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10Gb/s Ultra-Wideband Wireless Transmission Based on Multi-Band Carrierless Amplitude Phase Modulation

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Abstract—In this paper, for the first time, a record UWB transmission of 10Gb/s is experimentally demonstrated employing a multi-band approach of carrierless amplitude phase modulation (MultiCAP). The proposed solution complies with the restrictions on the effective radiated power established by both the United States Federal Communications Commission and the European Electronic Communications Committee, achieving a BER below the limit for a 7% overhead FEC of $3.8 \cdot 10^{-3}$ up to respective wireless distances of 3.5m and 2m.

I. INTRODUCTION

Demand for high data rate multimedia applications is massively increasing and new approaches are required to increase the available throughput in the limited available wireless spectrum. Ultra-wideband (UWB) transmission is one of the most attractive alternatives for low-power high-speed wireless communication systems over short distances and a suitable low cost cable replacement technology. The popularity of UWB systems stems from the fact that they can be used as an overlay to existing systems, operating in parallel to existing wireless systems, as a narrowband receiver will only see the interference power within its own system bandwidth, i.e. a small fraction of the total transmitted UWB power [1]. Furthermore UWB communications allow unlicensed operation, provided standards and regulations for maximum radiated powers are met [2], [3].

UWB wireless transmissions is identified as an alternative option in the wireless technology industry [4], [5] and have attracted significant research interest [6]–[10]. UWB communication systems can provide data rates of several Gbit/s [6]–[8] while maintaining very low level of power emission. To the best of our knowledge, the current record of an UWB wireless transmission compliant with the regulations of the United States Federal Communications Commission (FCC) is 4 Gbit/s over a distance of 4 m [6].

Currently the two main UWB modulation format schemes for high capacity UWB are multi-band orthogonal frequency division multiplexing (MB-OFDM) [9], [10] and impulse radio UWB (IR-UWB) where a series of pulses form the basis for data transmission [6]. Under dynamically changing conditions MB-OFDM has been shown to provide the flexibility to adapt

to channel conditions and to comply with current and future regulatory UWB standards around the world [2], [3], [5].

In this paper we experimentally demonstrate transmission of a 10 Gbit/s signal, employing a multi-band approach for carrierless amplitude phase modulation scheme (MultiCAP) for UWB short-range high data rate communications. Transmission with bit error rates (BER) below the limit of $3.8 \cdot 10^{-3}$ for a commercial 7% overhead (OH) forward error correction (FEC) is achieved under the effective radiated isotropic power (EIRP) masks established by the Electronic Communications Committee (ECC) and the FCC, reaching respective distances of 2 m and 3.5 m. To the best of our knowledge the achieved data rate and distances constitute a new record for both the considered EIRP masks.

This paper is organized as follows: section II briefly describes conventional carrierless amplitude phase modulation (CAP) and its multi-band approach MultiCAP, while section III discusses how to employ MultiCAP for signal shaping to make effective use of the allowed transmission levels under the ECC and FCC spectral emission masks. Section IV describes the transmission system and experimental setup and section V presents the achieved transmission results, finally section VI summarizes and concludes the paper.

II. MULTI-BAND CARRIERLESS AMPLITUDE PHASE MODULATION

Carrierless amplitude phase modulation (CAP) is a multilevel and multidimensional modulation scheme [11], [12], similar to phase shift keying (PSK) and quadrature amplitude modulation (QAM) in transmitting two channels of data separately – i.e. in-phase (I) and quadrature (Q) channels. It does however not rely on a pure sinusoidal tone to generate the orthogonal I and Q components and the two channels of the CAP signal rather are generated with two orthogonal pass-band filters from the time-domain multiplication between the pulse shaping function – here a root raised cosine (RRC) – and a cosine/sine for I and Q components respectively:

$$f_I(t) = g(t)\cos(2\pi f_c t) \quad (1a)$$

$$f_Q(t) = g(t)\sin(2\pi f_c t) \quad (1b)$$

Fig. 1. Block diagram of MultiCAP transmitter and receiver

The main parameters of the CAP filters are: i. the cosine/sine frequency determining the central frequency of the transmitted band; ii. the roll off factor α of the RRC which determines the excess bandwidth consumed (i.e. with an RRC pulse shape the total pass-band bandwidth of a CAP signal is $1 + \alpha$ times the baud rate); iii. the filter length in the number of samples which affects both performance and complexity of the system. For short lengths the overall system is simpler, but performance decreases significantly [12].

A CAP signal is generated by mapping the original binary sequence with an M-ary QAM or M-ary PSK encoder, the mapped symbols are up-sampled – i.e. zeros are inserted between the symbols – in order to perform a time-domain convolution with the CAP filters. After filtering, the signals from the I and Q channels are added and transmitted. At the receiver, to separate the two channels, two filters matched to the pass-band filters described in Eq. (1a) and (1b) are employed [13]. Then the two channels are separately down-sampled and the data decoded.

The multi-band approach of CAP modulation (MultiCAP) relies on simultaneous transmission of several CAP signals assigned to different frequency bands, ensuring bands are non-overlapping. This is achieved by using not only one pair of orthogonal filters, but several pairs which different cosine/sine frequencies assigned to each frequency band. Fig. 1 shows the block diagrams of a MultiCAP transmitter and receiver.

The flexibility offered by MultiCAP allows to independently choose the modulation format scheme, order, and signal power – i.e. allows power loading – in each band, alleviating the need for a flat frequency response of the channel which is required for reliable transmission of conventional CAP and QAM signals. The combination of power loading and use of a different signal constellations in each band makes MultiCAP a prime candidate for wireless links where frequency selectivity of the channel and uneven antenna gain over the operating frequency range cause significant degradations.

III. SIGNAL SHAPING FOR UWB TRANSMISSION

To allow non-problematic coexistence with (possibly licensed) radio services – such as mobile and WiFi networks, as well as the global positioning system (GPS) – the power spectral density of unlicensed ultra-wideband (UWB) system signals must be limited to a level where within its own bandwidth a traditional narrowband receiver will see the UWB

Fig. 2. Comparison of the regulatory spectral emission masks set by the ECC and FCC and the resulting effective masks when antenna gain is taken into account

as ‘noise’. The FCC has established a spectral emission mask for indoor applications, consisting of a single flat window with a permitted average effective isotropic radiated power (EIRP) of at most -41.3 dBm/MHz between 3.1 GHz and 10.6 GHz [2].

For Europe the ECC has established regulations specifying a spectral emission mask with the same maximum permitted EIRP, but unlike in the FCC case a gap in the mask defines two usable windows with frequency ranges of 3.1–4.8 GHz and 6–9 GHz [3]. Due to this segmentation attaining high data rates under the ECC mask poses a greater challenge when compared to the FCC mask. Fig. 2 shows the FCC and ECC EIRP masks for indoors applications and compares them to the resulting effective masks for the transmitted signal, when the gain of the transmitting antenna is taken into account; antenna gain over frequency is also shown in Fig. 2.

The flexibility of MultiCAP allows the allocation of a set of bands with different signal constellations, baud rates, and power values, thus enabling to fit and achieve high data rates under both spectral emission masks. Taking into account the variation of antenna gain over frequency, the parameters of a set of well shaped MultiCAP signals were determined and are shown in Tables I and II for transmission under the FCC and ECC masks respectively (power values are normalized to the band with least transmitted power). With the freedom offered by the FCC mask, transmission of 10 Gbit/s can be achieved using eight identical bands and quadrature phase shift

Fig. 3. Effective spectra of the shaped signals, fitting the (a) FCC and (b) ECC spectral emission masks

TABLE I
MULTICAP PARAMETERS FOR FCC MASK

Band	Baud rate [GBd]	Constellation	Bit rate [Gbit/s]	Central Frequency [GHz]	Normalized Power [dB]
1	0.625	QPSK	1.25	4.1219	3.0
2	0.625	QPSK	1.25	4.7656	2.0
3	0.625	QPSK	1.25	5.4094	2.0
4	0.625	QPSK	1.25	6.0531	1.0
5	0.625	QPSK	1.25	6.6969	0.5
6	0.625	QPSK	1.25	7.3406	0.0
7	0.625	QPSK	1.25	7.9844	0.5
8	0.625	QPSK	1.25	8.6281	1.5

TABLE II
MULTICAP PARAMETERS FOR ECC MASK

Band	Baud rate [GBd]	Constellation	Bit rate [Gbit/s]	Central Frequency [GHz]	Normalized Power [dB]
1	0.833	BPSK	0.833	3.5225	5.1
2	0.833	QPSK	1.667	4.3808	4.5
3	0.833	8-QAM	2.5	6.4292	1.1
4	0.833	8-QAM	2.5	7.2875	0.0
5	0.833	8-QAM	2.5	8.1458	0.8

keying (QPSK); under the ECC mask however, it is necessary to employ binary phase shift keying (BPSK) to compensate for the low antenna gain at the lower edge of the UWB range and to employ 8-QAM in the higher frequency window to ensure a data rate of 10 Gbit/s is achieved.

The spectrum of the generated signal is measured using an electrical spectrum analyzer (ESA) with the FCC and ECC prescribed settings for UWB compliance testing – 1 MHz root mean square (RMS) average power measurement with 1 ms time averaging [2], [3]. The measured frequency spectra are combined with the magnitude of the antenna gain over frequency and the resulting effective spectra are checked for compliance with the FCC and ECC spectral emission masks as shown in Fig. 3.

IV. EXPERIMENTAL SETUP

The MultiCAP electrical signal was generated using an arbitrary waveform generator (AWG) with a sampling rate of 65 GSa/s and a vertical resolution with an effective number of bits (ENOB) of 5. A set of attenuators – along with the power loading technique – ensured that the antenna EIRP was within the permitted levels. After wireless transmission, the

Fig. 4. Laboratory setup for UWB MultiCAP transmission: (a) 40 GSa/s DSO, (b) 65 GSa/s AWG, (c) 26 dB gain LNAs, and (d) bow-tie type UWB antenna

received signal was filtered by a pass-band filter (3.4–9.9 GHz) and amplified by two low noise amplifiers (LNA) with a gain of 26 dB each and a typical noise figure of 3 dB. For off-line digital signal processing (DSP), the signal was recorded with a digital storage oscilloscope (DSO) at a sampling rate of 40 GSa/s and with 8 bits of vertical resolution. The experiments were performed using a set of bow-tie type antennas for both the transmitter and receiver. Fig. 4 shows the laboratory setup while Fig. 5 shows a schematic of both signal processing and system setup.

V. EXPERIMENTAL RESULTS

Fig. 6 shows the bit error rate (BER) versus wireless distance curves for each MultiCAP band alongside its corresponding modulation scheme. Successful 10 Gbit/s transmission with a BER below the limit of a commercial 7% OH FEC of $3.8 \cdot 10^{-3}$ was achieved over distances of 2 m and 3.5 m under the ECC and FCC mask restrictions respectively. A shorter distance was reached for the ECC mask for two main reasons, first the bandwidth available is less than under the FCC mask and therefore, for some of the bands, higher order modulation schemes were employed, being less tolerant to low signal to noise ratios (SNR) than QPSK, and secondly it was necessary to transmit one of the bands close to the lower limit of the mask at 3.1 GHz where antenna gain is lowest.

Fig. 5. Schematic of the UWB MultiCAP transmission setup

Fig. 6. BER versus wireless distance for 10 Gbit/s UWB transmission under the (a) FCC and (b) ECC spectral emission masks

In the demonstrated transmission, assuming a 7% OH FEC, the total effective bit rate achieved is 9.346 Gbit/s. The experimental results validate the ability of MultiCAP transmission to adapt to different scenarios, while achieving record data rates for UWB applications.

VI. CONCLUSIONS

The proposed approach for high-speed UWB communication systems over short distances represents a flexible solution that can be easily adapted to comply with current and future regulatory UWB standards.

To the best of our knowledge the presented results are the first time that 10 Gbit/s UWB wireless transmission is achieved over distances of 2 m and 3.5 m under the ECC and FCC spectral emission masks.

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