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A Land-Mobile Satellite Experiment on a DBF Self-Beam Steering Array Antenna

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1. Introduction

Mobile radio communications with high gain antenna require spatial acquisition and tracking of an arriving signal. Since the environment changes the channel profile rapidly, depending on movement of the terminal, the adaptation of the antenna to the environment must be rapid and stable.

Digital beamforming (DBF) antenna is a promising technique that meets such requirements by using active antennas that take advantage of spatial digital signal processing. The remarkable progress made in digital device technologies is making DBF antennas a possibility not only for military applications but also for commercial communication systems.

We have proposed a self-beam steering (SBS) array scheme for a DBF antenna used in mobile communication systems[1]. This scheme incorporates a self-phasing processor (SPP) between the received signals in the array elements. In this paper, the device is applied to multibeam outputs given by a spatial FFT of received signals, where the multibeam former works as a pre-processor of the signal combiner to recover the input SNR by an array factor. The SPP consists of an open-loop maximal-ratio combining (MRC) diversity for the multibeam outputs. Although the SBS array does not provide adaptive cancellation of interferences like adaptive arrays, it is expected to provide faster and stabler beam steering toward the direction-of-arrivals (DOAs) of desired signals than do closed-loop adaptive arrays. Moreover, it features diversity combinig of multipath signal arrivals, which improves quality and reliability of the combined signal by directional diversity (Figure 1).

To demonstrate and evaluate the performance of this DBF antenna, we developed a prototype system using field programmable gate arrays (FPGAs) and carried out an experiment by receiving an unmodulated signal transmitted from a Japanese ETS-V satellite. The FPGA is a kind of ASIC that allows re-construction of desired logic circuits with large scale integration. Accordingly, we were able to share a common platform with different types of DBF algorithms. An array antenna was mounted on a van to evaluate the signal tracking capability in a down-link satellite channel. The results show the expected performance in an actual mobile-satellite environment.

2. DBF SBS array configuration

The SBS array comprises RF and IF components and a digital beamformer DSP having quasi-coherent detectors (Q-DET), a multibeam former and an SPP. The block diagram is shown in Figure 2.

a. RF and IF components

The antenna consists of a 16-element square (4x4) array of ring patch antennas with an element spacing of a half-wavelength. The frequency is in the L-band (1.54GHz). Each element has an LNA module behind the antenna substrate to make an active array. The RF signals are directly converted to the intermediate-frequency (IF) signals at 32kHz by down-converters (D/Cs). The IF signals are routed into the BPFs at a bandwidth of 11kHz and digitized by A/D converters at 128kHz with 8-bit quantization.

b. Quasi-coherent detectors and a multibeam former[2]

The digitized IF signals are fed to the DSP, which is custom designed with 10 FPGAs on a printed circuit board (344mm x 233mm). One FPGA chip has 25,000 gates. All of the processings described in this and the next section are implemented on one board. We can switch different types of algorithms on one DSP board by loading those configuration data from a personal computer via its serial port.

In the DSP, a digitally-oscillated common local carrier is mixed with the input digital signals in the antenna branches for a quasi-coherent detection, where the detectors give orthogonal base-band signals in in-phase (I) and quadri-phase (Q) channels. The inequalities of the ampitude and phase between the antennas and the detectors are calibrated in advance by adjusting the local signals provided to the antenna branches.

The detector outputs are led into the multibeam former by a spatial 2-dimensional (2-D) FFT, providing orthogonal multiple beams on the broad side of the antenna. By this processing, the received signals are transformed from element-space to beam-space, roughly enhancing SNR by the array factor. This is accomplished by simply selecting the beams with higher power than an arbitrary threshold level.

Usually, the phase center for vector rotation in an FFT is located at an end element in the array. This causes phase difference between the FFT output beams and results in a phase jump of the reference beam for self-phasing, which will be described in the next section, when the DOA changes. This is not desired for demodulation. To avoid this, the phase centers of the selected beams are shifted to a geometric array center prior to the self-phasing.

c. Self-phasing processor (SPP)

The multibeam former, however, is not satisfactory for steering since the beams are discrete and fixed if maximal gain is needed in the DOA. If there is not serious interference and it is only necessary to steer the sharp beam of the array antenna to a DOA of the desired signal, a diversity-combining array can be a feasible approach. To obtain SBS capability, MRC is applied to the selected output beams of the multibeam former. In our prototype system, up to four beams are selected. The DBF antenna allows the MRC processing by simply using the following open-loop operation in base-band:

$$y = \sum_{u,v}(W_{u,v} \cdot B_{u,v}) \Big/ \sqrt{\sum_{u,v}|W_{u,v}|^2} \qquad (1)$$

where $B_{u,v}$ denotes one of the output beams from the 2D-FFT. $W_{u,v}$ is a weight for MRC in the (u, v) branch given by

$$W_{u,v} = F(B_r \cdot B_{u,v}^*). \qquad (2)$$

where B_r denotes a reference beam selected with the maximum power and * denotes a complex conjugate. The Σ in eq. (1) is performed within the selected beams. The numerator in eq. (1) gives both self-phasing and amplitude weighting for MRC. The denominator is for normalization of array weights $W_{u,v}$. $F(\cdot)$ denotes a low-pass filter to suppress the errors caused by thermal noise and envelope variation due to modulation. For this filter, we used a first-order IIR filter with a feedback factor of 0.992. The phases of the B_r and the combined output beam y are continuous by the phase center-shift described in the previous section, even if the reference beam is switched according to the DOA change.

Since this algorithm does not contain the closed-loop structure, the initial beam acquisition can be very fast, and robust tracking capability is expected. Moreover, it features beam steering to multipath signals in a fading environment, which coherently provides MRC of the Doppler-shifted multipath signals according to the receiving level.

3. Experimental system

We received an unmodulated signal in L-band (1.54GHz) transmitted from the geo-stationary satellite, ETS-V. The antenna was horizontally mounted on the rooftop of a van as illustrated in Figure 3. The receiving carrier-to-noise power density ratio (C/No) by a single element was about 47dBHz. Receiving bandwidth was 11kHz. The angle of elevation of the satellite was 47° from our test site, Kyoto Japan. The major system parameters are listed in Table 1.

We drove the van on a playground and through streets in suburbs and towns at speeds ranging between 10-40 km/h to get data in typical land-mobile satellite environments. Through the experiment, we collected the selected multibeam outputs, the combined signal output, the received signal by one element, and the calculated beam weights at a sampling period of about 8.5 msec. We also used an electronic compass to record the heading, pitch and roll of the van for data analysis.

4. Results

a. Self-beam steering and tracking

Figure 4 shows an SBS array output and the largest multibeam output measured when the van was driven in a circle on a flat playground under the line-of-sight condition at an angle speed of 13°/sec (10 km/h). The level drops between the multiple beams are compensated and the level variation is reduced by using the SBS processing. The residual level drop is due to lost power by the beam selection. This will be reduced by selection of more beams.

Figure 5 shows azimuth patterns in the elevation angle to the satellite (a) and elevation angle patterns in the azimuth to the satellite (b) at several time instances in Figure 4. Those patterns are obtained from the collected beam weights at those time instances. An approximate element pattern is assumed in the calculation of the elevation angle patterns. As shown, the self-beam steering is successfully achieved in a mobile satellite environment.

b. Steering recovery from shadowing

Figure 6 shows the response when the van was driven under a 4m-wide overpass at the speed of 40 km/h.

Element antenna output is also depicted to see the timing of shadowing. Since the sampling rate is not so fast, we could not observe a detailed acqusition rate; however, it is obvious that the acquisition rate with the SBS is no later than the recovery of the multibeam output.

c. Steering to multipath signal arrivals

To confirm the features of beamforming to multipath signals, we drove and approached the van at slow speed toward a building's wall from a direction perpendicular to the wall. Figure 7 shows measured azimuth patterns in the satellite elevation angle at several time instances. The satellite azimuth with respect to the car heading was about -115° in this measurement, and so it is obvious that the primary beam is always steered in the satellite direction. Additionally, another peak grows at around -55° according to approaching to the wall. This direction is considerd to be that of a signal reflected by the wall, and the expected directional diversity beamforming is observed.

5. Conclusions

We presented experimental results of the DBF SBS array antenna carried out in land-mobile satellite environments. In the experiment, we tested self-beam steering capability to a desired signal and secondary beam steering to a multipath signal, which cannot be easily provided by conventional analog-based phased array antennas even with expensive RF components.

Since the driving speed of the van could not be so fast, we could not measure the potential tracking speed with this antenna. Also, we could not conduct tests with modulated signals in this experiment. However, in principle, the SBS array scheme has a rapid response and can also be applied to modulated signals, including envelope variations. We could confirm the fundamental performances of those features through this experiment. More detailed experiments are planned using a radio anechoic chamber.

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References

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[2] T. Tanaka, R. Miura, I. Chiba and Y. Karasawa, "An ASIC Implementation of Digital Beamforming Multibeam Antenna", IEICE Trans. (B-II), J78-B-II, No. 9, pp. 602-610, Sep. 1995.

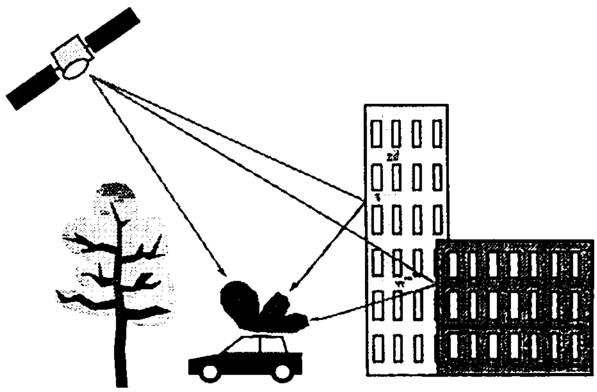


Fig. 1 Self-beam steering to the DOAs of multipath signals.

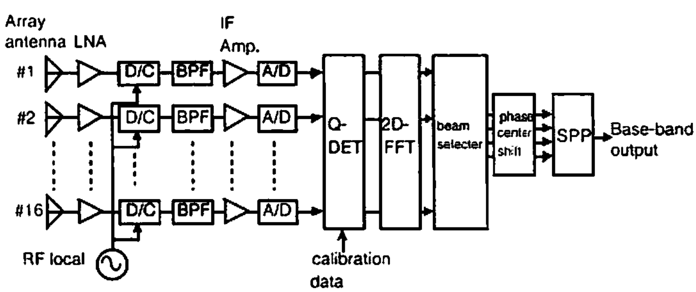


Fig. 2 Block diagram of SBS array antenna.

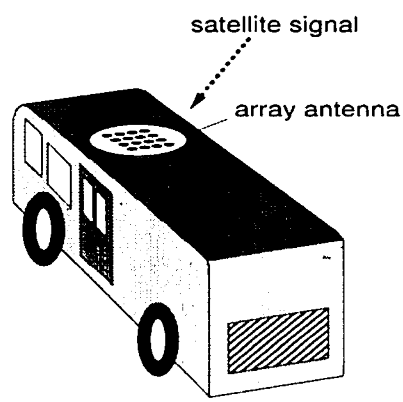


Fig. 3 Array antenna mounted on the rooftop of a van.

Table 1 Experimental parameters.

RF freq.	1.543GHz (CW)
Satellite	ETS-V(47° elevation angle from Kyoto, Japan)
RX antenna	4×4 square array of MSA with λ/2 element spacing
IF freq.	32kHz
Bandwidth	11kHz
RX C/No per elem.	47dBHz
A/D sampling rate	128kHz
A/D quantization	8bits
ASIC for DSP	FPGA(25,000 gates)×10 (on one PCB)
Master clock freq.	7.04MHz

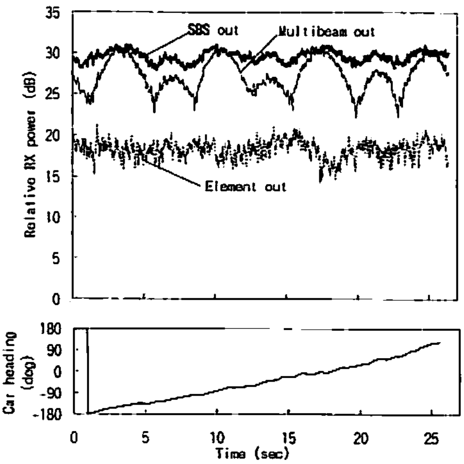
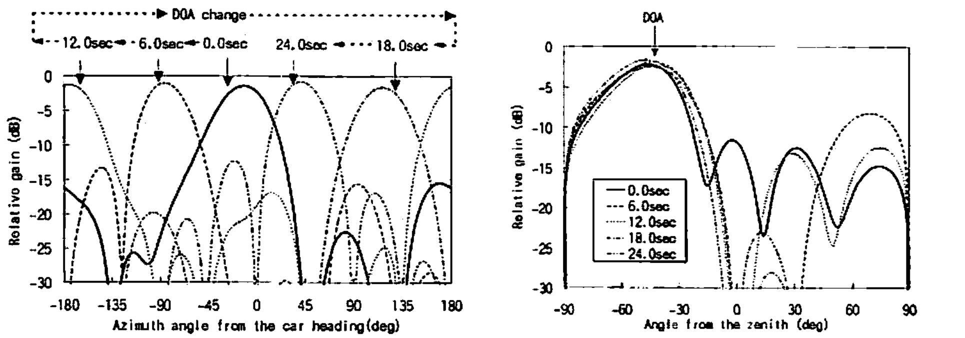


Fig. 4 Receiving power by SBS array with van circling at 360°.



(a) Azimuth patterns in the elevation angle to the satellite

(b) Elevation angle patterns in the azimuth to the satellite

Fig. 5 SBS beam patterns with van circling at 360°.

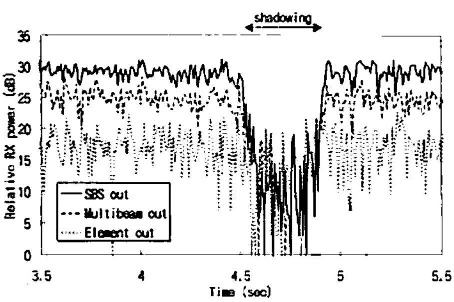


Fig. 6 Steering recovery from shadowing by an overpass.

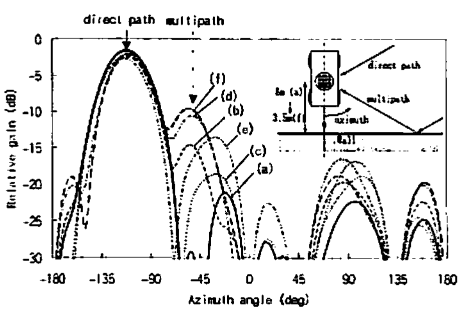


Fig. 7 Beam steering to multipath with van approaching a wall.