Wireless Power Transfer via Air and Building Materials Using Multiple Repeaters

Minh Quoc Nguyen, Souvik Dubey, Smitha Rao and J.-C. Chiao
Electrical Engineering Department, The University of Texas at Arlington, Texas, USA

***Abstract*—In this paper, we investigate wireless power transfer using multiple repeater antennas through air and building materials. The system architecture includes one transmitter antenna, one receiver antenna and repeater antennas in a cascade arrangement. All antennas were loop coils made of Litz wires with 15 cm-radii and 10 turns. The transmitter antenna was driven by a high efficiency class-E power amplifier (PA) while receiver antenna was connected to a load. System efficiency including both amplifier efficiency and wireless link efficiency was determined as the ratio between the output power received at the load and the input power fed into the amplifier. Theoretical model based on circuit theory was introduced to calculate the system characteristics such as power transfer, wireless efficiency and power loss induced in each antenna. Experiment setups up to two repeaters were built and conducted to validate the theory model. Experimental and theoretical results agreed well and the results confirmed the parasitic effects of building materials to the wireless power transfer system performance.**

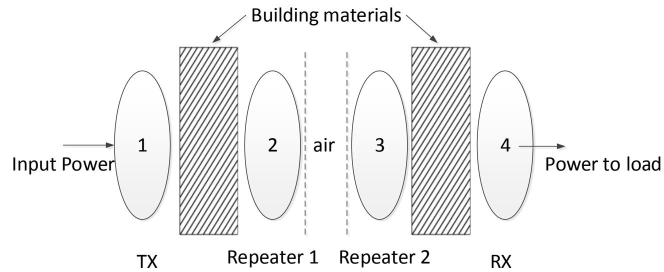
Keywords—wireless power transfer, inductive coupling, wireless efficiency, multiple repeaters, building materials.

I. Introduction

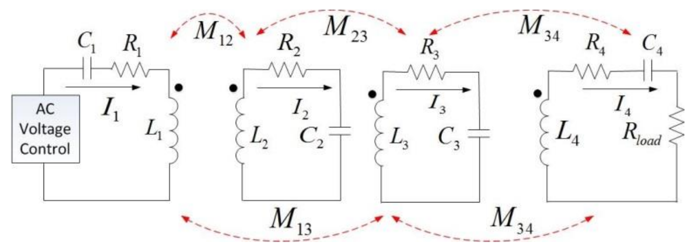
Wireless power transfer technology gains significant attention recently due to its numerous applications including wireless powering and charging for medical implants [1,2] electric vehicles [3,4] and portable consumer electronics [5,6]. The power transfer distance limitation is still a main technical challenge since the electromagnetic fields decay rapidly as the distance increases. One practical method to enhance wireless power transfer over longer distances using multiple repeater antennas between transmitter and receiver antennas has been reported in [7,8]. The repeater antennas introduce a lower loss path to harvest power from transmitter and then redeliver it to the receiver and thus significantly increase the transfer efficiency over a longer distance. Currently results are obtained for cases of transferring power through air. Practical issues appear when transferring power wirelessly from outdoor to indoor of buildings. Building materials such as wood, lumber, plastic and concrete bricks with steel frames and pipes have been found to have parasitic effects for antennas and attenuate powers [9]. This paper focuses on studying the wireless power through air and investigates the impacts of building materials on wireless power system performance.

II. System Model

The system architecture for transferring powers through walls is shown in Fig. 1(a). Voltage equations for such a 4-coil wireless power system in Fig. 1(b) equivalent circuit can be expressed as [7]:



(a)



(b)

Figure 1: 4-coil wireless power transfer system (a) configuration and (b) its equivalent circuit.

$$\begin{bmatrix} Z_{11} & jwM_{12} & jwM_{13} & jwM_{14} \\ jwM_{21} & Z_{22} & jwM_{23} & jwM_{24} \\ jwM_{31} & jwM_{32} & Z_{33} & jwM_{34} \\ jwM_{41} & jwM_{42} & jwM_{43} & Z_{44} \end{bmatrix} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \\ I_4 \end{bmatrix} = \begin{bmatrix} V_1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \quad (1)$$

or $$\underline{Z}\times\underline{I}=\underline{V} \quad (2)$$

where w is the angular frequency; R_i and L_i are the resistance and inductance of the i[th] coil; R_{load} is the load resistance; C_i is the matching capacitance; M_{ij} is the mutual inductance between i[th] and j[th] coils; V_i, I_i are the voltage and current flowing in the i[th] coil. $\underline{Z}$ is the impedance matrix, $\underline{V}$ and $\underline{I}$ are voltage and current vectors, respectively.

In $\underline{Z}$ matrix, the diagonal element Z_{ii} represents the series impedance of i[th] coil. Z_{44} includes the load resistance connected to the coil 4. The off-diagonal element Z_{ij} represents complex mutual impedances between coils. In the resonance condition ($w = 1/\sqrt{LC}$), Z_{ij} can be simplified as:

$$Z_{ii} = R_i + j\left(wL_i - \frac{1}{wC_i}\right) = R_i \quad (3)$$

After obtaining currents from Eq. 1, the input power, load power, power loss in each coil, power transferred between i[th] and j[th] coils, and wireless link efficiency can be calculated respectively as:

$$P_{input} = \mathrm{Re}\{V_1 \overset{*}{I_1}\} \tag{4}$$

$$P_{load} = I_4^2 R_{load} \tag{5}$$

$$P_{loss\_i} = I_i^2 R_i \tag{6}$$

$$S_{ij} = jwM_{ij} I_i \overset{*}{I_j} = P_{ij} + jQ_{ij} \tag{7}$$

$$\eta_{link}\% = \frac{P_{load}}{P_{input}} \tag{8}$$

where S_{ij}, P_{ij}, and Q_{ij} are the complex power, real power and imaginary power transferred from the i[th] to j[th] coils, respectively.

Inductance of a loop coil can be estimated as [10]:

$$L = N^2 R \mu_0 \left[\ln\left(\frac{8R}{a}\right) - 2 \right] \tag{9}$$

where R is the coil radius, a is the coil thickness, N is the number of turns and μ_0 is the free-space permeability.

For coaxial filament loops used in Fig. 1(a), the electrical current is assumed to be uniformly distributed along the coil length as the physical length of each coil is much shorter than the carrier wavelength. Thus mutual inductance can be expressed in the closed form [11]:

$$M = \mu_0 N_1 N_2 \sqrt{R_1 R_2} \left[\left(\frac{2}{g} - g\right) K - \frac{2}{g} E \right] \tag{10}$$

where R_1 and R_2 are the radii of coils; N_1 and N_2 are the turns number; K and E are the complete elliptic integrals of the first kind and second kind to the modulus g, respectively, and

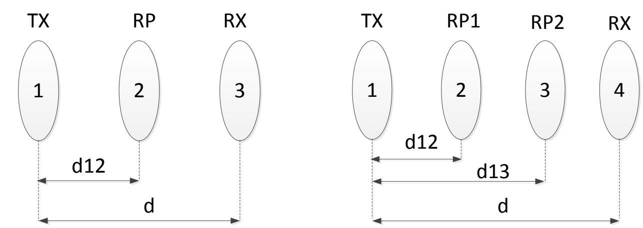
$$g = \sqrt{\frac{4R_1 R_2}{(R_1 + R_2)^2 + d^2}} \tag{11}$$

in which d is the distance between coils. The AC electrical resistance of coil is a frequency-related parameter considering both skin effect and proximity effect. A detailed investigation of such effects has been reported in [12]. In a practical wireless power system, the frequency was typically in the range of 500 kHz to 1 MHz in which such effects are negligible and thus DC values are used as a close approximation.

The performance of a wireless power system in the resonance condition depends on the Z matrix elements in Eq. 1. The wireless efficiency can be enhanced by either increasing off-diagonal elements $Z_{ij}=jwM_{ij}$ which means increasing flux linkages between coils or decreasing diagonal elements $Z_{ii}=R_i$ by reducing resistive losses in each coil. Flux linkages between coils can be improved by providing more coil turn numbers or increasing the system carrier frequency. However, increasing coil windings will add more resistive losses and affect the efficiency while increasing frequency creates more AC resistance due to skin and proximity effects. Therefore, parameters such as system bandwidth and turns number of coil should be examined as trade-off consideration in designs to obtain a maximum efficiency.

III. Experiments

Experiment setups were conducted with 1 repeater and 2 repeaters as shown in Fig. 2. System frequency was chosen at 900 kHz. An n-channel MOSFET RF510 (Fairchild) was used



(a) (b)

Figure 2: System arrangement with (a) 1 repeater and (b) 2 repeaters.

in the class-E amplifier. The transistor was switched by a 5-V_{pp} square waveform with a duty cycle of 50% at the Gate. DC power supply of 6 V was fed into the Drain. The overall distances from the transmitter to receiver are 40 cm and 60 cm. Load resistance was 36 Ω which was also the impedance of an LED light bulb tested. All coils were made of 145 strands/46 AWG - Litz wires with radii of 15 cm and 10 turns. Coils were tuned in resonance with matching capacitors. Coils inductance and resistance were 98.1 μH and 5 Ω, respectively. AC power was measured at the load as the output power while the total input power was measured from DC power supply. The overall system efficiency (*n%*) was then defined as the ratio between output power and input power which includes both amplifier efficiency ($n_{PA}\%$) and wireless link efficiency calculated in Eq. 8.

$$n\% = n_{PA}\% \times n_{link}\% \tag{12}$$

Class-E amplifier efficiency was measured at approximately 90% after proper impedance matching [13].

Figures 3 and 4 show the variation of system efficiency as a function of repeater position with the overall transfer distances between TX and RX of 40 cm and 60 cm, respectively. The experiments were conducted in air. As observed in the plots, there exists an optimum position of the repeater where the efficiency is maximized. The system efficiency reaches almost 60% when the repeater is at the center between TX and RX, shown in Fig. 3. In this case, equal spacing between coils is the optimal arrangement. When the overall distance increases to 60 cm, the maximum system efficiency significantly drops from 60% to 30%. In this setup, the optimal position of repeater is 33 cm, which slightly moves toward to the RX and an equal spacing between coils does not provide optimum arrangement.

Since system efficiency with only one repeater drops to 30% at a distance of 60 cm, one additional repeater could be utilized to enhance the system performance. The configuration is shown in Fig. 2(b). Two repeaters were cascaded with centers aligned. The experiment was conducted with spacing varied.

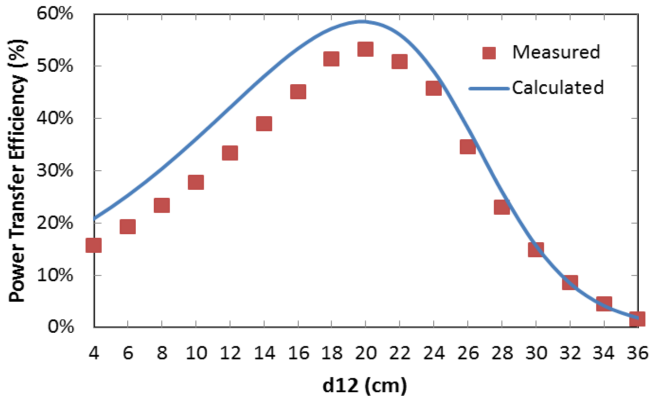


Figure 3: Power transfer efficiency as a function of one repeater position. The total distance is 40 cm from TX to RX in air.

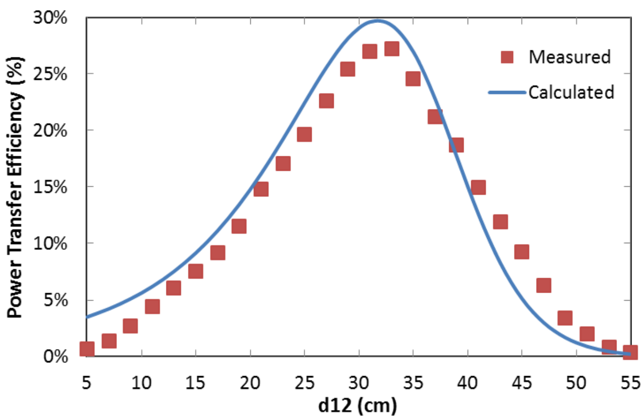


Figure 4: Power transfer efficiency as a function of one repeater position. The total distance is 60 cm from TX to RX in air.

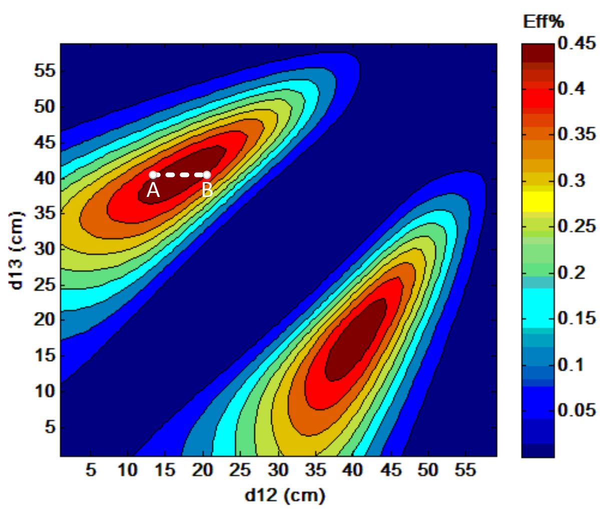


Figure 5: Power transfer efficiency as a function of 2 repeater positions (repeater 1 as d_{12} and repeater 2 as d_{13}). The total distance is 60 cm from TX to RX in air.

Figure 5 shows the efficiency variations with respect to the two repeater positions. The plot is symmetric in terms of repeaters relative positions because repeater coils are identical. The efficiency can be boosted up to 48.74% from 30% by using one additional repeater. The optimal spacing of repeaters are d_{12}=18 cm and d_{13}=41 cm. At equal spacing (d_{12}=20 cm and d_{13}=40 cm), the efficiency reaches 44.95%. Although efficiency was not maximized at equal spacing, system could still achieve high performance over a larger position variation of repeaters. For example, with a fixed position of repeater 2 (d_{13}=40 cm), system efficiency can maintain above 45% due to repeater 1 displacement from d_{12}=14 cm (marked with "A") to d_{12}=20 cm (marked with "B"). This provides a better tolerance for coil locations.

IV. Building Materials Setups

The results above were conducted in air. In the next experiments, we used 3 different building materials to investigate the power attenuation effects. The materials include wood, concrete block and concrete block with steel frame reinforcement (Fig. 6). The wood and brick materials are 30 cm × 30 cm and 5 cm thick. The metal strips formed a 25 cm × 25 cm grid to represent the steel frame structure in buildings. The frames were tapped in both sides of the concrete block.

(a) (b) (c)

Figure 6: Photos of building materials tested. From left to right, they are (a) wood, (b) concrete block and (c) concrete which has a metal grid mimicking steel frame.

The efficiency of the 4 coils system with equal spacing was first measured in air. The total distance from TX to RX was 60 cm. Then the materials of the same type were placed between TX and repeater 1 as well as between RX and repeater 2 while there is only air between repeater 1 and repeater 2, as shown in Fig. 1(a). Efficiency was measured with different materials in the same coil spacing configuration.

TABLE I. Power Transfer Efficiency in Different Media

Medium	Efficiency%
Air	48.75%
Wood	48.51%
Concrete block	48.27%
Concrete block with metal grid	13.60%

Table 1 shows the experiment results with air and 3 different materials used. The system efficiency was highest in air as 48.75%. It slightly decreased in wood (48.51%) and in concrete (48.27%). The decrease is not obvious which may be due to the parasitic effect from moisture in the materials that slightly varies the effective dielectric constant resulting in a deviation from the resonance and creates losses. In the case of concrete with metal grids, the system efficiency significantly reduced to 13.60%. In such a case, the metal grids form an equivalent circuit acting as another repeater with self-resonance frequency different from the system resonance frequency. These additional elements detune the circuit from the resonance condition and degrade the overall system performance. In Fig. 7, we put concrete blocks between the TX and repeater 1 (R_1) spacing, wood between repeater 2 (R_2) and RX spacing while there was only air between R_1 and R_2 spacing. All 4 coils were equally spaced by 20 cm. The input power was measured as 50-W at the resonant frequency of 900 kHz. The output load was replaced with a 24-W LED light bulb. This experiment demonstrated that wireless energy transfer in the 4-coil system powers a light source at a 60-cm distance through multiple construction materials of wall.

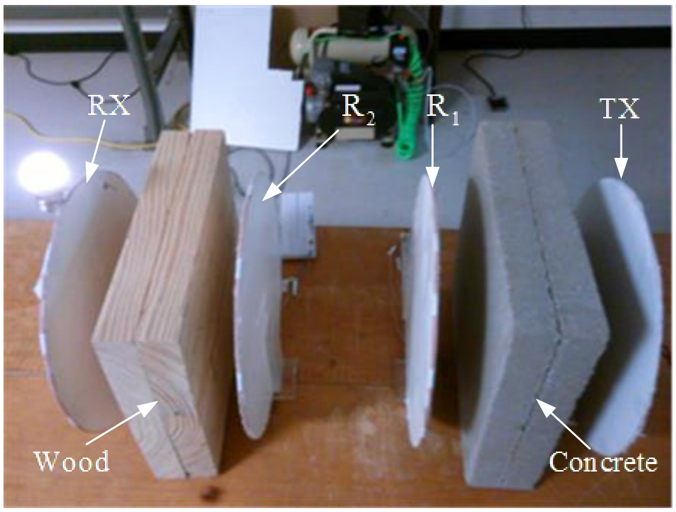


Figure 7: A demonstration of wireless power transfer from a transmitter to a receiver with 2 repeaters separated by different building materials. The setup shows that the wireless energy powers a 24-W light bulb with a 50-W input power.

V. Conclusion

The wireless power transfer system with multiple repeaters has been examined mathematically and verified with experiment results. The optimal spacing in settings of 3 and 4 cascaded antennas were tested for different spatial arrangements. The experiments also examined the feasibility of transferring wireless power from outdoor to indoor via different building materials with high efficiencies. System performance can be affected with the presence of conductive materials embedded in the door, wall or ceilings. This factor should be carefully considered in the system designs.

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