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A Dual-Band Planar Array of Connected Dipoles: Experimental Validation Based on Bistatic RCS Measurements

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Abstract—Rigorous equivalent networks representing connected arrays in transmission and reception are derived in this paper. These equivalent networks are not based on reciprocity but on Green’s functions. Thus, all components have well identified and physically meaningful roles. A dual-band connected array demonstrator is then presented to validate the theory. The matching properties of the array are characterized via Radar Cross Section (RCS) measurements without resorting to lossy and expensive feeding networks.

I. INTRODUCTION

Recently, there is an increasing need to integrate several functionalities on the same antenna aperture to achieve weight and physical size reduction in environments where real estate is limited or precious such as cars, aircrafts, spacecrafts or ships. For instance, in the design of military ship masts, multifunction antennas are necessary in order to satisfy the demand of a growing number of services to be installed on board, while still responding to the requirement of reducing the Radar Cross-Section (RCS) of the ship itself. In view of this, broadband or multiband planar antennas with large scanning capabilities are investigated.

Connected array technology is nowadays considered a very promising solution for such applications, as it promises both wideband properties and polarization purity [1]. However, as shown in [2], when these arrays are used in the presence of a backing reflector in order to maximize the efficiency, the frequency relative bandwidth is limited to about 40%, when scanning up to 45° for all azimuthal planes. In [3], a backing structure for such arrays was proposed, comprising a combination of a ground plane and a Frequency Selective Surface (FSS), designed to behave as perfect reflectors in two different frequency ranges. In particular, for lower frequencies, where the FSS is transparent for the impinging field, the backing reflector of the array is the real ground plane, whereas in the upper frequency range the FSS behaves as perfect reflector. The double backing structure was designed to obtain a dual-band operation for combined X-band (8.50-10.50 GHz) radar and Ku-band (14.40-15.35 GHz) Tactical Common Data Link (TCDL) applications.

Since the wideband performance of connected arrays is associated with large dimensions in terms of the wavelength, realistic demonstrators should include many antenna elements. In order to evaluate the matching properties of the array one is typically obliged to build a realistic feeding network that is lossy and expensive. Even by doing so, it is difficult to isolate the effect of the feeding lines from the properties of the radiating part of the antenna.

In this paper, the properties of the connected arrays in transmission are evaluated by interpreting the properties measured in reception, when no feeding network is considered and all elements are closed in matched loads. In order to achieve this goal, the Green’s Function of connected arrays in reception is derived by generalizing the procedure introduced in [2] and [3]. While the formulation differences are relatively minor, the extension to reception cases is of importance because it allows the derivation of a rigorous equivalent circuit for the antenna array elements in reception without resorting to reciprocity theorem. This equivalent circuit presents an analytically evaluated component for each geometrical design parameter of the array.

A 32×32 prototype demonstrator has been manufactured, and the performance of the array in terms of matching and efficiency as a function of the scanning angle are discussed by comparing the measurements with the results of the equivalent network and full wave simulations. The excellent agreement of the simulation methods and the measurements indicates that a good comprehension of the dominant connected array phenomena is obtained.

II. PROBLEMS WITH STANDARD EQUIVALENT CIRCUITS IN RECEPTION

Standard equivalent circuits for antennas (see for instance [4], pp.80-85), present an evident asymmetry when they are used in transmission and in reception. In fact, while in
transmission the generator only depends on the characteristics
of the source, in reception the voltage generator contains in
itself the information about the antenna shape, and not only
the characteristics of the source alone (i.e. the incident field).
In fact, with reference to the equivalent circuit of a receiving
atom[4], $V_i = -E_i h$, that is the scalar product of the
incident field and the effective height of the antenna. This
choice imposes a value for the impedance of an equivalent
Thevenin generator: $Z_{\text{Thevenin}} = Z_{\text{antenna}}$. However, as in all
Thevenin equivalent circuits one cannot associate a physical
meaning to this equivalent impedance (see in [5], p. 354, to
this regard). In our view, a more useful equivalent circuit
should be derived, that sees the antenna as a transition
between two guiding structures, the dominant Floquet waves
on one side and the guided waves on the other. This
representation should not resort to Thevenin equivalence to
represent the antenna but to Green’s functions. In the
following, such a circuit is derived for connected arrays in
reception.

### III. Equivalent Circuits for Connected Arrays of
Loaded Dipoles

The connected array of dipoles in Fig. 1(a) is investigated.
The array is composed of an infinite number of $x$-oriented
dipoles, periodically spaced by $d_x$ along $y$. Each dipole is fed
at locations displaced by $d_y$ by a voltage generator $V_i$ with
load impedance $Z_l$. The loads are represented by assuming
equivalent distributed surface impedance over the gaps region,
as depicted in Fig. 1(b). Accordingly, we can impose
boundary conditions as follows:

$$e^{\text{tot}} = Z_{\text{surf}} i_x \times (h_{x}^{\text{tot}} - h_{x}^{\text{surf}}),$$

where $h_{z}^{\text{tot}}$ represent the total magnetic fields for $z > 0$, respectively. This equation is valid on the entire array surface
$\Sigma_c \cup \Sigma_g$, if we assume that the surface impedance $Z_{\text{surf}}(x, y)$
is a discontinuous function which is equal to zero on the
conducting part of the dipoles, and different from zero on the
gaps.

The total electric field can be expressed as the
superposition of the incident and the scattered field. Focusing
only on the longitudinal ($x$) component of the electric field, eq.
(1) can be expressed in integral form as follows

$$\int_{\Sigma_c \cup \Sigma_g} j_x(r) g_{xx}(r,r')dr' = -e_{x}(x,y) + Z_{\text{surf}} j_x(x,y),$$

where $g_{xx}$ is the free space GF, and $e_{x}$, $j_x$ are the $x$-
components of the incident field and the equivalent electric
surface current density, respectively.

Eq. (2) can be solved with a procedure similar to the one
presented in [1], leading to the following expression for the
current distribution on the zero-th dipole:

$$i(x) = \frac{1}{d_x} \sum_{m=-\infty}^{\infty} \frac{-E_i(k_m) + Z_{\text{surf}} \text{sinc}(k_m \delta / 2)}{D_j(k_m)},$$

where

$$D_j(k_m) = (1/d_x) \sum_{m=-\infty}^{\infty} J_0(k_m w / 2) G_{xx}(k_m, k_m),$$

Eq. (3) can be rendered explicit by evaluating $i_{x=0}$, which
leads to

$$i_{x=0} = \begin{cases}
\frac{V_i}{Z_0 + Z_{\text{surf}}} & \text{in Transmit} \\
\frac{Z_0 - e_x \text{sinc}(k_0 \delta / 2)}{Z_0 + Z_{\text{surf}}} & \text{in Receive}
\end{cases}$$

The input admittance (impedance) of a connected array of
dipoles was derived in [2] and is equal to:

$$Y_i = \frac{1}{Z_0} = \frac{1}{d_x} \sum_{m=-\infty}^{\infty} \frac{-\text{sinc}^2(k_m \delta (n)/ 2)}{D_j(k_m)}.$$
1) one associated with the fundamental mode \( m_x=0, m_y=0 \), which is the only propagating mode representing the plane wave transmitted by the infinite array \( (Z_{\infty}) \);
2) a series term accounting for the higher order transverse modes, \( (m_x=0, m_y \neq 0) \), mainly depending on the dipole width \( (Z_{\text{dipole}}) \);
3) a parallel term accounting for the higher order longitudinal modes, \( (m_x \neq 0, m_y \neq 0) \), which models the capacitance associated with the feeding gap \( (Z_{\text{gap}}) \).

An equivalent circuit representation of the input impedance at the terminals of a dipole element of the array in transmission is shown in Fig. 2. With reference to this circuit, one can represent the fundamental Floquet mode as a series of two transmission line associated with transverse electric (TE) and transverse magnetic (TM) components of the radiated or incoming plane wave, respectively. The characteristic impedances of the two TE and TM transmission lines are equal to \( Z_{\text{TE}} = \zeta_0 \cos \theta \), \( Z_{\text{TM}} = \zeta_0 \cos \theta \) and we introduced two transformers with transformation ratios \( n_{\text{TE}} = \cos^2 \phi \frac{J_0(k_y \omega w/2)}{\text{sinc}^2(k_x \omega \delta/2)} \), \( n_{\text{TM}} = \sin^2 \phi \frac{J_0(k_y \omega w/2)}{\text{sinc}^2(k_x \omega \delta/2)} \).

Note that the presence of the backing reflector is accounted for by representing the lower medium as a short circuit stub at \( z = -h \). For an array in free space a similar equivalent circuit would apply, but the lower transmission lines would be infinite as the upper ones, rather than short circuited.

IV. EFFICIENCY OF RECEIVING CONNECTED ARRAYS

The equivalent circuit presented in section III can be used to predict the performance of a connected array in transmission (Tx) and reception (Rx). The main advantage of this equivalent circuit based on Green’s functions is that the antenna is represented as a transition between a plane wave representing the fundamental Floquet mode and a guided wave, and so the same explicit equivalent circuit can be used in Tx and Rx.

While the Thevenin equivalent circuit for receiving antennas leads to the wrong conclusion that all antennas are bound to absorb only half of the incoming power, the equivalent circuit here proposed permits demonstrating, as in [7], that this conclusion is not generally true, but only in particular cases. In fact, from an analysis of the circuits in Fig. 2, it can be proved (steps are omitted for brevity) that, for an array in free space, only half of the power can be absorbed by the antenna loads, while the other half is scattered by the antenna. However, when a backing reflector is present, the array in reception has fully efficiency, i.e. can receive the entire incoming power.

Moreover, it can be shown that the matching of the array in Tx is equal to the matching of an incident plane wave in Rx. Thus, one can characterize the matching properties of the array in transmission without having to design complicate feeding network, but investigating the receiving properties of the array from RCS measurements.

V. ARRAY PROTOTYPE

A prototype demonstrator that has been manufactured to validate the design procedures presented in [2] and [3]. The demonstrator represents a receiving connected array composed of 32×32 elements operating on two separate frequency bands (8.5-10.5 GHz and 14.40-15.35 GHz), for simultaneous radar and Tactical Common Data Link (TCDL) applications. The dual band operation is achieved by backing the dipole arrays with a combination of a ground plane and a Frequency Selective Surface (FSS), designed to behave as perfect reflectors in two different frequency ranges. In particular, at lower frequencies the FSS is transparent for the impinging field, and the ground plane act as a backing reflector, whereas in the upper frequency range the FSS behaves as perfect reflector.
The unit cell stratification is presented in Fig. 3. The dipoles are printed on a thin dielectric substrate from Rogers, LG4002 ($\varepsilon_r=2.89$, 0.075mm thickness). This layer is glued on a foam from Rohacell ($\varepsilon_r=1.06$, 4.117mm thickness) by means of an adhesive film from Arlon, CuClad 6250 ($\varepsilon_r=2.32$, 0.039mm thickness). With the same procedure, the FSS is printed and glued on a foam layer (2.756mm thickness). The two boards are then glued by means of adhesive Arlon, CuClad 6250 and a metallic plate is then fixed at the bottom of the foam. The array and FSS elements together with the geometric dimensions are depicted in Fig. 4. The feeding point of each dipole is composed by a double-gap configuration and a ‘S’-shaped line in order to improve the matching by adjusting capacitive and inductive energy associated with the feed.

The FSS element is a four-legged dipole as shown in the right hand side of Fig. 4. Such element has good performance against angular variation and, since the total element length can be kept quite small [6], it allows a very packed lattice, with a further gain in angular independence. On the other hand, the more packed the elements the less steep the roll-off, due to the capacitive coupling between the elements. For this reason a proper trade off has been performed.

VI. EXPERIMENTAL RESULTS

Active reflection coefficients, are shown in Fig. 6, for scanning at broadside and at $\theta = 45^\circ$ in the two main planes. Measured results are compared with the equivalent circuit model proposed in this work and with full-wave simulations performed via HFSS.

The array is loaded with resistors equal to the characteristic impedances that would be used to match the array fed in transmission. The HFSS simulations are related to infinite array in transmission, while the equivalent circuit and the measurement to array in reception. The measured reflection coefficient has been evaluated as the Radar Cross Section (RCS) of the array normalized to the RCS of a metal plate with the same physical dimension of the array.

VII. CONCLUSIONS

Thevenin equivalent circuits are often used to describe the antenna in reception. However, the impedance of the Thevenin generator has no physical meaning, and it is erroneously in some textbooks associated with the power scattered by the antenna. In fact, this is true only for some particular cases, but not in general.

In this paper, we have proposed an equivalent circuit for connected arrays, based on Green’s functions, that presents an analytically evaluated component for each geometrical design parameter of the array. This circuit allows demonstrating that the matching of a transmitting array in the presence of a backing reflector is equal to the reflection coefficient of an incoming plane wave when the array is used in reception.
These theoretical findings have been used to characterize the matching properties of a prototype connected array demonstrator by only measuring the bistatic RCS of the antenna and thus avoiding the design and the manufacture of a complicate feeding structure.

REFERENCES


