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4 Gbps Impulse Radio (IR) Ultra-Wideband (UWB) Transmission over 100 Meters Multi Mode Fiber with 4 Meters Wireless Transmission

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Abstract: We present experimental demonstrations of in-building impulse radio (IR) ultra-wideband (UWB) link consisting of 100 m multi mode fiber (MMF) and 4 m wireless transmission at a record 4 Gbps, and a record 8 m wireless transmission at 2.5 Gbps. A directly modulated vertical cavity surface emitting laser (VCSEL) was used for the generation of the optical signal. 8 m at 2.5 Gbps corresponds to a bit rate - distance product of 20; the highest yet reported for wireless IR-UWB transmission.

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1. Introduction

Ultra-wideband (UWB) wireless communication is an emerging technology for short range and high speed communications, employing an extremely low power emission of less than -41.3 dBm/MHz over a wide bandwidth from 3.1 GHz to 10.6 GHz in order to comply with the regulations for indoor wireless transmission as described in [1] by the federal Communications Commission (FCC). Compliance with [1] not only ensures non-problematic coexistence with other wireless technologies, such as GPS, WiMax and UMTS, but also facilitates the use of wireless communication in radio frequency (RF) sensitive environments, e.g. hospitals and airplane cabins. The low emitted RF-power, however, has so far limited transmission distances to e.g. 65 cm at 500 Mbps [2] or 20 cm at 1.025 Gbps [3]. Moreover, due to the inability of the wireless UWB signals to penetrate walls, a fiber based in-home infrastructure is required for the distribution of the UWB signals around the house.

Various methods for photonic generation of UWB pulses have been investigated recently. Most these rely on either recombination of two Gaussian pulses with a π phase-offset, or on nonlinear signal processing. The first category includes [4], [5] and [6] where fiber Bragg gratings have been used to control the delay between the two pulses, [7] where modules with differential group delay have been used, [8] where a dispersive medium provided the delay between the pulses. UWB pulse generation by nonlinear processing has been demonstrated using a microwave differentiator [9], using nonlinear pulse shaping of fiber Bragg gratings [10], and using nonlinear modulation of electrooptic modulators [11], [12]. Additionally, in [13] UWB generation using a directly modulated laser together with chirp to intensity modulation was demonstrated, in [14] the carrier dynamics of an uncooled distributed feedback laser was used to generate the UWB signal, a demonstration of optical generation and transmission with included wireless transmission is presented in [15], a multi-hub system employing polymer fiber is demonstrated in [16], and an analysis of UWB transmission in FTTH networks is presented in [17].

In this paper, we propose and experimentally demonstrate a multimode fiber (MMF) based in-home system for optical distribution and wireless transmissions of FCC compliant IR-UWB signals. The UWB pulses were electronically generated by an arbitrary waveform generator (AWG) with a sampling rate of 24 GSamples/s. A 5th order Gaussian pulse shape was used due to its excellent compliance with the FCC regulations. The received signals were digitized using a digital sampling oscilloscope with a sampling rate of 40 GSamples/s, and demodulation was performed with digital signal processing. The optical link comprise a cost effective solution consisting of a directly modulated vertical cavity surface emitting laser (VCSEL) at 850 nm, 100 m 50 μ m core-size multimode fiber and a PIN photodiode. The wireless link sported an omnidirectional antenna for the transmitter and a high gain directional antenna for the receiver.

The measured bit error ratio was below the limit for error free detection after forward error correction (FEC) after a record 8 m wireless transmission at 2.5 Gbps and after 4 m wireless transmission at a record 4 Gbps bit rate.

2. Experimental setup

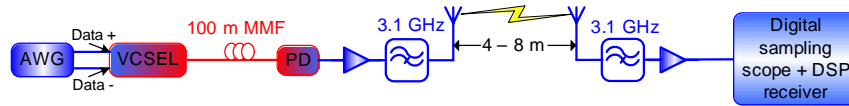


Fig. 1. Schematic of the setup used in the experiment. AWG denotes the arbitrary waveform generator, VCSEL the vertical cavity surface emitting laser, MMF the multi mode fiber, PD the photo diode and DSP digital signal processing in the receiver.

A simplified schematic of the setup used in the experiment is shown in Fig. 1. An arbitrary waveform generator (AWG) with a sampling rate of 24 GSamples/s was used to electrically generate the IR-UWB signal. The data-pattern was a pseudo random bit sequence (PRBS) of wordlength $2^{11} - 1$. The pulse shape used in the experiment was a 5th derivative Gaussian pulse chosen for its excellent compliance with the FCC mask. The pulse shape is described by equation 1

$$y(t) = \frac{A}{\sqrt{2\pi}} \left[-\frac{t^5}{\sigma^{11}} + \frac{10t^3}{\sigma^9} - \frac{15t}{\sigma^7} \right] \cdot e^{-\frac{t^2}{2\sigma^2}}, \quad (1)$$

where A is the amplitude, t is the time and σ is the standard deviation, which was 60 ps for 1 and 2.5 Gbps, and 55 ps for 4 Gbps. The latter was chosen to reduce overlap of leading and trailing edges of neighboring pulses.

A VCSEL with wavelength 850 nm was biased at 350 mA and directly modulated with the electrical IR-UWB signal from the AWG. In order to increase linearity and modulation bandwidth of the VCSEL, it was driven by a balanced electrical signal. Peak-to-peak voltage was 1 V. Photodetection was performed with a PIN photodiode. The optical link consisted of 100 m graded index multimode fiber (MMF) with coresize $50\mu m$ and cladding diameter $125\mu m$. Optical coupling from the VCSEL to the fiber and from the fiber to the photodiode was performed with receptacle type connectors. This solution provides low cost together with easy installation and handling. The drawback is reduced accuracy in the optical coupling in and out of the fiber.

After photodetection, the signal was high-pass filtered and amplified in order to comply with the FCC mask for indoor radiation, and fed to a SkyCross SMT-3TO10M-A omnidirectional antenna with a peak gain of 4.5 dBi at 4.5 GHz. After 4–8 m wireless transmission, the signal was received with a directional antenna directed at the transmitter. The receiving antenna was a bow-tie phased array with a gain varying from 4.65 dBi to 12.5 dBi in the frequency band 3.1–10.6 GHz, and with a gain of 8.8 dBi at the signal peak frequency of 5 GHz. This arrangement utilizes the high gain of a directional antenna at the receiver without compromising the excellent room coverage provided by an omnidirectional antenna at the transmitter. The received wireless signal was amplified using a two-stage low-noise electrical amplifier with a total gain of 49 dB. A digital storage oscilloscope (DSO) with a sampling rate of 40 GSample/s was used to digitize and store the signal.

Demodulation of the received signal after sampling was performed using digital signal processing (DSP). The demodulator consisted of the following steps: After initial high-pass filtering, the correlation with the original UWB pulse shape from equation 1 was calculated, and bit

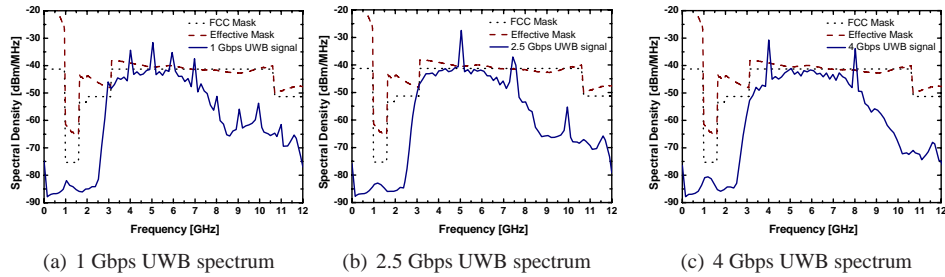


Fig. 2. Measured electrical spectral densities at the antenna input, together with the FCC mask and the effective mask.

synchronization was performed. Based on the synchronized bits, the optimum decision threshold was determined, and bit error ratio (BER) was calculated on a bit-by-bit basis. 10^5 bits were analyzed in all cases.

The electrical spectrum at the input to the transmitter antenna is shown in Fig. 2 for 1, 2.5 and 4 Gbps together with the FCC mask, and an ‘effective mask’, which takes into account the gain of the transmitter antenna. The effective mask was calculated from the transfer function of the transmission antenna according to the method described in [2]. The antenna transfer function was measured with a network analyzer. Two identical antennas were placed opposite each other and a sinusoidal signal was transmitted by one antenna and received by the other. The frequency of the sinusoidal signal was swept from 0 to 10 GHz. The transfer function of each antenna can be calculated as the square root of the frequency response of the two antennas. Absorbers were placed around the antennas in order to prevent reflections. From Fig. 2 it can be observed that the measured spectra are below the effective mask as required by the FCC regulation. The spikes at multiples of the bit rate exceed the effective mask by less than 20 dB in accordance with the FCC regulation [1].

3. Results

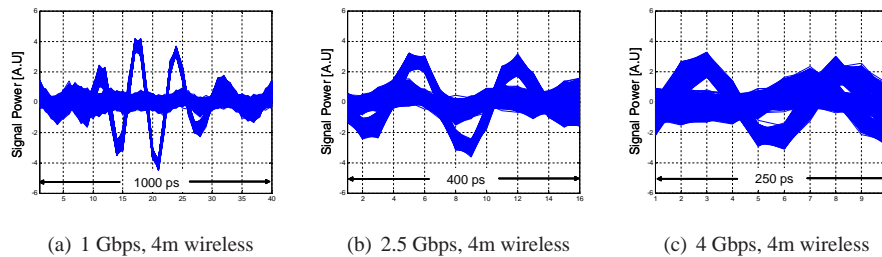


Fig. 3. Eye diagrams of the purely electrical signal measured after 4 m wireless transmission and demodulation by correlation with the original 5th order Gaussian pulse.

The eye diagrams after demodulation at 1, 2.5 and 4 Gbps is shown in Fig. 3. These signals were received after 4 m wireless transmission with the input signal to the transmitting antenna taken directly from the AWG, and the optical link therefore bypassed. The 5th order Gaussian pulse shape is clearly observed at 1 and 2.5 Gbps. At 4 Gbps, the pulse width is slightly higher than the available bit slot, resulting in only the central part of the pulse being identifiable in the eye diagram. This illustrates a trade-off between efficient utilization of the FCC allocated

bandwidth on one side, and good signal quality on the other. Narrowing the standard deviation of the pulse at 4 Gbps in order to completely avoid pulse overlap would have caused the spectral width of the signal to exceed the FCC mask.

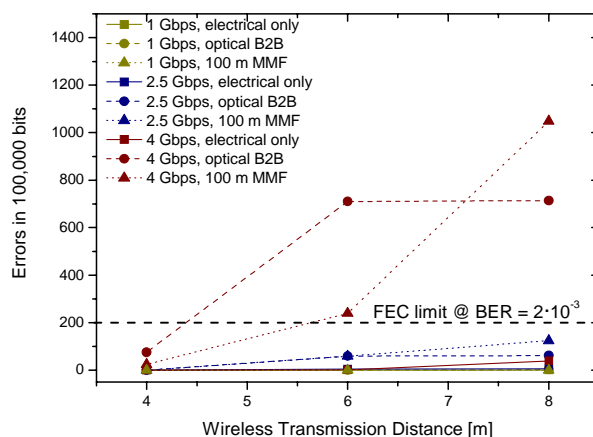


Fig. 4. Errors in 100,000 bits after demodulation. Forward error correction (FEC) limit is also shown.

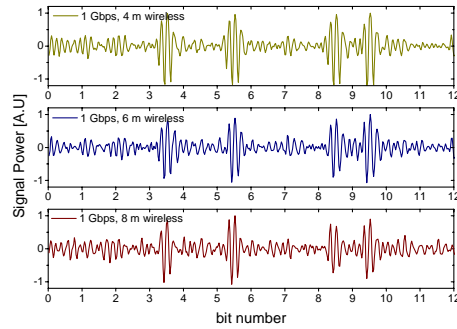
The number of errors in 100,000 bits is plotted as a function of wireless distance in Fig. 4 for 1, 2.5 and 4 Gbps. *Electrical B2B* is the results when the optical link is bypassed, and the signal to the transmitting antenna is taken directly from the AWG. *Optical B2B* includes the VCSEL and PIN photodiode, but not the 100 m MMF. Apart from 4 Gbps after 6 and 8 m wireless transmission, everything was received well below the FEC limit of a BER less than $2 \cdot 10^{-3}$. At 4 Gbps after 6 and 8 m wireless transmission, the BER exceeds the FEC limit. This is believed to be due to inter-symbol interference (ISI) caused by the pulse-overlap illustrated in Fig 3. At 4 Gbps after 6 m wireless transmission, a BER of $7.2 \cdot 10^{-3}$ was measured for the optical back to back case, whereas a BER of only $2.4 \cdot 10^{-3}$ was measured for the case including 100 m MMF. We believe this behavior is caused by sub-optimum coupling to the PIN photodetector in the back to back case.

A part of the received signal corresponding to the pattern '000101001100' is plotted in Fig. 5. At 1 Gbps, the 5th order Gaussian shape of the signal is clearly identified, and there is virtually no distortion even after 8 m wireless transmission. At 2.5 Gbps, in bits number 8 and 9, where the pattern constitutes two consecutive ones, there is no longer any gap between the pulses. At 4 Gbps, we observe increasing pulse overlap, leading to difficulties identifying the 5th order Gaussian pulse shape. Comparing with Fig 3, where the optical link was bypassed, it is noted that this is inherent in the electrical signal, and thus not a consequence of insufficient VCSEL bandwidth.

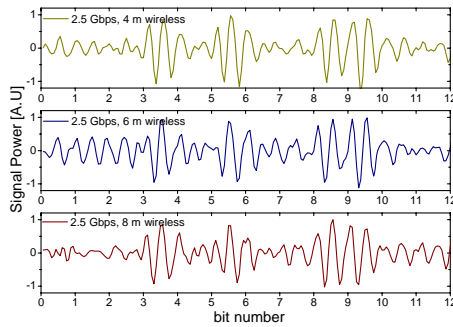
4. Conclusion

Using a combination of omnidirectional transmitting antenna and unidirectional (high gain) receiving antenna, we have succeeded in wireless transmission of impulse radio (IR) ultra wide-band (UWB) signals over 8 meters @ 2.5 Gbps, and 4 meters @ 4 Gbps with a received BER below the FEC limit of $2 \cdot 10^{-3}$. Prior to the wireless transmission, the signals were transmitted through a 100 m MMF based in-building fiber link, employing direct modulation of a VCSEL for a simple, low-cost solution for the optical link.

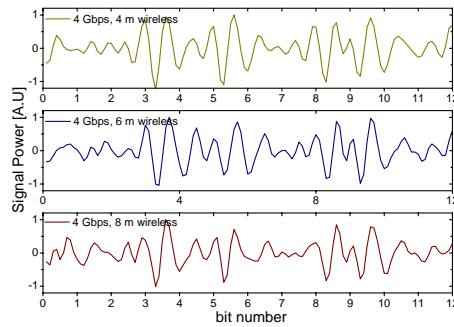
In the experimental demonstration, the UWB pulses were generated electronically using an



(a) 1 Gbps after 100 m MMF



(b) 2.5 Gbps after 100 m MMF



(c) 4 Gbps after 100 m MMF

Fig. 5. Part of the received signal corresponding to the pattern '000101001100' at bit rates 1, 2.5 and 4 Gbps measured after 4, 6 and 8 m wireless transmission

AWG. For a commercial realization, this can be replaced by a more simple signal generator dedicated to producing 5th order Gaussian pulses for IR-UWB transmission. Using DSP in the receiver requires sampling of 20 GSamples/s in order to resolve the high-frequency content of the signal. Such high-speed analog to digital (A/D) converters are available today, but currently at a high cost. On the other hand, the development in this area is impressively fast, so high speed A/D converters are likely to be available at considerably lower cost in a few years. Moreover, if half-wave rectification and envelope detection of the received signal is employed, the A/D converters and DSP can be avoided.

We believe that the bit rate-distance product of 20 achieved in the 8 meters 2.5 Gbps case is the highest yet reported for IR-UWB signals. Moreover, through the simple solution for the optical link, we have demonstrated IR-UWB as a strong candidate for future in-building networks employing wireless connectivity and fiber-optic routing.

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