation and BER measurements. Synchronisation is

obtained using the Schmidl and Cox [11] method while the demodulation of m -CAP signals may be referred to in [2, 5]. A photograph of the experimental setup is shown in Fig. 2.

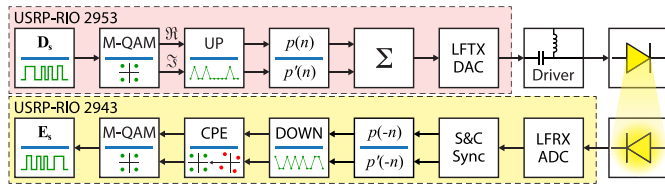


Fig. 1. System block diagram (simplified)

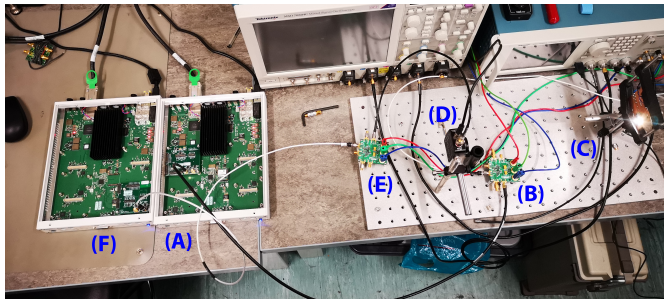


Fig. 2. Photograph of demonstrator test setup: (A) transmit USRP-RIO; (B) transmitter amplifier; (C) transmit driver and LED; (D) photodetector; (E) receiver amplifier and (F) receiver FPGA

III. RESULTS

The total accumulated BER is shown in Fig. 3, and $> 10^6$ symbols were transmitted. A clear trend is evident; a low order of m indicates a high BER, which reduces as m increases. The reason for this is due to inter-symbol interference (ISI) caused by attenuation of high frequencies as documented in [2]. However, there is another contributor to this, which is the slight impact of fluorescent light bulbs present in the laboratory. A dark environment is unrealistic in a real-world scenario, and hence, a 500 kHz frequency offset was introduced to the signals allow co-existence of fluorescent bulbs alongside the VLC system, as illustrated in Fig. 4, which resulted in minor intermodulation. This effect reduces with increasing m as the aggregated roll-off at the bandwidth edges becomes sharper. The transmission rate is sufficient to demonstrate HDTV streaming.

IV. ABOUT THE DEMONSTRATOR AND CONCLUSION

This demonstration is a self-contained and flexible test environment that supports HDTV video streaming in real time. Modulation formats can be adapted in real-time, albeit with an interruption in service before data recovery. Attendees will be able to block physically the optical path and observe the impact of a degradation in BER on the video quality. Wireless internet access will also be available via the VLC system through the demonstrator, which reports a real-time m -CAP VLC system, for the first time.

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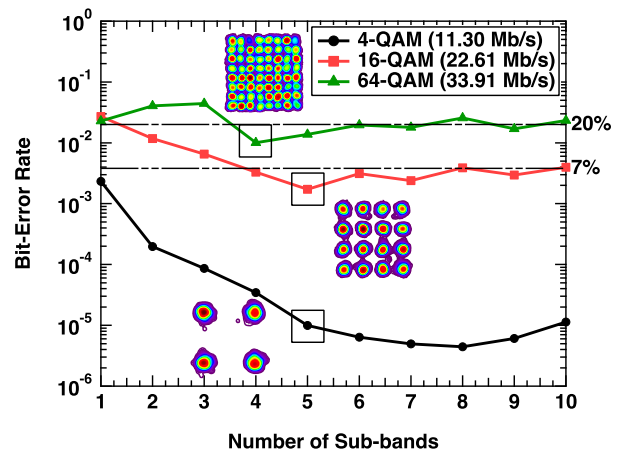


Fig. 3. Measured real time BER performance of 4-, 16- and 64-QAM. Transmission can be supported with 4- and 16-QAM with a 7% FEC code at 11.3 Mb/s and 22.61 Mb/s, respectively, and with a 20% FEC code for 16-QAM at 33.91 Mb/s.

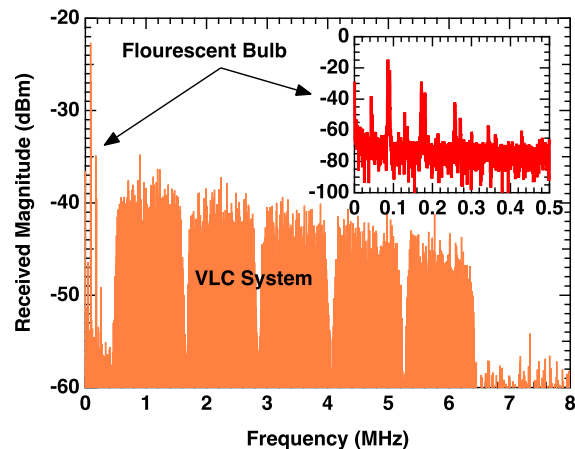


Fig. 4. The received electrical signal spectrum for a 5-CAP system, and inset, the flourescent component (0-500 kHz).

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