Performance Evaluation of a 60-GHz Multi-band OFDM (MB-OFDM) Ultra-Wideband Radio-Over-Fibre System

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Abstract: In this paper, we present a performance analysis of a Multi-band, Orthogonal Frequency Division Multiplexing (MB-OFDM) Radio-Over-Fibre (RoF) system for Ultra-Wideband (UWB) applications in the 60-GHz radio band. We have made use of two cascaded Mach-Zehnder modulators (MZMs) to carry out optical upconversion of the MB-OFDM signal to the 60 GHz band. The impact of the non-linearity of the MZM, fibre transmission and the received optical power are investigated through a simulation model of the complete UWB RoF system. System performance is evaluated at 1.92 Gb/s bit rate using Error Vector Magnitude (EVM) measurements as a performance metric.

1 Introduction.

In recent years, Ultra-wideband (UWB) radio communications have attracted growing attention due to the advantages UWB offers in terms of low power consumption, low cost, wide bandwidth and high data rate [1]. In 2002, the Federal Communications Commission (FCC) permitted unlicensed operation in the 3.1 GHz to 10.6 GHz band for use of UWB communication devices [2].

Currently, there are two major UWB implementations. The first one is based on OFDM and is called Multi-Band OFDM UWB (MB-OFDM UWB) while the other is called Impulse Radio UWB (IR-UWB) and involves transmission of pulses with a very short duration of a few nanoseconds [3]. According to the IEEE 802.15.3a standard [4], the 7.5 GHz UWB spectrum is divided into 14 non-overlapping frequency sub-bands, each with a bandwidth of 528 MHz [5]. These 14 sub bands are further organised into 5 groups. Groups 1 to 4 have 3 channels while group 5 only has 2 channels [6]. According the WiMedia specification v1.2 [2], the maximum capacity in actual UWB equipment is 480 Mb/s per band, giving 6.72 Gb/s aggregated bit rate per user when the fourteen UWB bands are used.

The FCC restricts the maximum Equivalent Isotropic Radiated Power (EIRP) spectral density of UWB to -41.3 dBm/MHz [7]. This limits the wireless range of UWB systems to a few meters, making co-axial cable transmission very expensive [3, 6]. In order to increase the transmission distance of UWB, a low-cost solution is to employ transmission over fibre. This enables us to combine the above-mentioned advantages of UWB with the advantages optical fibre offers in terms of wide bandwidth and low attenuation loss to increase the wireless coverage of the UWB system to hundreds of meters, distributing UWB signals to multiple base stations [8].

By operating in the license-free 60-GHz radio band (within 57-66 GHz), the UWB transmission reach can be further extended by increasing the EIRP spectral density from -41.3 dBm/MHz to 13 dBm/MHz. In addition, single-chip solutions already exist for UWB. This allows UWB to be used in devices that have precise power and space requirements, like mobile phones [8]. UWB in the 60-GHz band has also been considered as a feasible solution for providing WPAN connectivity in interference-sensitive environments such as in aircraft cabins.

In this paper, we investigate the performance of an UWB RoF system in the 60-GHz radio band with focus on the ECMA-368 standard [5] using MB-OFDM. Various parameters such as the MZM non-linearity, fibre transmission and the received optical power at the photodetector are systematically investigated to illustrate their effects on system performance. In section 2, we present the simulation setup for the MB-OFDM RoF system. EVM results are presented in section 3 to evaluate the performance of the system. Finally, conclusions are given in section 4.

2. Simulation Setup.

The simulation setup of the MB-OFDM UWB RoF system in the 60-GHz is shown in Fig. 1. For the simulations, we make use of OPTSIM. We utilise the MATLAB-OPTSIM co-simulation functionality that enables custom component for MATLAB modules (CCMs) to be created and used in OPTSIM. These CCMs are configured to act as the MB-OFDM transmitters and receivers for conducting the system performance tests. The CCMs interface with the OPTSIM simulator scheduler to run a MATLAB subroutine which generates the OFDM signal in the case of the transmitter. In the receiver case, the MATLAB subroutine is responsible for carrying out equalisation, demodulation, EVM computation and demapping of the received MB-OFDM signal.

We generate the first three MB-OFDM bands corresponding to Band Group #1 according to the ECMA-368 standard [5]. Each band has 128 subcarriers. Out of these, 100 are data tones, 12 are pilots, 10 are guard tones and the remaining 6 are null tones. An FFT size of 128 and a cyclic prefix length of 32 samples are used for each band. The guard tones are obtained by copying the edge data tones. The null tones are zero-valued and are assigned to the remaining 6 FFT inputs, with the FFT input 0 reserved for the D.C term.

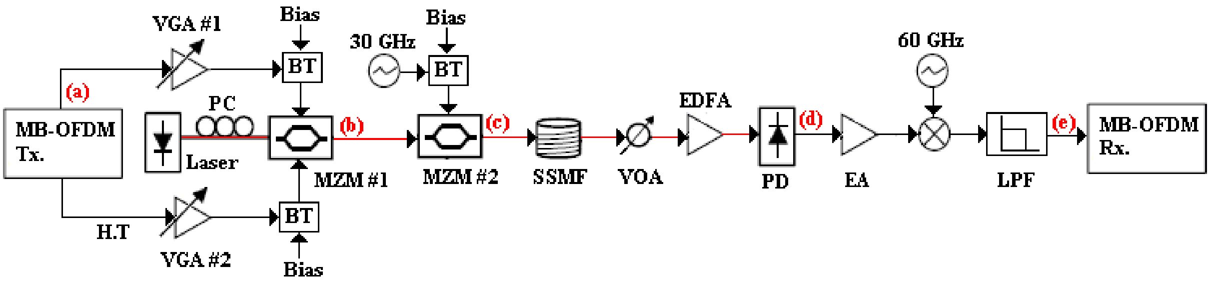

Fig. 1. Simulation schematic. H.T: Hilbert Transform. VGA: Variable Gain Amplifier. PC: Polarisation Controller. BT: Bias Tee. MZM: Mach-Zehnder Modulator. SSMF: Standard Single Mode Fibre. VOA: Variable Optical Attenuator. EDFA: Erbium Doped Fiber Amplifier. EA: Electrical Amplifier. PD: Photo Diode. LPF: Low Pass Filter

The three bands are modulated using 4-QAM and have a bandwidth of 528 MHz, centred at frequencies 3.432, 3.96 and 4.488 GHz respectively as shown in Fig. 2. With these simulation parameters, the OFDM symbol duration for each band is 312.5 ns. Consequently, the bit rate of each band is 640 Mb/s, providing an aggregate bit rate of 1.92 Gb/s for the three bands.

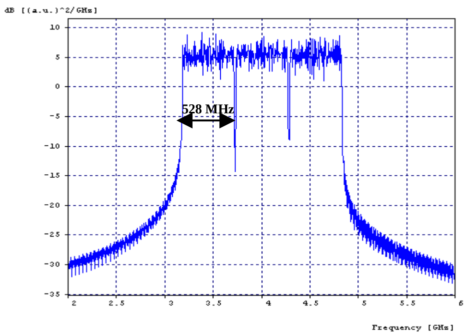

Fig. 2. Simulated MB-OFDM electrical spectrum at point (a) in the schematic of Fig. 1

To optically up-convert the MB-OFDM signal to the 60 GHz band, we make use of two cascaded MZMs as proposed in [9]. The MB-OFDM transmitter has two outputs. The first output is the MB-OFDM signal while the second output is the frequency-domain Hilbert transform of the MB-OFDM signal. These two transmitter outputs are used as the electrical drive to MZM #1. MZM #1 has a V_{π} of 10 V and is biased at quadrature to yield an optical SSB MB-OFDM signal as shown in Fig. 3(a). Variable Gain Amplifiers (VGA #1 and 2) placed at the outputs of the MB-OFDM transmitter allow variation of the amplitude of the electrical drive to MZM #1. The laser source is a CW laser with a linewidth of 10 MHz, centre emission wavelength of 1550 nm and output power of 10 dBm.

The optical SSB MB-OFDM signal generated from MZM #1 is used as the optical input to MZM #2 which is biased at the minimum transmission point to enable optical carrier suppression. MZM #2 is driven by a local oscillator at a frequency of 30 GHz. The output optical signal from MZM #2 is shown in Fig. 3(b) where we can see that there is a 60 GHz separation between the two optical carriers. It is important to note that an ideal extinction ratio has been assumed for both MZMs.

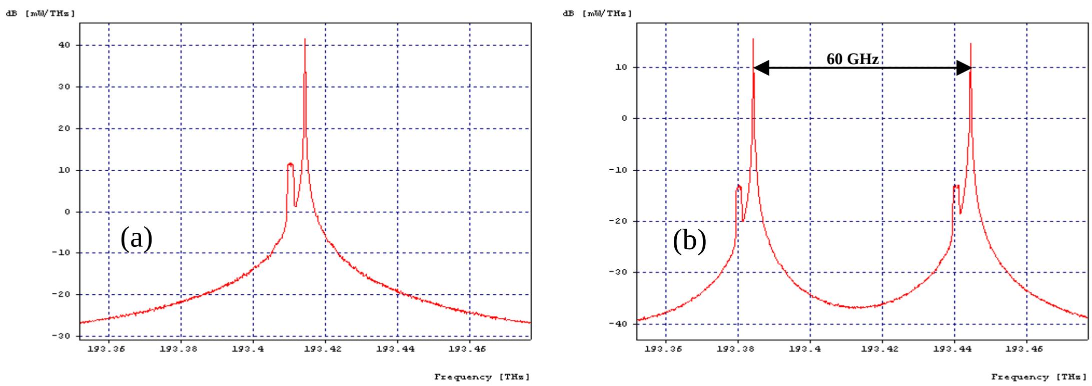

Fig. 3. Optical Spectra at points (b) and (c) in the schematic of Fig. 1:(a) Output of MZM #1. (b) Output of MZM #2

The modulated Lightwave from MZM #2 is sent through 20 km SSMF with a dispersion parameter *D* of 16 ps/nm/km and attenuation loss of 0.2 dB/km. The optical signal is then amplified by an EDFA before it is directly detected by a photodiode with 0.8751 A/W responsitivity. The gain of the EDFA is adjusted as appropriate to set the maximum average power input to the photodiode at 10 dBm. The received optical power is decreased by varying the attenuation of the VOA. After photodetection, the MB-OFDM signal is amplified and downconverted by mixing with a local oscillator at a frequency of 60 GHz. The downconverted MB-OFDM signal is shown in Fig 4(b). This signal is then passed to the MB-OFDM receiver for demodulation and EVM computation.

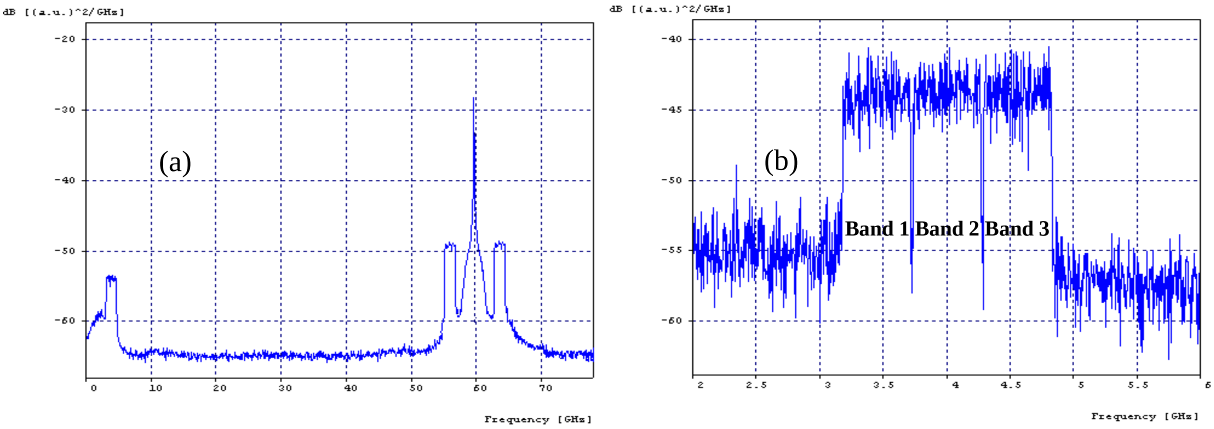

Fig. 4. Electrical Spectra at points (d) and (e) in the schematic of Fig. 1: (a) MB-OFDM signal in the 60 GHz band. (b) Down-converted MB-OFDM signal

3. Simulation Results.

For the investigation into the impact of the MZM non-linearity, we fix the fibre length at 20 km. We then adjust the amplitude of the driving MB-OFDM signal by varying the gain of VGAs #1 and 2 from -12 dB to 4dB. It is important to note that for the simulations, a negative gain refers to an attenuation. For each value of gain, the EVM is computed. Fig. 5(a) shows the variation of the measured EVM with the electrical gain of VGAs #1 and 2 for all the 3 bands transmitting simultaneously over 20km SSMF.

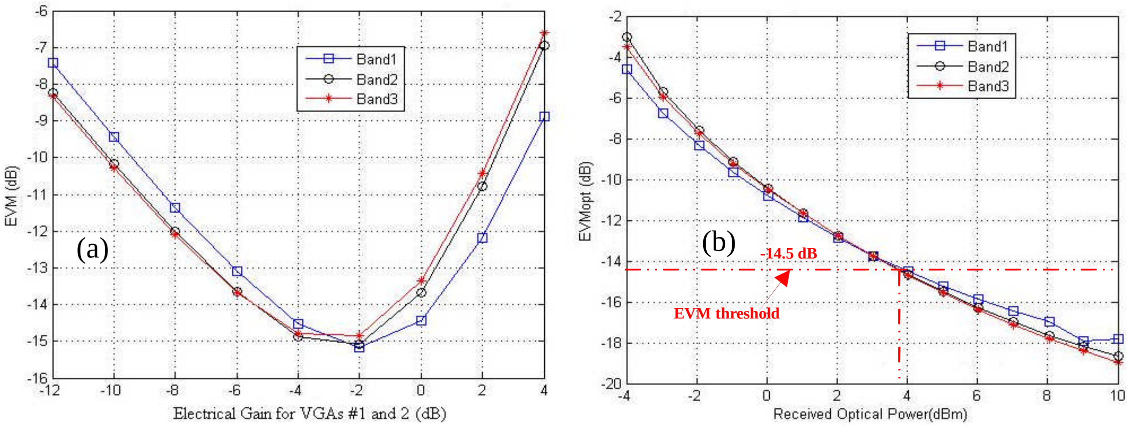

Fig. 5. (a) EVM vs. VGA Gain. (b) EVMopt vs. Received optical power

As we can see from Fig. 5(a), the EVM for all the bands first reduces with increasing amplification because the electrical SNR increases. The EVM keeps on reducing till the amplification gets to the optimum value of -2dB where the EVM is lowest. We refer to the EVM at this optimum amplification point as EVM*opt*. Beyond the optimum amplification point, the EVM starts increasing because the MB-OFDM signal starts getting affected by the MZM non-linearity.

To see the effect of the received optical power on system performance, we operate the system such that only one band transmits at a time. The gain of VGAs #1 and 2 is set at -2dB to yield EVM*opt*. We then vary the attenuation of the VOA in steps of 1 dB to enable the received optical power to be varied. Fig. 5(b) shows that EVM*opt* for each band increases with decrease in the received optical power due to a reduction in the received SNR. Considering an EVM threshold of -14.5 dB as specified by the ECMA-368 standard, the optical receiver sensitivity for successfully recovering the three MB-OFDM bands is around 3.7 dBm.

In order to investigate the impact of fibre transmission, we fix the value of the amplification of the VGAs at the optimum value of -2 dB. Using band 2 as the test band, we then vary the length of the fibre from 5 to 40 km. For each fibre length, the gain of the EDFA is adjusted to keep the power input to the photodiode fixed at 10 dBm and EVM*opt* is computed. Fig. 6(a) shows a plot of the measured EVM*opt* vs. fibre length for band 2 transmission. Here, we can see that EVM*opt* degrades with increasing fibre length. The reason behind this degradation can be attributed to the phase distortion induced by fibre chromatic dispersion. This phase distortion is expressed as:

$$\Phi_D(f_k) = \pi.c.D.L.\left(f_k^{\,2}/f_o^{\,2}\right) \quad (1)$$

where $\Phi_D(f_k)$ is the phase delay due to chromatic dispersion for the kth subcarrier, f_k is the frequency for the kth subcarrier, c is the speed of light, D is the chromatic dispersion parameter in ps/nm/km and L is the length of the fibre in km.

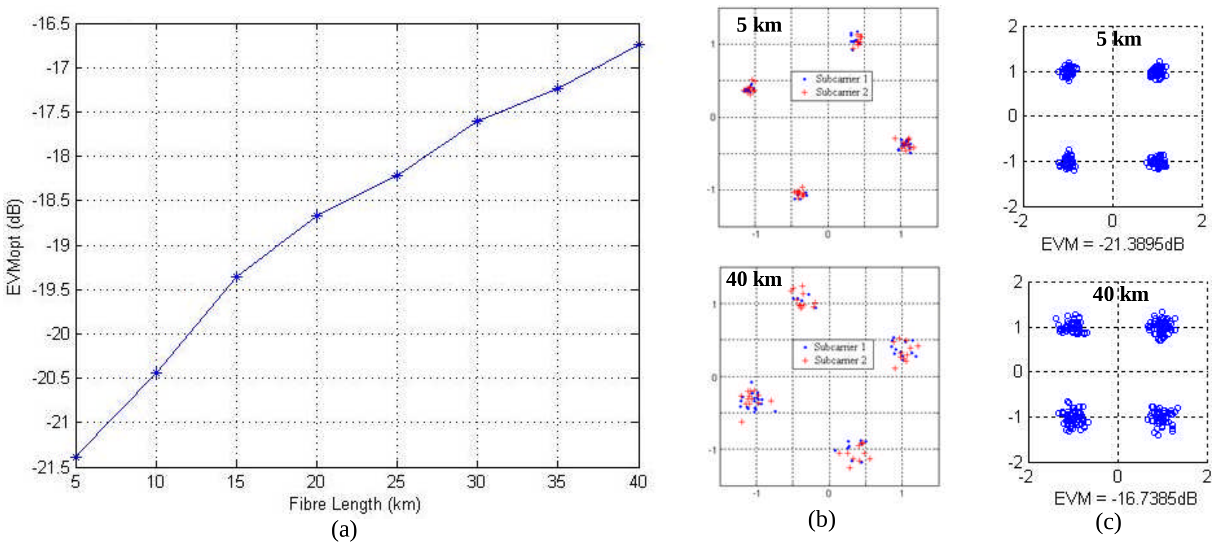

Fig. 6. (a) EVMopt vs. fibre length for band 2 transmitting alone. (b) Band 2 unequalised constellation for subcarriers 1 and 2 for 5 km and 40 km SSMF transmission. (c) Band 2 equalised constellation for 5 km and 40 km SSMF transmission.

Chromatic dispersion causes a rotation of each subcarrier's constellation point around the origin. Equation (1) shows that an increase in the fibre length, *L* would result in an increase in the degree of rotation. This is confirmed from Fig. 6(b) which shows the unequalised constellation for subcarriers 1 and 2 for 5 km and 40 km fibre transmission respectively. Here, we can clearly see that degree of rotation increases with increase in the fibre length from 5 km to 40 km. This causes the EVM to degrade. Fig. 6(c) shows the equalised constellation for all 128 subcarriers for band 2 where the constellation points become more spread as the fibre length increases.

4. Conclusion.

In this paper, we have evaluated the performance of MB-OFDM UWB in the 60 GHz band. Using EVM measurements, we have been able to evaluate the impact of various impairments such as the MZM non-linearity, fibre chromatic dispersion and the received optical power on system performance. We have made use of two cascaded MZMs to carry out optical upconversion of the MB-OFDM signal to the 60 GHz band. It is found out that the EVM for all the bands reduces with increasing values of drive until it gets to the optimum value where the EVM is lowest. Beyond the optimum point, the MB-OFDM signal starts getting affected by the MZM non-linear distortion and the EVM starts increasing.

With optimum drive conditions to achieve EVM*opt*, the value of EVM*opt* increases with increasing fibre lengths because of the phase distortion induced by chromatic dispersion. In addition, we have also found out that EVM*opt* decreases with increase in the received optical power because of increase in the received SNR.

5. References.

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