Two Multiple-Antenna-Port and Multiple-User-Port Antenna Tuners

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1. Introduction

- A radio device uses several antennas simultaneously in the same frequency band.

- A MAPMUP antenna tuner is intended to be inserted between the antennas and the radio device.

- The MAPMUP antenna tuner allows an adjustment of $Z_U$, using a selection of the reactance values of its $p$ adjustable impedance devices. Thus, it is possible to compensate a variation in $Z_{Sant}$.
2. A MAPMUP antenna tuner specification

☐ A circular antenna array made up of \( n = 4 \) parallel dipole antennas is intended to operate in the frequency band 700 MHz to 900 MHz.

☐ At the center frequency \( f_c = 800 \) MHz, \( Z_{Sant} \) is approximately given by:

\[
Z_{Sant} \approx \begin{pmatrix}
8.6 - 8.9j & 3.8 + 4.9j & 1.7 + 2.2j & 3.8 + 4.9j \\
3.8 + 4.9j & 8.6 - 8.9j & 3.8 + 4.9j & 1.7 + 2.2j \\
1.7 + 2.2j & 3.8 + 4.9j & 8.6 - 8.9j & 3.8 + 4.9j \\
3.8 + 4.9j & 1.7 + 2.2j & 3.8 + 4.9j & 8.6 - 8.9j
\end{pmatrix} \Omega
\]

☐ At any frequency, \( Z_{Sant} \) is symmetric and circulant.
Entries of $Z_{Sant}$ versus frequency:

- $\text{Re}(Z_{Sant\ 11})$ is curve A;
- $\text{Im}(Z_{Sant\ 11})$ is curve B;
- $\text{Re}(Z_{Sant\ 12})$ is curve C;
- $\text{Im}(Z_{Sant\ 12})$ is curve D;
- $\text{Re}(Z_{Sant\ 13})$ is curve E;
- $\text{Im}(Z_{Sant\ 13})$ is curve F.

The problem to be solved is the design of a lossless antenna tuner such that $Z_U$ can approximate $Z_{UW} = r_0 \mathbf{1}_n$ at any frequency in the 700 MHz - 900 MHz band.
Let $Z$ be an impedance matrix of size $q \times q$. As a measure of the proximity of $Z$ and $r_0 \mathbf{1}_q$, we can use a scalar figure of merit such as the return figure $F_{dB}(Z)$ given by

$$F_{dB}(Z) = 20 \log(|||S(Z)|||_2)$$

where $||| \cdot |||_2$ denotes the spectral norm and $S(Z)$ is a scattering matrix defined by

$$S(Z) = (Z + r_0 \mathbf{I}_q)^{-1}(Z - r_0 \mathbf{I}_q) = (Z - r_0 \mathbf{I}_q)(Z + r_0 \mathbf{I}_q)^{-1}$$

We show that, for a passive device, $|||S(Z)|||_2 \leq 1$. Thus, $F_{dB}(Z_U) \leq 0$ dB and $F_{dB}(Z_{Sant}) \leq 0$ dB.

An ideal match $Z_U = r_0 \mathbf{1}_n$ corresponds to $F_{dB}(Z_U) = -\infty$ dB.

A possible design target is $F_{dB}(Z_U) < -10$ dB.
3. Case of a MAPMUP antenna tuner made of multiple SAPSUP antenna tuners

☐ The MAPMUP antenna tuner has \( p = 3n \) adjustable impedance devices, or less.

☐ For \( n \geq 3 \), we have

\[
p < n (n + 1)
\]

☐ Thus, there is no possibility of independently controlling the \( n (n + 1) \) real parameters which define \( Z_U \), to obtain \( Z_U = Z_{UW} \).
For the problem defined in § 2, \( r_0 = 50 \ \Omega \), and at \( f_c = 800 \) MHz, a numerical analysis leads us to conclude that:

- it is not possible to obtain \( Z_U = r_0 \ 1_n \); 
- the lowest possible value of \( F_{dB}(Z_U) \) is \(-4.65 \) dB ;
- the corresponding \( Z_U \) is

\[
Z_U \approx \begin{pmatrix}
72.7 - 3.0j & -42.4 - 10.1j & 25.2 + 20.5j & -42.4 - 10.1j \\
-42.4 - 10.1j & 72.7 - 3.0j & -42.4 - 10.1j & 25.2 + 20.5j \\
25.2 + 20.5j & -42.4 - 10.1j & 72.7 - 3.0j & -42.4 - 10.1j \\
-42.4 - 10.1j & 25.2 + 20.5j & -42.4 - 10.1j & 72.7 - 3.0j
\end{pmatrix} \Omega
\]

whereas

\[
Z_{UW} \approx \begin{pmatrix}
50 & 0 & 0 & 0 \\
0 & 50 & 0 & 0 \\
0 & 0 & 50 & 0 \\
0 & 0 & 0 & 50
\end{pmatrix} \Omega
\]
4. Results obtained with a new MAPMUP antenna tuner

☐ The MAPMUP antenna tuner has \( p = n (n + 1) \) adjustable impedance devices.

☐ Thus, there is a possibility of independently controlling the \( n (n + 1) \) real parameters which define \( Z_U \), to obtain \( Z_U = Z_{UW} \).

☐ For the problem defined in § 2 and for \( r_0 = 50 \, \Omega \), we can find \( L \) such that it is possible to obtain \( Z_U = r_0 1_n \) at any frequency in the 700 MHz - 900 MHz band.
The design of the lossless antenna tuner may be based on 3 formulas:

- To compute a possible $C_U$ for a given $C_A$

  \[
  \omega C_U = \left[ g_0 G_{Sant} + g_0 (B_{Sant} + \omega C_A) G_{Sant}^{-1} (B_{Sant} + \omega C_A) - g_0^2 1_n \right]^{1/2}
  \]

  where $Z_{UW} = (1/g_0) 1_n = r_0 1_n$ and $Z_{Sant}^{-1} = G_{Sant} + jB_{Sant}$

- To compute $L$ for a given $C_A$ and a given $C_U$

  \[
  \omega L = \left[ g_0^2 1_n + (\omega C_U)^2 \right]^{-1} \omega C_U + \left[ B_{Sant} + \omega C_A + G_{Sant} (B_{Sant} + \omega C_A)^{-1} G_{Sant} \right]^{-1}
  \]

- To compute a possible $C_A$ for a given $L$

  \[
  \omega C_A = (\omega L)^{-1} - B_{Sant} + G_{Sant} \left[ (g_0 G_{Sant})^{-1} (\omega L)^{-2} - 1_n \right]^{1/2}
  \]
For one of the possible designs, we obtain:

Entries of $Z_U$, for a tuning at 800 MHz:

- $\text{Re}(Z_{U_{11}})$ is curve A;
- $\text{Im}(Z_{U_{11}})$ is curve B;
- $\text{Re}(Z_{U_{12}})$ is curve C;
- $\text{Im}(Z_{U_{12}})$ is curve D;
- $\text{Re}(Z_{U_{13}})$ is curve E;
- $\text{Im}(Z_{U_{13}})$ is curve F.
The return figure versus frequency, for the tuning at 800 MHz:

$F_{dB} (Z_U)$ is curve A;

$F_{dB} (Z_{Sant})$ is curve B.
The return figure versus frequency, for a tuning at 875 MHz:

- $F_{dB} (Z_U)$ is curve A;
- $F_{dB} (Z_{Sant})$ is curve B.
Capacitances of the adjustable impedance devices which realize $C_A$, versus the tuning frequency:

$C_{AG}$ is curve A;
$C_{AN}$ is curve B;
$C_{AF}$ is curve C.
Capacitances of the adjustable impedance devices which realize $C_U$, versus the tuning frequency:

- $C_{UG}$ is curve A;
- $C_{UN}$ is curve B;
- $C_{UF}$ is curve C.
5. Compensation of variations in the medium surrounding the antennas

- We consider strong variations in the electromagnetic characteristics of the volume surrounding the antennas, created by a vertical PEC plate.

- A new problem to be solved is the design of a lossless antenna tuner such that $Z_U$ can approximate $Z_{UW} = r_0 1_n$ at 800 MHz, in spite of the PEC plate.
Some entries of $Z_{Sant}$, versus $D$, at 800 MHz:
Re($Z_{Sant\ 11}$) is curve A; Im($Z_{Sant\ 11}$) is curve B; and the four other curves are Re($Z_{Sant\ 12}$), Im($Z_{Sant\ 12}$), Re($Z_{Sant\ 13}$) and Im($Z_{Sant\ 13}$).

It was shown that a design of the new MAPMUP antenna tuner can provide an exact match for any $D$ greater than about 7 mm.
6. Conclusion

☐ A new antenna tuner having the structure of a multidimensional \( \pi \)-network is able to provide an ideal match (i.e., decoupling and matching).

☐ 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.

☐ It can provide an ideal match over a frequency band, and in the presence of variations in the medium surrounding the antennas.

☐ An iterative technique can be used to take losses into account in the design of the antenna tuner.