A Novel Planar Array Smart Antenna System with Hybrid Analog-Digital Beamforming

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Abstract — **In this paper, a novel design of smart antenna system based on hybrid analog-digital beamforming is proposed. The goal of the design is to construct smart antenna beamforming systems with high data rate throughput. The speed bottleneck in DSP I/O congestion is relieved using analog beamforming at the IF frequency, while the advanced signal processing capability of DSP chip is kept. The data throughput of a 20Mbps for BPSK is reported for an 8-element adaptive array. DOA estimation and beamforming result based on this new beamforming concept is demonstrated.**

I. INTRODUCTION

Recently, Wireless Local Area Networks (WLAN) have received increased popularity due to their flexibility and convenience. High-speed data rate is necessary in order to comply with the requirements of advanced services, such as internet broadcasting and conferencing. In the U.S., about 300 MHz bandwidth in the Unlicensed National Information Infrastructure (U-NII) band from 5.2~5.8 GHz has been allocated for potential high-speed WLAN applications. However, with higher frequencies, higher data rate and higher user density, multipath fading and cross-interference become more of a serious issue, resulting in degradation of Bit Error Rate (BER). To combat with these problems and to achieve higher communication capacity, smart antenna systems with adaptive beamforming capability have proven to be very effective in suppression of the interference and multipath signals [1].

There are basically two types of beamforming approaches in smart antenna systems. The analog architecture is usually based on expensive RF phase shifters, while digital beamforming systems commonly consist of a digital signal processor (DSP) that calculates and applies weight vectors to each sampled data. The latter approach has the advantages of simplicity, flexibility and lower power dissipation. However, current DSP technology has a speed bottleneck in data I/O with contrast to the high CPU speed it can offer. For a typical DSP system, the input-process-output procedure takes about 20 clock cycles. Therefore, the maximum data throughput is around 50 MBytes/sec even if the state-of-the-art DSP chip with CPU clocks up to a few GHz is used. In smart antenna systems, the data throughput is the product of the number of channels and the data rate. Thus, congestion in the DSP I/O happens for an 8-channel system with a data transfer rate around 5Mbps.

To overcome this problem, a hybrid analog-DSP configuration has been proposed. In [2], phase-controlled local oscillator (LO) signals are used to form the beam and downconvert the RF signals simultaneously. While this configuration has potential advantage for high-speed data throughput, the dynamic range of beamforming is limited because of the limited dynamic range of the LO. Furthermore, since only the output of the beamformer is sampled instead of the input vector, it disables the implementation of advanced adaptive algorithms.

In this work, we propose a smart antenna system with a novel hybrid analog-digital beamforming network. The essential idea is to separate the tasks to throughput intensive and computation intensive. Based on RF quadrature downconverters, throughput intensive tasks such as real-time beamforming is carried out using analog multipliers in IF frequency, while computation intensive tasks like the calculation of the complex weighting coefficients can be performed using the DSP by sampling the signal periodically. In this way the DSP I/O congestion is relieved. With the current implementation, it can easily provide data transfer rate up to a few hundreds of MBits/sec. Other advantages of the new configuration include the compactness of the system and the “plug and play” property with any standard IF receiver.

In this paper, a smart antenna system is built using planar circuits. Direction Of Arrival (DOA) estimation is performed and the beamforming result is presented. The performance on interference and multipath fading suppression is demonstrated. Finally, data transfer rates up to 20Mbps for BPSK signal (40Mbps for QPSK) are realized.

II. HYBRID ANALOG-DIGITAL BEAMFORMER

In indoor wireless applications, since most mobile terminals are either stationary or move at a moderate speed, the system does not need to sample all of received signals to calculate weighting vectors for finding signal direction, rather only a snapshot for certain time period is needed. The weighting vectors can be periodically assessed and updated to efficiently track mobile terminals. The computational load and requirement of data bus speed of DSP can thus be significantly reduced.

Based on this idea, the hybrid analog-digital beamformer is proposed as shown in Fig.1. The RF signal received by the antenna array is downconverted to IF frequency. For each channel, both in-phase and quadrature-phase signal are generated by using quadrature mixers. Then the IF signal are splitted in two ways. First, the in-phase signal is sampled sporadically and transferred to the DSP chip. The reason to sample in-phase signal only is to further reduce the DSP I/O load and the quadrature-phase signal can always be calculated using Hilbert transform. Weighting coefficients are thus generated by applying advanced DOA and beamforming algorithms. At the same time, both I and Q signal are weighted using analog multipliers in the manner of complex weighting. The weighting coefficients are provided by the DSP chip and the signals are finally combined to form the output signal to IF receivers. In this way, real-time beamforming with non-stop data flow is achieved.

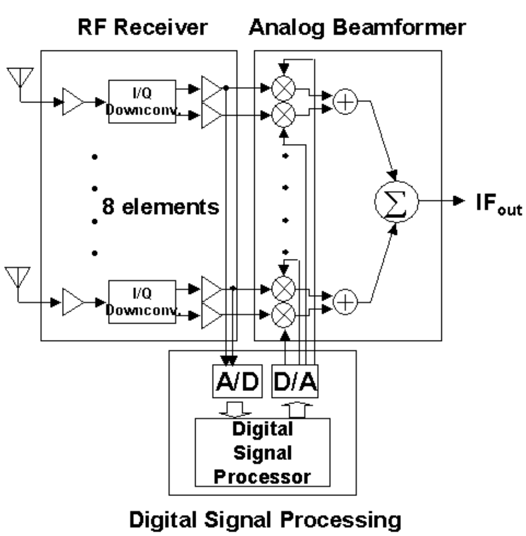

Fig. 1 Hybrid analog-digital beamformer system

III. CIRCUIT OVERVIEW

Fig. 2(a) shows the RF receiver connected with an array of planar quasi-Yagi antennas with half-wavelength spacing at 5.8 GHz. The quasi-Yagi antenna has 50% bandwidth, which satisfies broadband communication requirements, and 15dB front-to-back ratio and mutual coupling below –20dB, making it suitable as an array element [3]. Each element has a low-noise amplifier and second-harmonic mixers, which convert C-band RF signal to 30MHz IF signal. LO power of each mixer is 0dBm, so LO power to drive 16 mixers for eight elements requires only +12dBm. In order to implement in-phase and quadrature-phase mixers, 45° delay line is applied to LO signal path in order to achieve uniform quadrature IF signals over a broad RF bandwidth.

Fig. 2(b) shows the analog part of the hybrid beamformer which includes IF amplifiers and multipliers.

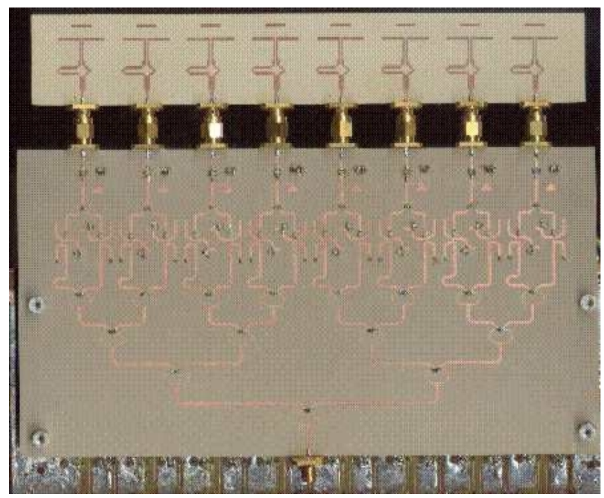

Fig. 2(a) RF receiver

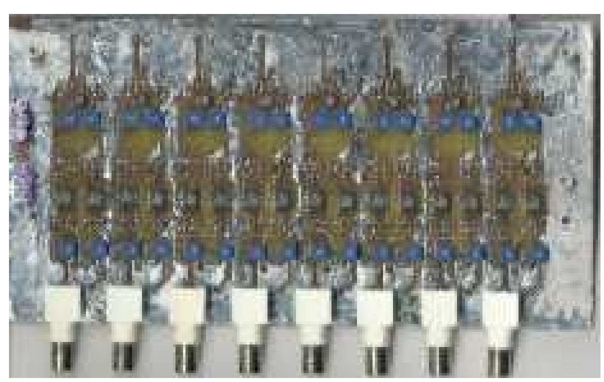

Fig. 2(b) Analog part of the hybrid beamformer including IF amplifiers and analog multipliers

Circuit calibration is done at IF band signal to minimize DOA estimation error, since MUSIC algorithm requires very strict calibration. To accomplish the optimal performance, calibration is needed periodically. Such periodic calibration can be accomplished by automated calibration methods such as that proposed in [4].

In this experiment, eight in-phase IF signals were sampled at 200MHz by an eight-channel digital oscilloscope in lieu of fast A/D converters and a computer is used instead of DSP. The sampled signal was taken through GPIB, and weight vectors are calculated using MATLAB and subsequently applied to the analog multipliers.

IV. MEASURED RESULTS

A. DOA Estimation

DOA estimation is conducted at various angles by using two algorithms, ESPRIT and MUSIC. The DOA in -60°~+50° range is estimated approximately within ±5° error. It is found MUSIC algorithm requires very precise and accurate array calibration, while ESPRIT is relatively insensitive to array calibration.

B. Beamforming Result

In this measurement, the Signal-Of-Interest (SOI) and the Signal-Not-Of-Interest (SNOI) were located at +20° and -20° respectively at the same distance from the receiver. The signals were unmodulated sinusoidal waves. The measurement is done in a big conference room where the multiple reflections are inevitable. After calculating and applying weight vectors, the antenna pattern of beamformer was obtained by measuring power of the accumulated IF signal from –60° to +60°. When the DOA is estimated by ESPRIT, the signal bearings detected were +20.2° for the SOI and –22.6° for the SNOI. From these estimated results, the weight vectors are calculated using pseudo inverse method. Fig. 3 shows the main beam directed towards +20° and a null located at –22°. The sidelobe is a little high which may attribute to the environment. Fig. 4 shows both the combined signals with applied beamforming weight vectors and combined signals with uniform weight vectors. For the uniform weight vectors, the received signal displays not only smaller amplitude, but also stronger amplitude modulation, which is due to SNOI interference with the SOI since beam direction is not tailored to suppress the SNOI.

The Signal-to-Interference Ratio (SIR) was measured at several angles to evaluate the performance of beamforming. When the SOI was located at +20° and –30°

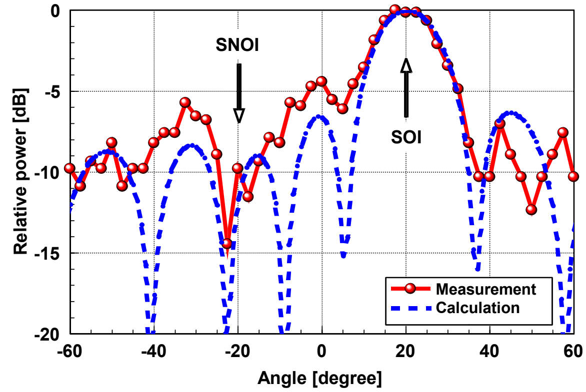

Fig. 3. Beamforming result (SOI : +20° , SNOI : -20°)

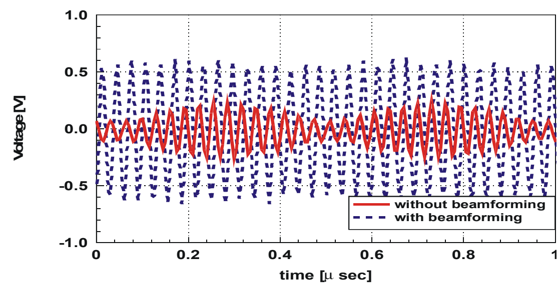

Fig. 4. Received signals with uniform WC and beamforming WC

Table 1. Signal-to-Interference-Ratio (SIR)

SOI	SNOI	SIR [dB]
+20°	-20°	21.37
-30°	-20°	21.17
-25°	-20°	17.09

(SOI transmitting power : +10dBm
SNOI transmitting power : +5dBm)

with SNOI at -20° in both cases, SIR was about 21dB resulting in 16dB improvement of SIR. However, when SOI was moved to -25°, very close to the SNOI, the improvement is down to 12dB as expected.

C. Multipath Condition

To examine the system performance under multipath fading, the SOI is a BPSK signal modulated by 20Mbps data with "1010" pattern. The transmitting-receiving experiment is carried out in a lab office that is full of equipments and furniture. Strong multipath fading is expected in this environment. The signal DOA is estimated again using ESPRIT and the antenna beam is steered toward the angle of the maximum incoming signal. In this way, multipath signal arriving the antenna from other directions can be well suppressed. Fig. 5 shows the demodulated signal after applying beamforming (signal 1) and the demodulated signal from one of the eight IF channels (signal 2). The amplitudes of the two signals are normalized for easy comparison. From Fig.5, we can see the signal before beamforming has unclear edges which are due to the phase error caused by the multipath fading. After beamforming, the signal has very clearly defined edges which implies a good demodulation benefiting from the suppression of multipath fading.

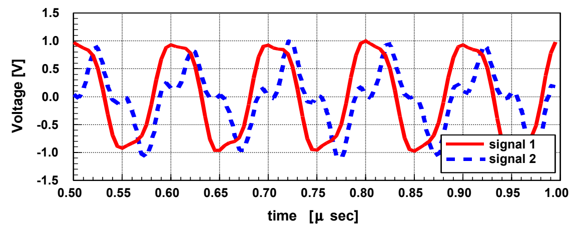

Fig. 5. Comparison of demodulated signals from beamformed signal and one of eight-element signals received

V. Conclusion

A planar array smart-antenna system test bed based on a novel hybrid analog-digital beamformer has been implemented and tested. Based on this test bed, various signal processing experiments has been carried out, which validates the system performance. DOA estimation within ±5° accuracy in the range of –60°~+50° and 16dB overall improvement of output SIR have been attained. The system has also proven to be highly effective in the suppression of multipath fading effects. This system approach has the potential to realize high data rates on the order of hundreds of Mbps. In the experiments carried out, a 20Mbps data rate for BPSK signal (40Mbps for QPSK) has been reported.

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