Reconfigurable and Adaptive Coupled Relay Resonator Platform for a Moving Receiver

Xingyi Shi
Electrical and Computer Engineering
University of Washington
Seattle, WA, USA
xingyi@ieee.org

Joshua R. Smith
Computer Science and Electrical Engineering
University of Washington
Seattle, WA, USA
jrs@cs.washington.edu

***Abstract*—Linearly arranged passive relay resonators have been shown to be able to extend wireless power transfer range. However, extending this relay concept to a 2-D planar array with the intention to cover a larger area presents challenges; naïvely constructing a plane of tessellated relays results in a poor efficiency of power transfer due to complex interactions between relays as the number of relays increases [1]. In this paper, we implement the first electronically reconfigurable relay transmitter system, which allows efficient transfer in large relay arrangements and can track a moving receiver across its coverage area. We propose a receiver tracking method and algorithm which can scan the entire coverage area over 2000 times per second and, once found, can configure the relay array to efficiently deliver power to the receiver.**

***Index Terms*—wireless power, relay, coupled resonator, reconfigurable, algorithm, tracking, moving receiver**

I. Introduction

Magnetic resonance systems have proven to be the most power efficient method of wireless power transfer that does not require close contact [2]. The most common construction of a magnetic resonance transmit antenna consists of a loop and a coil, where the loop is connected to the power signal and the coil is a high quality-factor resonator that amplifies the magnetic field [2]–[5].

With a growing demand for charging sensors, implanted medical devices, and robots, a platform that is designed to deliver power to a moving target in a large space is desired [4]. Passive resonators acting as relays have shown promising results in extending power transfer in one dimension ([5], [6]). In this work, we focus on how to make a reconfigurable 2D planar relay platform efficient, by routing power adaptively based on receiver location. A different method of localization with a planar relay array is demonstrated in [7].

Our contributions in this work are as follows:

- We introduce the reconfigurable passive relay array topology shown in Fig. 1.
- We design a control algorithm to adaptively reconfigure the relay transmitter based on the movement of a receiver. This algorithm is based on unique characteristics of the passive relay array, which are described.

This work was supported in part by the Paul G Allen Family Foundation's Allen Distinguished Investigators program and by NSF award CNS-1305072.

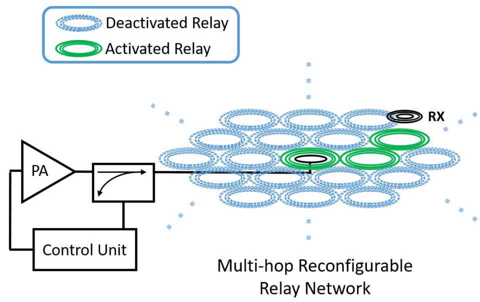

Fig. 1. Illustration of a planar reconfigurable relay wireless power transfer system.

- Finally, we implement and evaluate a functional prototype based on the relay array design and algorithm.

In Section II, we describe the characteristics of the relay array which will be used in the algorithm design, and go on to describe the algorithm for adaptive reconfiguration of the relay array. In Section III, we describe the implementation of the reconfigurable relay transmitter prototype. Lastly, in Section IV, we characterize and evaluate the prototype performance.

II. Design

The design goals of the reconfigurable relay system are twofold: 1) Efficient delivery of power to any point within a large area, and 2) Ability to quickly react to receiver movement.

In this section we first introduce the new transmitter topology. We then describe key characteristics of multi-hop passive relay systems, which will be useful in determining how to design and control the relay array. This section culminates in the design of the control algorithm itself, which rapidly and efficiently searches through relay configurations to identify a configuration capable of delivering power to the receiver.

A. Reconfigurable passive relay transmitter topology

A passive relay is a resonator that sympathetically resonates when it is placed in an existing oscillating field which has the same frequency as its resonant frequency [5]. By placing relays in the correct arrangement, the resonant field can be extended [6]. Thus relays have been employed as a means of extending wireless power transfer.

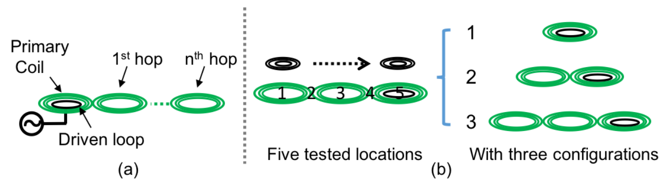

Fig. 2. (a). A relay configuration with one leg and n hops. (b). Test setup for S parameter measurement.

This works well in co-axial configurations, where the relays are on the same axis as the transmiter. However, it doesn't work in most co-planar configurations. We show in prior work [1] that, when constrained to a single operating frequency, even a simple linear path of arranged planar relays (Fig.2a) cannot transfer power efficiently to every location along the linear path. We refer to this linear relay arrangement, which has one path that connects the transmitter and the receiver as **1-leg-n-hop**. If the receiver is at the end hop, the relays form a good power transfer channel at their common natural resonant frequency, but if the receiver is placed at any other location along the path, transfer efficiency becomes inconsistent due to detrimental interactions between relays.

Thus, to effectively route power throughout a plane, we propose to use coplanar, electronically reconfigurable relays that adaptively switch to the most suitable 1-leg-n-hop configuration based on the receiver location. Relays are placed in a hexagonal grid so that spacing between neighboring relays are consistent, making each path with the same number of hops the same length. We choose to use a maximum of 2 hops between transmitter and receiver to avoid analytical complexity. Prior work shows that relays with more hops share similar characteristics [1].

The proposed relay transmitter consists of nineteen hexagonally arranged coils, as shown in Fig.1. A driven loop is placed under the center coil and driven by a class E power amplifier, a commonly used topology which has proven to be highly efficient in wireless power transfer systems [8].

A control system is given a means to switch on and off each relay resonator. In order to decide on the optimal relay configuration, that controller needs to be able to detect the presence or absence of the receiver on a particular candidate configuration. To do this, we choose to observe the reflection coefficient via a directional coupler placed at the output port of the power amplifier. This choice will be further explained in Section II-C.

B. Input Impedance Characterization

Understanding the unique characteristics of input impedance of the adaptive multi-hop system is important in predicting and optimizing efficiency, because power amplifier efficiency varies with load impedance. Specifically, there are two cases to address: 1) When the relay array is searching for but has not found a receiver, and 2) when the receiver has been located. While scanning, we want the input impedance of the relay system to be an impedance at which the amplifier dissipates the least power, as any power used in this state is wasted.

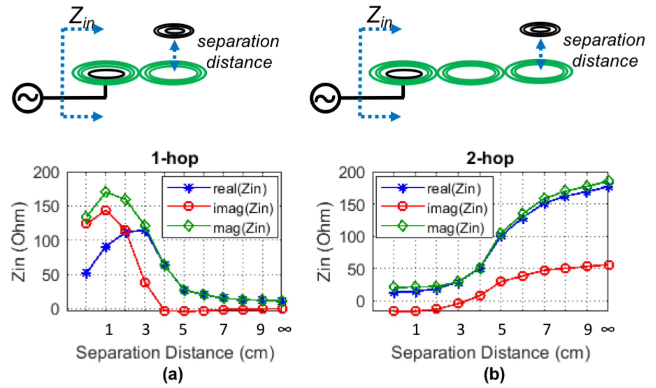

Fig. 3. Change of input impedance of (a) 1-hop and (b) 2-hop relay systems as the receiver separation distance changes.

When the relay transmitter has located a receiver, the input impedance of the relay system (with a matched load) should conjugate-match the output impedance of the power amplifier for optimal efficiency. This work describes for the first time a relationship between input impedance of a multi-hop relay resonator and the number of hops between transmitter and receiver, which can be used to predict and optimize efficiency.

We model the input impedance of the 1-hop and 2-hop case as a matched load receiver moves vertically at the end hop. Fig.3 show the test setup and input impedance results. The relays for both experiments have identical geometries; five-turn PCB coils with a Q of 120. The impedance is measured at 13.47 MHz, which is their resonant frequency.

The results show that impedance trends between 1-hop and 2-hop systems are opposite. The 1-hop input impedance changes from low to high as the receiver comes closer, while the impedance of 2-hop changes in the opposite way. In the open-load condition where no receiver is present, Z_{in} of the 1-hop system is around 12 Ω (Fig.3a), and Z_{in} of the 2-hop system is around 180 Ω (Fig.3b).

To minimize the power consumed while scanning for a receiver, we prioritize the types of patterns used in scanning based on a consideration of the power amplifier characteristics and system input impedance. The Class E power amplifier used in this work has similar power consumption with both the 12 Ω 1-hop impedance and 180 Ω 2-hop impedance [9], so in our case we elect to prioritize longer-range 2-hop configurations to scan for the receiver. Depending on topology and implementation, other amplifiers will exhibit differing power consumption with the 1-hop and 2-hop no-load impedances, possibly leading the system designer to choose to prioritize 1-hop configurations for scanning.

For both 1-hop and 2-hop patterns, when the receiver moves to 4 cm away, the impedance is closest to the 50 Ω impedance matched condition that is optimal for power transfer efficiency. Thus, the relay system can deliver power most efficiently to the test receiver when it is around 4 cm away.

C. Design of a Fast Receiver Tracking Algorithm

In this section, we use the characteristics of the relay array platform described above to develop a control algorithm which

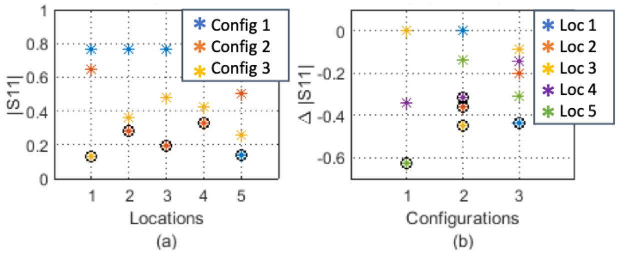

Fig. 4. (a). $|S_{11}|$ measured across three relay configurations, with receiver placed at each of five test locations. (b). Change in $|S_{11}|$ seen with each configuration when a receiver is present at each of the five test locations. The circled data in both (a) and (b) are the datapoints where maximum $|S_{21}|$ was observed, representing best efficiency. Note that test cases where $|S_{11}|$ is lowest, or changed the most, correlate with the best $|S_{21}|$ values and thus best power delivery to the receiver.

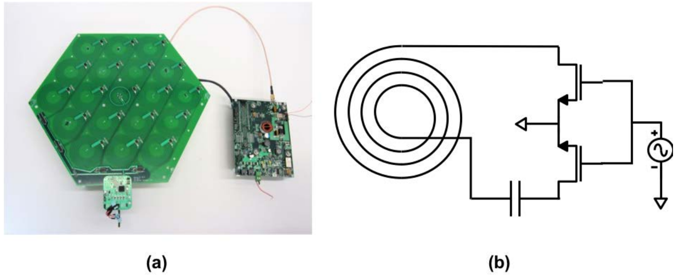

Fig. 5. (a). Hardware prototype of a relay transmitter system. (b). Circuit diagram of a reconfigurable unit relay.

meets the goals of high efficiency and fast receiver tracking.

A multi-hop system can be regarded as a passive 2-port system, where port 1 is the transmitter and port 2 is the receiver. For efficient power transfer, the goal is to optimize $|S_{21}|$. However, S_{21} would be very difficult to practically measure during system operation, as it requires instrumentation of both transmitter and receiver. To address this, we propose to use S_{11} as a proxy for S_{21}. Because reflection coefficient, which is equivalent to S_{11} when the load is matched, can easily be measured from the transmitter side, this would greatly simplify system topology. As an added benefit, the change of S_{11} happens instantaneously with the change in load condition, making the tracking inherently fast.

We use the well known rule that the sum of $|S_{21}|^2$ and $|S_{11}|^2$ is no more than 1 for a passive 2-port system, as seen in Eq.1.

$$|S_{11}| <= \sqrt{1 - |S_{21}|^2} \tag{1}$$

From Eq.1, large $|S_{21}|$ implies small $|S_{11}|$, but small $|S_{11}|$ does not necessarily mean large $|S_{21}|$. To show that this converse relationship is also generally true, we compare actual $|S_{11}|$ measurements at various receiver locations with corresponding $|S_{21}|$ measurements. Fig.2b shows the tested area are divided into five receiver locations, with the relay array configured into each of three options at each location. Fig.4a shows the corresponding S parameter results when a receiver is separated by 4 cm, the location that makes the input impedance of the multi-hop network 50 Ω. At each location, the configuration that has the minimum $|S_{11}|$ has the maximum $|S_{21}|$.

However, we are not able to detect the receiver position by merely finding the relay configuration with the minimum $|S_{11}|$ result. This would cause the system to incorrectly settle on a relay configuration with the lowest $|S_{11}|$, even when no receiver is present, rather than continuing to search.

One approach to resolve this issue is to use the change in $|S_{11}|$ as an indicator of a receiver's presence. Fig.4b shows the change in $|S_{11}|$ seen by each configuration when a receiver is present at each of the five test locations. If the change in $|S_{11}|$ from some baseline value exceeds a threshold for a particular configuration, we decide that the receiver must be powerable via that configuration. However, because the amount of change in $|S_{11}|$ (Fig.4b) is different for different relay configurations, receiver locations, and receivers, optimizing tracking accuracy would mean tediously characterizing all possible loading conditions to determine the threshold setting for each configuration. Even though this approach is fast during run time operation, it requires prohibitively complex prior calibration of the system.

Based on the above insights, we propose a tracking algorithm consisting of three sequential tasks: **calibration**, **rough-scanning** and **focused-scanning**.

1) The **calibration** process can take place once after manufacture of the relay array, or on each system boot. In calibration, the S_{11} value of all selected relay configurations are measured automatically one-by-one and saved as system calibration values.
2) During normal operation, the **rough-scanning mode** is the way each receiver search cycle starts. In rough-scanning, we switch between a prioritized set of possible configurations until we detect a change of S_{11} from the calibration value. The threshold of change detection is small. The first configuration in which a change in S_{11} is detected is called the **pilot configuration**.
3) The configurations that share *any one* of the unit relays in the pilot configuration are referred as the **related configurations**. After the pilot configuration has been identified, we enter the **focused-scanning mode**, where we switch between all the related configurations and select the one with the largest change in $|S_{11}|$ for the detected receiver.

In the following section we describe the implementation of a reconfigurable relay array transmitter, and show how this algorithm can be applied to produce an efficient and fast adaptive system.

III. Implementation

In order to validate the design of the system, a prototype was implemented as shown in Fig.5a.

The relay transmitter consists of two parts: a reconfigurable relay board and a relay control board. The relay board is implemented on a four-layer FR4 PCB, has nineteen hexagonally arranged coils, and is 31 cm in diameter at its widest point. Each coil has five turns and has a diameter of 59 mm.

The driven loop is mounted under the center coil of the board, and is connected in series with a 91pF tuning capacitor and a pair of BUK7K134-100E MOSFET switches that share a source and gate as shown in Fig.5b. When the gate voltages are high, the series switches allow current flow and the relay may resonate. When the gate voltages are low, the switches block current flow, pushing the resonant frequency very far from the system's operating frequency and thus effectively shutting off the relay. The control signals that reconfigure all relays are generated by a microcontroller, then level shifted to 10 V.

As shown in Fig.5a, the power signal is provided by an existing power transmitter, the same used in [4]. It consists of a 13.56 MHz signal source and a Class E amplifier designed for a 50 Ω load. At the output of the power amplifier, a SYDC-20-22HP+ directional coupler is connected in series. The reflection coefficient from the coupler is processed by an AD8302 gain and phase detector.

The control algorithm is implemented using the TI MSP432P401R. This microcontroller is chosen because of its fast and high-resolution 1-Msps, 14 bit ADC, which is used to collect samples from the output of the gain and phase detector. A monolithic RC low pass filter, the ELK-EV333FA, is placed between the detector and ADC to reduce noise at the carrier frequency. For each reflection coefficient data point, seven consecutive samples are taken and digitally averaged to further reduce the impact of noise. The entire controller firmware uses 5.7 kB of MSP432 program memory.

The calibration procedure is triggered once on system power-on and used to provide the baseline reflection coefficient value for each configuration. Once a possible receiver has been identified in the rough scanning mode, the algorithm transitions to focused scanning mode. At the end of the focused scan the prototype will remain in the configuration which best targets the receiver. The prototype continues sampling the reflection coefficient until it observes a significant change, which may indicate that the receiver has moved, at which point it returns to rough scanning mode.

IV. Experiments and Results

In this section we characterize the performance of the system with regards to efficiency, coverage, and tracking speed. To evaluate the power routing performance of the reconfigurable relay system, we compare the measured $|S_{21}|$ with an HP8753ES vector network analyzer between the relay transmitter and a single coil transmitter optimized for efficiency from [4].

The receiver used in the experimentation is an eight-turn PCB coil with 2 cm diameter and Q of 90. The receiver is separated by 5 mm and 1.6 cm respectively above the single transmitter and the relay transmitter for the measurements. Results in Fig.6 are measured at dotted locations, and then extrapolated to the rest of the surface area based on symmetry. The figure shows that the relay transmitter attains a much higher average $|S_{21}|$ than the single coil transmitter. Additionally, the locations that are near the center of each relay coil have better efficiency than locations in between relays.

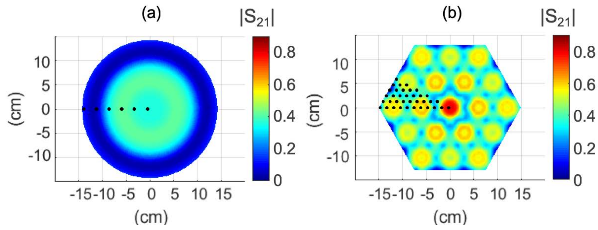

Fig. 6. Comparing the $|S_{21}|$ between (a) a single coil transmitter and (b) the relay transmitter from this work with the same coverage area. The dots represent the XY locations where measurements are taken.

These results suggest that the relay transmitter can effectively extend the coverage of wireless power transfer. Because the goal of this work is to demonstrate the reconfigurable system and tracking algorithm, future work can continue the process of optimizing coil design for improved efficiency.

The rough scanning mode scans the entire search space 2083 times per second. Once a pilot configuration is found, the focused scan takes only 120 microseconds. With this fast tracking algorithm, power is automatically routed to the receiver as it moves, at a rate faster than the eye can detect.

V. Conclusions and Future Work

In this work, we have proposed and implemented a system for delivering wireless power over a large area to moving receivers with reconfigurable coupled relay resonators. The proposed tracking algorithm enables fast receiver tracking. Future work can focus on improvements to relay coil design for better efficiency.

References

[1] X. Shi and J. R. Smith, "Large area wireless power via a planar array of coupled resonators," in *2016 International Workshop on Antenna Technology (iWAT)*, pp. 200–203, Feb 2016.

[2] A. Kurs, A. Karalis, R. Moffatt, J. D. Joannopoulos, P. Fisher, and M. Soljačić, "Wireless power transfer via strongly coupled magnetic resonances," *Science*, vol. 317, no. 5834, pp. 83–86, 2007.

[3] A. Sample, D. Meyer, and J. Smith, "Analysis, experimental results, and range adaptation of magnetically coupled resonators for wireless power transfer," *Industrial Electronics, IEEE Transactions on*, vol. 58, pp. 544–554, Feb 2011.

[4] B. H. Waters, *Adaptive Wireless Power for Ventricular Assist Devices*. Ph.D. dissertation, Dept. of Elect. Eng., Univ. Washington, Seattle, 2015.

[5] F. Zhang, S. A. Hackworth, W. Fu, and M. Sun, "The relay effect on wireless power transfer using witricity," in *Digests of the 2010 14th Biennial IEEE Conference on Electromagnetic Field Computation*, pp. 1–1, May 2010.

[6] C. K. Lee, W. X. Zhong, and S. Y. R. Hui, "Effects of magnetic coupling of nonadjacent resonators on wireless power domino-resonator systems," *IEEE Transactions on Power Electronics*, vol. 27, pp. 1905–1916, April 2012.

[7] A. Hashizume, Y. Narusue, Y. Kawahara, and T. Asami, "Receiver localization for a wireless power transfer system with a 2d relay resonator array," in *2017 IEEE International Conference on Computational Electromagnetics (ICCEM)*, pp. 127–129, March 2017.

[8] J. J. Casanova, Z. N. Low, and J. Lin, "Design and optimization of a class-e amplifier for a loosely coupled planar wireless power system," *IEEE Transactions on Circuits and Systems II: Express Briefs*, vol. 56, pp. 830–834, Nov 2009.

[9] X. Shi, A. N. Parks, B. H. Waters, and J. R. Smith, "Co-optimization of efficiency and load modulation data rate in a wireless power transfer system," in *2015 IEEE International Symposium on Circuits and Systems (ISCAS)*, pp. 698–701, May 2015.