Equivalent Circuit of a Two-Element Spherical Small Antenna

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Introduction

For convenient portability mobile devices need to be small. To reduce their size, a small antenna is strongly required because the antenna is one of a mobile device's largest components. In addition, the antenna's bandwidth needs to be wide because the recent development of many kinds of multimedia services requires a large bandwidth. Designing a small antenna with a wide bandwidth is not easy, however, because an antenna's bandwidth is inversely proportional to the antenna's radiation Q-factor, the lower bound of which is determined by the radius of the virtual sphere, which includes the antenna's whole structure.

Previous studies have presented techniques based on multiple resonance or multiple-element structures for enlarging an antenna's bandwidth [1]-[2]. A recent study proposed the analysis method for a multiple-element structure, which is based on a numerical analysis and helps to generate an equivalent circuit [3]. This paper proposes a different viewpoint from which to analyze multi-element antennas, which is based on considering each of an antenna's elements as a resonator, according to its impedance.

Equivalent Circuit of an Antenna

An antenna's input impedance is composed of real and imaginary parts. The real part represents the radiation loss and ohmic dissipation, and the imaginary part represents the stored power near the antenna. Generally, an antenna's input impedance is purely resistive at its operating frequency, because an antenna is conjugate-matched to maximize its radiated power. This impedance behavior of antennas is the same as the impedance behavior of a resonator at its resonant frequency, so an antenna can be represented approximately as an RLC resonant circuit. For example, a dipole antenna can be modeled as a series RLC resonant circuit by its impedance behavior.

Equivalent Circuit of Coupled Lossless Resonators

The coupling between resonant elements in proximity is generated by their electric and magnetic fringing fields. Therefore, it is categorized as either electric, magnetic and mixed coupling, depending on which kind of field dominantly contributes to the coupling. Over-coupling implies two resonant peaks because of resonant mode splitting, and the coupling structure can be represented by an equivalent circuit using the mutual inductance and mutual capacitance, as presented in [4]. The mutual inductance and mutual capacitance can be evaluated from the different resonant frequencies for each coupling mode. Each resonant frequency is found under the condition that the equivalent circuit's reference plane is replaced with an electric or magnetic wall according to coupling modes. The equivalent circuit for mixed coupling in [4] cannot be applied to the coupling between series LC resonators, however, because the circuit is composed of series mutual inductance and shunt mutual capacitance. Coupling series LC resonators requires adopting the modified equivalent circuit proposed in [5].

Equivalent Circuit of Coupled Antennas

Because an antenna can be equivalently represented as a resonator, it is possible to analyze multiple-element antennas as coupled resonators. However, there is a definite difference between a lossless resonator and an antenna. Antennas are fundamentally lossy due to their radiation loss, even if their conductive loss is low enough to be ignored; so a conventional coupling equivalent circuit cannot describe a coupled antenna's structure. The following presents an analytical method and a modified coupling circuit for coupled antennas.

When antennas are coupled in different coupling modes, their radiation resistance changes because each antenna's current distribution is superimposed or nearly cancelled according to the coupling mode. Therefore, the variation in the radiation resistance, as well as the resonant frequency, needs to be considered to generate an equivalent circuit of coupled antennas. If each antenna is considered a series resonant circuit, the equivalent circuit for two coupled antennas can be proposed as presented in Fig. 1, where each antenna's radiation resistance R_r, self-inductance L_a and self-capacitance C_a are modeled. The coupling is represented by the mutual capacitance C_m, the mutual inductance L_m and the additional resistances (R_1 and R_2), which are used to consider different radiation resistances for each mode. If the reference plane in Fig. 1 is replaced by an electric wall (or a short-circuit), the resonant frequency and the radiation resistance are given by

$$f_e = \frac{1}{2\pi}\sqrt{\frac{C_m - C_a}{C_a \cdot C_m \cdot (L_a - L_m)}} \tag{1}$$

$$R_e = R_1 \,. \tag{2}$$

Similarly, after replacing the reference plane with a magnetic wall (or an open circuit), the resonant frequency and radiation resistance are found as

$$f_m = \frac{1}{2\pi}\sqrt{\frac{C_m + C_a}{C_a \cdot C_m \cdot (L_a + L_m)}} \tag{3}$$

$$R_m = 2R_r - R_2 \,. \tag{4}$$

Two-element Spherical Antenna

The proposed circuit is applied to analyze the small two-element spherical antenna that was studied for a recently published paper [3]. This antenna consists of non-interconnected unit elements, as shown in Fig. 2. The analysis is evaluated by using a commercial EM software package with a lossless PEC conductor; and the parameters are set to the following values: radius = 75cm, gap = 60cm, separation = 15cm and trace width = 5cm (same as [3]).

The unit element's impedance is evaluated from the single-element EM simulation, and the equivalent circuit's elements are determined by the well-known relationship between impedance and Q-factor [6]. An additional capacitance representing higher order modes is connected in parallel for accurate modeling, as in [5]. The circuit parameters related to mutual coupling are determined from the above equations.

The simulation results from the equivalent circuit are shown in Fig. 3.

Conclusion

This paper proposes a new equivalent circuit for analyzing multi-element antenna structures. Each unit element of the antenna is considered a series RLC resonant circuit according to its impedance characteristic, and the antenna's entire structure is analyzed based on a mixed coupling equivalent circuit. The proposed circuit is applied to analyze a small two-element spherical antenna, and agrees well with the EM-simulation results.

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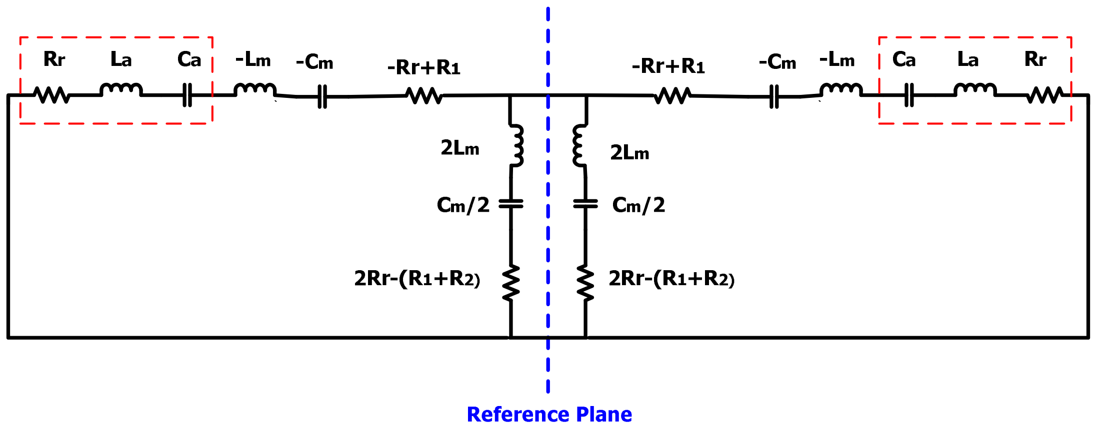

Fig. 1. Equivalent circuit of two coupled antennas

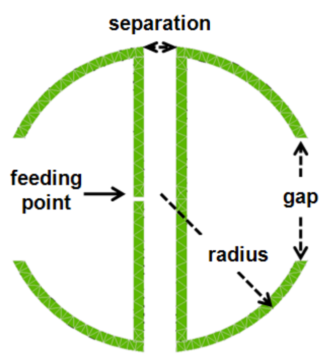

Fig. 2. Small two-element spherical antenna

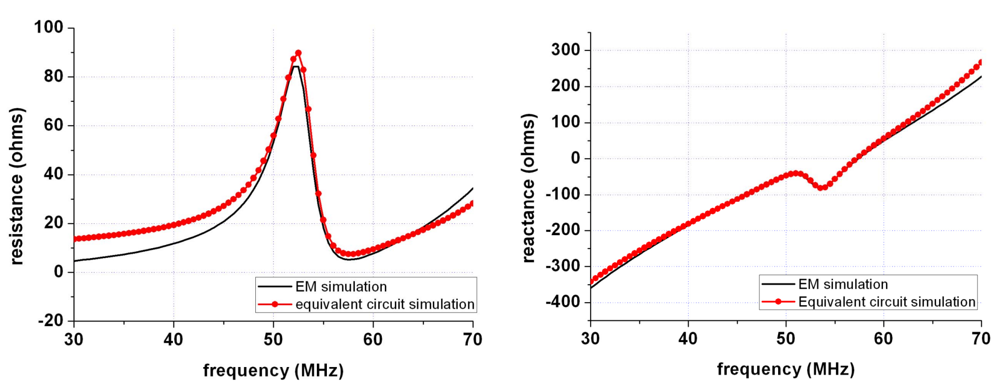

Fig. 3. Input impedance of two-element spherical antenna (a) resistance, (b) reactance