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Digital Double Sideband Frequency Translation for Transmission of RF MIMO Signals over Fiber

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Abstract— **In this letter, we demonstrate digitization, digital frequency translation and pre-distortion compensation using ADC and DAC for transmitting analog radio frequency (RF) multiple-input-multiple-output (MIMO) signals over a single fiber without wavelength division multiplexing (WDM). This technique allows more flexible signal manipulation than the previous purely analog implementations. With the digital pre-distortion compensation for a Mach Zehnder modulator (MZM), a 6-dB reduction in the intermodulation distortion is achieved for a 10-km RF over fiber link.**

Index Terms— **Multiple-input-multiple-output (MIMO), digital signal processing (DSP), radio-over-fiber (RoF) and pre-distortion compensation.**

I. Introduction

Multiple-input-multiple-output (MIMO) wireless technology not only improves radio communications reliability through spatial diversity, but also increases data throughputs by spatial multiplexing due to the rich multipath environments in buildings. As a result, MIMO wireless technology is now an integral part of most commercial wireless communications standards including the IEEE 802.11 (WiFi), the fourth generation (4G) Long-Term Evolution (LTE) and the fifth generation (5G) broadband cellular networks [1,2]. For example, the IEEE802.11ax standard supports up to eight MIMO streams in different directions in the 2.4 GHz and 5 GHz bands with a maximum 12Gbps data rate [3].

Broadband wireless over fiber technology can be used to improve indoor radio signal coverage by connecting a number of antenna units using fiber to a radio base station [4]. Although it is straightforward to use a radio frequency (RF) power combiner to combine different wireless services occupying different frequency bands before transmission over a single fiber, and to use microwave filters to separate them after fiber transmission, it is less straightforward to do so for MIMO as all the MIMO channels use the same carrier frequency.

Existing techniques for delivering RF MIMO channels over a single fiber include using wavelength division multiplexing (WDM) [5,6], polarization division multiplexing (PDM) [7,8], sub-carrier multiplexing (SCM) [9] and frequency division multiplexing (FDM) [6]. For the SCM and FDM techniques, one local oscillator (LO) is required to frequency shift one MIMO channel to an intermediate frequency, which is often very far from the original MIMO carrier frequency. For example, if three 2.4 GHz MIMO channels were to be transmitted over a single optical fiber, two of them would need to be frequency shifted using two LOs to, say, 100 MHz and 200 MHz, respectively, so that the three MIMO channels now at 100 MHz, 200 MHz and 2.4 GHz can be combined and transmitted over fiber together. However, existing radio-over-fiber (RoF) systems already deployed might not be able to support such wide range of frequencies because they would have narrowband impedance matching networks for the directly modulated laser diodes and the other microwave amplifiers designed for operation around 2.4 GHz only.

One of the authors previously proposed and demonstrated the phase-quadrature double sideband (DSB) [10], and the single sideband (SSB) frequency translation techniques [11], in which the MIMO channels are frequency offset with a low frequency (MHz) local oscillator before fiber transmission and then restored afterwards. The main novelties of these techniques are that two of the MIMO channels are frequency offset using just one LO. Therefore, for high numbers of MIMO channels, this represents a significant cost saving in terms of the number of required LOs compared to SCM and FDM. Furthermore, the MIMO channels are frequency offset by only a few tens of MHz so that all the MIMO channels remain in the vicinity of their original carrier frequency of, say, 2.4 GHz, which is important for the narrowband impedance matching networks mentioned above. Our previously proposed DSB technique requires stringent orthogonal phase relation and equal amplitude to be maintained between the lower and upper sidebands. As a result, the demonstrated symbol rate at the time was only 1MSymb/s per MIMO channel using the DSB technique. The SSB technique, on the other hand, does not have such requirements and a higher 11 MSymb/s symbol rate was achieved. Yang *et al*. later showed that our DSB technique has an inherent 3 dB signal-to-noise advantage over the SSB due to the fact that although the sidebands are added coherently, when they are translated back, the noise is added incoherently [12]. They also overcame the equal amplitude requirement for the

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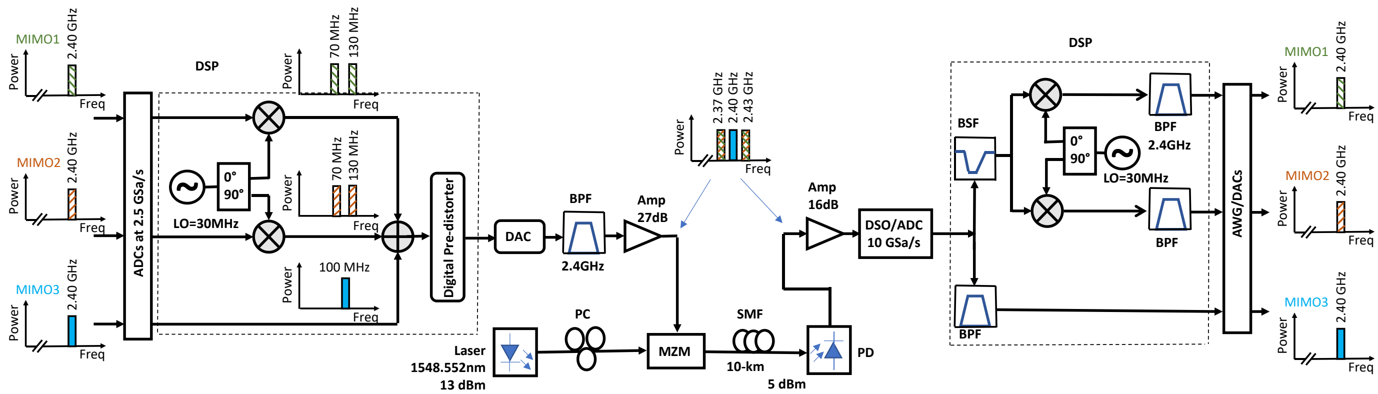

Fig. 1. Experimental arrangement for transmission of three MIMO channels over fiber using digital DSB frequency translation employing ADCs/DACs and DSP. Bandpass filter (BPF), Bandstop filter (BSF), digital oscilloscope (DSO), photodiode (DP), Mach Zehnder modulator (MZM), polarization controller (PC).

DSB technique by using a simple power equalizer. Yang *et al*. further developed the DSB technique into a quadruple sideband (QSB) one and showed experimentally that the QSB technique improved the 3rd order spurious-free dynamic range (SFDR) by 2.7 dB compared to the intrinsic radio over fiber link [13].

In both of our previously demonstrated DSB and SSB techniques, custom-made microwave filters or diplexers are required for the specific MIMO channel frequency/bandwidth and so they are rather inflexible. Also, these purely analog approaches do not readily support other signal processing steps often done in the digital domain which would improve the performance of the signal transmission such as pre-distortion compensation for the nonlinear Mach Zehnder modulator (MZM) transfer function. To overcome these limitations, we propose and demonstrate in this letter a novel application of analog-to-digital converters (ADCs) and digital-to-analog converters (DACs) together with digital signal processing (DSP) to perform DSB frequency translation for delivering three 2.4 GHz MIMO channels over a single fiber. Effectively, the combination of ADC/DAC with DSP frequency offsets the MIMO channels before fiber transmission and return them to their original 2.4 GHz after transmission. Because the three MIMO channels first go through the digitization process, digital predistortion is also implemented to compensate the MZM nonlinear transfer function, which is another novel aspect of the current technique that would not have been possible with the previous purely analog approaches [10, 11].

II. Experimental Arrangement and Results

In the experimental arrangement in Fig.1, three independent 10 MS/s 16-QAM RF MIMO channels all at a carrier frequency of 2.4 GHz are generated with a multichannel Keysight M8195A Arbitrary Waveform Generator (AWG). Two dual-input ADCs AD9208-3000EBZ from Analog Devices are synchronized and then used to digitize the three generated MIMO channels at a sampling frequency of 2.5 GSa/s using bandpass sampling. The digitized samples are then captured with an FPGA evaluation board ADS7-V2EBZ from Analog Devices via an FMC+ connector and then transferred to a computer for offline processing. The three digitized MIMO channels, now referred to as DMIMO-1, DMIMO-2 and DMIMO-3, respectively, are now located at 100 MHz in the digital domain as a result of the bandpass sampling. To perform DSB frequency translation, DMIMO-1 and DMIMO-2 are respectively multiplied with the in-phase and quadrature versions of a 30 MHz digital sinusoidal local oscillator (LO) signal, producing a pair of sidebands at 70 MHz and 130 MHz from DMIMO-1 and DMIMO-2 each. These two orthogonal pairs of sidebands overlap in frequency and are added to the 100 MHz untranslated DMIMO-3, forming a composite signal in the digital domain. In SCM or FDM, however, no frequency overlap happens among any of the channels.

To take further advantage of employing DSP, the composite signal is digitally pre-distorted using the well-known arcsine function to compensate, later, for the raised cosine nonlinear transfer function of the MZM [14,15]. The next step is to convert the digitally pre-distorted composite signal back to the analogue domain with a 2.5 GS/s Analog Devices AD9162 digital-to-analogue converter (DAC). A fixed bandpass filter centered around 2.4 GHz with a 100 MHz bandwidth is used to select the three MIMO components at 2.37 GHz, 2.4 GHz and 2.43 GHz in the second Nyquist zone from the DAC output. The total output power from the DAC containing the three frequency offset MIMO components is around -19 dBm which is further amplified with a gain of 27 dB before being sent to drive a MZM, which is part of the Thorlabs optical transmitter MX10B with an internal tunable laser outputting a 13 dBm continuous wave (CW) or unmodulated light to the MZM. The optical transmitter wavelength is set at 1548.552 nm with an average modulated output optical power of around 6 dBm. After transmission over a 10-km standard single mode fiber (SMF), the received optical signal, of around 5 dBm, carrying

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the three frequency offset MIMO components is photo-detected by a 5 GHz InGaAs photodiode (Thorlabs DET08CFC/M), amplified, and then digitized at 10 GSa/s with a real-time digital oscilloscope (DSO) acting as a high-speed ADC. Using offline DSP, the non-frequency-translated DMIMO-3 is simply separated with a digital bandpass filter (BPF). The remaining two pairs of sidebands at 2.37 GHz and 2.43 GHz go through a reverse DSB frequency translation to regenerate the original DMIMO-1 and DMIMO-2 at 2.4 GHz after further bandpass filtering. Finally, DMIMO-1, DMIMO-2 and DMIMO-3 are converted back to the analog form using the multichannel Keysight M8195A AWG acting as three DACs.

In proposed technique, the frequency translation is performed in DSP, all ADCs and DACs are synchronized, which ensures exact frequency precision and phase stability. Fig. 2 shows the electrical spectra of the transmitted composite signal measured by the DSO with and without digital pre-distortion, which shows that digital pre-distortion has reduced the intermodulation distortion products at 2.34 GHz and 2.46 GHz by about 6 to 7 dB. One would usually expect to see a larger improvement with digital pre-distortion. In our experimental arrangement, however, part of the generated pre-distortion products was removed by the bandpass filter in the transmitter, leading to a reduced improvement in the intermodulation distortion level after the MZM.

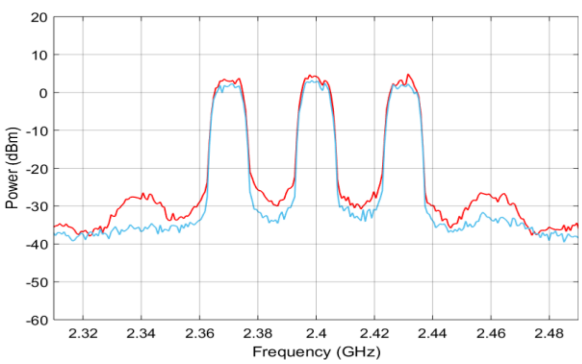

Fig. 2. Electrical spectra of the transmitted composite signal measured by the DSO with (blue) and without (red) digital pre-distortion.

TABLE I
PERFORMANCE SUMMARY OF THE RF MIMO TRANSMISSION OVER FIBER

	Input Channel Power (dBm)	Output Channel Power (dBm)	Channel Gain(dB)	Output Noise Power Spectral Density (dBm/Hz)	Channel Noise Figure (dB)	EVM%
MIMO1	-7.9	-7	0.9	-145.3	27.8	2
MIMO2	-7.9	-7	0.9	-145.3	27.8	1.8
MIMO3	-7	-5.5	1.5	-145.5	27	1

Table I summarizes the performance of all three MIMO channels, which shows that all three channels had similar channel gains and noise figures. Fig. 3 shows the received spectra and measured 10 MS/s 16-QAM constellation diagrams of the three MIMO channels. After demodulating the 16-QAM signals, MIMO3 had the smallest error vector magnitude (EVM) of 1% while the two frequency translated MIMO channels had an EVM of up to 2%. These low EVM values should support error free transmission.

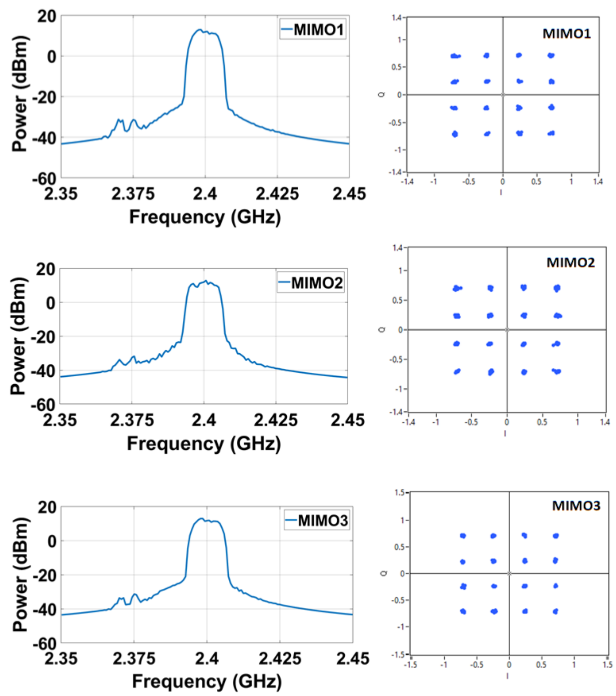

Fig. 3. Measured spectra and constellation diagrams of the three MIMO channels each modulated 10 MS/s.

III. CONCLUSION

We have demonstrated a digital DSB frequency translation technique using ADCs/DACs with DSP for transmitting RF MIMO signals over a single fiber without WDM. Compared to the original purely analog approach, this proposed technique further allows digital pre-distortion and flexible reconfiguration of the DSP according to the frequency and bandwidth of the MIMO signals. To measure and present the raw transmission performance such as the channel power gain, noise figure and EVM accurately, no MIMO specific algorithm was implemented in our experiment and the measured data shows that all three MIMO channels were successfully combined, transmitted together and finally separated almost completely. All the DSP was performed offline, meaning that the existing arrangement is not yet configured for real-time signal processing and transmission. To deliver RF MIMO signals in real-time using the proposed technique, an FPGA board, with the necessary ADCs/DACs, should be used to perform all the frequency translation and DSP steps in real-time which is currently being pursued.

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