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Over-The-Air Calibration of a Dual-Beam Dual-Polarized 28-GHz Phased-Array Channel Sounder

Sung Yun Jun, Derek Caudill, Jelena Senic
RF Technology Division
National Institute of Standards and Technology
Boulder, CO, USA
{sungyun.jun; derek.caudill; jelena.senic}@nist.gov

Camillo Gentile, Jack Chuang, Nada Golmie
Wireless Networks Division
National Institute of Standards and Technology
Gaithersburg, MD, USA
{camillo.gentile; jack.chuang; nada.golmie}@nist.gov

***Abstract*—This paper describes an over-the-air (OTA) calibration procedure for the impulse response of a 28-GHz phased-array antenna channel sounder. The silicon-germanium (SiGe) antenna board is composed from two 8x8 planar arrays; each array can generate a distinct beam in the vertical and horizontal polarizations that can be steered in both azimuth and elevation within ±50° and ±25°, respectively. As part of the calibration procedure, unique pre-distortion filters were designed per steer angle, achieving a peak-to-sidelobe ratio in the impulse response of up to 56.5 dB, with less than 1 dB variation across the steer angles. Critically, we show that performance degraded up to 10.1 dB when applying the pre-distortion filter designed at one steer angle to the other steer angles, underscoring the need for angle-specific filters. Finally, we show that performance between both polarizations is comparable thanks to the array symmetries in the fabrication process.**

Keywords—channel sounder; 5G wireless communications; propagation channel; calibration; wireless communication

I. INTRODUCTION

The millimeter-wave (mmWave) frequency bands are drawing attention amid growing interest for fifth-generation (5G) communications [1]. While these operating frequencies enable high-bandwidth and high-speed links, they suffer from greater propagation loss. To overcome the latter, phased-array antennas paired with beam-steering to achieve high-gain directional systems have been recently considered for 5G wireless networks [2].

Previously, channel sounders at the mmWave frequency bands of 28 GHz, 60 GHz, and 83 GHz based on time-multiplexed switched antenna arrays were developed by the National Institute of Standards and Technology (NIST) [3]-[4]. The calibration procedure to estimate and remove systematic distortions caused by the IF (Intermediate frequency) and RF (Radio frequency) sections of the system was based on a back-to-back method in which waveguide attenuators were directly connected between the transmitter (TX) and receiver (RX) after removing the antennas. When dealing with phased-array antennas, the back-to-back method cannot be applied because the RF components in the SiGe chips on the printed circuit board – which also distort the system impulse response – are not accessible through connectors. As such, OTA methods must be used instead.

In this paper, we extend the work in [5] to a 3D-steerable dual-polarized 28-GHz phased-array antenna. In Section II, the system architecture of the 28-GHz channel sounder is described following by the OTA calibration procedure and results in Section III. Lastly, the conclusion and the future work are described in Section IV.

II. CHANNEL SOUNDER ARCHITECTURE

Our 28-GHz dual-beam dual-polarized phased-array channel sounder is a correlation-based system using a pseudo-random noise (PN) code as the probing signal. Fig. 1 shows the schematic block diagram of the channel sounder calibration. An arbitrary waveform generator (AWG) at TX provides the binary phase shift keying modulated IF signal of 2.5 GHz using a PN code with degree of 11 (2047 chips). A chip rate of 1 Gbits/s with 2 GHz null-to-null bandwidth is used. The IF frequency is up-converted to RF with center frequency at 28.5 GHz. The received RF signal is down-converted back to IF of 2.5 GHz and digitized using an analog-to-digital converter (ADC) sampling at 10 Gsample/s. A single 10 MHz rubidium-disciplined crystal oscillator is used as the frequency reference. Two rubidium devices are used when channel sounding to enable untethered time synchronization of PN codes between TX and RX.

Details of the 28 GHz dual-beam dual-polarized phased-array in our system are described in detail in [6]. The array consists of 2x64 patch elements driven by sixteen 2x4 SiGe dual-beamformer transmit/receive (TRX) chips, placed on a low-cost printed-circuit board (PCB) and operated with 6 bits of phase control and 22 dB of gain control. The scan angle range of the array with vertical- (V) and horizontal- (H) polarized beams in the azimuth and elevation planes is ±50° and ±25°, respectively. Given the limited azimuthal scan range of each board, four boards – each scanning ±45° – are mounted at right angles with respect to each other in order to extend the total scan to an omni-directional view (360°). The array can generate V- and H-polarized beams simultaneously.

III. IMPULSE-RESPONSE CALIBRATION

In order to obtain optimal performance, we calibrate the system impulse response through pre-distortion filtering to account for the hardware non-idealities of the channel sounder. As seen in previous work [4]-[5], the pre-distortion filter is designed in a multi-step procedure: In the first step, the ideal PN code is transmitted and the code distorted by the system is

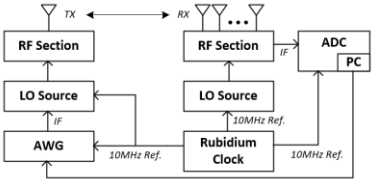


Fig. 1. Block diagram of the channel sounder calibration setup.

received; next, the received code is deconvolved from the ideal code, what we refer to as the *pre-distorted code*; finally, the pre-distorted code is sent instead of the ideal code so that what is received after distortion by the system is a quasi-ideal code. The calibration procedure was applied iteratively to deal with the non-linearities of the system; three iterations were necessary for convergence to optimal performance. Details of the calibration procedure can be found in [4].

Fig. 2 displays the OTA calibration set-up: It employs a scalar feed horn at the TX with 16.6 dBi gain and a phased-array board at the RX. The RX was placed in a semi-anechoic environment on a precision mechanical rotator with 1.6 m separation from the TX; the purpose of the rotator was to align the antenna boresights while investigating different phased-array steer angles. Fig. 3(a) displays the normalized power delay profile (PDP) with and without pre-distortion filtering for the V-polarized beam at 0° azimuth steer angle in the elevation plane and Fig. 3(b) for H-polarized beam; thanks to array symmetries in the fabrication process, the results for both polarizations are comparable. Calibration greatly reduced the peak Interval Of Discrimination (IOD_{pk}) between the correlation peak and the sidelobes: in the correlation tail, non-ideal spurious peaks were down at least 54.8 dB in both polarizations; also, the cross-polarization rejection between beams was measured as approximately 22.7 dB and 24.4 dB in V- and H-polarized beams, respectively.

Table I compares the IOD_{pk} for the response calibrated at several azimuth steer angles (in the elevation plane) versus the uncalibrated response: the IOD_{pk} is similar across the steer angles. In contrast, the pre-distortion filter designed at 0° azimuth steer angle was then applied to the other steer angles, what we refer to as a *semi-calibrated response*: the IOD_{pk} suffered by up 10.1 dB, suggesting that calibration per steer angle is essential. Cross-polarization rejection remained within 1 dB of original values.

IV. CONCLUSION AND FUTURE WORK

This paper presents results for the impulse-response calibration of a dual-beam dual-polarized 28-GHz phased-array channel sounder. The study shows that the results, expressed in terms of the peak-to-sidelobe correlation ratio, are essentially invariant across the various steer angles of the phased-array antenna so long as a unique calibration is performed per steer angle; in contrast, we show that when a single calibration is performed and merely applied to other steer angles, the ratio can suffer by up to 10.1 dB. Finally, we show that results are similar between the V- and H-polarized beams due to the array symmetries in the fabrication process. So far, we have only investigated performance with variation in the azimuth plane; in future work, we shall investigate joint variation in the azimuth and elevation planes.

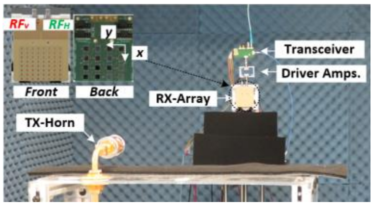
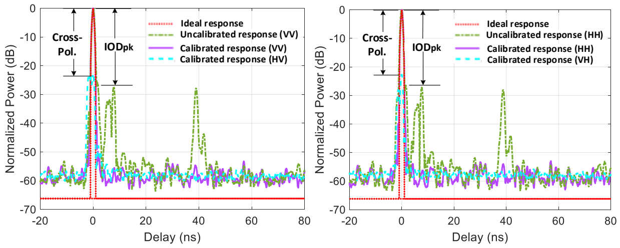


Fig. 2. Measurement setup for the OTA impulse response calibration.



(a) (b)

Fig. 3. Normalized PDP with uncalibrated and calibrated response at 28.5 GHz at boresight (a) V-polarized beam (b) H-polarized beam.

TABLE I. IOD_{PK} (IN dB) THE ELEVATION PLANE

Steer Angle (Azimuth)	***Uncalibrated Response***		***Calibrated Response***		***Semi-Calibrated Response******	
	VV	**HH**	**VV**	**HH**	**VV**	**HH**
-22.5°	27.2	26.9	55.6	54.9	48.1	48.1
-13.5°	27.5	26.9	55.3	54.9	46.2	51.9
-4.5°	27.3	27.0	55.2	55.0	47.3	52.0
0°	27.2	27.0	54.8	54.1	54.8	54.1
4.5°	27.4	27.1	55.5	55.7	48.3	53.3
13.5°	27.3	27.0	56.5	53.4	46.4	47.9
22.5°	27.3	27.1	55.2	54.4	49.9	53.5

* Pre-distortion filter designed at 0° azimuth steer angle and applied to other steer angles.

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