An Analog Aerial Beamforming Approach to Trained and Blind Smart Antennas

Takashi OHIRA

ATR Adaptive Communications Research Laboratories

2-2-2 Hikaridai, Seikacho, Kyoto 619-0288 Japan
Email: ohira@atr.co.jp

ABSTRACT

This paper presents an analog beamforming scheme that drastically simplifies the architecture of smart antennas, eliminating the arrays of frequency converters and analog-digital converters used in conventional DBF antennas. Electromagnetic coupling among varactor-loaded parasitic radiators carries out signal processing spatially. To control this scheme adaptively, two kinds of innovative criteria are proposed: Maximum Cross Correlation Coefficient “MCCC” with training sequence, and Maximum Moment Criterion “MMC” for blind operation without resorting to training codes. The criterion-based feedback control automatically compensates the inherent inaccuracy of analog devices. This approach promises breakthroughs to new and wider application fields of consumer wireless systems.

1. INTRODUCTION

Due to recent trends in electronic circuits for wireless devices, even the antenna beamforming network (BFN) has been investigated for fruitful ways of employing digital-based architectures. The digital-beamforming (DBF) network offers several effective functionalities, including programmable control of the antenna radiation pattern, direction-of-arrival (DOA) estimation, and adaptive steering of its beam and nulls to enhance the signal-to-interference-noise ratio (SINR) [1]. It is widely assumed that these advantages cannot be maximized without implementing digital technology.

The analog approach, on the other hand, is re-emerging to establish an alternative architecture of adaptive array antennas. The concept of analog beamforming itself was proposed more than forty years ago [2]. However, according to the conventional wisdom, it is practically impossible for an analog system to provide the smart functionalities that DBF does. If analog beamforming were utilized in the RF stage of adaptive array antennas, it could drastically improve both dc power dissipation and fabrication costs, since it could reduce the number of frequency converters and analog-digital converters to one each for the same number of array branches.

This paper proposes a novel beamforming approach to smart antennas. Parasitic radiators are loaded with variable reactors (varactors) and are arrayed around an active radiator. Beamforming is carried out not in the circuit but by the electromagnetic coupling among the radiators. To control this beamforming scheme in a smart way, two kinds of innovative criteria are proposed: Maximum Cross Correlation Coefficient (MCCC) with training sequence, and Maximum Moment Criterion (MMC) for blind operation without training codes. They are analogous to the Minimum Mean Square Error (MMSE) and Constant Modulus Algorithm (CMA), respectively, used for conventional DBF antennas. The theoretical basis of this approach is described, and computer simulations demonstrate that this smart beamforming successfully extracts the desired wave from the interference for both trained and blind signal environments.

2. ANALOG AERIAL BEAMFORMING

The history of practical analog beamforming antennas dates back to the Butler matrix [2], which consists of hybrid matrices and fixed phase shifters. Since the beam steering function is carried out with a selective RF switch, the steering angle is only discrete. Some modern analog beamforming antennas have been reported [3][4], but they still use a switch-based operation that does not meet the demands of continuous steering. In attempts to achieve continuous beam steering, unique architectures of analog beamforming [5][6] have been proposed. They offer continuous beamforming but unfortunately cannot control the direction of their nulls. A state-of-the-art GaAs MMIC chip [7] provided continuous beam and null steering, but it still needs RF amplifiers because it’s intended for use in active phased arrays. A possible solution for drastic reduction of both dc power dissipation and fabrication is aerial beamforming (ABF) [8] by coupled parasitic radiators.

Figure 1 shows a practical configuration of an ABF antenna that consists of a single quarter-wavelength vertical monopole radiator cabled to an RF receiver. Six parasitic radiators are positioned around the center radiator at equal intervals, and a varactor is loaded in the bottom of each parasitic radiator. Variable beamforming is carried out by...
controlling the reactance of the varactors. Since the element factor of our structure is approximately the same as that of a single monopole without parasitic radiators (omni-directional in the azimuth plane), the far-field directivity is mainly dominated by its array factor [9], explicitly formulated as

\[ D(\theta, \phi) = 2z_0 a(\theta, \phi) \frac{T}{T} \{Z + \text{diag}[z_0, jx_1, jx_2, \ldots, jx_6] \}^{-1} u_0 \]

where \( z_0 \) is the RF receiver's input impedance, \( Z \) is the impedance matrix characterizing the mutual coupling among the radiators, \( x_k \) is the \( k \)-th varactor’s reactance, and \( u_0 \) is a unit vector with its first component of unity. Due to the circular layout of the parasitic radiators, the steering vector \( a(\theta, \phi) \) has a symmetric and cyclic form expressed by

\[ a(\theta, \phi) = [1, \exp \left\{ j\beta d \cos \phi \phi \right\}, \exp \left\{ j\beta d \cos \phi (\phi - \pi / 3) \right\}, \ldots, \exp \left\{ j\beta d \cos \phi (\phi - 5\pi / 3) \right\}]^T \]

as a function of the arrival elevation angle \( \theta \) and azimuth angle \( \phi \), where \( \beta \) is the propagation phase constant in free space and \( d \) is the distance between radiators. This steering vector is similar to that of a conventional circular array except for the first component, which is unity. It is clear in this formulation that the directivity is a non-linear function of the reactance. This means that the beam control of these varactor-loaded parasitic radiators is more complicated than the weight control of conventional phased arrays or DBF antennas.

3. TRAINING-BASED ADAPTIVE BEAMFORMING

It is critical for smart antenna to find the optimal set of reactance values that maximize the output signal to interference plus noise ratio (SINR) when not only the desired wave but also interference arrives. The primary objective is to extract the desired signal from the mixed received signal, even when the arrival directions of the waves are unknown to the receiver. To distinguish the desired signal from interference, a training code is inserted in wireless packet frames of the desired signal. To estimate the difference between the received signal and the training code, a Minimum Mean Square Error (MMSE) criterion is generally used for DBF antennas. This criterion is unsuitable for the ABF antenna because it cannot adjust the amplitude of the received signal. In stead of the above function, we propose a new criterion employing the cross-correlation coefficient:

\[ \frac{E \left[ y(t)^2 \right]}{E \left[ r(t)^2 \right]} \rightarrow \max : y(t) = \sum_{k=1}^{K} D(\theta_k, \phi_k) s_k(t) + n(t) \]

This criterion is called the Maximum Cross Correlation Coefficient or “MCCC,” which is pronounced “MC-cube.” The received signal \( y(t) \) is the directivity-weighted superposition of all arriving signals \( s_k(t) \) plus noise \( n(t) \). Since this criterion is normalized by the magnitude of both the received signal \( y(t) \) and training code \( r(t) \), the waveform comparison between them is properly executed even with unwanted amplitude deviation in the wireless link. If this coefficient is maximized by using a function optimizer such as a steepest gradient algorithm or Hamiltonian algorithm [10-12], the reactors are adaptively controlled so that interference is sufficiently suppressed to effectively extract the desired signal.

4. BLIND-BASED ADAPTIVE BEAMFORMING

A challenge of greater importance is to find the optimal set of reactance values when the transmitted signal includes no training codes or when the signal waveform is unknown to the receiver. The objective of blind beamformers is to extract the desired signal from the mixed received signal without relying on any prior information on the transmission. To carry out blind beamforming, the Maximum Moment Criterion (“MMC”) is newly defined:

\[ \frac{E \left[ y(t)^2 \right]}{E \left[ y(t)^2 \right]} \rightarrow \max : y(t) = \sum_{k=1}^{K} D(\theta_k, \phi_k) s_k(t) + n(t) \]

This criterion uses the first-order moment in the statistics of the amplitude normalized by the power of the received signal. It is mathematically equivalent to minimizing the received signal’s amplitude deviation and analogous to CMA in blind DBF antennas. Table 1 summarizes the criteria for smart beamforming. The unique feature of MMC is that you can apply it to ABF antennas even if the target amplitude is unknown to the receiver. Figure 2 shows numerical examples of computer simulations run to verify the performance of this blind adaptive beamforming technique. After adaptation, directivity successfully converges and achieves a radiation pattern that orients the main beam and null in the directions of the desired signal and interference, respectively.
5. CONCLUSION

Analog beamforming drastically simplifies the configuration of adaptive array antennas. The frequency converters and analog-digital converters used in DBF antennas are eliminated. Spatial combining of signals is carried out by electromagnetic coupling among radiator elements. Furthermore, the inherent inaccuracy of analog devices is automatically compensated by using cross-correlation and feedback control. Both the trained- and blind-based adaptive approaches proposed in this paper offer potential breakthroughs to new and wider application fields of wireless systems, especially the development of battery-operated consumer wireless devices.

REFERENCES


Fig. 1 Aerial beamforming architecture with trained- or blind-smart feedback control.
### Table 1 Criteria for smart beamformers.

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<th>ABF</th>
<th>DBF</th>
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<td>trained</td>
<td>$\text{MCCC} \quad \frac{\mathbb{E} \left{ y(t)^* r(t) \right}}{\mathbb{E} \left</td>
<td>y(t) \right</td>
</tr>
<tr>
<td>blind</td>
<td>$\text{MMC} \quad \frac{\mathbb{E} \left</td>
<td>y(t) \right</td>
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Both desired signal and interference arrive at a power level 10 dB over the noise.

Fig. 2 Blind beamforming simulation results in power pattern.