Effect of Load Fluctuation in Data Transmission for Wireless Power Transfer

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SUMMARY Recent interest in wireless power transfer research has been attracting a great deal of attention. To transfer power efficiently and safely in wireless power transfer system, information, such as frequency, required power and element values, need to be transmitted reliably. However, the bandwidth, which is used for exchanging information, is affected by the change of load at the receiver when it is charging. This paper investigates the effect of load fluctuation in data communication using orthogonal frequency division multiplexing (OFDM) modulation in resonant-type wireless power transfer systems. The equivalent circuit used in the transmitting and receiving antennas is a band pass filter (BPF) and its bandwidth is evaluated through circuit simulations. Numerical results obtained through computer simulation show that the bit error rate (BER) performance is affected by the load fluctuation and the efficiency of power transfer.

key words: OFDM, wireless power transfer, BPF, load, communication

1. Introduction

Wireless power transfer is currently achieved via some techniques, with each system possessing different characteristics in terms of distance and power transfer efficiency. Especially in the resonant coupling technique, two antennas are tuned at the same resonant frequency. Power transfer efficiency is approximately 50% over a distance of several tens of centimeters [1]. In 2006, the Massachusetts Institute of Technology (MIT) announced the magnetic resonant coupling system, which has been attracted a great deal of attention [2], [3].

Transmitting and receiving antennas in the resonant coupling system need to induce a non-radiative magnetic field. A practical implementation can be applied by using loop antennas, in which changes to induced magnetic field are affected by the number of turns [4]. However, the self-resonant antennas rely on the interplay between distributed conductance and distributed capacitance, which affects the power transfer efficiency. The power transfer efficiency is affected by the change of load at the receiver [5], [6]. To enable fast reaction, it is desirable to have the ability to change the power signal according to the request of the receiver when providing power at the transmitter. When change is detected at a transmitter, information such as frequency, required power and element values should be transmitted shortly and adapt to the desired power signal accordingly [6], [7]. Therefore, it is very important for wireless power transfer systems to transmit these data fast and reliably.

In wireless power transfer, the bandwidth, which is used for the data communication, is affected by the load fluctuation at the receiver when it is charging. This paper investigates the effect of load fluctuation in the data transmission process. The equivalent circuit used in the transmitting and receiving antennas is a band pass filter (BPF) and its bandwidth is evaluated through circuit simulations. In this paper, the transfer function $|S_{21}|$ as calculated from the circuit model is evaluated. The bandwidth to transmit the data information is then decided. To satisfy the conditions for the high speed communication and reliability, orthogonal frequency division multiplexing (OFDM) is applied as modulation scheme. The primary advantage of OFDM based schemes is its robustness to severe multipath channels, which is caused by the splitting resonant frequency in wireless power transfer. Bit error rate (BER) is calculated through MATLAB simulations. In order to observe the effect of propagation loss in wireless power transfer on BER, we use the transmission power to evaluate BER.

This paper is organized as follows. Section 2 introduces the system model. In Sect. 3, simulation results obtained through computer simulation are presented. Section 4 gives our conclusions and directions for future work.

2. System Model

2.1 Single Antenna and Resonant Coupling System

In this wireless transfer system, we assume that the signal generator provides AC power. This power is input into an amplifier and the resulting power is transferred to the receiving antenna. The antenna arrangement used in both the transmitting and receiving antennas is shown in Fig. 1. The equivalent circuit is shown in Fig. 2 [8]. In Fig. 2, $L$ represents self-inductance, $R$ represents the resistance of the antenna, $C$ represents the capacitance of the antenna, and $Z_0$ represents the characteristic impedance. $d_z$ represents the load impedance, $d_y$ is the distance between antennas and $dy$ is the gap of central axis of antennas. The conductor losses caused by the skin effect are ignored in the circuit model.

From Neumann’s formula, the mutual inductance, $M$,
is given by

\[ M = \frac{\mu_0}{4\pi} \int \oint \frac{d\ell_1 \cdot d\ell_2}{r_{12}}, \]  

(1)

where \( d\ell_1 \) and \( d\ell_2 \) are small line elements on an antenna, and \( r_{12} \) is the thickness of the antenna [9].

The mutual inductance between the antennas is given by

\[ M = k \sqrt{L_1 L_2}, \]  

(2)

where \( k \) is the coupling coefficient, and \( L_1, L_2 \) are the self inductance of transmitting and receiving antenna. In this paper, it is assumed that \( L_1 = L_2 = L \), therefore \( M \) is given as

\[ M = kL, \]  

(3)

where \( k \) depends on the distance between the antennas. When the distance between the antennas is short, \( k \) becomes large and the splitting resonant frequency is observed.

2.2 Power Transfer Efficiency and Load Fluctuation

In this paper, the secondary load \( Z_L \) in Fig. 2 is changed from 25 \( \Omega \) to 300 \( \Omega \), which is presented in [10], [11], to examine the relationship between the bandwidth and the transmitting efficiency \( \eta \) by load fluctuation [12]. \( S_{21} \) and the efficiency \( \eta[\%] \) is given as

\[ S_{21}(\omega) = \frac{2j\omega M \sqrt{Z_0 Z_L}}{(Z_G + R + j\omega L + \frac{1}{j\omega C})(Z_L + R + j\omega L + \frac{1}{j\omega C}) + M^2 \omega^2}, \]  

(4)

\[ \eta = |S_{21}|^2 \times 100, \]  

(5)

\[ Z_0 = Z_{in}. \]  

(6)

In wireless power transfer system, the reflected power is varied by load fluctuation. The reflected power is consumed as loss in the primary side, and the efficiency \( \eta \) is deteriorated. In this paper, the evaluation of BER is based on the efficiency of power transfer.

2.3 Communication Model

In the communication model for data transmission, the equivalent circuit used in the transmitting and receiving antennas is regarded as a BPF, which has to be custom designed not to cause the interference. To satisfy this constraints, OFDM is applied for data transmission in the power transfer system. Suppose the information symbol on the kth subcarrier is \( s[k] \) (\( k = 0, ..., N-1 \)), the OFDM symbol is given as

\[ u[n] = \frac{1}{\sqrt{N}} \sum_{k=0}^{N-1} s[k] e^{j2\pi kn/N}, \]  

(7)

where \( n (n = 0, ..., N-1) \) is time index and \( N \) is the number of subcarriers. The guard interval is added before the data transmission. The baseband signal at the output of the filter is given by \( x(t) = \sum_{n=0}^{N-1} u[n] C_s(t-nT_s) \), where \( C_s(t) \) is the impulse response of the transmitting filter, \( P \) is the length of the impulse response, and \( T_s \) is the OFDM symbol duration. In this system, the antennas are fixed and multipath fading is not assumed. The received signal is given as

\[ y(t) = \sum_{n=0}^{P-1} u[n] h(t-nT_s) + v(t), \]  

(8)

where \( v(t) \) is the additive white Gaussian noise (AWGN), \( h(t) \) is the impulse response of the composite channel and is given by

\[ h(t) = C_s(t) \otimes C_r(t), \]  

(9)

where \( \otimes \) denotes convolution and \( C_r(t) \) is the impulse response of the receiving filter. The frequency response of channel in the communication model, \( H \), is equivalent to \( |S_{21}| \) in the power transfer system.

3. Simulation Results

3.1 \( |S_{21}| \) Characteristic

\( |S_{21}| \) characteristic in Fig. 2 is calculated by circuit simulation and shown in Figs. 3 and 4. The coupling coefficient, \( k \), on the circuit simulator is set to 0.037 and 0.100. In the data transmission system, OFDM is employed for the 2nd modulation, and the bandwidth of OFDM is designed to fit the relatively large impulse response of the channel in the guard interval period. Thus, the number of the subcarriers is derived to satisfy this condition:
\[ \frac{N}{T_s} \leq \Delta W. \]  

(10)

Here, \( \Delta W \) is the bandwidth of the composite filters, which is measured at half-power points (3 dB) from the peak. The values of parameter of bandwidth \( \Delta W \) and the efficiency of power transfer \( \eta \) are shown in Table 2.

In Fig. 4, the curves of \( Z_L = 25 \Omega, 50 \Omega, 100 \Omega \) show the splitting of resonant peak. As the coupling between the antennas at the transmitting and receiving antenna becomes stronger, the peak splits into two. However, it can be seen from Table 2 that the bandwidth \( \Delta W \) of \( k = 0.100 \) becomes wider than that of \( k = 0.037 \).

### 3.2 BER Performance

#### 3.2.1 Simulation Conditions

BER performance is evaluated through computer simulation. The simulation conditions are shown in Table 3. Information bits are modulated with 64 quadrature amplitude modulation (QAM) on each subcarrier. The number of discrete Fourier transform (DFT) points is set to 16, which is fit to \( \Delta W \) given from \( |S_{21}| \) characteristic as shown in Table 2. Here, \( \Delta W \) is set to the bandwidth when \( Z_L = 50 \Omega \). The guard interval is set to 4, which is 1/4 of the number of subcarrier \( N \). The channel model used is a quasi-static multipath channel, which is the path between the transmit antenna and the receive antenna. The phase compensation
is assumed to be perfect.

3.2.2 Simulation Results

The BER performance for the cases when \( k \) is 0.037 and 0.100 are shown respectively in Figs. 5 and 6. The bit energy is defined based on the efficiency of power transfer and the \( x \) axis represents supplied bit energy per noise (SEb/N0).

In Figs. 5 and 6, BER performances appear extremely degraded compared to the AWGN theoretical curve. This is because the BER performances in Figs. 5 and 6 are strongly affected by the efficiency \( \eta \).

4. Conclusions

In wireless power transfer system, information, such as frequency, required power and element values, need to be transmitted to ensure power transfer safely and effectively. The effect of load fluctuation in the data transmission for wireless power transfer systems has been investigated in this paper. The transfer function \( |S_{21}| \) is given from calculation on the circuit model when the secondary load is changed. In the data transmission model, OFDM is used as the 2nd modulation and the BER performance at the receiver is evaluated based on power transfer efficiency. From the simulation results, BER performance is degraded compared to the AWGN theoretical curve. This is because the passband is affected by the load fluctuation and power transfer efficiency. For transmitting data in wireless power transfer, the propagation loss must be considered. Further work will consider the experimental evaluation of power transfer efficiency with data transmission.

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