Proceedings of the 2015 IEEE Radio & Wireless Week,
RWW 2015, January 2015, pp. 41-43.

A New Multiple-Antenna-Port and Multiple-User-Port Antenna Tuner

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***Abstract* — A new multiple-antenna-port and multiple-user-port antenna tuner has the structure of a multidimensional π-network. It is shown that it is able to provide decoupling and matching in the presence of strong variations in the electromagnetic characteristics of the volume surrounding the antennas.**

***Index Terms* — Antenna tuning, impedance matching, radio receiver, radio transmitter, MIMO radio communication.**

I. Introduction

The impedance matrix presented by a multiport antenna array and the associated feeders, denoted by $\mathbf{Z}_{Sant}$, is a function of frequency. It also depends on the electromagnetic characteristics of the volume surrounding the antennas. This dependency may give rise to a time-dependent $\mathbf{Z}_{Sant}$ in cases where these characteristics vary. This for instance occurs for a multiport antenna array built in a portable transceiver such as a mobile phone using multiple antennas simultaneously for MIMO communication, because in this case $\mathbf{Z}_{Sant}$ is affected by surrounding objects and by the body of the user.

The antenna ports of a multiple-antenna-port and multiple-user-port (MAPMUP) antenna tuner may be coupled to the n antennas of the multiport antenna array, as shown in Fig. 1. The impedance matrix presented by the m user ports of the MAPMUP antenna tuner, denoted by $\mathbf{Z}_U$, can be adjusted to equal or approximate a wanted impedance matrix $\mathbf{Z}_{UW}$.

It has been proposed to use a MAPMUP antenna tuner made up of several uncoupled single-antenna-port and single-user-port antenna tuners [1]. However, the tuning capabilities of this type of antenna tuner is limited, so that MAPMUP antenna tuners which cannot be separated into independent and uncoupled antenna tuners have also been disclosed [2] [3] [4].

This paper shows that a new MAPMUP antenna tuner, coupled to an array of strongly coupled antennas, can be used to obtain that $\mathbf{Z}_U$ equals a diagonal $\mathbf{Z}_{UW}$, that is to say, decoupling and matching, in spite of varying electromagnetic characteristics of the volume surrounding the antennas. Section II presents the new antenna tuner. Section III describes an antenna array subject to varying electromagnetic characteristics of its environment. Section IV presents the predicted antenna tuner performance.

II. A New MAPMUP Antenna Tuner

A new antenna tuner has the structure of a multidimensional π-network [5]. It is shown in Fig. 2, in the case $n = 4$. Assuming that $\mathbf{Z}_{Sant}$ is symmetric, $\mathbf{Z}_U$ is symmetric because the circuit is reciprocal. Thus, there is a possibility of independently controlling the n (n + 1) real parameters which define the symmetric matrix $\mathbf{Z}_U$, because this antenna tuner comprises n (n + 1) adjustable impedance devices presenting a negative reactance, represented as variable capacitors in Fig. 2.

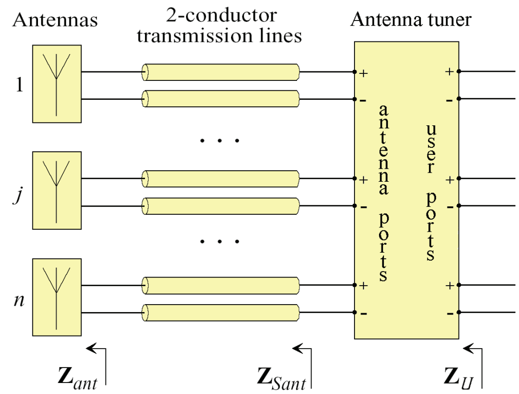

Fig. 1. An array of n antennas coupled to a MAPMUP antenna tuner, through n uncoupled 2-conductor transmission lines.

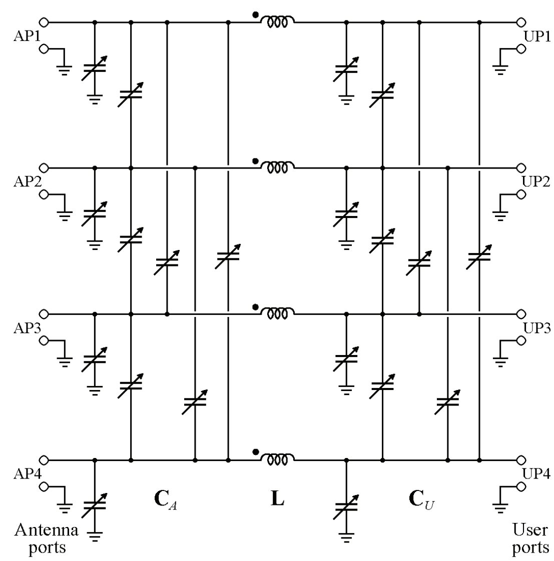

Fig. 2. The new MAPMUP antenna tuner, shown in a configuration having $n = 4$ antenna ports, labeled AP1 to AP4, and $m = 4$ user ports, labeled UP1 to UP4.

Let $\mathbf{C}_A$ be the capacitance matrix of the n (n + 1)/2 adjustable impedance devices each coupled to one of the antenna ports, $\mathbf{L}$ be the inductance matrix of the windings and $\mathbf{C}_U$ be the capacitance matrix of the n (n + 1)/2 adjustable impedance devices each coupled to one of the user ports. $\mathbf{Z}_U$ is given by

$$\mathbf{Z}_U = \left[\left[\left[\mathbf{Z}_{Sant}^{-1} + j\omega\, \mathbf{C}_A \right]^{-1} + j\omega\, \mathbf{L} \right]^{-1} + j\omega\, \mathbf{C}_U \right]^{-1} \tag{1}$$

We specify $\mathbf{Z}_{UW} = (1/g_0)\, \mathbf{1}_n = r_0\, \mathbf{1}_n$, where $\mathbf{1}_n$ is the identity matrix of size $n \times n$ and where the conductance g_0 and the resistance r_0 are real. To obtain $\mathbf{Z}_U = r_0\, \mathbf{1}_n$, we need to solve

$$\left(g_0 \mathbf{1}_n - j\omega\, \mathbf{C}_U \right)^{-1} = \left(\mathbf{Z}_{Sant}^{-1} + j\omega\, \mathbf{C}_A \right)^{-1} + j\omega\, \mathbf{L} \tag{2}$$

Let $\mathbf{G}_A$ and $\mathbf{B}_A$ be real matrices satisfying $\mathbf{Z}_{Sant}^{-1} = \mathbf{G}_A + j\mathbf{B}_A$. The design of an antenna tuner providing $\mathbf{Z}_U = r_0\, \mathbf{1}_n$ at a given frequency f_A, in the presence of variation in the electromagnetic characteristics of the volume surrounding the antennas, may for instance be carried out as follows:

step 1 — determine a set of typical values of $\mathbf{Z}_{Sant}$ at the frequency f_A and select one of them for the steps 3 and 4;

step 2 — select an arbitrary physically realizable capacitance matrix $\mathbf{C}_A$;

step 3 — compute $\mathbf{C}_U$ compatible with $\mathbf{Z}_U = r_0\, \mathbf{1}_n$ at f_A and for the $\mathbf{Z}_{Sant}$ selected at the step 1, using

$$\omega\, \mathbf{C}_U = \left[g_0 \mathbf{G}_A + g_0 (\mathbf{B}_A + \omega\, \mathbf{C}_A) \mathbf{G}_A^{-1} (\mathbf{B}_A + \omega\, \mathbf{C}_A) - g_0^2 \mathbf{1}_n \right]^{1/2} \tag{3}$$

step 4 — compute $\mathbf{L}$ providing $\mathbf{Z}_U = r_0\, \mathbf{1}_n$ at f_A and for the $\mathbf{Z}_{Sant}$ selected at the step 1, using

$$\omega\, \mathbf{L} = \left[g_0^2 \mathbf{1}_n + (\omega\, \mathbf{C}_U)^2 \right]^{-1} \omega\, \mathbf{C}_U + \left[\mathbf{B}_A + \omega\, \mathbf{C}_A + \mathbf{G}_A (\mathbf{B}_A + \omega\, \mathbf{C}_A)^{-1} \mathbf{G}_A \right]^{-1} \tag{4}$$

step 5 — determine whether $\mathbf{C}_U$ and $\mathbf{L}$ are realizable; if no, go back to step 2; if yes, a physically realizable solution of $\mathbf{Z}_U = r_0\, \mathbf{1}_n$ at f_A has been obtained for the selected $\mathbf{Z}_{Sant}$;

step 6 — $\mathbf{L}$ being fixed, at f_A, for any $\mathbf{Z}_{Sant}$ lying in the set determined at step 1, determine $\mathbf{C}_U$ and $\mathbf{C}_A$ providing $\mathbf{Z}_U = r_0\, \mathbf{1}_n$, using (3) and

$$\omega\, \mathbf{C}_A = (\omega\, \mathbf{L})^{-1} - \mathbf{B}_A + \mathbf{G}_A \left[(g_0 \mathbf{G}_A)^{-1} (\omega\, \mathbf{L})^{-2} - \mathbf{1}_n \right]^{1/2} \tag{5}$$

step 7 — determine whether all $\mathbf{C}_A$ and $\mathbf{C}_U$ obtained at step 6 are realizable; if no, go back to step 2; if yes, a physically realizable antenna tuner has been obtained.

III. The Antenna Array and its Environment

As a theoretical problem, we consider a circular antenna array of $n = 4$ vertical 224.8-mm-long dipole antennas. We will only consider operation at the frequency $f_A = 800$ MHz, at which the spacing between the closest antennas is about 0.212 times the wavelength. Each antenna has a 60 mm long feeder.

A large vertical plate made of a perfect electrical conductor (PEC) lies at a distance D of the antennas 1 and 2 of the array,

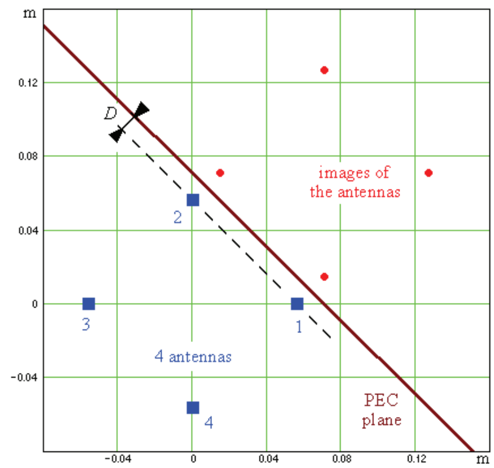

Fig. 3. In an horizontal plane, positions of the 4 vertical antennas (numbered from 1 to 4), of the vertical PEC plate and of the virtual images of the antennas formed by the PEC plate.

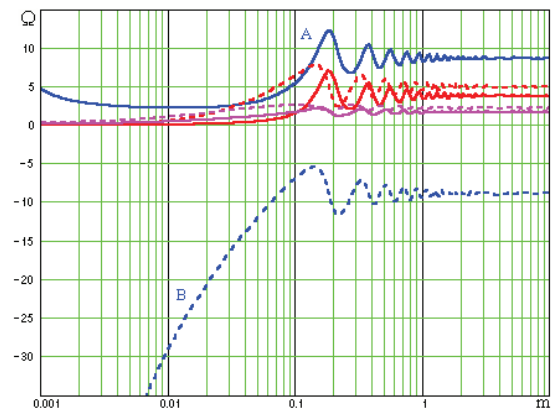

Fig. 4. Some entries of $\mathbf{Z}_{Sant}$ versus D: Re($\mathbf{Z}_{Sant\,11}$) is curve A; Im($\mathbf{Z}_{Sant\,11}$) is curve B; the 4 other curves are Re($\mathbf{Z}_{Sant\,12}$), Im($\mathbf{Z}_{Sant\,12}$), Re($\mathbf{Z}_{Sant\,13}$) and Im($\mathbf{Z}_{Sant\,13}$).

as shown in Fig. 3. This parameter of the electromagnetic characteristics of the environment of the array may be varied. At the step 1, we compute all entries of $\mathbf{Z}_{Sant}$ when D varies in the range 1 mm to 10 m. Some of these entries are shown in Fig. 4.

IV. Performance of the Antenna Tuner

The design target being that $\mathbf{Z}_U$ approximates a wanted impedance matrix $\mathbf{Z}_{UW} = r_0\, \mathbf{1}_n$, we will use the return figure as a measure of the proximity of $\mathbf{Z}_U$ and $\mathbf{Z}_{UW}$. In decibels, the return figure is given by [5]

$$F_{dB}(\mathbf{Z}) = 20 \log\left(|||\mathbf{S}(\mathbf{Z})|||_2 \right) \tag{6}$$

where log is the decimal logarithm, where $\mathbf{Z}$ is an impedance matrix of size $q \times q$, where $\mathbf{S}(\mathbf{Z})$ is a scattering matrix defined by

$$\mathbf{S}(\mathbf{Z}) = \left(\mathbf{Z} + r_0\, \mathbf{I}_q \right)^{-1} \left(\mathbf{Z} - r_0\, \mathbf{I}_q \right) = \left(\mathbf{Z} - r_0\, \mathbf{I}_q \right) \left(\mathbf{Z} + r_0\, \mathbf{I}_q \right)^{-1} \tag{7}$$

and where the spectral norm $|||\mathbf{A}|||_2$ of a matrix $\mathbf{A}$ is the square root of the largest eigenvalue of $\mathbf{AA}^*$, and the largest singular value of $\mathbf{A}$ [6, § 5.6.6 and § 7.3.10]. If $\mathbf{Z}$ is the impedance matrix

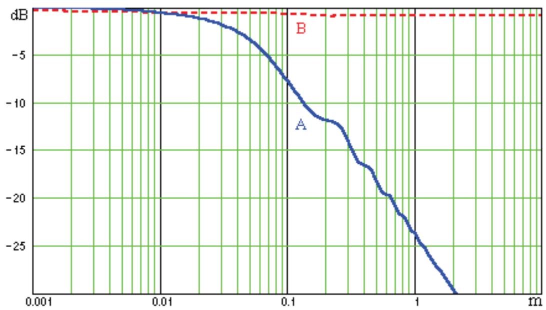

Fig. 5. The return figure versus D, at 800 MHz: $F_{dB}(\mathbf{Z}_U)$ for a tuning at D = 100 m is curve A, and $F_{dB}(\mathbf{Z}_{Sant})$ is curve B.

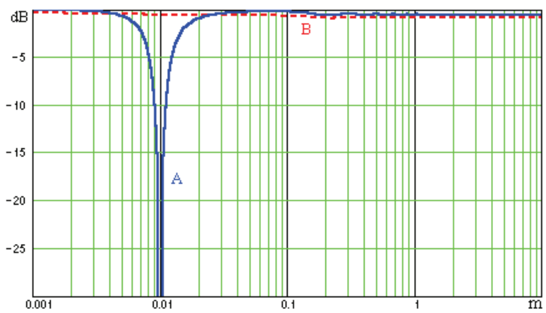

Fig. 6. The return figure versus D, at 800 MHz: $F_{dB}(\mathbf{Z}_U)$ for a tuning at D = 10 cm is curve A, and $F_{dB}(\mathbf{Z}_{Sant})$ is curve B.

of a passive device, it is known that $\mathbf{1}_q - \mathbf{S}(\mathbf{Z})\mathbf{S}(\mathbf{Z})^*$ is positive semidefinite, so that by the corollary 7.7.4 of [6], we have $|||\mathbf{S}(\mathbf{Z})|||_2 \leq 1$. An ideal match $\mathbf{Z}_U = r_0\, \mathbf{1}_n$, which realizes decoupling and matching, corresponds to $|||\mathbf{S}(\mathbf{Z}_U)|||_2 = 0$.

We now require r_0 = 50 Ω. The values of $\mathbf{L}$ obtained at the step 4 of the last iteration caused by the steps 5 and 7 is

$$\mathbf{L} \approx \begin{pmatrix} 2.171 & 0.814 & 0.753 & 0.814 \\ 0.814 & 2.171 & 0.814 & 0.753 \\ 0.753 & 0.814 & 2.171 & 0.814 \\ 0.814 & 0.753 & 0.814 & 2.171 \end{pmatrix} \text{nH} \quad (8)$$

For this value of $\mathbf{L}$, we find that:

- for the values of $\mathbf{C}_A$ and $\mathbf{C}_U$ providing a tuning at D = 100 m, $F_{dB}(\mathbf{Z}_U)$ plotted in Fig. 5 shows that a good match is obtained at large values of D;
- for the values of $\mathbf{C}_A$ and $\mathbf{C}_U$ providing a tuning at D = 10 cm, $F_{dB}(\mathbf{Z}_U)$ plotted in Fig. 6 shows that an ideal match $\mathbf{Z}_U \approx 50\ \Omega \times \mathbf{1}_4$ is obtained at this value of D.

At the step 6, at each value of D, which corresponds to a value of $\mathbf{Z}_{Sant}$, we compute a new value of $\mathbf{C}_A$ and of $\mathbf{C}_U$ providing $\mathbf{Z}_U = r_0\, \mathbf{1}_n$ at the frequency f_A. For $\mathbf{L}$ given by (8), we find that the computed $\mathbf{C}_A$ and $\mathbf{C}_U$ are real matrices. Each new value of $\mathbf{C}_A$ corresponds to values of the capacitances of the 10 adjustable impedance devices coupled to one of the antenna ports (see Fig. 2). The maximum and the minimum values of these capacitances are the curves A and B of Fig. 7. Each new value of $\mathbf{C}_U$ corresponds to values of the capacitances of the 10 adjustable

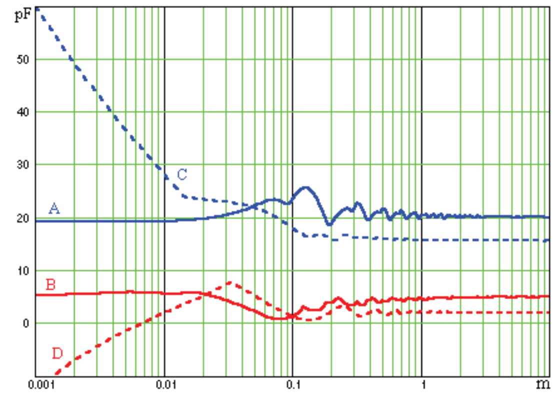

Fig. 7. Capacitances of the 20 adjustable impedance devices. For $\mathbf{C}_A$, the maximum value is curve A and the minimum value is curve B. For $\mathbf{C}_U$, the maximum value is curve C and the minimum value is curve D.

impedance devices coupled to one of the user ports. The maximum and the minimum values of these capacitances are the curves C and D of Fig. 7. $\mathbf{C}_A$ and $\mathbf{C}_U$ are realizable if and only if these capacitance values are nonnegative. Since the curve D of Fig. 7 indicates negative minimum values for D less than about 7 mm, we may conclude that, for $\mathbf{L}$ given by (8), an exact match is achievable for any D greater than about 7 mm.

V. Conclusion

A new antenna tuner having the structure of a multidimensional π-network is able to provide decoupling and matching of n antennas. It comprises $n\,(n + 2)$ circuit elements, among which $n\,(n + 1)$ adjustable impedance devices. It cannot be separated into independent and uncoupled antenna tuners.

A design method is proposed for the ideal case of lossless circuit elements, to get decoupling and matching in the presence of variations in the environment of the antennas. The method is presented for a single frequency, but it can be modified to obtain decoupling and matching over a frequency band [5].

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