N94-22745

Adaptive Array Antenna for Satellite Cellular and Direct Broadcast Communications*

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ABSTRACT

Adaptive phased-array antennas provide cost-effective implementation of large, light weight apertures with high directivity and precise beamshape control. Adaptive self-calibration allows for relaxation of all mechanical tolerances across the aperture and electrical component tolerances, providing high performance with a low-cost, light-weight array, even in the presence of large physical distortions. Beam-shape is programmable and adaptable to changes in technical and operational requirements. Adaptive digital beam-forming eliminates uplink contention by allowing a single electronically steerable antenna to service a large number of receivers with beams which adaptively focus on one source while eliminating interference from others. A large, adaptively calibrated and fully programmable aperture can also provide precise beam shape control for power-efficient direct broadcast from space.

This paper describes advanced adaptive digital beamforming technologies for: (1) electronic compensation of aperture distortion, (2) multiple receiver adaptive space-time processing, and (3) downlink beam-shape control. Cost considerations for space-based array applications are also discussed.

SATELLITE ANTENNA DESIGN

High density RF communications traffic requires satellite antennas with high gain, precise beam pointing, and electronic speed and steering agility. If this is to be supplied with a large phased array antenna, problems of size, weight, cost, and performance arise. As uplink traffic becomes more intense or diverse, the need for multiple receivers and adaptive interference suppression adds to the cost.

Conventional approaches to maintaining antenna gain, suppressing interference, and controlling beam shape are dependent upon maintaining very stringent tolerances across the aperture. Even if rigidity and precise control is provided during manufacture, once the satellite is deployed it will be subject to (1) distortion of the structure after repositioning, (2) thermal distortion across the array, and (3) potential revised beam requirements due to changing business plans. The risk is of reduced operational performance due to gain degradation, increased sidelobe interference for uplink signals, and high sidelobe energy spillover for downlink traffic and for direct broadcast.

As an alternative to using sophisticated structural components and/or auxiliary subsystems to measure and correct for deformations and other sources of error, a class of self-calibrating adaptive digital beamforming techniques has been developed by GSI. These procedures compensate for aggregate errors without regard to their source: structural deformations, mutual coupling, solid state module phase errors, RF delay errors, and propagation anomalies. These procedures complement adaptive interference cancellation approaches. The cost savings due to reduced reliance on tight electrical and mechanical tolerances is greater than the cost of the digital

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* The conceptual design approaches described herein take advantage of signal processing algorithms proprietary to GORCA Systems, Inc.

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beamforming needed for multiple beam formation and adaptive interference suppression. The gain control achievable for direct broadcast saves prime power. The procedures may permit the antenna structure to be non-rigid and deformable resulting in a major weight reduction and consequently a reduced launch cost with improved performance. Advantages and benefits of adaptive processing are listed below.

TABLE 1. ADAPTIVE ARRAY ADVANTAGES

Antenna Array

- 30% to 40% reduction in mass
- complex RF components replaced by solid state electronics with firmware algorithms
- 100:1 easing of mechanical tolerances
- adaptive response provides immediate recovery from mechanical, electrical and RF disturbances
- design approach takes advantages of technology advancements in MMIC, VLSI, etc.
- low cost assembly and test due to relaxed mechanical requirements, ability to correct for errors, etc.

Satellite

- 10:1 reduction in system pointing requirement and "fine" attitude control, due to adaptive calibration of antenna and beam steering capability
- up to 50% reduction in satellite mass, some of which can be applied to increased on-orbit life
- significant reduction in solar array and battery power, due to more effective use of RF power
- conventional attitude control components could be replaced by attitude and position sensing using the array electronics
- self-calibrating features provide immunity to thermal or other mechanical distortions
- immunity to contentious uplinks due to antenna nulling
- low cost integration and test, and accelerated schedules
- significant reduction in cost of launch services

Communications Applications

- lower uplink RF power, or higher G/T margin, due to more precise beamshaping
- higher effective downlink EIRP due to precise spot beams
- software beamforming allows operational flexibility to meet changing requirements, traffic diversity, business plans, etc.
- very large number of users accommodated
- digital beam steering and software beam shaping provides instantaneous response to changing requirements
- very large aperture systems can be developed which could otherwise not be built

ADAPTIVE DIGITAL BEAMFORMING

We consider a phased array antenna consisting of transmit/receive modules with a receiver and A/D converter behind each. By sampling the aperture we obtain complete software control over transmit and receive beam formation. This includes the ability to (a) adaptively determine sets of weights that compensate for mechanical, electrical, and environmental errors, (b) adaptively home in on a transmitted signal while simultaneously suppressing contending signals, (c) digitally form multiple simultaneous receive beams, and (d) design and revise the transmitter footprint for broadcast operation.

Digital beamforming weights an array so as to (1) sense a desired signal and (2) attenuate interference. The received signal at each array element is assumed to have been heterodyned, filtered, sampled, and digitized so that $e_n(t)$ is a complex number representing the in-phase and quadrature components of the wavefront at the n^{th} array element at time t. The beamforming concept is illustrated in Figure 1.

A beam is formed in the digital processor as a linear combination,

$$y = \sum_{n=1}^{N} w_n^* e_n = \mathbf{w}^h \mathbf{e} \ , \quad (1)$$

where $\mathbf{w}^h = (w_1^*, w_2^*, \ldots, w_N^*)$ is a vector of complex weights to be applied to the components, $e_1, e_2, \ldots, e_N$, of the received data vector, $\mathbf{e}$. The weights are obtained as the conjugate transpose (h) of the optimum weight vector,

$$\mathbf{w} = \alpha \mathbf{R}^{-1}\mathbf{s} \ , \qquad (2)$$

where s is a low-sidelobe "steering vector" that would be used if interference were spatially homogeneous ($\mathbf{R}=\sigma^2\mathbf{I}$) such as thermal noise. The directionality of the interference is accounted for in the NxN correlation matrix, **R**, whose ij^{th} element is the correlation between the interference wavefront at elements i and j,

$$\mathbf{R} = E\{\mathbf{e}\,\mathbf{e}^h\}.$$

Note that many beams may be formed simultaneously by choosing a different steering vector for each.

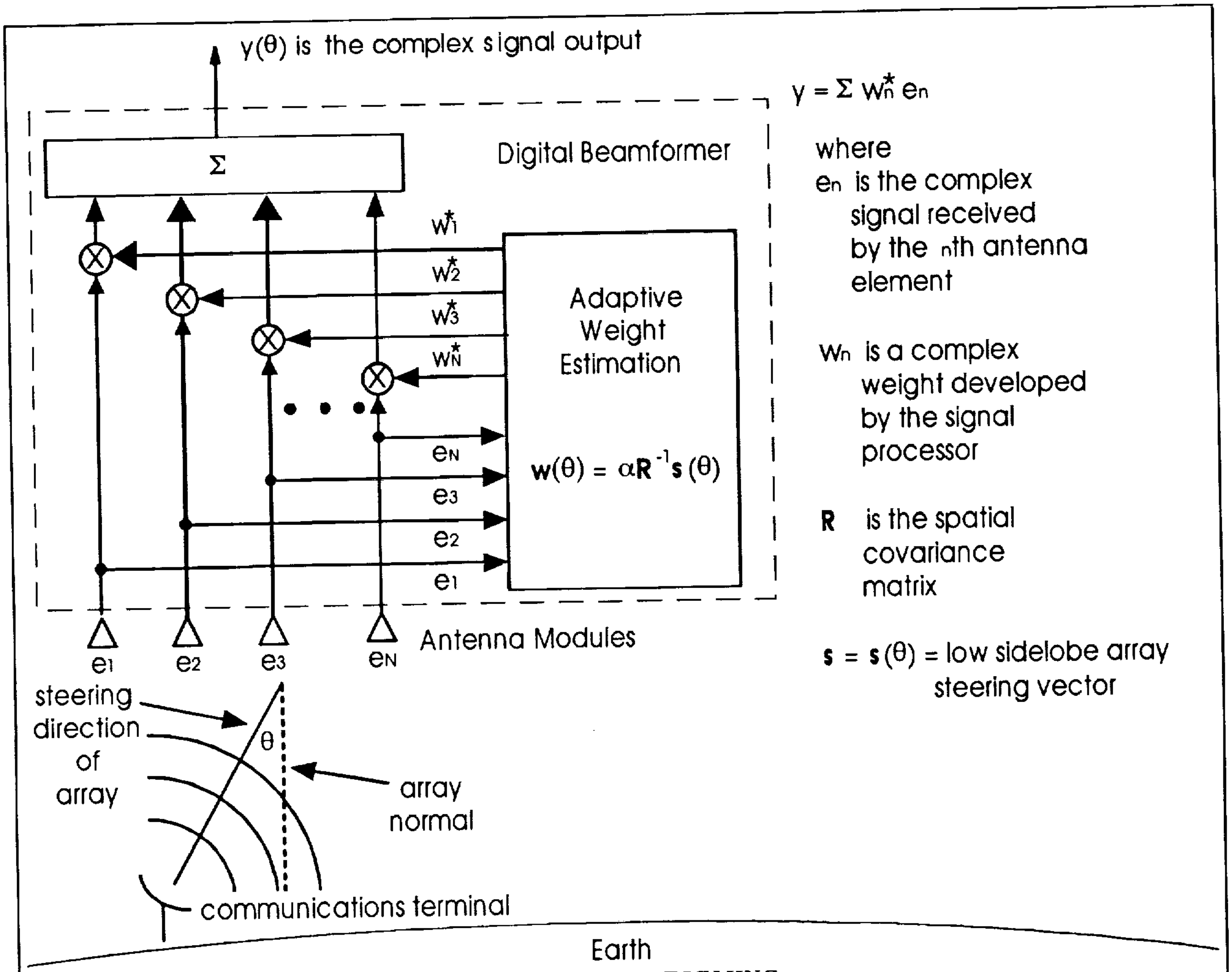

FIGURE 1. BEAMFORMING

Beamforming is said to be *adaptive* if the weight vector is computed on the basis of received signals (as opposed to being specified a priori). We note that there are two parts to adaptive beamforming. One relates to using received signal data to estimate the steering vector, **s**. The other relates to using received interference data to estimate $\mathbf{R}^{-1}$.

Estimating **s** is called self calibration, self cohering, or adaptive focusing. Estimating $\mathbf{R}^{-1}$ is called adaptive nulling or interference cancellation. GSI is in the forefront of both aspects of adaptive beamforming. We will discuss the self-calibration aspect first.

ELECTRONIC COMPENSATION FOR APERTURE DISTORTION

Table 2 summarizes a number of adaptive self calibration algorithms that were developed for radar applications. They involve the use of a variety of phase synchronizing sources to furnish the calibration pilot signal and they have been successfully applied to the calibration of real apertures, synthetic apertures, and inverse synthetic apertures. When used to establish a phase reference across a synthetic aperture they are equivalent

TABLE 2. SELF-COHERING TECHNIQUES

Dominant Scatterer
- Minimum Variance Algorithm - Steinberg (U of P)
- Multiple Scatterer Algorithm (MSA) - Attia (GSI)
- MSA with Subarray Processing - Attia/Kang (GSI/UofP)
- Phase Gradient Autofocus Algorithm - Jakowitz (Sandia)

Spatial Correlation
- Spatial Correlation Algorithm (SCA) - Attia (GSI)
- Multiple Lag SCA - Subbaram (GSI)
- Shear Averaging - Feinup (ERIM)
- Iterative SCA - Attia (GSI)

Phase History Reconstruction
- Image Plane Differential Phase Smoothing - Kupiec (MITLL)
- Aperture Plane Differential Phase Smoothing - Stockburger

Energy Constraint Method - Tsao/Subbaram (GSI) to motion compensation or auto-focus techniques for SAR or ISAR imaging.

The key concept is that signals from the earth are received by individual array elements and combined in order to establish a phase reference that compensates for all errors. Correction for mechanical shape distortion is illustrated in Figure 2.

The simplest algorithms use the wavefront at the aperture from a strong signal as a phase synchronizing source for all array elements. Other algorithms use multiple sources, estimate parameters of an aperture distortion model, or adapt in an iterative manner. The spatial correlation algorithm correlates the signals received at adjacent array elements and introduces a time shift determined by the time of the correlation peak as well as a phase correction. This allows for correction of large distortions without ambiguity.

SPACE-TIME PROCESSING

Since the aperture samples the wavefront in both space and time, the signals can be simultaneously processed in both domains to separate signals according to angle of arrival and spectral content. In Figure 1, Equation (1) is applied in the spatial domain to implement a process called beamforming. In general, Equations (1) and (2) refer to to linear space-time processing. The temporal counterpart of beamforming is filtering and the temporal counterpart of self calibration is channel equalization. In the special case where $w=s=E\{e|\text{signal}\}$, the spatial weights represent a matched field steering vector and the temporal weights represent a white-noise matched filter for the signal.

With reference to Equation (1) and Figure 1, the formation of multiple beams to service multiple ground stations while eliminating uplink contention is relatively straight forward. The N dimensional data vector, **e**, is processed in an on-board digital processor to produce a set of K linear combinations of N complex numbers: y_1, y_2, ..., y_K. Each output

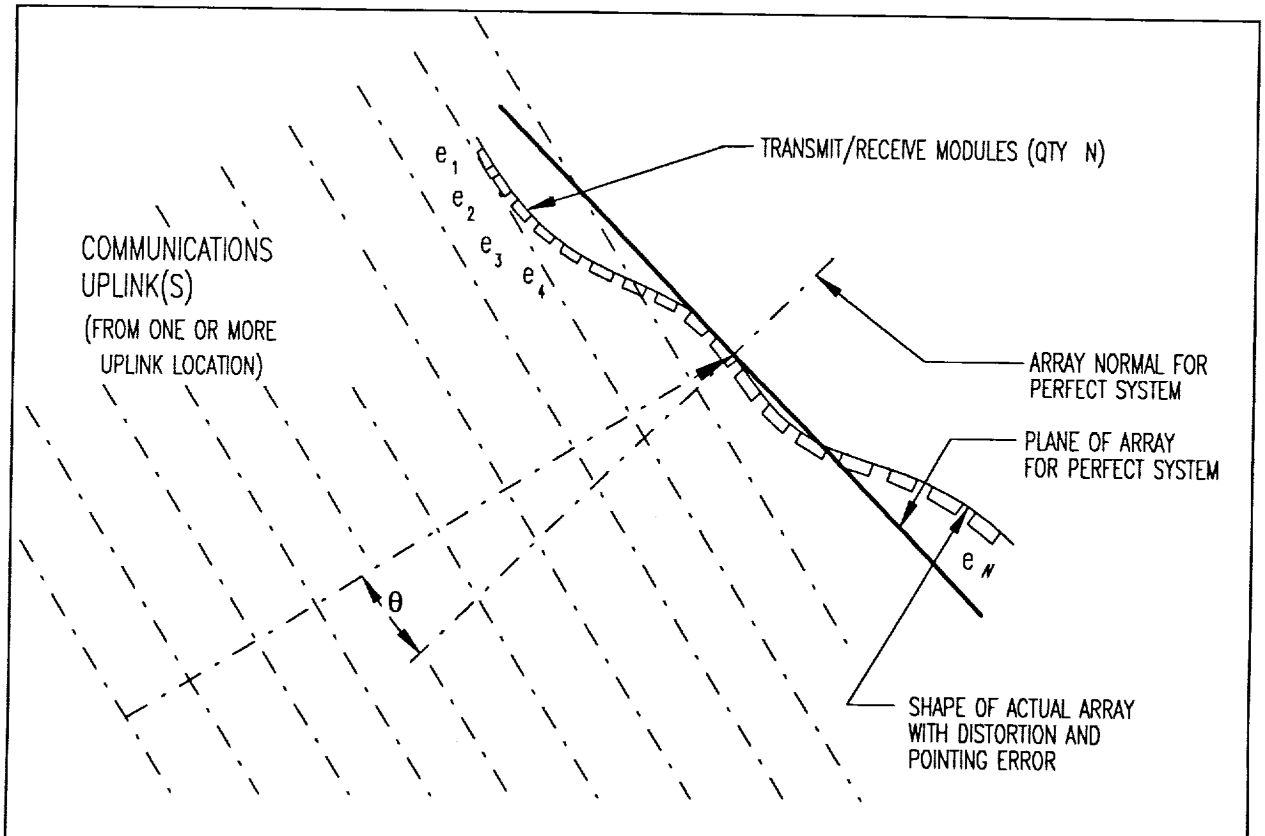

FIGURE 2. ELECTRONIC CORRECTION FOR MECHANICAL DISTORTION & POINTING ERROR

represents the signal received from one ground station. If θ_d represents the location of a particular ground station, then y_d is formed using Equation (1) with $\mathbf{w}=\mathbf{w}(\theta_d)$. In applying Equation (2) to obtain this weight vector, each component of the steering vector is given the same phase as the phase of that same component of a data vector, $\mathbf{e}(\theta_d)$, that would be received from that station. The NxN correlation matrix could even be pre-computed as a diagonally loaded version of the rank K-1 matrix whose mn^th^ component is

$$\sum_{\substack{k=1 \\ k \neq d}}^{K} e_m(\theta_k) e_n^*(\theta_k).$$

The resulting y_d supplies a receiver with one signal while nulling all other signals.

DOWNLINK BEAMSHAPE CONTROL

For a properly calibrated array, the aperture illumination function, $f(x,y)$, and the azimuth-elevation far-field pattern, $F(u,v)$, are related by a two dimensional Fourier transform. The larger the aperture, the finer the control on where power is directed. At an altitude of h, the diffraction limited resolution (or pixel diameter) on the ground is at least $h\lambda/D$, where λ is the rf wavelength and D is the aperture diameter.

The desired intensity distribution $|F(u,v)|^2$, is specified as 1 for values of $u=\sin\theta$ and $v=\cos\phi$ corresponding to the location of cities that must be reached in a direct broadcast application. A criterion can be devised such as minimizing the average power outside of a given region. We specify F as 0 for values of (u,v) outside of the coverage region and as 1 for the location of target cities, and we find the least squares solution of the set of equations for f.[1] If the set of equations is underdetermined, the minimum norm solution for f is the desirable one because the norm of f represents the required transmitter power. Thus, if the array is well formed or properly calibrated, open-loop beamshaping by computer is relatively straight forward.

As described earlier, the problem of calibrating a large *receiver* array, using signals transmitted from the ground, has a reasonably precise solution. Data is collected at each element and processed so that the signals add coherently. The crucial question is whether it is possible to use the receive calibration corrections to correct errors in the transmitted wavefront.

This problem turns out to be more difficult. The signals transmitted from all array elements must be synchronized so that they add coherently in the target region. If errors exist in the transmitter chain, a closed loop procedure is required. Transmitter time or phase synchronization requires the return of a transponding signal from the target on the earth so that the two way propagation can be measured. While phased array receiver calibration is relatively well established [1,2], retrodirective transmitter calibration is a relatively new technology. However, GSI personnel have established feasibility in a ground based demonstration [3]. While further development is still needed, the potential payoff for adaptive transmitter self calibration is enormous.

COST CONSIDERATIONS

Many advanced array systems have been proposed and studied for space applications and less advanced array systems have been developed and built. Space-based applications include both remote sensing and communications, but the degree to which array technology has been actually deployed has been limited due to cost considerations.

The cost drivers include cost of electronics, due to the large number of array element modules; structural cost of arrays and space-

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[1] Acually, if only the power density $|F|^2$ is specified, then only the the spatial autocorrelation function of the aperture illumination is constrained.

$$<f(x+a,y+b)\, f^*(x,y)> = R(a,b)$$

where R and $|F|^2$ are a Fourier transform pair.

craft, to meet launch loads and minimize thermally-induced distortion or pointing error when on-orbit; the high cost of integration and test, for both payload and satellite; and launch cost, driven by the increased mass of the array structure and the spacecraft which are needed to meet system performance objectives.

The cost of electronics is being addressed via MMIC technology advancements, efficient signal processing electronics, design innovations and manufacturing efficiencies achievable with a large number of array modules. However, the other cost drivers have not been sufficiently addressed to make many advanced array concepts economically viable. As an example, a typical application of array technology to achieve power efficient satellite communications [to achieve very small spot beams which can be dynamically moved to match communications traffic requirements] results in a very large, complex satellite which also results in high launch costs.

The design concepts presented herein address these other cost drivers. The array structure can be built using very low cost, low mass designs since stiffness and distortion requirements are minimal. The allowable satellite and array pointing errors can be greatly relaxed, further simplifying other satellite subsystems and satellite operations, and significantly reducing over-all on-orbit mass. The costs of integration and test are minimized since alignment and component precision issues largely disappear. Finally, the launch costs are greatly reduced due to the large reduction in lift-off mass. A typical communications satellite constellation could be deployed with a net savings of tens of millions of dollars.

SUMMARY AND CONCLUSIONS

The performance obtainable by space-based array systems for communications and other applications is well known; however, the implementation of array technologies into operational systems has been limited due to the high cost of arrays, satellites and launch services. The adaptive array design approach described herein applies advanced signal processing technology originally developed for radar systems to next generation communications satellites. All of the advantages of array systems, for communications or remote sensing applications, are retained while making it possible to develop and deploy operational systems at affordable cost.

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[3] E.H. Attia and K. Abend, "An Experimental Demonstration of a Distributed Array Radar," *IEEE AP-S International Symposium Digest*, pp. 1720-1723, London, Ontario, June 1991.

GORCA Systems, Inc. [GSI], an aerospace engineering company based in Cherry Hill, NJ, has made innovative contributions to the aerospace industry in the fields of commercial space, government, civil, and DoD space systems, advanced signal processing and remote sensing systems technologies and applications. GSI has also developed several spin-off technologies for commercial products. Phone:609-273-8200.

Dr. Kenneth Abend is Director of GSI's Advanced Signal Processing Laboratory. He is an expert on adaptive space-time processing and coherent imaging with distorted apertures. He has thirty five years experience in research, development, and analysis of advanced digital systems and techniques as applied to radar, sonar, communications, and pattern recognition.

Charles R. Horton, President of GSI, has a diverse background which includes technical and management contributions to NASA, DoD and commercial space systems and specialized components [both space and ground segments]. His background also includes development of advanced consumer electronics products.