DEVELOPMENT AND IMPLEMENTATION OF AN ADAPTIVE DIGITAL BEAMFORMING NETWORK FOR SATELLITE COMMUNICATION SYSTEMS

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ABSTRACT

The use of adaptive digital beamforming techniques has, until recently, been largely restricted to high performance military radar systems. Recent advances in digital technology, however, have enabled the design of single chip digital beamforming networks. This, coupled with advances in digital signal processor technology, enables complete beamforming systems to be constructed at a lower cost, thus making the application of these techniques to commercial communications systems attractive.

This paper describes the design and development of such an adaptive digital beamforming network by ERA Technology for the European Space Agency. The system is being developed as a proof of concept laboratory based demonstrator to enable the feasibility of adaptive digital beamforming techniques for communication systems to be determined. Ultimately, digital beamforming could be used in conjunction with large array antennas for communication satellite systems. This will enable the simultaneous steering of high gain antenna beams in the direction of ground based users and the nulling of unwanted interference sources, such as radar systems, to be performed.

Introduction

Future generations of communications satellites will increasingly be used for communication both with mobile ground based users and communication between satellites. Such users would require large numbers of individual antenna beams to be directed towards each transmitting source and antenna pattern nulls steered towards potential sources of interference. In addition, due to the movement of transmitting sources and interference both from adjacent users and from interference sources such as high power radar systems, this type of application requires a highly flexible reconfigurable antenna array. This paper describes a prototype adaptive digital beamforming network (ADBFN), capable of continuously modifying the antenna pattern to maximise the received signal power relative to noise and interference, currently under development by ERA Technology.

The technique used to synthesis the antenna patterns is that of digital beamforming. This technique is further combined with adaptive signal processing algorithms in order to optimise the antenna pattern for a given signal and interferer scenario. Such techniques have been previously limited to implementation in high performance phased array Radar systems and therefore the application of adaptive techniques to a communication satellite system represents a unique development which will enable the system to accomplish electronic beam steering, adaptive interference rejection and automatic user acquisition.

In order to demonstrate the potential of such techniques for satellite communications, an 18 element adaptive beamforming network has been constructed. This is based around the MAM antenna array shown in Fig.1. This antenna array comprises a total of 18 elements spaced 42 cm apart and operates at 1.6 GHz. In a communication satellite, the array would operate at geo-stationary orbit and thus is required to generate beams within a conus of 10 degrees, corresponding to the angle subtended by the earth at this range. This array has been considered for evaluation purposes and it is highly likely that future arrays will consist of a much larger number of elements, typically 100. Furthermore, the ADBFN does not directly interface to the MAM array, but instead synthesises the equivalent antenna pattern from the geometry of the MAM array.

The ADBFN system has been designed as a proof of concept demonstrator and has therefore sufficient flexibility to enable the overall system performance to be determined for a wide range of potential communication scenarios. The system is capable of generating either BPSK or spread spectrum modulated signals over a wide range of CNR ratios (-36 to +10 dB) and data rates (1 Kbps to 3 Mbps). In addition, the system can generate interference from two additional sources to simulate CW, pulsed or noise interference. Two such potential communication scenarios have been considered during the development of the ADBFN, the Mobile scenario and the Data Relay Satellite (DRS) inter satellite scenario. Key features of the mobile scenario include BPSK modulation, element level CNR ratios of between 30 and 38 dBHz and channel bandwidths of 5 kHz. Key features of the DRS scenario include spread spectrum modulation, CNR ratios, depending on the length of the spreading sequence, of -36 to -4 dB and data rates of 1.5 to 160 kbps. In order to accommodate both scenarios in the design of the ADBFN, the CNR ratios and date rates of the Mobile scenario have been scaled to occupy the same 5 MHz base bandwidth as the DRS scenario.

In order to direct the beam to the user, the beam has to be electronically steered to the direction of the user. The direction of the user will be initially unknown and so the direction of the user must be first acquired. This process is known as user acquisition. Two main techniques have been considered during the course of the development of the ADBFN. These are temporal reference acquisition, where a Phase Locked Loop (PLL) is used to acquire a pilot tone and to supply an adaptive processor with a reference signal, and super resolution techniques, where the source vectors, corresponding to the directions of the users, are derived using either MUSIC methods or Maximum Likelihood Methods (MLM).

Adaptive Digital Beamforming : Theoretical Overview

Before considering the implementation of the ADBFN, a number of theoretical principles are first briefly reviewed. The basic principle of digital beamforming involves firstly the down conversion and complex digitisation to zero IF followed by the multiplication and accumulation of the resulting complex data array with a complex weight vector. This beamforming process is illustrated in Fig.2. For example, for a linear antenna array of N elements with a user at an angle Θ the weight vector which steers the array in the direction theta is given by :

$$W(k) = e\frac{(j2.\pi k \sin(\theta))}{\lambda} \text{ for } k = 1, N$$

The advantages of performing this beam formation process digitally rather than using analogue techniques are typically a high degree of accuracy and repeatibility and the fact that the complete vector of signals is available in digital form. In addition, digital technology is likely to be more cost effective than alternative analogue techniques.

The problem of adaptive digital beamforming reduces to one of modifying the weight vector to maximise the array gain in the direction of the user and steering nulls in the direction of interference sources. A wide range of adaptive algorithms may thus be applied to this problem. In analytical form, the optimum, or Weiner, weight vector which gives this result may be expressed as follows.

$$W = R^{-1} {}^{*}.S$$

where W is the complex weight vector used in the beamformer, R is the covariance matrix of element level received signals and S* is the complex conjugate of the wanted signal direction. In practice, iterative techniques are used to evaluate this matrix inverse to minimise computational requirements. The adaptive approach adopted in the ADBFN is based on the use of the General Sidelobe Canceller (GSC) as shown in Fig.3. The upper arm of the GSC may be considered as the fixed beamformer which defines the look direction of the array. The lower arm is used to generate an auxiliary beam which, when subtracted from the upper arm, minimises the output in the direction of interfering sources. A blocking matrix is used to prevent the adaptive processor in the lower arm of the GSC cancelling the wanted signal. Any suitable adaptive technique may then be used to obtain the optimum weight vector. The ADBFN implements the Least Mean Squares (LMS), Recursive Least Squares (RLS) and Direct Matrix Inversion (DMI) adaptive algorithms for this purpose.

An example of adaptive beamforming in operation is given in Fig.4. The look direction of the array is defined as zero degrees. Two interference sources are introduced at -20 and +60 degrees. The antenna pattern is then adapted to steer -40 dB nulls in the direction of these interference sources.

It is possible to synthesise nulls within the main beam of the antenna pattern with the careful use of constraints. Two types of constraint have been considered during the development of the ADBFN. Directional constraints simply fix the gain of the array in the look direction to a nominal value. Derivative constraints can be further used to reduce the sensitivity of the array to pointing errors in the look direction. This is particularly important in the low CNR scenarios encountered in satellite applications. These constraints are introduced in the ADBFN by modification of the blocking matrix, A, in the lower arm of the GSC.

The problem of user location can be reduced to one of estimating the source vector, S, corresponding to the look direction of the user. Two methods for this process have been included in the design of the ADBFN. The first of these is based on the use of a temporal reference signal, derived from a PLL, in conjunction with a LMS adaptive processor to vary the weight vector. This process is illustrated in Fig.5. Here, the adaptive processor modifies the weight vector until the minimum error with respect to the reference signal produced by the PLL is obtained. Therefore, consideration of the dynamics of the PLL in conjunction with the adaptive spatial processor is required. This weight vector then defines the look direction of the array to the user. The second class of techniques are known as super resolution techniques. The ADBFN implements two of these techniques, the weighted MUSIC method, based on an eigenvalue decomposition of the covariance matrix, R, and the Normalised Maximum Likelihood Method (NMLM) where the weight vector that gives the maximum array output is estimated. This technique, however, require a large amount of averaging of the covariance matrix, over 1000 snapshots, to work reliably in the low element level CNR scenarios encountered here.

Computer Simulation Results

Before detailed design of the ADBFN was undertaken, a number of computer simulations were performed in order to determine the expected performance of the system for each of the scenarios outlined previously. The effect of interference on the overall end to end communications performance, as measured by the bit error rate (BER) or EbNo, was used as the main measure of performance. This was measured for both spread spectrum and BPSK modulated signals and in the presence of interference. The effects of pointing errors, element amplitude and phase mismatch errors, derivative and directional constraints, choice of adaptive algorithm and the number of bits used to quantise the data snapshots and the weight vector were all assessed. This final point was particularly important for the design of the digital beamforming ASIC described later in this paper. Finally, user acquisition using temporal reference techniques was simulated.

An example of the output of this simulation package is shown in Fig.6. This diagram shows the effect of look direction pointing error on the overall system EbNo at varying CNRs with and without derivative constraints. The scenario under consideration is representative of a mobile communication scenario. The interference was in the main lobe of the antenna pattern, at an angle of three degrees, and the RLS routine was used to adapt the weight vector. This diagram shows that derivative constraints reduce the system sensitivity to pointing errors for positive CNR ratios (greater than 0 dB).

In order to assess the effects of finite precision arithmetic on the depth of the antenna pattern null that may be synthesised with the use of finite precision beamforming, the data snapshots and weight vector were quantised in the simulation. The data was quantised to 8 bits and the weight vector was quantised to 11 bits. One result from this series of simulations is shown in Fig.7. This illustrates the main lobe null, two degrees from the look direction, that may be formed with the 18 element MAM array and with quantised data. In particular, the effects of truncation and rounding in the beamforming process on the depth of null are shown. This shows that truncation of twos complement format partial results, produced by the complex multiplier, towards zero produces the optimum null depth, with respect to the ideal case of rounding. The full floating point precision null depth is shown as a reference.

The extensive use of computer simulation techniques during the early phases of the project have highlighted the optimum choices of algorithm for each of the expected communication scenarios. In addition, the detailed performance of the digital beamforming ASIC has been simulated and verified. This simulation also provided test patterns to enable a digital functional simulation of the ASIC to be performed using a digital simulator.

ADBFN Architecture

The overall architecture of the ADBFN system is shown in Fig.8. A total of 18 quadrature downconverter modules sample the incoming data to a resolution of 8 bits at a sample rate of 8 MHz. The downconverter is designed to sample any 5 MHz portion of the input bandwidth of 26 to 50 MHz. The quadrature signal generation is performed using a quadrature hybrid operating at 110 MHz. The fixed amplitude, phase and quadrature mismatch errors can be calibrated out by suitable modification of the weight vector. However, residual errors, caused by differential frequency response mismatches lead to a maximum theoretical null depth of -40 dB. This figure was derived by performing a decorrelation error budget based on the specified and measured frequency responses of all analogue components in the array of downconverters.

Digital Beamforming ASIC

The realtime digital beamforming function is implemented by a cascade of five digital beamforming (DBF) ASICs. The DBF ASIC performs complex multiplication and accumulation operations at a rate of 32 MHz. A block diagram of the DBF ASIC is given in Fig.9. Data samples from the downconverter modules are quantised to 8 bits whilst the weight vector coefficients are quantised to 11 bits. Note that the precision of internal partial results is expanded at each stage of the internal processing in order to avoid numerical overflow and underflow occurring. The final precision of the DBF ASIC output is then 16 bits. The

ASIC may be configured to process between two and 128 elements of data, with the constraint that the maximum operation rate is 32 MHz. The ASIC also includes a data store which can be synchronised across the array of ASICs to enable vectors of element level data to be stored. Dual weight vector stores are provided to enable a new weight vector to be written to the ASIC without affecting the current beamforming operation. The switching of these weight vector memories can be also synchronised across the cascade of ASICs. A processor interface is provided to enable a digital signal processor to access the contents of the data store and the weight vector store as well as to configure the operation of the beamforming ASIC.

The data store can be used in calibration mode to acquire a contiguous array of 128 complex samples from a single element. This enables array calibration to be performed by using a Fast Fourier Transform (FFT) to calculate the various array mismatch errors described previously. A correction matrix may then be calculated to equalise the response of each element. This array calibration matrix then acts as a preprocessor for the adaptive weight vector calculations.

The DBF ASIC has a large degree of flexibility incorporated within the design. This enables the ASIC to operate as a digital beamformer for arrays consisting of between four and 128 elements. In addition, up to 32 ASICs can be cascaded together to process larger arrays of antenna elements. Up to 4096 antenna elements may then be processed at a sample rate of 250 kHz. This degree of flexibility enables system designers to construct a wide range of beamforming networks with minimal processing hardware.

The DBF ASIC is fabricated in a 1 μm standard cell CMOS process and comprises approximately 200,000 transistors. The device is packaged in a 120 pin Ceramic Pin Grid Array and consumes 0.75 W.

ADBFN Hardware and Software Development

The digital signal processor used for adaptive processing is the TMS320C30 floating point precision digital signal processor. This processor has a maximum performance of 33 MFlops and uses a pipelined structure to maximise performance. The use of floating precision arithmetic for all adaptive processing enables maximum precision to be maintained, after data quantisation, and reduces performance limitations due to numerical affects. The cascade of five ASICs is connected to the TMS320C30 via the processor interface, enabling off-line adaptive processing to be performed. The system is capable of performing a complete adaptive weight vector update once every millisecond. This assumes an array of 18 elements and the use of the GSC with the RLS routine to update the adaptive portion of the weight vector.

As shown in Fig.8, a temporal reference processor is connected to the output of the digital beamformer. This module performs the following functions:

1. Forms a temporal reference signal, derived from a digital PLL to enable user acquisition to be performed.
2. Performs de-spreading and demodulation of spread spectrum and BPSK modulated signals.
3. Enables on line measurements of EbNo to be made digitally with the use of programmable digital notch filters.

Each of the above functions may be modified by the user to enable performance evaluations to be carried out. The temporal reference card operates at the fundamental system clock rate of 8 MHz and is implemented with a combination of complex FIR filter devices, complex multipliers and a numerically controlled oscillator (NCO). Overall control is provided by a TMS320C25 scalar digital signal processor. The reference signal is sampled from the output of the NCO and fedback, via a high speed synchronous serial link, to the floating point digital signal processor on the beamforming module. This processor then carries out the LMS adaptive processing for weight vector calculation.

In order to test the adaptive beamforming hardware, an antenna simulator network has been developed. The antenna simulator enables up to four signal wavefronts to be synthesised simultaneously by using an array of analogue RF phase shifters and attenuators as is shown in Fig.10. This unit simulates operation at an RF frequency of 1.6 GHz and is capable of simulating wavefronts arriving at the MAM array within a conus of ±10 degrees. In order to achieve the required performance, a novel phase shifter has been designed with a phase variation of only ±0.7 degrees over a 5 MHz bandwidth. Signals are output to the beamforming network at a frequency of 26 to 50 MHz, via 18 RF cables. Uncorrelated noise is introduced at each element to simulate spatial noise. The effects of element mismatches and failure on the beamforming operation can be assessed by inserting attenuation at the element level outputs. The entire sub-system is software controllable via the IEEE-488 instrument bus.

Overall control of the ADBFN system is performed by a standard PC-AT computer, connected via the IEEE-488 bus to each of the sub-systems. The PC-AT computer is also used for user interface functions such as the graphical display of antenna patterns. Extensive use of structure, top down software engineering techniques has been made during the development of the ADBFN, with all software being written in the high level programming language, C.

Conclusions

This paper has described the development of an Adaptive Digital Beamforming Network (ADBFN) for satellite communications applications. This system will enable the evaluation of digital beamforming techniques for such applications to be performed. In particular, the design of a realtime digital beamforming ASIC has been presented. The incorporation of a number of different DSP technologies in the design of the ADBFN also demonstrates how particularly high levels of performance and flexibility may be achieved. The system also shows the viability of adaptive digital beamforming techniques in this new range of application areas.

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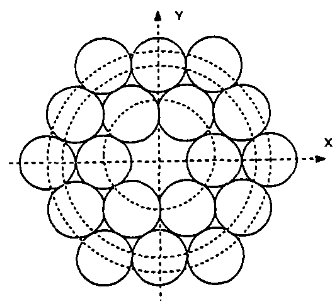

Fig.1: MAM antenna

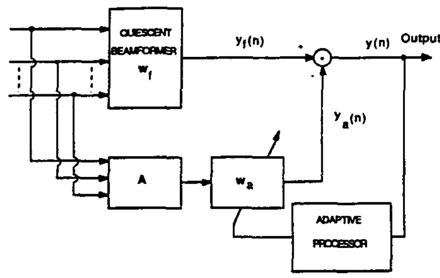

Fig.3: Generalised sidelobe canceller

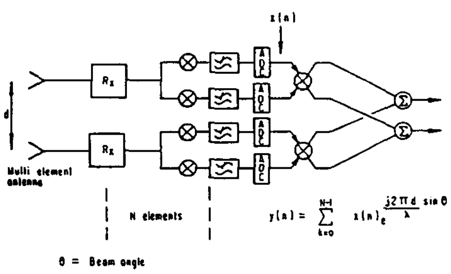

Fig.2: The principle of digital beamforming (shown for a Linear Antenna Array)

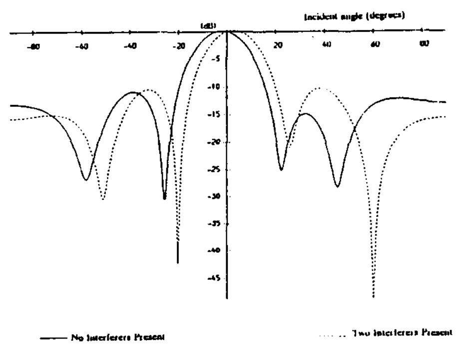

Fig.4: Adaptive control of the beam pattern

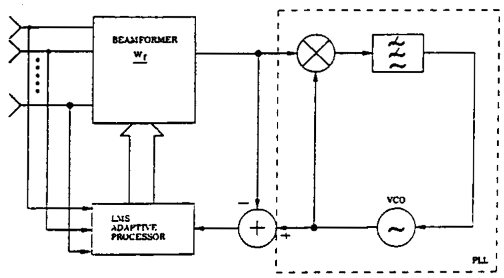

Fig.5: Temporal Reference Acquisition

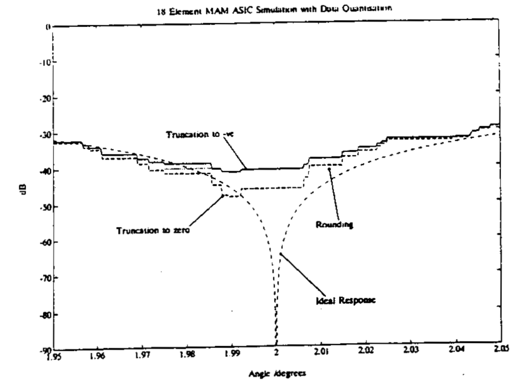

Fig.7: Effect of multiplier output truncation or MAM response
Phase reference to centre of array

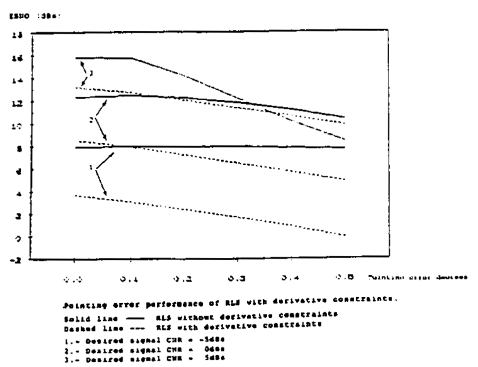

Fig.6: Simulated pointing error performance
BSPK 3 Mbps signals
Main lobe (3 degrees) 5 dBs of
CNR interference

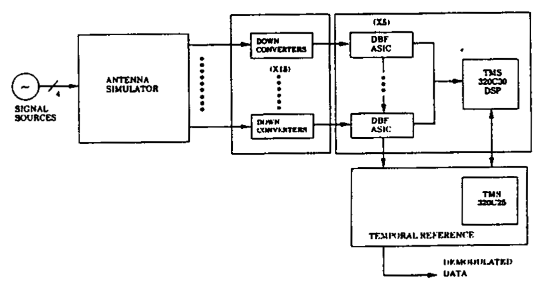

Fig.8: ABDFN Architecture

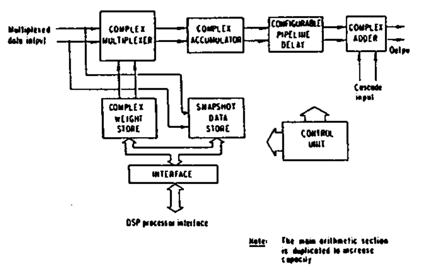

Fig.9: Simplified block diagram of the digital beamforming ASIC

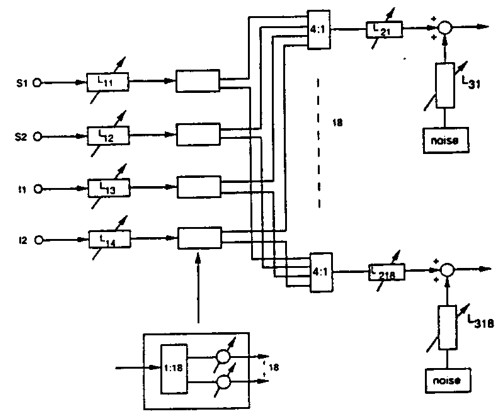

Fig.10: Antenna simulation block diagram