Proceedings of ISAP2012, Nagoya, Japan

Wireless Reactive Networks
– A Paradigm for Near Field Coupled Antenna Systems –

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1. Introduction

The usage of electrically very small antennas in near field region (NFR) is fundamentally different from the usage in far field region (FFR). FFR and NFR are compared and summarized in Table.1. The principal target in the design of the FFR applied electrically small antennas is to lower the Q factor whose limit has been given by L.J. Chu in 1948 [1]. On the contrary, the NFR applied antennas are desired to be non-radiative and lossless with as high Q value as possible. The Copernican-like revolution is necessary in the designer's mind.

This paper proposes *wireless reactive networks* as a new paradigm for antenna design in NFR applications.

General NFR systems are addressed in 2. with the introduction of the conjugate image impedance. The typical nature of NFR systems is revealed in 3. by considering the equal TX and RX antennas with no radiation approximation, followed by examples in 4..

Table 1: FFR and NFR.

design goals	TX & RX	impedance to be matched	Q
FFR	independent	radiation impedance	as low as possible
NFR	dependent	image impedance	as high as possible

2. Near Field Coupled Antennas and Conjugate Image Impedance

Fig.1 shows an equivalent circuit for a coupled antennas system, where the black box is for the antennas and the surrounding space which are characterized by the impedance matrix $Z = R + jX$ or by the admittance matrix $Y = G + jB$. In general cases, where the transmitting and the receiving antennas are different, the optimum energy/signal transfer is achieved when the conjugate image impedances [2] are matched to the port impedances.

The definitions of the conjugate image impedances are schematically shown in Fig.2..

The concept of the conjugate image impedance has been first published by Roberts in 1946 [2], in which he writes:

> *A load having the conjugate impedance of the generator to which it is connected receives the maximum amount of power and is said to be matched on conjugate-image basis. $\cdots$ In contrast, an analysis based on the usual image basis gives these results only if the image impedances happen to be pure resistances.*

Robert's solutions for the conjugate image impedances in terms of the admittance matrix elements, $Y_{ij} = G_{ij} + jB_{ij}$ are as follows.

$$\theta_g = \sqrt{\left(1 - \frac{G_{12}{}^2}{G_{11}G_{22}}\right)\left(1 + \frac{B_{12}{}^2}{G_{11}G_{22}}\right)}, \quad \theta_b = \frac{G_{12}B_{12}}{G_{11}G_{22}}. \tag{1}$$

$$Y_t = G_{11}(\theta_g + j\theta_b) - jB_{11},\ Z_t = 1/Y_t, \quad Y_r = G_{22}(\theta_g + j\theta_b) - jB_{22},\ Z_r = 1/Y_r. \tag{2}$$

The real parts of $Z_t = 1/Y_t$, $Z_r = 1/Y_r$ are equated to the port impedances (R_1, R_2), and the imaginary parts to minus the reactance of the externally circuits $(-X_1, -X_2)$.

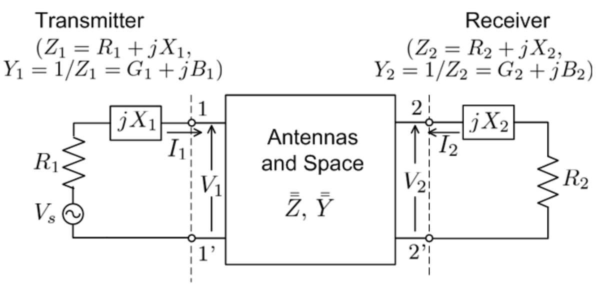

Figure 1: Coupled antennas system.

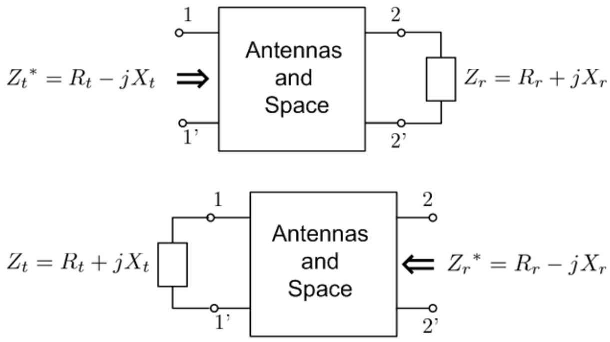

Figure 2: Conjugate image impedance.

3. Lossless Symmetric Cases and the Equivalent Circuit

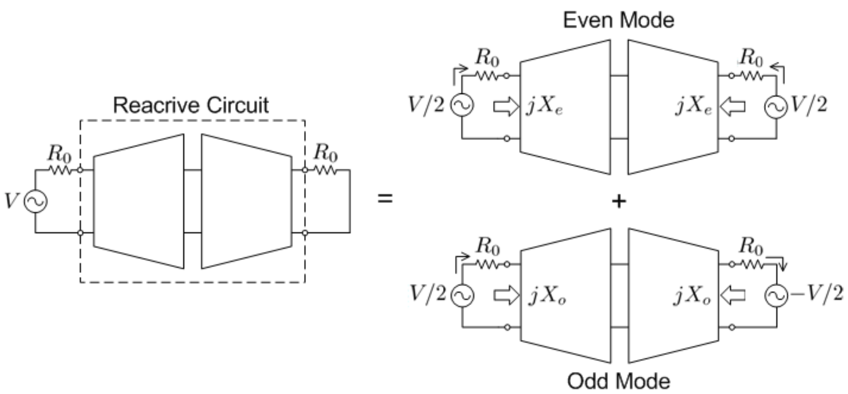

Figure 3: Lossless symmetric systems and the even- and odd mode decomposition.

It is possible to reveal the most typical nature of NFR applied antennas by considering symmetric cases whose radiation resistances are approximately zero. Such cases can be analyzed on the usual image basis. Fig.3. depicts such systems, being equivalent to the superposition of even- and odd mode excitations. The image impedance for the total system is equal to that for the one-half of the system, and it is expressed in terms of the even mode input reactance X_e and the odd mode input reactance X_o as

$$Z_I = \sqrt{-X_e X_o} \tag{3}$$

X_e and X_o satisfies the Foster's reactance theorem [3]. The theorem states:

The most general driving-point impedance $S \cdots$ is an odd rational function of the frequency $p/2\pi$ and which is completely determined, except for a constant factor H, by assigning *the resonant and anti-resonant frequencies, subject to the condition that they alternate and include both zero and infinity.* $\cdots$

The antennas under consideration are classified according to the geometrical shapes into two types, a closed path type(CPT) such as loops and an open path type(OPT) such as dipoles. CPT antenna is just an inductor at low frequency with zero input reactance. OPT antenna is just a capacitor at low frequency with zero input susecptance.

3. 1 Equivalent Circuits

The profound insight into the above mentioned properties of CPT and OPT antennas lead to the equivalent circuits, which represent the real system with high degree of approximation [4].

3. 1.1 CPT

The even- and odd mode input impedances satisfy the Foster's theorem.

Z_e and Z_o takes the form

$$Z(s) = L\frac{s(s^2 - {s_2}^2)}{s^2 - {s_1}^2} = sL_0 + \cfrac{1}{sC_1 + \cfrac{1}{sL_1}}. \quad (4)$$

Examining the continued fraction forms for Z_e and Z_o, we reach to the equivalent circuit of Fig.4. Both the mutual inductance L_m and the mutual capacitance C_m contribute to the coupling between TX and RX. According to the magnitudes of the inductive coupling coefficient $k_i = L_m/L_s$ and the capacitive coupling coefficient $k_c = C_m/C_s$, the system is classified to magnetic field dominated coupling, electric field dominated coupling, or electromagnetic field coupling.

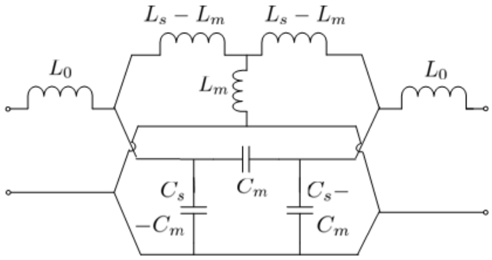

Figure 4: Equivalent circuit for CPT systems.

3. 1.2 OPT

OPT is dual to CPT, and the similar analyses apply.

The input admittances for the even- and odd mode excitations take the form of (5), and lead to the equivalent circuit as shown in Fig.5. The system classification according to the magnitudes of the inductive and capacitive coupling coefficients is also the same.

$$Y(s) = C\frac{s(s^2 - {s_2}^2)}{s^2 - {s_1}^2} = sC_0 + \cfrac{1}{sL_1 + \cfrac{1}{sC_1}} \quad (5)$$

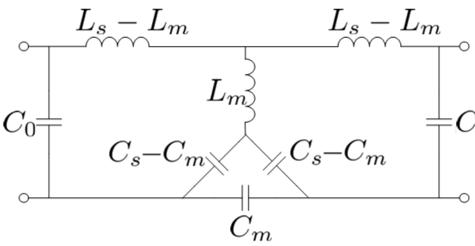

Figure 5: Equivalent circuit for OPT systems.

3. 2 Image Impedance Patterns

Image impedances have zeros at the resonant frequencies and poles at the anti-resonant frequencies of Z_e, Z_o , respectively. Hence the patterns of the frequency dependence are distinguished by the order of the four frequencies , as shown in Fig.6 : Left to Right Waterfalls(LR-WF) pattern, Valley and Hill(VH) pattern, Right to Left Waterfalls(RL-WF) pattern, and Hill and Valley(HV) pattern. The frequency at which the impedance matching being possible is easily found from these charts.

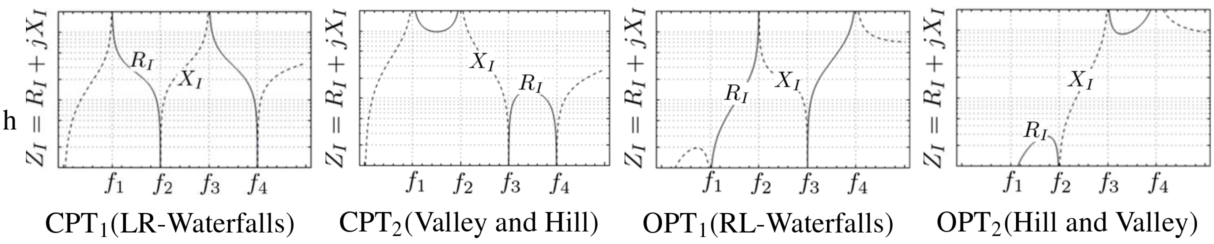

Figure 6: Image impedance patterns distinguished by the orders of four frequencies.

4. Examples

The theory has been successfully applied to various systems including the helical monopoles pair as shown in Fig.7 [5]. The evaluated values of S_{21} by the simulations by equivalent circuit and by full wave analysis, and by the experiment are in good agreement as in Fig.8.

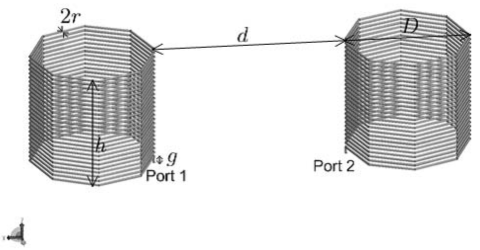

Figure 7: An example of OPT antenna: helical monopoles pair on ground plane.

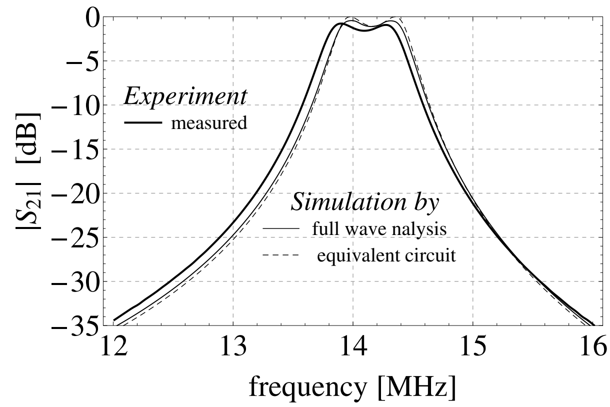

Figure 8: Comparison of $|S_{21}|$ obtained by full wave analysis with conductors conductivity of $\sigma = 5.8 \times 10^7$S/m, the analyses by the lossless equivalent circuits, and the measurement ($Z_0 = 50\Omega$, $h = D = 90$mm, $g = 5$mm, $r = 0.45$mm, $d = 25$cm).

5. Conclusions

Wireless reactive networks as a paradigm for near field coupled antenna systems are studied, and the useful theoretical results are summarized. No radiation approximation applies to wide variety of systems, and provides facility in the design of these systems.

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