Co-optimization of Efficiency and Load Modulation Data Rate in a Wireless Power Transfer System

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***Abstract*—In-band load modulation as a means of transferring information from a wirelessly-powered client device to a power provider in a wireless power transfer (WPT) system has long been considered to have an unacceptable impact on the efficiency of power transfer. Conventional load modulation involves either completely or severely detuning the receive coil in order to produce a detectable amplitude shift at the power provider side and thereby transfer information. In this work, we analyze the impact of load modulation on system efficiency by considering the power consumption of the transmit power amplifier (PA) and identify a tradeoff between communication capability and end-to-end wireless power transfer efficiency. We also determine how to select a load modulation strategy which reduces the degradation in power transfer efficiency while maintaining high-contrast uplink signaling. Finally, we explore the use of coherent demodulation (IQ demodulation) to reduce the mismatch requirement on a load modulation system by improving the power provider's sensitivity to load modulated signaling.**

I. Introduction

Near-field wireless power transfer (WPT) has been intensively studied and developed, both in the consumer electronics industry and in academic research. The Qi and A4WP industrial standards have been created due to high commercial demands for wirelessly charged consumer electronics[1], [2]. Simultaneous in-band transfer of both power and data has also been studied in academia, typically targeting usage in medical implants because of the desire to charge wirelessly while transfering telemetry data back to the power provider[3], [4], [5], [6], [7]. The question of whether to use the same frequency band for both communication and power has been heavily debated. This paper focuses on analyzing the tradeoff between power efficiency and communication using load modulation, and proposes a codesign strategy which optimizes both power efficiency and communication capability.

Load modulation is a low power communication mechanism involving changing the wireless power receiver's loading condition in order to produce a reflection detectable at the power provider. Load modulation is implemented in NFC (near-field communication) systems and allows passive NFC tags to communicate with their reader (typically a smartphone) simply by detuning their receive antenna. Shorting or severe detuning of the receiver in order to produce a strong reflection is acceptable in these low power systems where communication contrast is prioritized over power transfer efficiency. However, when designing high power systems we must consider efficiency as a first class citizen in order to avoid unwanted symptoms of low efficiency such as power wastage and heating issues. The efficiency impact of load modulation must therefore be considered.

In practical systems, the power amplifier (PA) plays a critical role in determining end-to-end efficiency. When the effective load of the PA changes, the PA's output power and consumed power both change, and therefore efficiency changes. Thus, the load modulation strategy used in a high-power system should be designed around the power amplifier. To allow understanding and careful selection of optimal impedance states at the load and their impact on efficiency and communication capability, we must therefore consider the impedance transformation effect of the wireless power transfer coil network as well as the transient response of this network.

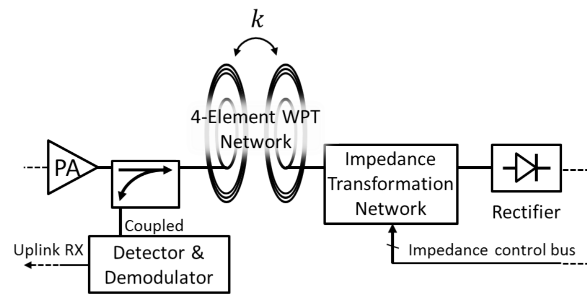

Fig. 1. A wireless power transfer system employing load modulation to transfer data from the power client to the power host. The effective load impedance is altered by a controllable impedance transformation network in order to produce detectable changes in the reflected signal. This work aims to optimize both load modulation capability and system efficiency.

The architecture of our proposed load modulation system is shown in Figure 1. The power provider on the left delivers power to a client device on the right, and the client intelligently modulates its impedance with knowledge of the provider-client channel in order to improve communication contrast while minimizing end-to-end efficiency impact. In Section III, we describe the design of the system in Figure 1 and discuss how such a system could be implemented with known and proven primitives from other work, including a digitally controllable impedance matching network at the load side, and a coherent IQ receiver at the power provider side. Further, we describe the tradeoff between communication contrast and power transfer efficiency as a function of load modulation impedance states. In Section IV and V, we present the simulation setup and simulated results to inform our design decisions.

II. Related Work

Generally, the communication architecture design for a WPT system is based on its application, power requirement, and data rate. Communication solutions can be grouped into two classes: in-band communication and out-of-band communication. In a WPT system, in-band communication refers to using the same antenna, at the same frequency, for both

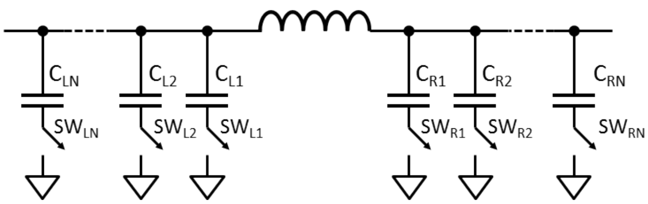

Fig. 2. The proposed switching pi-match topology allows for a wide range of impedance transformations. One switch configuration will produce the maximal efficiency case Z_{MATCH}, and another will correspond to the load modulation impedance Z_{LM}.

power and communication. Out-of-band communication refers to adding an addional antenna or an additional frequency band for communication purposes, to separate the communication and power link.

The most popular industrial standards for WPT systems, Qi and A4WP, implement in-band communication and out-of-band communication, respectively[1], [2]. Neural implant systems in research have used out-of-band load modulation, modulating an isolated secondary coil instead of the primary coil used for power transfer. These systems have demonstrated high communication rate and low energy per bit [3], [4]. However, this architecture raises the added challenge of eliminating cross-coupling between the power and communication coils[4]. Still others have demonstrated in-band load modulation for neuro implants that obtain high data rate and low efficiency degradation [5].

One argument for out-of-band communication is given in [8], in which a theoretical analysis of the tradeoff between quality factor (Q) of the resonant coupled network (a factor in wireless power efficiency) and achievable communication bandwidth is given. While a thorough discussion of achievable data rate is outside the scope of this work, we present results indicating that 100s of kbps is achievable even with low order modulation schemes.

III. Design

A. System Overview

This paper focuses on the data link from the power client to the power host, which we will refer to as the uplink. The downlink, which is defined as communications from the power host to the power client, is not in the scope of this work. The power host includes a Class E power amplifier, a directional coupler which is used as a receiver for the uplink data, and an In-phase/Quadrature (IQ) demodulator for decoding the uplink data. A four-coil system of magnetically coupled resonators connects the power host and power client. The power client includes a pi-match network with switchable tuning capacitor banks, a full-bridge rectifier, and a load.

B. Load Modulation Model

Traditionally, to get a clean signal, a load modulation system is often designed to switch between the load impedance states that give the highest contrast. Detuning the receive coil by switching in a single component only covers a small portion of the impedance space. In order to provide more degrees of freedom, we design a network to achieve more general impedance transformations during load modulation.

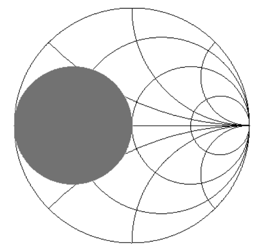

Fig. 3. The shaded region shows unattainable impedance values for the proposed pi-match topology and a capacitive rectifier load.

Due to the difficulty of serially switching in and out components in an RF system, and the additional challenges of inductor switching, the low pass pi-match network in Figure 2 is chosen, where the serial inductor doesn't need to be switched. During pure power transmission, the pi-match network transforms the rectifier impedance such that the PA experiences a conjugate match to the transmit coil, resulting in maximum power efficiency. When doing load modulation, our topology simultaneously switches in and out capacitor or capacitor pairs on both sides of the pi-match such that the resulting load impedance experienced by the PA moves between the matched condition and a desired mismatched impedance Z_{LM}.

Theoretically, the pi-match network can transform the rectifier impedance value to any other impedance value to achieve an arbitrary Z_{LM}, but this complete coverage would require changing all three component values in the pi-match system. Because practical constraints prevent the switching of serial inductance values, the serial inductor must be a fixed value that is dictated by the need to achieve the maximum power point match condition Z_{MATCH} when not performing load modulation. Thus, achievable load modulation impedances will be those outside the shaded region of the Smith chart in 3. To summarize, the real part of admittance for achievable modulation impedances must be smaller than 20mS.

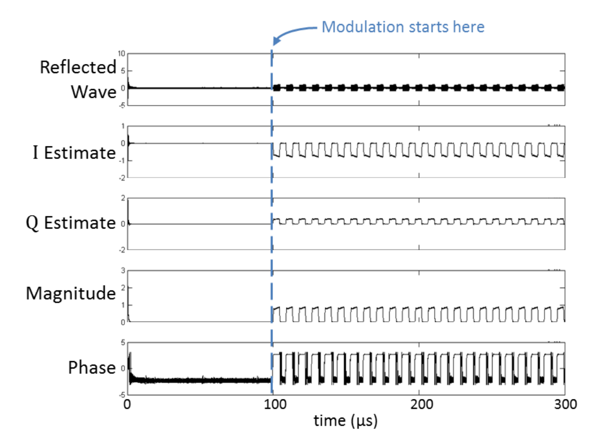

Fig. 4. The time domain response of the reflected signal (as seen at the directional coupler) is shown along with the extracted In-phase (I) and Quadrature (Q) components of that signal and the corresponding magnitude and phase values. Note that this work uses the vector distance between points on the IQ plane to decode transmitted data, similar to a conventional coherent radio receiver.

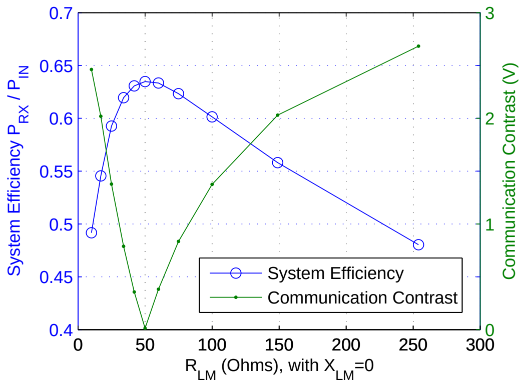

Fig. 5. Communication contrast (the distance between points on the IQ plane, in Volts) and wireless power transfer efficiency as a function of real part of impedance seen by the power host's PA.

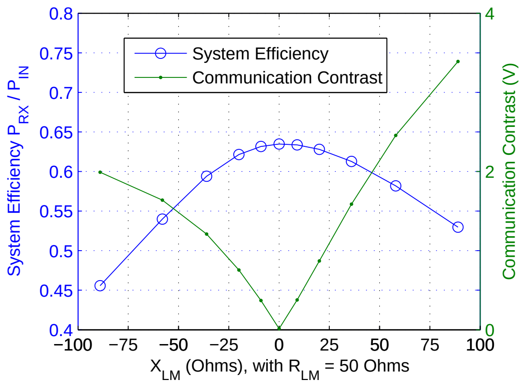

Fig. 6. Communication contrast (the distance between points on the IQ plane, in Volts) and wireless power transfer efficiency as a function of imaginary part of impedance seen by the power host's PA, when the real part is nearest the matched condition (50 Ohms).

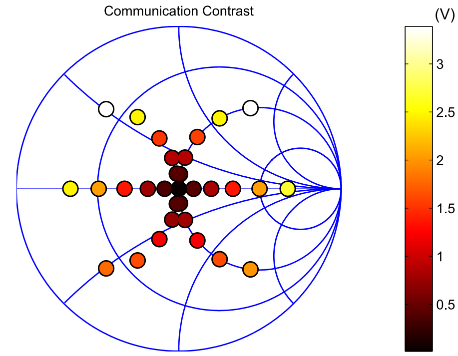

Fig. 7. Communication contrast (the distance between points on the IQ plane, in Volts) as a function of effective load modulation impedance Z_{LM} experienced at the power host's PA. The power client switches between Z_{MATCH} and Z_{LM} at a rate of 100 kHz.

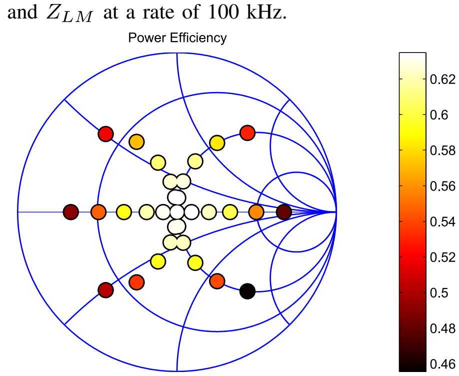

Fig. 8. Wireless power transfer efficiency (fraction of 1) as a function of effective load modulation impedance Z_{LM} experienced at the power host's PA. The power client switches between Z_{MATCH} and Z_{LM} at a rate of 100 kHz.

C. Choosing Load Modulation Impedance Value

The Class E amplifier is designed for a 50 Ω output impedance, so Z_{LM} values are selected around 50 Ω. To provide different contrast, impedances are chosen along constant VSWR circles (1.2, 1.5, 2, 3, and 5). For each constant VSWR circle, we test all the real impedances, all impedances with 50 Ω resistance, and all impedances with 20 mS conductance. Though purely resistive Z_{LM} valuese over 50 Ω can't be achieved with the pi-match topology used herein, the trend of the system characteristics is still of interest as other matching topologies could potentially be used to achieve these impedances if desired.

D. IQ Demodulator

The communication contrast in this paper refers to the distance on the IQ constellation plot between each Z_{LM} and matched condition. The IQ demodulator is conventionally used in the radio communication system, but it is not commonly seen in near-field load modulation system. Using the IQ signal rather than magnitude and/or phase signal can help to improve contrast between different load conditions. Another benefit of decoding the load modulated signal with IQ theory is that different load impedance can be different constellation point set for high order quadrature amplitude modulation (QAM). It means that the load modulation frequency is considered as symbol rate instead of bit rate, which means for same symbol rate, the link can have higher bit rate.

IV. Simulation Setup

We use a simulated system to explore the tradeoff between communication link budget and power transfer efficiency. We model a single-ended class E amplifier as the PA [9]. The output of the class E is connected to the input port of a directional coupler. The coupled port represents the reflected wave at the output port. The output port is connected to the transmitter coil. The loop and coil parameters of a real four-coil system are extracted using a vector network anaylyzer (VNA) and computed through Matlab script based on the work in [10]. The transmit loop-coil and the receive loop-coil are critically coupled (coupling values selected such that impedance looking through the coil network is the same as the load impedance). As the focus of this simulation is to get the general case result (not considering specific rectifier characteristics), passive network loads are employed to model both the Z_{MATCH} and Z_{LM} load conditions. These two loads are selected by an ideal switch, which is controlled by a digital signal modeling the information-carrying signal sent by the power client to the power host. The matched load condition Z_{MATCH} is set by default in the beginning of the transient simulation to give the Class E amplifier time to stabilize. Load modulation begins at 100 μs and involves alternating between load impedances of Z_{MATCH} and Z_{LM}. The reflected wave as measured through a simulated directional coupler is used as

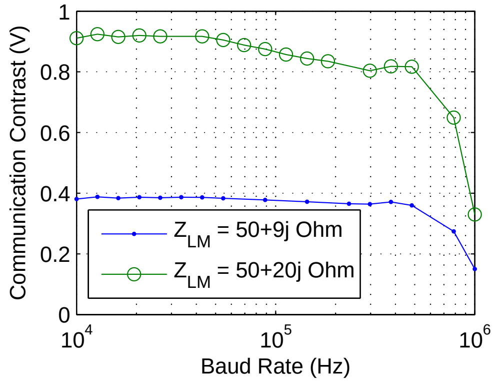

Fig. 9. Communication contrast (the distance between points on the IQ plane, in Volts) as a function of the load modulation baud rate (symbol rate), in Hz. With a typical binary shift keying modulation scheme, the data rate (bps) will be equivalent to the baud rate. Using higher order modulation schemes such as QAM allows multiplicative increases in data rate.

the raw data for communication, which is saved to be decoded by an IQ demodulator implemented in Matlab. The received power P_{rx} is calculated as the sum of the average power of the two load impedance, and the input power P_{in} is measured with the DC power supplied to the PA. Because the PA is a non-linear switching amplifier, the input power at the MOSFET gate is constant, so we consider drain efficiency rather than power added efficiency for the PA. Thus, we define our system efficiency as P_{rx}/ P_{in}.

V. Results

A. Power versus Communication Tradeoff

Figure 4 shows one sample of the recorded uplink data with the decoded result for I and Q, magnitude and phase with Z_{LM} to be $50 + 20j$. With this Z_{LM}, the system efficiency is 62.8% during load modulation mode while the maximum power efficiency is 63%, and the communication contrast at this point is 0.87 V (Figure 5). Because the communication contrast is low, the efficiency drop is only 0.2%.

Figures 5 and 6 explore the tradeoff between power transfer efficiency and communication contrast as a function of Z_{LM}. Figure 5 illustrates the dependence of the two metrics on the real part of the load modulation impedance (R_{LM}), and Figure 6 illustrates their dependence on the imaginary part (X_{LM}), assuming a matched real part. Figures 7 and 8 show the two metrics separately, as a function of the load modulation impedance as shown on a Smith chart. The points shown on the Smith charts for these two plots represent the equivalent reflected impedance seen by the PA, and follow the Z_{LM} values selected in the design section.

The results demonstrate the inverse relationship between communication contrast and power efficiency. However, as Z_{LM} increases, the load impedance seen by the Class E PA is more mismatched, resulting in a reduction in the DC supply power of the PA. This reduced consumption slows the trend of efficiency degradation. For a typical use case, a constant and stable load power is desirable. In order to maintain a constant load power as data transfer is occurring, the amplitude of the transmit signal could be adjusted during load modulation. This can be done automatically via a feedback loop as in [11], but implementing automatic load power tracking is outside the focus of this paper.

B. Frequency Response

As the load modulation frequency increases, the impact of the ringing effect of the coil system becomes more significant. Figure 9 shows that the frequency response of Z_{LM} with 50+9j Ω and 50+20j Ω. The two impedance values characterize the frequency response of communication degradation with small and medium mismatch case respectively.

VI. Conclusion

We have concluded that load modulation can be achieved with minimal impact on efficiency by careful selection of load modulation impedance. Future work includes comparing our modeled results against a physical system and implementing an algorithm for determining the optimal load modulation impedance during system operation.

VII. Acknowledgements

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