A Flexible Low-Cost Hybrid Beamforming Structure for Practical Beamforming Applications

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***Abstract*— In this paper, a simplified yet flexible half-duplex hybrid beamforming (HBF) architecture along with the adaptive beam scanning and direction-finding methodology for the 360° HBF system has been proposed. The structure is constructed using up to 4 units of n × 4 antenna arrays with choice of gain and coverage sector, which is powered by only 4 RF beamforming chains. In addition, the flexible beamforming structure is able to enable beamforming function of any legacy transceiver. The proposed architecture exhibits prominent advantages in reducing the hardware complexity and cost of the HBF system by 4 folds and offers the field-friendly feature with the flexible gain and coverage concept that allow only the necessary array to be installed.**

Keywords—hybrid beamforming; smart antenna; direction finding

I. Introduction

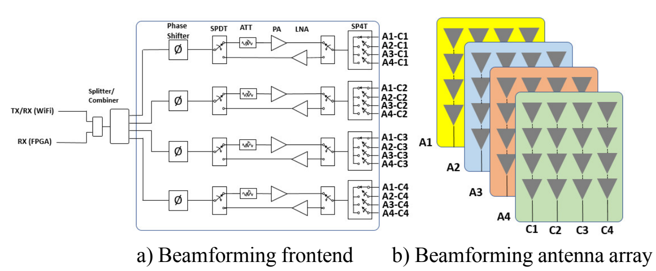
In the wireless infrastructure research area, the smart antenna is a hot topic amongst the researchers who have been working restlessly to mitigate the sticky issues such as interference due to air space congestion, high infrastructure cost, etc. The smart antenna is designed to allow beam steering to focus on the targeted direction and null the interference directions, thus, the interference and congestion issue can be mitigated. Over the years, various beamforming techniques were developed. The digital beamforming [1] is realized by a complex hardware architecture and requires a heavy software processing that leads to the high implementation cost. Analogue beamforming [2] is the lowest cost amongst all, with lower resolution and usually deployed in the consumer wireless products where precision is not a concern. Hybrid beamforming technique (HBF) [3] can be implemented at a lower cost while performs close to the digital beamforming, and many research efforts have been poured in to reduce the implementation cost of the HBF that targets to increase the popularity of the smart antenna in the commercial and industrial world where cost is the major decision factor.

In the HBF world, the phase shifter (PS) was identified as the main cost contributor to the entire HBF system, and various elegant methods have been developed to reduce the number of PS or utilize the lower cost PS with lower resolution combined with sophisticated software algorithm to achieve the phase shift function needed. For example, in [4], the cost-effective HBF structure was proposed, the cost reduction was achieved by utilizing the fixed phase shifter (FPS) structure and an effective alternating minimization (AltMin) algorithm was developed to minimize the quantity of the phase shifter needed in the system. An efficient iterative algorithm was proposed in [5] to make use of the low-resolution analog precoder to overcome the high phase shifter cost in hybrid precoding system. In [6], reduction of the phase shifter in the HBF system by RF switches was proposed.

In this paper, we are investigating the problem in a different angle such as the deployment friendliness, deployment flexibility, and maintainability aspects in the transportation market where the infrastructure and maintenance cost is always a key decision factor. For instant, a base station installed at the straight road may require just 180° coverage instead of 360°, a right-angle turning road may require just 90° beam coverage. In addition, small gain's antenna may be installed at the shorter road to improve interference performance. As a result, A simplified yet flexible half-duplex HBF architecture along with the adaptive beam scanning and direction-finding function for the 360° HBF systems was proposed, the structure is constructed using up to 4 units of n × 4 antenna array [7] with choice of gain and coverage sector, and powered by just 4 RF beamforming chains, importantly, the flexible beamforming structure is able to enable beamforming function on any legacy transceiver. The proposed architecture is expected to improve the hardware complexity and the deployment cost of the HBF system by 4 folds, this can be realized by the flexible RF beamforming structure with only 4 RF beamforming chains using the RF switches technique and proposed DOA scanning methodology.

This paper is organized as follows. Section II presents the proposed simplified half-duplex HBF architecture, Section III elaborates the proposed beam scanning and direction-finding methodology. Section IV concludes the paper.

II. Proposed half-duplex hybrid beamforming frontend



a) Beamforming frontend   b) Beamforming antenna array

Fig. 1. Proposed Hybrid Beamforming Structure

The proposed hybrid beamforming structure is presented in Fig. 1. The flexible structure consists of up to 4 units of 90° phase arrays (A1 – A4) to cover the entire 360° service angle, each array consists of 4 horizontal feeding ports (C1 – C4) to support beam steering in the 90° sector. The 4 units of 4 × 4 arrays with 16 antenna ports are supported by 4 RF beamforming chains. Switching of the antenna ports during the beamforming process can be realized by the fast switching single pole four throw (SP4T) RF switches. The 4 RF chains are combined into a single RF port by a power combiner to interface with the radio transceiver, a portion of the RF signal will be further split and fed into a signal processing module where the directional of arrival (DOA) and beamforming process takes place. Beamforming weighting and transmitter/receiver switching can be controlled by field programmable gate array (FPGA) via input-output (IO) ports, analog to digital converter (ADC) and digital to analog converter (DAC) that directly interact with the circuit components inside the RF chains.

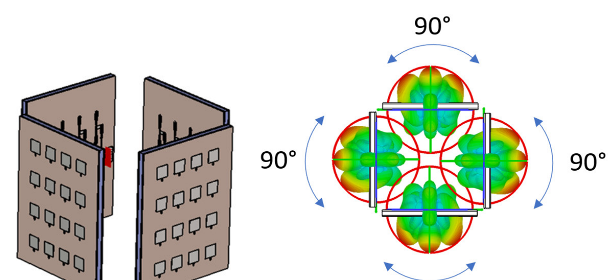
The proposed flexible antenna structure is designed with the following deployment friendly features.

a. Pre-populated with 1, 2, 3 or 4 arrays depends on deployment coverage requirement 90°, 180°, 270° or 360°.
b. Choice of gain, 13.6 (1×4 array), 15.5 (2 × 4 array) and 17.9 (4 × 4) dBi.

Together with the beamforming capability, it can perform as good as the conventional smart antenna and re-configurable antenna with added following benefits.

a. No waste materials, lower cost, only desired arrays installed.
b. Good field maintainability with fewer components.
c. Faster processing time, thus lesser processing power (only need to focus on the dedicated sectors).
d. Further interference reduction (only radiate and scan on the array installed)

A. *Antenna Arrays Arrangement*



a) Isometric view b) 3D radiation pattern

Fig. 2. Antenna arrays arrange in the flexible beamforming antenna structure

The high gain and wide bandwidth 4 × 4 microstrip patch (MPA) linear phase array has been designed and will be used in this work for beamforming frontend development. Each antenna array has a wide operating frequency band from 4.9 – 5.9 GHz, a gain of 17.9 dBi, 25° beamwidth and -13.29 dB side lobe level, capable of performing - 45° to +45° beam steering. Fig. 2a. is the isometric view of the flexible antenna system and Fig. 2b. illustrates the CST microwave studio simulation result of the beamforming with the 4 units of 4 × 4 antenna arrays structured placed in a perpendicular manner, each of the array is dedicated to support 90° sector. Each sector can be configured to support i) 90° by activating 1 of the 4 antenna ports. ii) beamforming with 25° beamwidth covering the 90° sector by activating all antenna ports with a different phase shift. The simulated gain for each array was 15.5 – 17.9 dBi and beamwidth of 24.5° – 34.2° over the ± 41° beam steering angle.

B. *Beamforming front-end design*

The detailed block diagram of the RF beamforming chain is presented in Fig. 3. Each RF beamforming chain consists of a SP4T for antenna switching, two single pole two throw (SPDT) switches to toggle between the transmit and receive path, a phase shifter to vary the phase of each RF chain for antenna beam shaping, a low noise amplifier (LNA) for receiver and a power amplifier (PA) for transmitter which were added to boost the RF signal and compensate the insertion loss exhibited by the phase shifter, SP2T, SP4T, and power combiner. The RF attenuator was populated to provide 30 dB dynamic transmit power range. The RF beamforming chain is controlled by an external FPGA via the control terminal. The RF beamforming frontend was designed and fabricated, the outline of the prototype is shown in Fig. 4. and it is currently undergoing the experimental test.

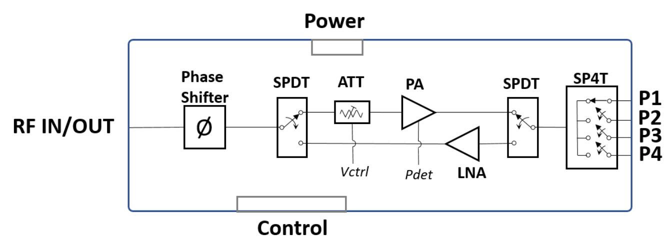


Fig. 3. Block diagram of the RF beamforming chain

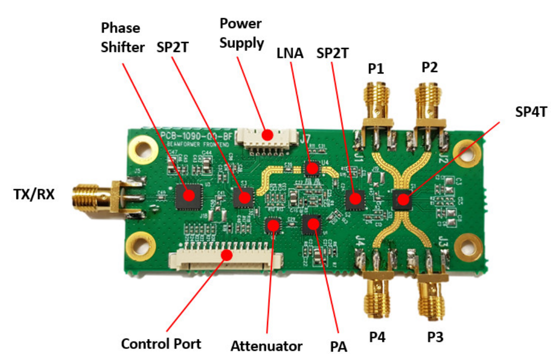


Fig. 4. Prototype of RF beamforming chain

The components of the RF chains are carefully selected to cover the whole 4.9 – 5.9 GHz band, and the key parameters are listed below, the RF switch SP2T (ADRF5020) with 60 ns switching speed, and SP4T (ADRF5044) from ADI with 4 ns switching speed, the low insertion loss phase shifter (HMC1133LP5E) from ADI which provides 360° phase shift coverage and 5.625° resolution, the LNA (HMC717ALP3E) from ADI with 14.5 dB gain, a high gain PA (TQP5525) with 32dB gain and P1dB of 32 dBm from Qorvo, and the RF attenuator (IDTF2258NLGK) from IDT with 33.6 dB attenuation range.

III. DOA SCANNING METHODOLOGY

The proposed direction of arrival (DOA) estimation is carried out via 2 scanning steps, namely, sector scanning and direction finding.

A. *Sector scanning*

Sector scanning is to scan the coarse direction of the targeted client over the 360° angle, shown in Fig. 5, this can be done with 4 scanning iterations by switching between A1, A2, A3, and A4, during the scanning, the phase shifter is disabled, and only one of the antenna columns in the array is enabled to cover the wide angle 90° scanning.

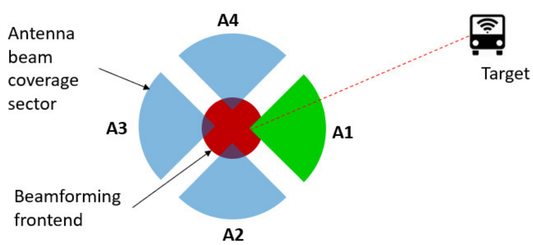


Fig. 5. Sector scanning in the proposed design

B. *Direction finding*

The next step is to focus on the particular antenna array sector to estimate the actual direction of the targeted client, refer to Fig. 6, all the 4 column elements C1, C2, C3, and C4 on array A1 will be activated with respective phase differences to generate the antenna beam within the 90° array. It will take 4 iterations to determine the target in the 25° beam by scanning in 25° step over the 90° area, and additional 5 iterations can be added to finetune the scanning resolution to 5° by scanning the targeted 25° area in 5° step.

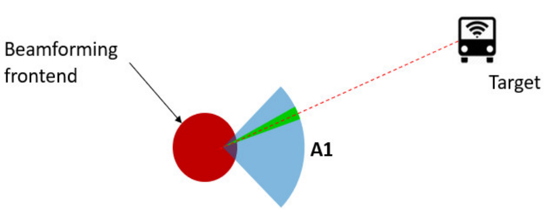


Fig. 6. Direction finding in the proposed design

IV. CONCLUSION AND FUTURE WORKS

In this paper, a flexible HBF beamforming antenna structure was proposed, it consists of up to 4 units of n × 4 arrays supported by 4 RF beamforming chains. The antenna arrays arrangement and RF beamforming frontend were designed and simulated, followed by the DOA scanning methodology through sector scanning and direction finding. The future works include the experimental evaluation on the flexible beamforming structure with the combination of RF beamforming chain and the proposed DOA scanning methodology.

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