ELECTRONICALLY STEERABLE PARASITIC ARRAY RADIATOR ANTENNA
– PRINCIPLE, CONTROL THEORY AND ITS APPLICATIONS –

Makoto Taromaru and Takashi Ohira

ATR Wave Engineering Laboratories
2-2-2 Hikaridai, Keihanna Science City, Kyoto 619-0288 Japan
email: taromaru@atr.jp, web: http://www.atr.jp/wel/

ABSTRACT

Principle, control theory, and application of the ESPAR (Electrically Steerable Parasitic Array Radiator) antenna are introduced. A typical ESPAR antenna consists of monopole or dipole elements, one of which is the radiator (fed element) and the others are the parasitic radiators with variable reactance devices loaded on them. It can provide a lower-cost solution as an adaptive array antenna or angle diversity antenna, since it needs only a single receiver circuit. ESPAR antennas can be applied to adaptive beam formers, diversity receivers, and DoA (Direction of Arrival) finders. This paper shows the principle of ESPAR antenna from the viewpoint of radio system design and applications.

INTRODUCTION

The ESPAR (Electrically Steerable Parasitic Array Radiator) antenna consists of one active radiator and some parasitic elements loaded with reactance devices [1]-[3], as shown in Fig. 1 and 2. The elements are monopoles or dipoles and the space is typically a quarter wavelength. Element #0 is the active radiator (the fed element) and the other elements are the parasitic radiators which are loaded with variable reactors at the bottom. Fig. 2 shows the configuration of a seven-element ESPAR antenna. It can provide a lower-cost solution to system needs as an adaptive array antenna or pattern diversity antenna, since it needs a single receiver circuit only. The ESPAR system changes its radiation pattern not with RF switches but with variable reactors loaded on the parasitic elements. The reactors are usually varactor (varicap) diodes that cost less than GaAs FET RF switches. ESPAR antennas can be applied to adaptive beam forming with steepest descent methods, diversity reception, and DoA (Direction of Arrival) estimation. However, the methods or algorithms for conventional digital beamformers with adaptive array antennas cannot be directly applied to the ESPAR antenna, because the element weights cannot be controlled directly and the mapping from the reactance set to the equivalent weight is non-linear.

This paper shows the principle of ESPAR antenna from the viewpoint of radio system design and applications. First, the basic configuration and principle is described. For the second, the control and operation methods for adaptive beamforming are expressed. Finally, DoA finders [4] and a diversity antenna for digital TV[5] are introduced as its typical applications.

THE ESPAR ANTENNA AND ITS DIRECTIVITY

Here, we derive the ESPAR antenna’s beam pattern with “equivalent weight vector method” [3],[5],[6]. Since a beam pattern of an array antenna can be calculated by the normalized complex current on each element in transmission mode, we can think of the current as the element weight of conventional adaptive array antenna. Fig. 3 shows the configuration of a three-element ESPAR antenna. Let $x_k$ and $i_k$ be the loading reactance and the current, respectively, at the feed point of the $k$-th element, and let $z_s$ and $v_s$ be the drive impedance and open voltage of the transmitter, respectively, as shown in Fig. 1.

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The voltage for each feed point is expressed as \( \mathbf{v}_i = \mathbf{x}_i \mathbf{u}_i \), where \( \mathbf{v}_i = (i_0, i_1, i_2, \ldots, i_N)^T \), \( \mathbf{X} = \text{diag}(\mathbf{z}_1, \mathbf{f}_1, \mathbf{f}_2, \ldots, \mathbf{f}_N) \), \( \mathbf{u}_i \) is the unit vector of \((1, 0, 0, \ldots, 0)^T\), and superscript \( T \) denotes the matrix transpose. \( \mathbf{Y} \) is the admittance matrix of the array elements as a network, assuming \( \det(\mathbf{Y}) \neq 0 \), and it is also a constant determined by the physical structure. By normalizing each current by \( \mathbf{v}_i/(2\mathbf{z}_i) \), we introduce “equivalent weight vector” \( \mathbf{w} \) so that \( \mathbf{w} \cdot \mathbf{v}_i/(2\mathbf{z}_i) = 1 \). We obtain
\[
(Y^T + X)\mathbf{w} = 2\mathbf{z}_i \mathbf{u}_i \quad \text{or} \quad \mathbf{w} = 2\mathbf{z}_i (Y^T + X)^{-1} \mathbf{u}_i,
\]
where we assume that \( \det(Y^T + X) \neq 0 \) and that \( z_i \) is real. Therefore, \( \mathbf{w} \) determines the radiation pattern and is the same as combining weights of digital beamformers or common adaptive array systems. \( \mathbf{w} \) is a function of the loading reactance set \( \mathbf{x} = (x_1, x_2, \ldots, x_N)^T \) and here we call the space where \( \mathbf{w} \) exists “Esparr Weight Space” \( W_E \). Let \( \mathbf{a}(\phi) \) and \( \mathbf{b}(\phi) \) be the steering vectors depending on the structure and the direction, respectively. The beam pattern is expressed in complex form as
\[
D(\phi) = \mathbf{w}^\dagger \mathbf{a}(\phi).
\]

THEORETICAL ANALYSIS

The authors found some properties of the mapping between \( \mathbf{w} \) and \( \mathbf{x} \). These are important and the base to design beam patterns and adaptive algorithms of ESPAR antenna. It can be proven through mathematical analysis [5] that:

1. The conversion, \( \mathbf{x} \) to \( \mathbf{w} \), is one-to-one mapping. \( \mathbf{x} \) can be unique when any \( \mathbf{w} \in W_E \) is given if \( w_k \), the \( k \)-th factor of \( \mathbf{w} \), is always non-zero for any \( k \).
2. For certain \( k \), with fixed \( w_i \)'s for all \( i \neq k \), the mapping from \( x_k \) to \( w_k \) and to \( w_o \) is conformal and a bilinear transform.
3. For certain \( k \), with fixed \( w_i \)'s for all \( i \neq k \), the trajectory of \( w_k \) with \( x_k \) varied is a circle departing and terminating at the origin. Note that
\[
w_k \to 0 \quad \text{when} \quad |x_k| \to \infty.\]

This is clear because it is a conformal mapping.

Using the property of a bilinear transform, it is derived that \( w_k \) rotates \( \theta \) on its trajectory circle whenever \( w_i \) rotates \( \theta \) and the direction is the same with one another. Fig. 4 shows an example of the trajectories of \( \mathbf{w} \) on the complex plane in the case of three element [5].

ADAPTIVE BEAMFORMING

The beam pattern of an ESPAR antenna can be controlled adaptively so as to minimize a cost function through an iteration process of steepest descent method, similarly to conventional adaptive array antennas [3],[7]. Through these algorithms described below, adaptive beam control forming a lobe and nulls toward the desired signal and interference respectively is performed in the same way of conventional digital beamforming antennas.

As a typical control criterion, we show here the normalized mean square error about the cross correlation coefficient (CCC) between the received signal \( y(t) \) and the reference signal \( r(t) \) [1],[6]. The cost function is simply represented by
\[
J = 1 - \rho_{yr}^2 = \frac{E[\mathbf{y}(t)\mathbf{r}^*(t)]}{E[\mathbf{y}(t)]E[\mathbf{r}(t)]},
\]
where \( \rho_{yr} \) denotes the ensemble average and the superscript * represents the complex conjugate. Since the goal of the iteration is to maximize the CCC, we also call this algorithm a maximum CCC (MCCC) algorithm. In this optimization problem, the system parameters are the reactance values, which are controlled by the bias voltages at varactors. The desired beam pattern is obtained by changing the reactance values through iterations. It is necessary to calculate the gradient of the optimization search route in a deterministic manner at each step of the iteration. Let \( \mu_o \) the step size.
at the $m$-th iteration respectively. The reactance values $\mathbf{x}=[x_1 \ x_2 \ldots \ x_M]^T$ or the bias voltage values onto the varactors $\mathbf{v}=[V_1 \ V_2 \ldots \ V_N]^T$ are updated as follows

$$\mathbf{x}(m+1) = \mathbf{x}(m) - \mu_n \nabla J$$

$$\mathbf{v}(m+1) = \mathbf{v}(m) - \mu_n \nabla J,$$

where $\nabla J = \left[ \frac{\partial J}{\partial x_1} \ \frac{\partial J}{\partial x_2} \ \ldots \ \frac{\partial J}{\partial x_N} \right]^T$ or $\nabla J = \left[ \frac{\partial J}{\partial V_1} \ \frac{\partial J}{\partial V_2} \ \ldots \ \frac{\partial J}{\partial V_N} \right]^T$ respectively. Each gradient value can be estimated directly by perturbation method as $\frac{\partial J}{\partial x_n} \approx \frac{J_n^{+} - J_n^{-}}{2\Delta_n}$ or $\frac{\partial J}{\partial V_n} \approx \frac{J_n^{+} - J_n^{-}}{2\Delta_n}$ where $J_n^{+}$ is the perturbed value of $J$ when the $n$-th reactance is perturbed as $x = x(m) \pm \Delta_n u_n$ or $v = v(m) \pm \Delta_n u_n$ respectively and $u_n$ is the $n$-dimensional unit vector having “1” at the $n$-th element. The step size $\mu_n$ and the perturbation size $\Delta_n$ can be chosen as a positive constant or a positive number series decreasing to zero or a sufficient small value. A more efficient algorithm to obtain the gradient vector is described in [3]. Fig. 5 illustrates an experimental result of formed beam patterns. Furthermore, blind beamforming is also proposed [8],[9].

**DIRECTION OF ARRIVAL ESTIMATION**

In the similar way to the conventional DoA estimation methods using an array antenna, the ESPAR antenna can be employed for them. The simplest one is Power Maximizing (PM) method [4]. It can be accomplished by selecting the beam pattern that provides the strongest signal among a pre-determined beam patterns having one main lobe. The main lobe should be narrow for a better resolution. Though this method can estimate DoA with a discrete value, a continuous angle of direction can be obtained with power pattern cross-correlation method [10]. It is necessary for these methods that the signal to sense has a constant signal power. In case of an amplitude modulation signal, however, RSSI (received signal strength indicator) signal is usually filtered or averaged in a short term so envelope fluctuation due to modulation is not significant. Fig. 6 is a prototype of DoA finder for 2.4 and 5.2 GHz bands. Super/high-resolution or vector subspace-based methods, like MUSIC and ESPRIT can be used with ESPAR antenna if the signal to sense contains a same part periodically, like a preamble located at the head of time slots [11]. These are accomplished with “reactance domain signal processing”. Conventional signal processing for an array antenna uses received signals from each array element or a beamforming network so it is sometimes called “space domain processing” or “beam space processing”. However, these cannot be used with an ESPAR antenna since it has a single port output. The reactance domain processing observes the received signal $y(t)$ from the single output port as it switches over a set of antenna patterns by changing the loaded reactance on the parasitic elements. It obtains a correlation matrix $\mathbf{R}_{yy} = E[\mathbf{y}(t)\mathbf{y}^H(t)]$ in reactance domain, where $\mathbf{y}$ is the received signal vector defined as $\mathbf{y} = [y(x_1, t^M+t_1) \ y(x_2, t^M+t_2) \ \ldots \ y(x_M, t^M+t_M)]^T$ and $y(x_m, t)$ denotes the $y(t)$ observed when the reactance set $x_m$ for the $m$-th beam pattern is loaded in the time range $t_m < t < t_{m+1}$. $t_1$ is the constant time period to observe it. By using this matrix, DoAs of coherent and incoherent signals can be estimated with MUSIC, ESPRIT, or other algorithms.

**REACTANCE DIVERSITY RECEPTION[5]**

Another interesting and most practical application of an ESPAR antenna is a diversity antenna. It can provide a much lower-cost solution as an angle diversity system. The ESPAR system changes the radiation pattern as the diversity branch not with RF switches but with varactors that cost less than the RF switches of GaAs FETs. Power consumption is less than PIN diode switches and there is no insertion loss in an ESPAR antenna. It switches the reactance set of the varactors to change the beam pattern. Switching is carried out with an algorithm according to the RSSI signal. It should be noted that the three-element ESPAR as illustrated in Fig.3 does

![Fig. 5. Beam patterns formed by MCCC criterion and steepest descent algorithm [3]. N denotes the iteration time.

![Fig. 6. Direction of arrival finders for 2.4GHz (left) and 5.2 GHz (right)

![Fig. 7. Bit error rate performance of reactance diversity with three-element ESPAR antenna](image-url)
not change its impedance by switching if the reactance is switched in the binary states, $(x_1, x_2) = (x_l, x_h)$ and $(x_h, x_l)$. Fig. 7 shows an example of a simulation result in case of BPSK coherent detection receiver in mobile terminal environment.

Fig. 8 is a prototype of dipole type three-element ESPAR antenna for the reactance diversity reception of terrestrial digital TV broadcasting in indoor environment. The specification of the design is as the followings:

- Frequency range: $470 - 550$ MHz
- Return loss: $> 6$ dB
- F/B ratio: $> 10$ dB

The F/B ratio specified above is required to get sufficient diversity performance. We made simulations to determine the element space $d$. The simulation result shows that the element space $0.05\lambda_0$ is good, where $\lambda_0$ is the wavelength at $500$ MHz, and it is confirmed in our measurements of the prototype.

CONCLUSION

The principle of ESPAR antenna from the view point of radio system design and applications are introduced. ESPAR antennas are adaptive antennas with low power consumption. They can be manufactured at very low cost especially when they can be built on printed circuit boards. It is ideal for mass production of consumer products.

REFERENCES