A Broadband Beamformer for Millimeter-Wave Systems Using Sub-Band Sampling

Seong-Sik Jeon, Ji-Yong Park, Yuanxun Wang, Tatsuo Itoh

Department of Electrical Engineering, University of California, Los Angeles,
405 Hilgard Ave., Los Angeles, CA 90095-1594, U.S.A
E-mail : sjeon@ee.ucla.edu

Abstract **— In this paper, a broadband beamforming system for millimeter-wave systems is proposed. DOA is estimated by sampling only part of signal spectrum, thus the beamformer system does not require high speed sampling rate of A/Ds. In addition, I/Q vector attenuation scheme was used for IF weighting process. For the weighting process, a balanced structure of reflection type variable attenuator was used in order to get a linear phase response within 500MHz bandwidth at IF of 2.75GHz.**

I. Introduction

The 57-64 GHz band has been allocated for unlicensed applications in U.S. [1]. Since the needs of wireless communications of multimedia applications are increasing, using millimeter-wave bands provide a good possibility for applications which require broad bandwidth. In addition, it has high atmospheric attenuation of about 15dB/km [2], so that the frequency can be reused in small region and it has an advantage for short distance communications.

In indoor wireless communication environments, however, reflections from walls, the floor, or the ceiling cause many signal propagation paths and delays, consequently degrading the received signal quality and receiver performance. One of possible solutions is a beamforming technique to direct antenna's main beam towards a transmitter and to direct nulls towards interference or multipath signal directions, such that incoming signals from reflection paths are suppressed while increasing the antenna gain for a desired signal direction. Thus, a transmitting power requirement can be also reduced.

Nowadays, digital beamforming has become popular with rapid advancements of DSP and A/D. It is very flexible and adaptive to various communication environments, and can generate multiple beam patterns. However, the sampling rate of the system must be increased as communication bandwidth increases and the system bandwidth which includes interface speed of DSPs, A/Ds and memories is also required to be high enough to accommodate the multiple times of sampling speed. Alternatively, parallel processing structures can be used. Thirteen DSPs are used in [3] to process 800kbps signal with 3.2MHz sampling rate of an eight element array using sub-band signal processing. Four DSPs are used in [4] to process 5MHz bandwidth signal with 40MHz sampling rate of an eight element array. It is reported that supporting CDMA signal is not possible due to high chip rate.

Therefore, even though recent technology can achieve very high speed for data conversions or calculations, the system implementation is still limited for high speed data rate communications. In order to resolve those problems, a hybrid analog-digital beamforming structure has been proposed in [5] and achieved 40Mbps data rate using QPSK at 5.8GHz RF.

This paper proposes an IF analog beamforming structure with sub-band sampling technique for 500MHz bandwidth at 61GHz RF. In order to relieve a high sampling rate requirement of A/Ds, this system samples only a part of signal spectrum, estimates DOA and calculates weighting coefficients. For a weighting process of throughput signals, the system uses bi-phase variable attenuators with quadrature network. A linear phase response of variable attenuator has been achieved using a balanced structure [6]. DOA estimations for 500Mbps BPSK signal have been successfully demonstrated and beam steering patterns within 500MHz bandwidth at RF carrier have a good

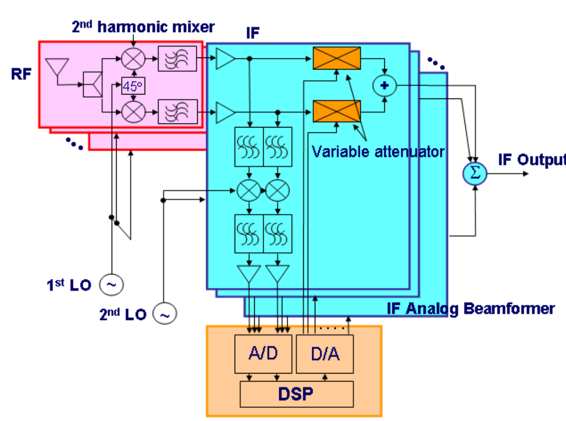


Fig. 1. Block diagram of broadband beamformer.

agreement with ideal array factor.

II. Broadband Beamforming System

Fig. 1 shows a block diagram of a broadband beamformer using sub-band sampling technique. The RF front-end array that consists of patch antennas, I/Q downconverters and Low Pass Filters (LPF) is constructed in UCLA microwave lab. The downconverters are 60GHz version of the structure reported in [7] for 40GHz operation. The RF of 61.78GHz is downconverted to IF of 2.75GHz with a second-harmonic mixer using an anti-parallel diode. Thus the LO frequency is 29.56GHz, equal to almost half of the RF.

The downconverted signal is amplified at IF stage and separated into two paths. In one path, the coupled signal from a -10dB coupler is pre-filtered with 100MHz Band Pass Filter (BPF) and then downconverted into low frequency again. Only 10MHz spectrum from this signal is filtered with a LPF, sampled by A/D and used for DOA estimation. Thus, the A/D sampling rate can be several tens MHz in spite of 500MHz signal bandwidth. The second LO frequency is carefully chosen to avoid aliasing effect because DOA estimation errors are caused by such an aliasing effect. The other path signal passes through a Balanced Variable Attenuator (BVA) for weighting process and all outputs of array elements are combined again. This output signal is fed into a regular receiver and demodulated. Fig. 2 shows this frequency downconversion process in detail. In the sub-band sampling path, each band limiting process at a BPF and a LPF lowers signal power by 7dB respectively. Therefore, a high gain baseband amplifier is needed in order to make proper signal level for A/Ds from power loss due to the coupler loss, mixer conversion loss and filter insertion loss and band limiting effect.

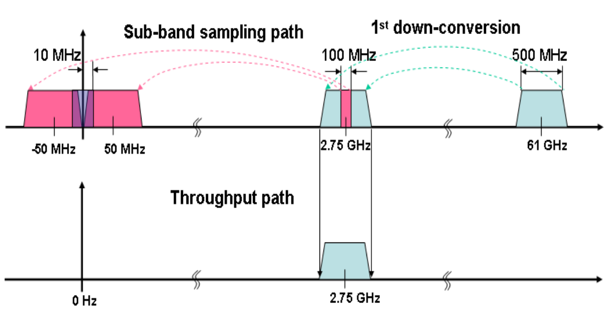


Fig. 2. Downconversion frequency allocation.

III. Circuit Overview

The RF front-end is constructed on 5mil thick Alumina substrate(ε_r=9.8) and 4 patch antenna array elements are placed with 0.6λ array spacing. The I/Q outputs are connected to 60dB IF amplifier blocks to amplify enough for IF beamformer stage.

In an IF beamformer circuit board, a 10dB coupler for separation of sub-band filtering signal path and data throughput path, a 100MHz BPF, a mixer for downconversion, a LPF, a baseband amplifier circuit and a BVA are combined. The eight amplifier blocks, the eight IF beamformers, a LO divider and a power combiner are assembled together as shown in Fig. 3(a).

Fig. 4 shows a structure of BVA. The variable attenuator needs a bi-phase response in order to apply positive or negative weighting coefficient values. A reflection type variable attenuator using a 90° broadband phase shifter and PIN diodes is used. However, since the PIN diode has parasitic elements, the phase response of attenuation is not linear. If it is combined in quadrature manner, the signal distortions become more severe. In order to compensate

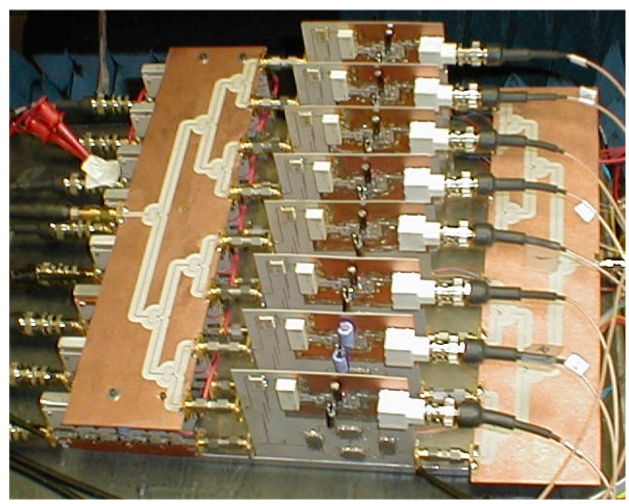


Fig. 3(a). Broadband beamformer.

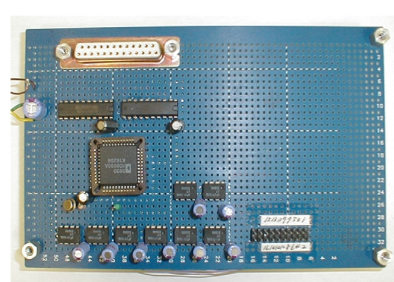


Fig. 3(b). D/A interface board for applying weighting coefficients.

for this effect, a balanced structure has been proposed in [6]. It uses 180° out of phase signals for input, attenuates each signal with a complementary voltage set and combines the attenuated signals. However, a differential output mixer or a 180° broadband phase shifter to generate 180° out of phase signals at 2.75GHz is not common in commercial products. In this paper, the input and output stage in the BVA are modified to use 90° broadband phase shifters and it achieves the same effect to compensate the PIN diode parasitic component effects.

In these experiments, an eight-channel digital oscilloscope was used to sample four I and Q signals. The sampled signals were transferred into a computer through GPIB. Using the sampled signal, DOAs were estimated and the weighting coefficients were calculated. These weighting coefficient values are corrected with calibration factors, converted into voltage levels to generate the corresponding attenuation ratio after normalization with maximum magnitude of the weighting. Then they are applied to PIN diodes through the D/A interface board shown in Fig. 3(b). The D/A interface board is built using an AD8600 which has 16 D/A converters to control eight element complementary voltage sets. The D/A interface board is controlled through a computer parallel port.

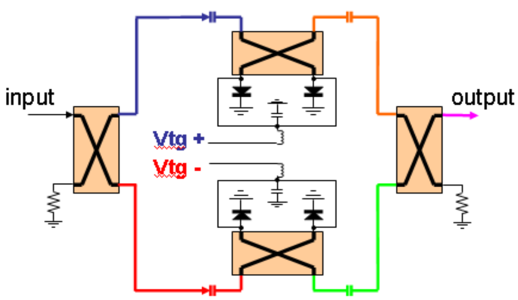


Fig. 4. Structure of Balanced Variable Attenuator.

IV. Measurement Results

Fig. 5 shows the S21 measurements of the balanced variable attenuator. By changing the complementary voltage set from +0.3V to +1.0V, the S21 magnitude changes from +0.7 to -0.7 resulting in 3dB transmission loss at no attenuation conditions. The loss comes from non-ideal isolation of the PIN diode and insertion loss of 90° phase shift hybrids. When I/Q signals are combined again after each I/Q attenuation, there is another 3dB loss due to power combining of 90° out of phase signal at no attenuation conditions. Therefore the total insertion loss becomes 6dB. Although power loss is a major drawback of the BVA, the phase response is linear, which is more important for beamforming process.

For the beam steering pattern measurements, the RF front-end was located on a rotator inside an anechoic chamber and a RF carrier from a RF source module

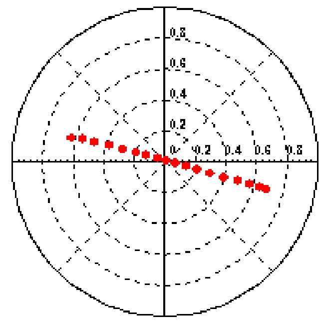
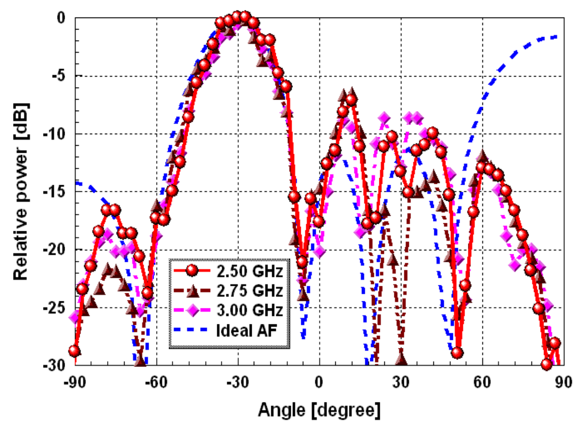
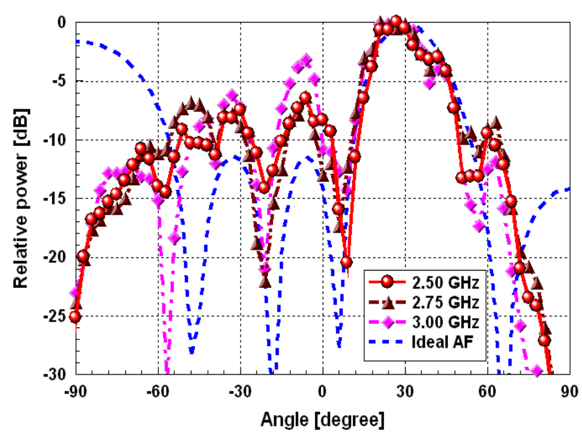


Fig. 5. S21 Response of Balanced Variable Attenuator.



(a) -30°



(b) +30°

Fig. 6. Antenna beam steering measurement results.

(Agilent 83557A) was transmitted. After placing the RF front-end to a fixed angle, DOA estimation was performed and weighting coefficients are applied to the BVAs. Fig. 6 shows beam steering antenna patterns towards -30° and +30° with different carrier frequencies. Although the side lobe is about 5dB higher at certain angles, the main lobe of antenna remains directed towards the transmitter and overall the beam patterns follow the ideal array factor. While the array factor shows part of grating lobe at +90° and -90° due to 0.6λ array spacing, element pattern of the patch antenna reduces this grating lobe.

For DOA estimation performance regarding different data rates, one transmitter which has a patch antenna and I/Q mixer was used to modulate BPSK signal. Fig. 7 shows the DOA estimation errors at different transmitter angles with different modulation rates. The DOA estimations are within ±10° error range. In this measurement, only one snap shot was used in DOA estimation, but in real situations, the estimated angle can be smoothed in order to decrease abrupt direction changes. Thus it is expected that statistical results will give more precise information.

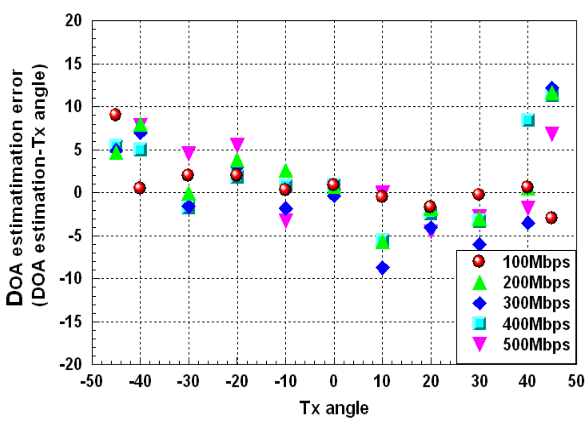


Fig. 7. DOA estimated results.

V. CONCLUSION

A new broadband beamformer for millimeter-wave applications is proposed. DOA estimations and beam steering is demonstrated. By using sub-band sampling technique which uses only a part of the signal spectrum for DOA estimation, the beamforming system could estimate correct signal incoming directions with data rate of 500Mbps and does not require high speed sampling rate of A/Ds.

ACKNOWLEDGEMENT

This work was supported by NSF under contract ECS-99-79286. The authors would like to acknowledge the helpful discussion with Dr. Dal Ahn.

REFERENCES

[1] M. J. Marcus, "Millimeterwave Spectrum Policy in the USA", *Third Topical Symposium on Millimeter Waves (TSMMW 2001)*, Yokosuka, Japan, pp 13-15, March 2001.

[2] Y.-S. Choi, Y.-S. Kim, J.-H. Lee, J.-H. Kim and H.-S. Lee, "Research Activities of 60 GHz Radio Propagation in ETRI", *Third Topical Symposium on Millimeter Waves (TSMMW 2001)*, Yokosuka, Japan, pp 67-70, March 2001.

[3] Y. Kamiya, "Development of an adaptive array based on subband signal processing," *Transactions of the Institute of Electronics, Information and Communication Engineers A,* vol.J83-A, no.12, Dec. 2000, pp.1413-24. Publisher: Inst. Electron. Inf. & Commun. Eng, Japan.

[4] J. Wu, "Smart antenna system implementation based on digital beam-forming and software radio technologies," *2002 IEEE MTT- S Int. Microwave Symp. Dig*., vol.1, pp.323-6, Piscataway, NJ, USA.

[5] S. S. Jeon, Y. Wang, Y. Qian, and T. Itoh, "A novel planar array smart antenna system with hybrid analog-digital beamforming," *2001 IEEE MTT-S Int. Microwave Symp. Dig*., vol. 1, pp. 121-124, May 2001.

[6] S. S. Jeon, Y. Wang and T. Itoh, "A balanced adaptive beamforming system for broadband wireless communications," *2002 IEEE MTT-S Int. Microwave Symp. Dig*., vol 2, pp.1357-60, Piscataway, NJ, USA.

[7] J. Y. Park, R. Miyamoto, J. Sor, C. Y. Hang, K. Leong, M. DeVincentis, Y. Wang, T. Itoh, "A uniplanar design of integrated antenna with even-harmonic I/Q mixers for millimeter-wave communications," *2002 Asia-Pacific Microwave Conference(APMC),* pp. 1691-94. Kyoto, Japan.