Experimental Test-Bed for Studying Multiple Antenna Beamforming over Ultra Wideband Channels up to 12 GHz

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***Abstract*—An experimental setup is designed and implemented to study the performance of transmit beamforming techniques over realistic UWB Multiple-Input Single-Output (MISO) configurations. This setup can be used to investigate practical issues which are not usually addressed in simulation models, such as imperfect channel estimation or coherency between the multiple transmitters. Our implementation is based on the use of optical delay lines to apply appropriate time shifts to the output of an electrical arbitrary waveform generator (AWG). In this paper we assess the experimental accuracy of our setup over a 4×1 MISO system using time reversal beamforming.**

***Index Terms*—Transmit beamforming, multiple input–single output (MISO), ultra-wideband (UWB).**

I. Introduction

ULTRAWIDEBAND(UWB) is an emerging technology which offers several unique advantages in applications such as short range high-speed wireless communications and tracking motions in multiple scattering environments [1-6]. Although UWB offers new possibilities compared to conventional narrowband systems such as multipath fading robustness and ultra high range resolution, there are a number of challenges. Due to the extraordinarily fine temporal resolution of UWB systems, received responses consist of numerous resolvable multipath components (MPCs). To capture and process the received energy which is dispersed over large number of MPCs, complex receiver systems are necessary [1]. In recent years intensive research has been performed to explore the opportunities of multiple antenna systems in connection with sophisticated transmit beamformings (e.g. Time Reversal (TR) or Minimum Mean Square Error (MMSE)) over the UWB channels [7]. Transmit beamforming shifts receiver complexity to the transmitter side and provides temporal and spatial focusing, which reduce respectively inter-symbol interference (ISI) in high speed wireless communications and inter-channel interference in multiple user networks. In addition, multiple antenna systems have been exploited to extend the UWB transmission range [8] and to achieve increased information rate and better spatial focusing and temporal compression compared to that possible with a single transmit-receive antenna pair [7-14].

Much of the previous research in multiple antenna systems for UWB is theoretical and based on simplified models [7-11] which do not address experimental challenges such as imperfect channel estimation or transmitter synchronization. For example, in [7-8] TR performance of Multiple-Input Single-Output (MISO) systems is studied based on simulations by computing auto- and cross-correlations of the measured impulse responses (IR) using virtual array antennas. All the IRs are gathered one at a time by moving an antenna element over a virtual grid. During the measurement which can take several minutes, the environment should be kept stationary. MISO-TR is simulated off-line with assumptions that all the measured data are noise free, the estimated IRs are perfectly accurate, and the predicted beamforming waveforms can be generated without error and with perfect synchronization. In this technique there is no guarantee to achieve the predicted performance gains in a real experimental setup.

A few researchers have studied UWB MISO systems experimentally by applying transmit beamforming (particularly TR in most cases) [12-14]. In [12-13], FPGA boards are used to test MISO-TR systems for two transmitters at a center frequency of 3GHz, with bandwidth specified as 800MHz at -10dB. Naqvi *et. al.* [14] used an AWG to study TR in a two transmit antenna configuration in a reverberation chamber over the frequency range of 0.7-2.7 GHz. These studies either cover only a small portion of the UWB or are completely out of the 3.1-10.7 GHz band.

Taking advantage of recent advances in electronic AWG and digital oscilloscope technology, we have recently demonstrated single inputsingle output (SISO) channel measurements and time reversal studies simultaneously over the 2-12 GHz range, fully covering the UWB band [15-16]. The lack of comprehensive experimental measurements over UWB multiple antenna systems has motivated us to extend our work to implement an experimental setup capable of testing the performance of different transmit beamforming designs in multiple antenna configurations over the frequency range of 2-12 GHz. To the best of our knowledge, this is the first experimental report of multiple antenna beamforming over the full UWB band. Implementation of our setup is based on using optical fiber delays to apply appropriate time shifts to the output of an electrical AWG. Although optical delay lines have been extensively reported for true-time-delay feeds of phased array radar antennas [17] over large bandwidth, our work is the first to apply fiber delay lines for UWB multiple antenna beamforming. Although this setup can be extended to study the performance of arbitrary number of transmit antennas in connection with any sophisticated beamforming design, we introduce it by implementing a 4×1 MISO-TR configuration. The emphasis of the current paper is to demonstrate the viability of our setup and assess its experimental accuracy in applying beamforming.

The remainder of this paper is organized as follows. Section II provides details of the physical measurement setup. Section

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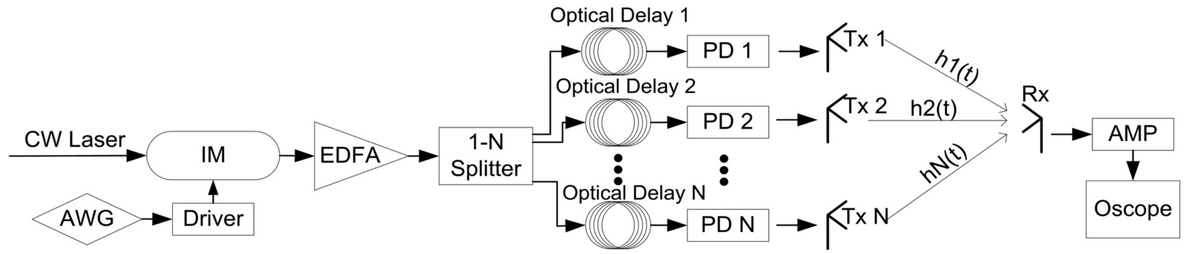

Fig. 1: Block diagram of the measurement system. CW laser: Continuous wave laser, AWG: Arbitrary waveform generator, IM: Intensity modulator, PD: Photodiode, Tx: Transmit antenna, Rx: Receive antenna.

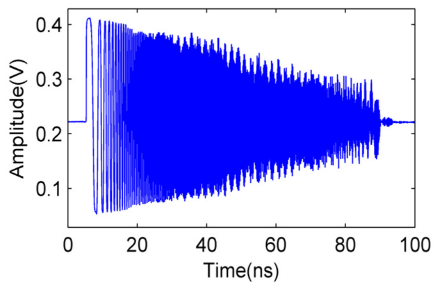

Fig. 2: Generated chirp waveform out of PD1. This waveform is used as a reference for applying post-processing deconvolution to extract IRs.

III describes our measurement methodology and an example of the experimental results. Finally, in section IV we conclude.

II. Experimental Setup

Fig. 1 shows a block diagram of the measurement setup. Tektronix arbitrary waveform generator 7122B is used in interleaving zeroing-on mode which gives the maximum available sampling rate of 24GS/s. The AWG not only provides sufficient bandwidth to probe channels over a frequency band spanning 2-12 GHz, which exceeds the full FCC UWB band, but also provides the flexibility to implement different transmit beamforming algorithms. Its main limitation is that only one output is operational in interleaving mode, which would normally suffice only for testing of single transmit antenna configurations [15-16]. To extend the capabilities of the AWG to study multiple antenna systems, we propose a photonic solution which exploits the long record length of the AWG (up to 64M points). The main concept is to use the AWG to generate a sequence of waveforms (e.g., TR signals for different channels in a MISO configuration) with relative delays which are longer than the maximum delay spread of the wireless channel. The electrical signal from the AWG is mapped to the optical domain and split to drive different photodiodes (PD) which are connected to the transmitting antennas. The individual transmit waveforms are aligned in time using optical fiber delay lines such that they arrive at the receiving antenna in synchronism. In this way we can concurrently excite different antennas with different transmit waveforms by using a single AWG.

Back to our setup in Fig. 1, to accomplish this idea, the output of AWG is amplified by a driver amplifier (Picosecond Pulse Labs Model 5865) which has 12 GHz bandwidth and maximum 26dB small signal gain. A commercial lithium niobate intensity modulator (IM) is used [18] to create an optical intensity that mirrors the electrical output of the AWG. A continuous-wave (CW) optical signal at 1.55μm wavelength is directed into the IM with DC electrical bias adjusted precisely for 3dB transmission and with the driver output connected to the RF input of the IM (Fig. 1). There is a trade-off between the dynamic range of the modulated optical waveform and the nonlinearity introduced by the sinusoidal response function of the IM, which should be considered to have an appropriate electronic to optical mapping. In our current experiments, we have used maximum modulation depth of $\sim$ 75%. The output of the IM is boosted by an erbium-doped fiber amplifier (EDFA Pritel SPFA-18) placed immediately before an optical splitter which ideally divides the incoming beam into N equal beams. Each output of the splitter is delayed appropriately by passing through a fiber delay line and converted back to the electrical domain using a photodiode (bandwidth > 12.3GHz). In our current setup, we use a 1$\times$4 splitter and directly connect the PD1 to the 1^{st} splitter output. Approximate delays of 600ns, 1200ns and 1800ns are respectively applied to the 2^{nd}, 3^{rd} and 4^{th} outputs of the splitter. The relative delay increment of 600ns is much longer than the maximum delay spread of the channel ($\sim$200ns). With optical amplification the electrical signals out of the PDs have $\sim$0.4 V peak to peak amplitude (e.g. Fig. 2) and are large enough to directly drive the antennas for impulse response sounding without electrical amplification. Wideband omni-directional antennas (ELECTRO-METRICS EM-6865 2-18 GHz) which have vertical polarization and uniform radiation pattern in the azimuth plane are used as transmitters (Tx) and receiver (Rx).

The output from the Rx antenna is passed through a low noise amplifier with 0.1-20 GHz frequency response and a minimum 31dB gain. The amplified signal is directly connected to a real-time oscilloscope (Digital Serial Analyzer, Tektronix DSA 72004B) with 20 GHz analog bandwidth and maximum real-time sampling rate of 50 GS/s. The oscilloscope is triggered by one of AWGs digital marker outputs which is synchronized with the transmitted waveform with timing jitter below 30ps. The average data acquisition mode, in which we average over 256 measurements, is used to reduce additive noise. The data acquisition time is approximately 400 ms, dominated by oscilloscope dead-time between successive measurements in averaging mode. This short acquisition time is one of the important advantages of this measurement methodology compared to the virtual array antennas technique.

Although we have conducted our experiments in several line-of-sight (LOS) and NLOS environments, in this paper the measurement methodology is explained over a specific but typical 4$\times$1 MISO indoor NLOS channel. The average propagation distance between Tx antennas and the receiver

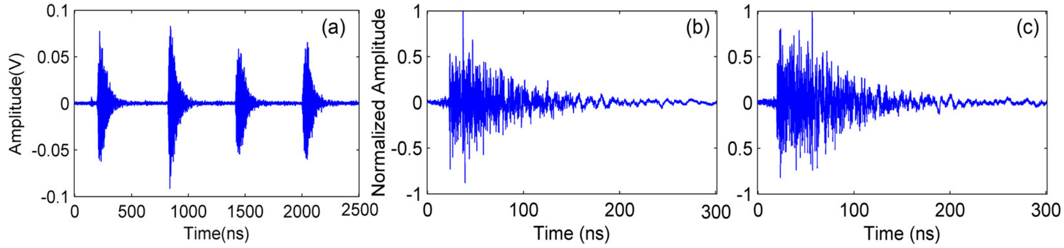

Fig. 3: (a) Received response from channel excitation (b) Measured IR from $h_1(t)$ link (c) Measured IR from $h_2(t)$ link.

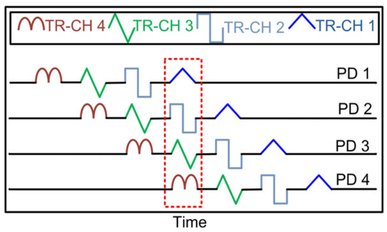

Fig. 4: The AWG waveform shows up with different delays at the PD outputs. The time slot depicted by a dotted rectangle shows the period during which all antennas are excited simultaneously.

(Rx) is 14m and there are two walls and a storage room (which contains large metallic desks and cabinets) in the direct paths of the Rx-Tx antennas. To show the accuracy of our setup, we compare experimental TR measurements with those predicted based on the estimated channel responses. As it is not straight forward to precisely simulate the mutual coupling between the antennas over this large frequency bandwidth, we place the transmitting antennas with the minimum inter-element distance of 70cm to avoid coupling effect between them. This distance is sufficient to have approximately decorrelated channels (i.e. correlation coefficients between MISO channels are on the order of 0.15) which is necessary to get spatial-temporal focusing gains in addition to power gain in a MISO system [9].

III. Measurement Methodology and Experimental Results

In the following we discuss the methodology and present experimental results first for the IR measurement and then for multiple-antenna beamforming.

A. Channel Impulse Response Measurement

We perform spread spectrum channel sounding to characterize IRs [15]. This technique not only provides higher dynamic range compared to the pulse excitation method [15], but also has a short acquisition time (compared to the frequency domain channel excitation method which uses vector network analyzers) which makes it more suitable for time varying channel measurements. In these experiments a linear up-chirp waveform defined over DC-12 GHz with 85.3ns time aperture at 24GS/s frequency rate is used for sounding. After the AWG is programmed for the chirp waveform, we first perform a calibration measurement in which we measure the waveforms after the PDs by directly connecting it to the real-time oscilloscope. Fig. 2 shows the recorded signal out of PD1, which is used as a reference signal in the post-processing method to extract IRs [15]. Other PDs also have similar outputs with relative time shifts due to the optical delay lines.

The roll off of the chirp waveform in time simply reflects the frequency response of the AWG, driver and IM. There is a DC bias in the output waveforms of the PDs (waveforms generated in photonic domain are always positive), which will be filtered by the high-pass characteristic of the antennas.

We excite the MISO channel with the chirp waveforms and record the received response by the oscilloscope (see Fig. 3(a)). The received waveform consists of 4 separate parts corresponding to MISO channels $h_1(t)$-$h_4(t)$. A single scope trace contains the IR information of all four channels, including relative delays due to the optical delay lines and propagation times (different channels have slightly different propagation distances). To extract IRs from the received waveforms deconvolution is applied between the recorded reference waveform (Fig. 2) and the received response (Fig. 3(a)). In this way, modulations of the transmitted power spectrum due to the system imperfections (e.g., frequency response of the band-limited AWG or nonlinearities of the IM) are compensated, and unbiased estimations are acquired. More details about our method, including assessments of its accuracy, are presented in [15]. Fig. 3(b) and 3(c) show two examples of the measured multipath IRs corresponding to the links $h_1(t)$ and $h_2(t)$. As we can see, the multipath components are distributed over time up to 150 ns [16]. Due to strong multiple scattering, the IRs from the different Tx antennas are nearly uncorrelated, although the delay spreads are similar.

B. Time Reversal Experiment

To experimentally apply MISO-TR, the measured response from the 4-antenna system (as in Fig. 3(a)) is sent back to the transmitter side through a feedback loop (wireless local area network) with 8 bit resolution. The waveform calculation for TR consists of resampling the obtained IR at 24 GS/s and inverting the result in time [16]. When the TR waveform propagates through the channel, it acts as a pre-matched filter which ideally compensates the channel spectral phase and results in peaking at the target receiver.

The beamforming process of our experimental setup is depicted schematically in Fig. 4. Each symbol represents a time reversed version of the IR from one of the Tx antennas. The overall waveform arrives at the various PD outputs with different delays. The dotted rectangle indicates the time period during which all antennas are excited simultaneously. Beamforming in the MISO configuration is achieved during this time period, resulting in a strong peak at the Rx. The extra waveforms outside the dotted rectangle result in lower amplitude, noise-like responses at the Rx and are clearly separated in time from the main signal.

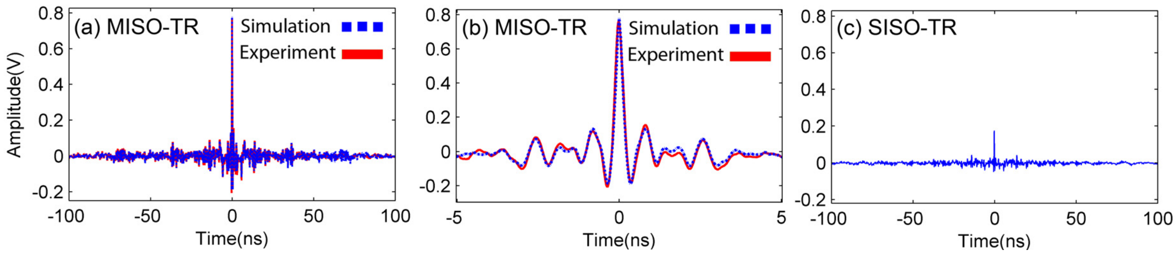

Fig. 5: Comparison between Time Reversal simulations and experiments for omni-directional 4×1 MISO in NLOS environment. (a) 200ns time window. (b) Zoom in on the main peak. (c) Experimental SISO-TR over $h_1(t)$.

Fig. 5(a)-(b) shows an example of the Rx response in TR MISO beamforming experiments. In this measurement, we have used equal maximum transmitted peak power over different MISO channels. The data are compared with the simulated response [16], equal to the sum of the autocorrelations of the measured impulse responses, $h_1(t)$-$h_4(t)$, timed such that the autocorrelation peaks are exactly synchronized. We can see data and simulation are extremely close. In this example the correlation coefficient between experimental and simulated traces is 0.98. This high level of agreement shows our accuracy both in measuring impulse responses and in aligning the received peaks in the MISO configuration. Comparing Fig. 5(a) and 3(b-c) demonstrates that significant compression is achieved by implementing MISO TR. The peak to average power ratio (PAPR) [16], measured over 200ns time window, for the MISO TR response is ∼12dB higher than for the uncompressed IRs (Fig. 3(b-c)).

To show an example of the achieved array gain and better temporal focusing of MISO systems compared to SISO, we turned off the transmitted TR signals from PD2, PD3 and PD4 and leave the PD1 unchanged. The received response from applying SISO-TR over $h_1(t)$ is shown in Fig. 5(c). As we see from these figures, an amplitude gain factor of ∼4.3 (peak power gain of ∼12.6 dB) is achieved in the MISO experiment, roughly as expected for a four antenna system. The PAPR for Fig. 5(a) is ∼2.4dB higher than for the SISO-TR shown in Fig. 5(c), which shows better sidelobe suppression of MISO configuration compared to SISO.

IV. Conclusion

In this work we introduce an experimental setup to study transmit beamforming over UWB multiple antenna configurations. Due to the practical difficulties of providing direct electrical delays, our implementation is based on photonics by taking advantage of low loss optical fibers to apply different appropriate time shifts to the output of an electrical AWG. Time-domain spread spectrum channel sounding (which has short acquisition time and high dynamic range) is used to simultaneously characterize system impulse responses. By exploiting the high quality impulse response data, we applied MISO-TR beamforming and prove our capability to carry out high accuracy measurement. The excellent accuracy of this setup makes it highly appropriate for practical investigations of different topics including temporal-spatial focusing, waveform design and polarization multiplexing over UWB channels for multiple antenna systems. To our knowledge, this is the first experimental report of multi-antenna beamforming over the full UWB band.

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