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Demonstration of Adaptive Analogue Beam Forming in the E-Band

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Abstract

In this paper, we report the test results of a small-scale prototype that implements an analogue-beam-formed phased antenna array in the E-band. A four-channel dual-conversion receive RF module for 71 ~ 76 GHz frequency band has been developed and integrated with a linear end-fire antenna array. Measured performance is very close to the simulated results. An ad-hoc wireless communication system has also been demonstrated. Low BER was measured for an 8PSK data stream at 1.5 Gbps with the receive array beam formed in the direction of arrival of the transmitted signal. To our knowledge this is the first steerable antenna array reported to date in the E-band.

Key words : Millimeter Wave Radio Communications, Antenna Arrays, Beam Steering.

Ⅰ. Introduction

High data rate millimeter-wave communication systems are of growing importance to the wireless industry. Future mobile and ad-hoc communications networks will require high bandwidth and longer range. An ad-hoc or mobile (e.g. Inter-aircraft) network that relies on high gain antennas also requires beam scanning. With the advance in digital signal processing techniques, the adaptive antenna array is becoming an essential part of wireless communications systems.

The use of adaptive antenna arrays for long-range millimeter-wave ad-hoc communication networks is particularly critical due to increased free space loss and reduced level of practically achievable output power [1]. Although pure digital beam forming allows for producing output signals with the maximum SINR, ease of on-line calibration and generation of many antenna patterns simultaneously, it is impractical for large wideband arrays due to two major reasons. Firstly, it is too costly since the cost of digital data processing is proportional to bandwidth and increases, at least, linearly with the number of elements. Secondly, the small separation of array elements in the E-band (71 ~ 86 GHz) leaves little room at the back of the array for connection of each RF chain associated with individual array elements to a digital beam former. A typical analogue RF chain tightly packed behind the antenna element includes a low noise amplifier(or power amplifier), frequency converter, local oscillator (LO), as well as the intermediate frequency(IF) or baseband circuitry. Each of these chains would require a number of DC, IF and control circuit interfaces. Therefore, a hybrid approach [1] ~ [3] where digital beam forming technique is applied to a smaller number of units (analogue beam formed sub-arrays) is preferable. This provides a significant saving in both the amount of digital signal processing and the number of physical connections between the RF front end and digital beam former. In this paper, we report the test results of a small-scale prototype that implements an analogue-beam-formed phased antenna array.

Ⅱ. Ad-Hoc-Hoc Communication System Prototype

2-1 System Block Diagram

The prototype has been developed to demonstrate a communications system with gigabit per second data rates using an electronically steerable array as an initial step towards fully ad-hoc communications systems. The prototype configuration is flexible and can be used for experimental verification of both analogue and digital beam forming algorithms.

The scannable beam receiver and a fixed beam transmitter form a prototype of the E-band communication system that implements an adaptive antenna array. Block diagram Fig. 1 shows configuration for analogue beam forming experiments. The receive RF module is mounted on a rotator providing mechanical steering in azimuth plane for the array pattern measurement. The demonstrator also includes the digital modulator and demodulator reported in [4].

Both the receiver and transmitter use dual frequency conversion with the baseband (IF2) frequency 1 ~ 2 GHz that enables re-use of the digital modems reported earlier in [4]. The receive IF module (Rx IF) has been de-

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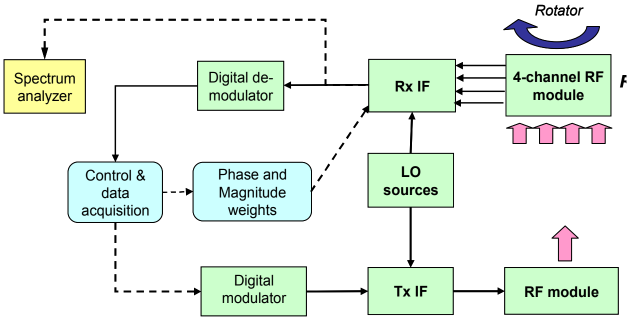


Fig. 1. Block diagram of the E-band communication system that implements a steerable receive antenna array.

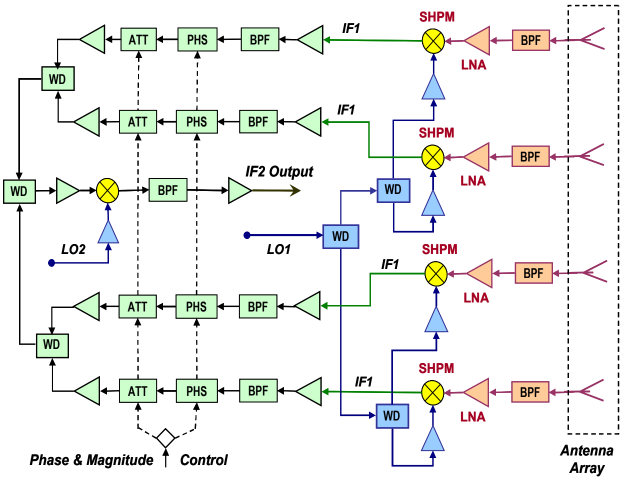


Fig. 2. Simplified schematic of the E-band steerable receive array configured for analogue beam-forming.

veloped in two versions. In the digital beam forming configuration, each of the IF channels is connected to a digital beam former that replaces the de-modulator. For the analogue beam forming configuration all IF outputs are combined before de-modulation as shown in Fig. 2 where BPF, LNA, SHPM, WD, PHS and ATT denotes a band-pass filter, low noise amplifier, sub-harmonically pumped mixer, Wilkinson divider, phase shifter and attenuator respectively. Phase and magnitude controls for each channel are implemented at IF using 6-bit digital phase shifters HMC649LP6 and attenuators HMC4214LP3 available from Hittite Microwave Corporation. They are used to equalize the channels frequency responses (initial calibration) and to apply required beam forming weights.

2-2 Transmitter

A single channel transmit module has been built using the up-converter reported in [5] that uses a sub-harmonically pumped (SHPM) GaAs Schottky diode mixer [6], with an addition of a commercial band-pass filter and a medium power amplifier, and a corrugated horn antenna with the gain of 22.5 dBi. The photograph of the RF transmitter is shown in Fig. 3. Bench test results have been reported in [1].

Fig. 3. Photograph of the transmit RF module assembly.

Measured to the antenna input of the RF transmitter, the small signal conversion gain and the output power at −1 dB gain compression was 35±1 dB and +15±1 dBm respectively over the operating frequency range of 71.5～72.5 GHz.

2-3 RF Module of a Steerable Receive Array

The main functional block of the prototype is a four-channel dual-conversion receive RF module [1] integrated with a four-element linear end-fire quasi-Yagi antenna array [7]. Array element spacing was 2 mm (or 0.48 wavelengths at the carrier frequency) to suppress appearance of grating lobes for scanning angles up to ±42 degree. Fig. 4 shows a photograph of the assembled RF module.

The RF module uses sub-harmonic frequency converters [6] at the LO frequency of 38 GHz. For each channel we have used a combination of CSIRO and commercial-

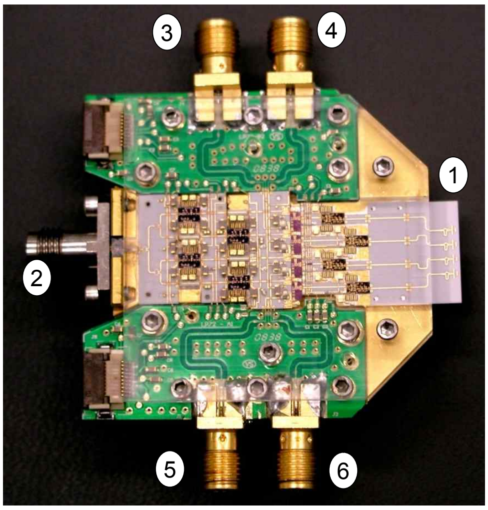


Fig. 4. Photograph of the RF module assembly where: 1 is the antenna array; 2 is the LO input; 3～6 are IF outputs.

off the-shelf MMICs similar to those reported earlier for a single-channel receiver [5].

The IF pre-amplifiers, interconnect, matching, and group delay equalization circuits have been developed using a standard commercial thin-film process on ceramic substrate. It includes 16 MMICs, 12 types of microwave boards (on 127 um alumina substrate), 140 microwave passives, and about 400 wire-bond connections. The receiver is usable over the frequency range of 71 to 76 GHz at the sub-harmonic LO of 38 to 39 GHz and intermediate frequency 1 to 7 GHz. Typical conversion gain was 6±1 dB over the operating RF and IF frequency range of 71.5~72.5 GHz and 3.5~4.5 GHz respectively. The maximum magnitude imbalance between each of four channels was below ±1.5 dB. Bench test results for the receive module have been reported in [1].

2-4 Antenna Array

A schematic of the quasi-Yagi array element [7], its parameters and dimensions are presented in Fig. 5. The antenna is characterized by a half-wavelength dipole driver of length LD, a director element with length LR, and a reflector formed by the ground plane of the microstrip circuit. The microstrip feed line attaches to a quarter-wave transformer, a balun, and then a coplanar strip transmission line, to provide the balanced feed required by the dipole driver element. The driver element may also be realized using a folded dipole, giving more flexibility in the design of the driver impedance value [8]. The impedance bandwidth (return loss greater than 10 dB) of the single element shown in Fig. 5, calculated using CST Microwave Studio [9], extends from 50.1~81.4 GHz. The calculated realized gain is 5.4 dBi from 71~76 GHz.

Before integration with the receive array, several four-element linear arrays were tested in isolation to confirm their performance. Schematics of two arrays are shown in Fig. 6, where the feed networks consist of microstrip power dividers and delay lines.

The array of Fig. 6(a) provides equal amplitude and phase excitation to each element for a 0° steering angle, while Fig. 6(b) provides equal amplitude with phase shifts of 57° between adjacent elements for a steering angle of 20° at 72 GHz. The tabs at the top of the schematics in Fig. 6 are part of the microstrip-to-waveguide transition, for interfacing with a WR-15 rectangular waveguide. Fig. 7 shows a prototype antenna fabricated on an alumina substrate using a thin-film process integrated with a brass microstrip-to-waveguide transition. Four arrays, each with different beam steering angles, were fabricated and their return loss and radiation patterns were measured. Radiation patterns were measured in the 12 m anechoic chamber at CSIRO. For all arrays, good agreement was achieved between measured and predicted radiation patterns. The measured gain for

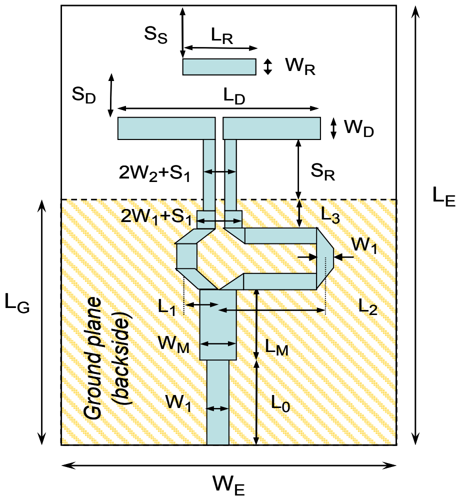
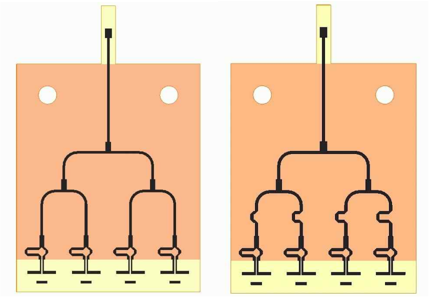


Fig. 5. A schematic of the quasi-Yagi antenna array element. L_E=3, W_E=2, W_1=0.12, L_0=0.45, L_G=1.54, L_M=0.54, W_M=0.205, L_1=0.22, L_2=0.7, L_3=0.1, S_1=0.06, W_2=0.06, L_D=1.29, L_R=0.488, W_D=0.12, W_R=0.12, S_R=0.516, S_D=0.323, S_S=0.383 (all dimensions in mm), substrate 127 um alumina (ε_r=9.9, tan δ =0.0003).



(a) (b)

Fig. 6. Schematics of four-element linear arrays of quasi-Yagi elements with integrated microstrip feed networks.

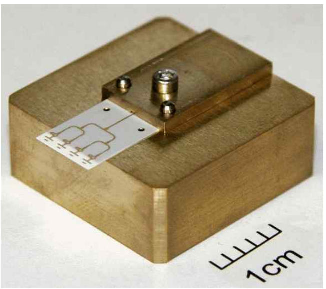


Fig. 7. Photograph of a four-element linear array prototype integrated with a microstrip-to-waveguide transition.

all arrays is 8～9 dBi at 72 GHz, which is about 1 dB lower than the simulated results. Mutual coupling between adjacent elements of the array was computed using CST Microwave Studio [9] and was typically less than −18 dB from 71～76 GHz.

2-5 Measurement Setup

All analogue beam forming measurements were conducted in the CSIRO 12 m far field anechoic chamber as shown in Fig. 8 where 1 is the receive array masked with absorbers, 2 is a rotator, 3 is the transmit antenna aperture and 4 is the de-modulator and power supply modules. Transmitter, digital modulator and control equipment were located on the outside of the chamber.

The available signal to noise ratio was above 33 dB for the measurement distance up to 6 m, but most of the tests were conducted at the distance of 2.2 m to minimize unwanted reflections from the walls and ceiling of the chamber.

Ⅲ. Test Results

3-1 Calibration

The receive array has been calibrated by cancelling the main beam to obtain a null at zero degree azimuth angle. The calibration procedure was as follows. With one channel at a time active, magnitudes of all channel outputs were set equal. Then, with channel pairs active in the sequence 2～3, 1～2 and 3～4, phase weights were adjusted to null each pair. Then a 180 degree phase shift was applied to the null calibration reference settings to peak the main beam at 0° azimuth. Fig. 9 shows the E-plane array patterns measured for the null reference and the main beam steered to a 0° azimuth. Simulated data from CST Microwave Studio [9] is shown for an array packaged in a waveguide test fixture depicted in Fig. 7.

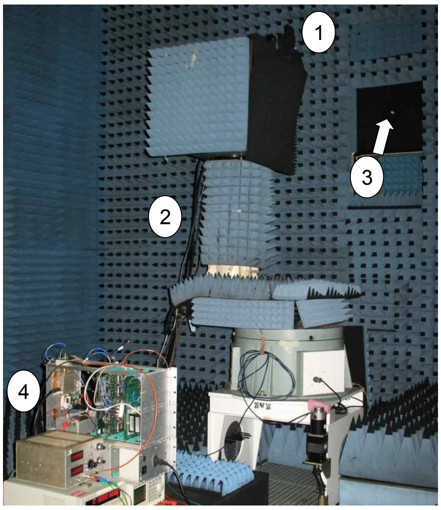


Fig. 8. System test setup in the 12 m far field anechoic chamber.

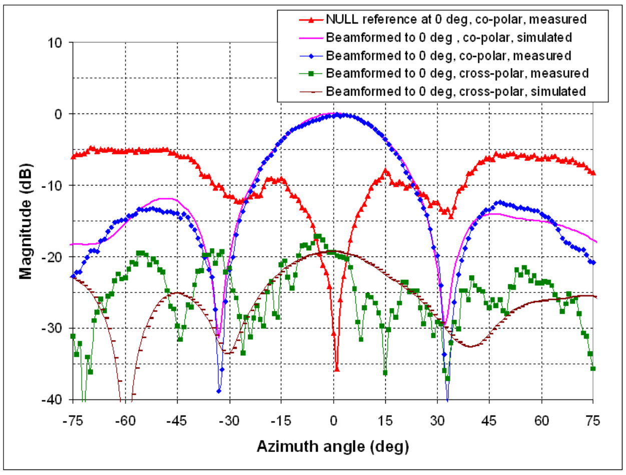


Fig. 9. Measured and simulated E-plane array co-polar and cross-polar patterns for the main beam formed at 0° azimuth and the measured pattern for the null calibration.

Experiments were conducted to validate obtained phase and magnitude weights by cancelling the main beam at a selection of azimuth angles as shown in Fig. 10. Labels appended to each pattern show actual measured null positions. Experimental results were in a very close agreement with analytical estimates (within 1 degree).

3-2 Measured Array Patterns

The array was steered to a selection of other positive

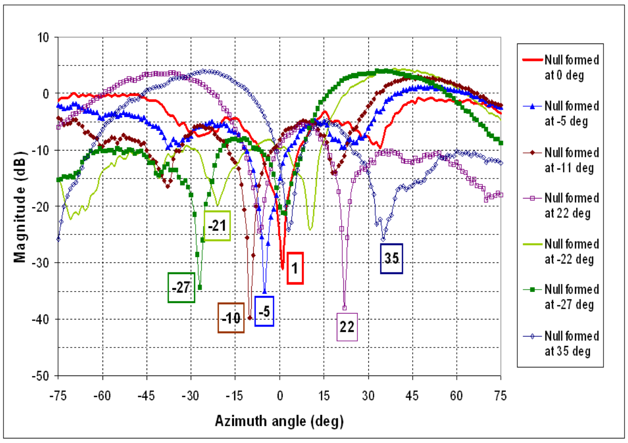


Fig. 10. Measured E-plane co-polar patterns for the array beam formed to cancel the main beam (form a null) at selected azimuth angle.

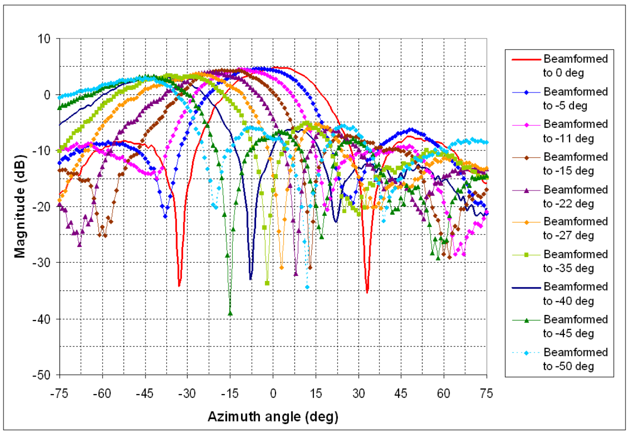


Fig. 11. Measured E-plane co-polar patterns for the array beam formed to a selection of negative azimuth angles.

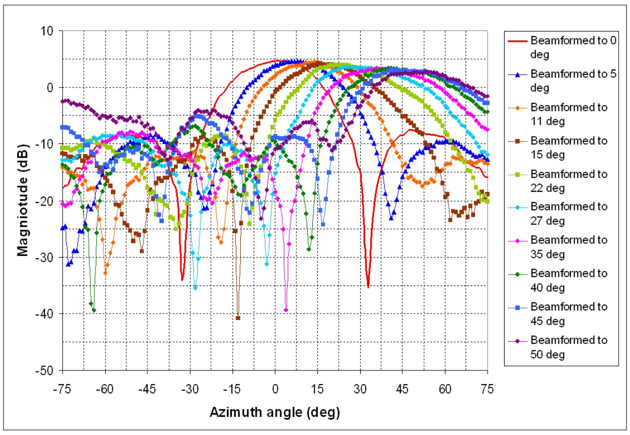


Fig. 12. Measured E-plane co-polar patterns for the array beam formed to a selection of positive azimuth angles.

and negative azimuth angles and E-plane antenna patterns were measured at each of the selected angles. The theoretical phase weights were applied to the null calibration reference settings to steer the beam to the non-zero azimuths. These weights were calculated using the array factor formula for an uniformly excited array. Examples of several measured E-plane co-polar antenna patterns are shown in Fig. 11 and Fig. 12. Cross-polar patterns have also been measured.

A summary of the E-plane measurements is shown in Fig. 13. Measured antenna array patterns were very close to those predicted by the electromagnetic simulation software [9] for steering angles ±40°.

Measured array gain was 9.5 dBi for steering angles below 22° and reduced to approximately 7.5 dBi at the maximum steering angle of ±42°. Grating lobes were observed only at the steering angles beyond ±43°. Beam steering accuracy of 1 deg has been achieved with 6-bit digital phase shift and magnitude control at IF.

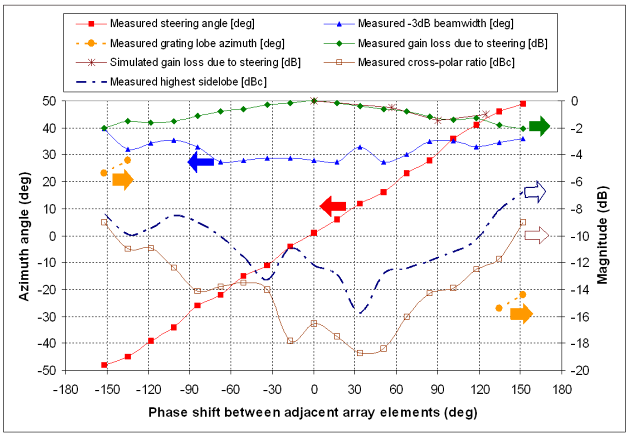


Fig. 13. Summary of the measurements.

3-3 Communication System Performance

A small ad-hoc point-to-point link has also been tested with reasonable bit error rate(BER) measured for selected angles using 8PSK modulation at 1.5 Gbps data rate. A single channel of the digital modem reported earlier in [4] was used for this experiment. The channel was centered at 1.5 GHz with the 625 MHz bandwidth and carried 1.5 Gbps Grey-coded 8-PSK random pseudo-noise (PN) sequences.

In Fig. 14 the frequency response without signal pre-distortion (the upper trace) has a clear 3 dB ripple due largely to: a) mismatches between the Rx antenna outputs and the RF pre-amp inputs, and b) mutual coupling between the Rx antenna elements. Rx antenna s-parameters measurements indicated a return loss of 10 dB was to be expected with a 50 Ohm termination. Pre-distortion of the transmitted IF signal to cancel the distortion introduced by the RF transmission channels

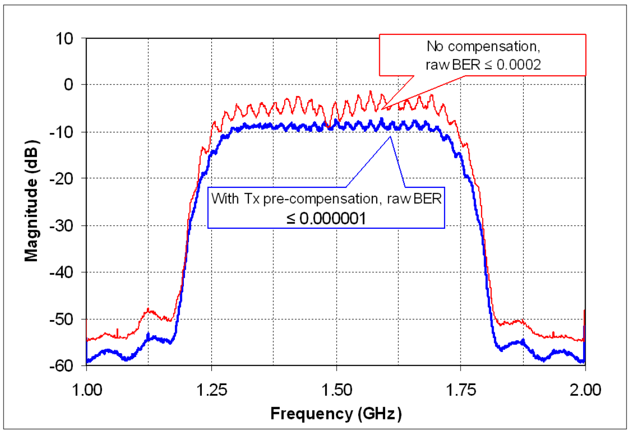
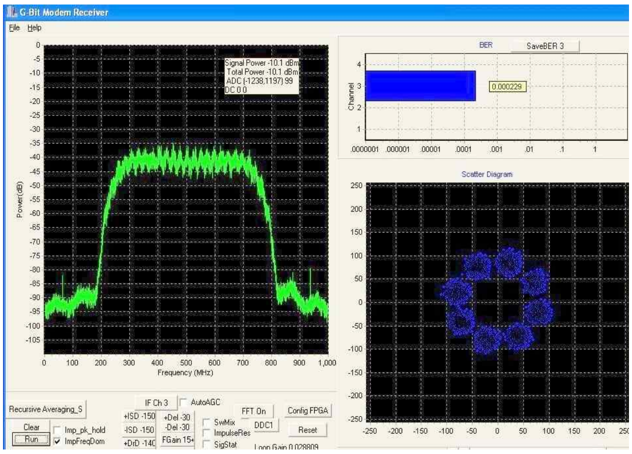


Fig. 14. Received signal at the output of A/D converter and measured BER for pre-compensated and un-compensated pseudo-random 8PSK symbols transmitted at 1.5 Gbps.

Table 1. Measured raw BER at selected azimuth steering angles.

Array position (deg)	Scan angle (deg)	Measured BER	Scan angle (deg)	Measured BER
−11	0	0.006	−11	0.0003
11	0	0.005	11	0.0002
−22	0	0.02	−22	0.0006
22	0	0.015	22	0.0005
−33	0	0.999	−33	0.001
33	0	0.99	33	0.009



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Signal Power -10.1 dBm
Total Power -10.1 dBm
ADC (-1238,1197) 99
DC 0 0
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Fig. 15. Image of the Rx modem GUI screen shows the received signal spectrum, BER data and symbol constellation.

can be seen (the lower trace in Fig. 14) to reduce the ripples to 1.5 dB, and consequently reduce the 0-degree azimuth BER by a factor of 100. Further improvement in BER would require better matching of the Rx antenna array and enhancement of the pre-compensation algorithm to better cancel the effects of mutual coupling. A sample of measured raw BER at a selection of physical positions of the array and electronic steering angles is given in Table 1.

Fig. 15 shows a snapshot image of the Graphical User Interface (GUI) of the Rx modem controller that shows the received signal spectrum at the output of the ADC, measured BER and the received 8PSK symbol constellation.

Ⅳ. Conclusion

A steerable E-band receive array demonstrator that implements a four-element linear antenna array has been tested using analogue phase-only beam forming at IF. Measured array patterns were close to EM simulated estimates for steering angles up to ±40 deg. Beam steering accuracy of 1 deg has been achieved with 6-bit digital phase shift at IF.

An ad-hoc wireless communication system has also been demonstrated. Low BER was measured for an 8 PSK data stream at 1.5 Gbps with the receive array beam formed in the direction of arrival of the transmit signal.

The developed demonstrator will be used for experimental verification of the digital beam forming algorithms for adaptive mm-wave antenna arrays. Digital beam forming tests are currently in progress. To our knowledge, this work represents the first experimental results on a steerable antenna array in the E-band.

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