Large Area Wireless Power via a Planar Array of Coupled Resonators

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***Abstract*—A method of enabling efficient wireless power delivery for a mobile receiver in a 3-D space is proposed. A reconfigurable planar array of coupled resonator (relay) coils is designed, and a method of choosing the optimal array configuration for a particular receiver position is proposed. Experimental results are obtained with a PCB implementation of the proposed planar relay array system operating near 13.56 MHz. Coverage improvements over conventional planar relay arrays are demonstrated.**

I. Introduction

Receiver mobility in wireless power delivery has become more of an interest nowadays when the power receiver will not stay at a fixed location. A patient moving around in a room, electronics charging at any location on a flat surface, and charging of a moving electric vehicle are examples of mobile receivers. Simply using one large transmit coil to cover the intended area with a relatively small mobile receiver will lead to a highly inefficient solution because of the weak coupling caused by large transmitter-to-receiver size ratios [1]. Several approaches using relay coils [2], [3] and phased array systems [4], [5] have been developed to attempt to overcome this challenge.

Phased array systems can increase the flexibility of receiver coil alignment, but efficiency is not hugely improved [4], [5]. Additionally, phased array systems require multiple transmitters, increasing system complexity. Relay coil systems increase the power delivery range, but at the cost of reduced efficiency [2]. For coils relaying power in the axial direction, the transmission loss can be minimized by optimizing the insertion location of the relay coils [6]. But in order to cover a larger area, axial relays are not sufficient. A planar array of relay coils is one accepted solution. However, planar coils with relays on the same plane present a more difficult design challenge, as multiple frequency modes will occur. Existing work involving relay systems makes use of a single driven coil and a tessellated array of synchronously tuned relay coils uniformly spread around it. Because the resonant mode at different location changes significantly, this existing method requires the use of impedance modulation at both the transmitter and receiver to improve the transfer efficiency [3].

This work presents a method for improving power transfer from a planar array of relay coils by selectively activating certain relay coils in the array to form isolated paths between the transmitter and the receiver(s). The position of these isolated paths are then time-multiplexed to cover the entire planar array.

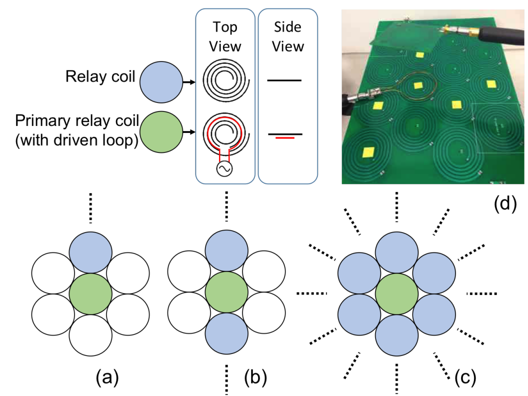

Fig. 1. a) represents the edge driven relay coil setup. b) represents the middle driven relay coil setup. c) represents the traditional sheet driven setup. e) is a photo of the experimental setup used for all results collection. The planar relay array is constructed on a 4-layer PCB, with planar coils, tuning capacitors, and enable/disable switches for each coil. The driven loop, protruding from the left of the image, is connected to one port of a vector network analyzer, and the receive coil is connected to the second port. The receiver is implemented as a resonant coil/capacitor combination tightly coupled to a receive loop.

Compared with an always-active planar array, this has the benefit of requiring no frequency tuning and no dynamic impedance matching at either the transmitter or receiver, reducing system complexity. The characteristics of the path are chosen to be symmetric, and it is shown that this results in a relatively stable system frequency response across differing receiver positions, an ideal characteristic considering regulatory constraints which only permit narrowband operation. It is demonstrated through experimental results that the efficiency for each receiver position in the relay path is improved using this technique.

Through experimentation, the proposed symmetric relay configuration will be compared to a single-ended relay and always-on relay sheet (Figure 1). Herein the the single-ended relay is also referred to as an **edge-driven relay** configuration, and the proposed symmetric form is also referred to as a **middle-driven relay**. Each side of the middle-driven relay is called a **leg**. The number of relay coils of each leg is called **n-hop**. For instance, the configuration in Figure 1b is called **2-leg-1-hop**. The loop connecting to the RF power source only drives one relay coil at a time and it is referred to here as the **driven loop**. The relay coil driven by the loop is called the **primary relay coil** in this work.

Section II discusses the design process of the proposed relay technique and the metric for evaluating the system. Section

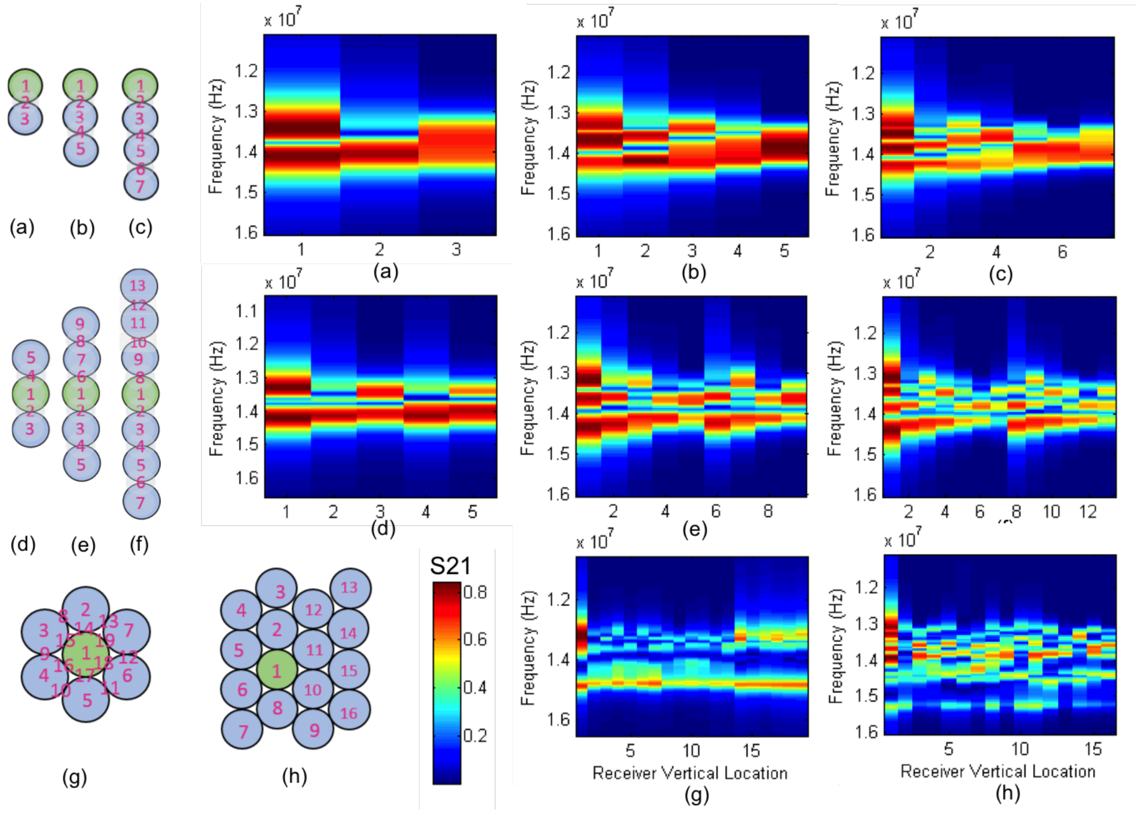

Fig. 2. a), b), and c) are edge-driven 1-hop, 2-hop and 3-hop configurations, respectively. d), e), and f) are middle-driven 1-hop, 2-hop and 3-hop configurations. g) and h) are relay sheet configurations used as points of comparison. S21 response across a frequency range along the relay path is determined for each configuration. In each test, the receiver is located on top of each labeled location in parallel with the transmitter plane, with a separation distance of 37 mm.

III compares the experimental results of the three different types of the relay configuration. Section IV describes how the experimental results conclude the proposed relay system.

II. Design

Different number and the alignment of the coupled resonator create different resonant mode [7]. So for a linear path of relay coils driven at one end, the number and frequency of the resonant modes will always change as a function of receiver position.

The key observation that informs the design of this work is the following:

- Driving a symmetric arrangement of paths of relay coils from the *center* (middle-driven) rather than the edge (edge-driven) produces a system where the resonant modes are far more stable as a function of receiver position, but only when secondary coupling (coupling between relay coils from different paths and the receiver) is negligible.

To ensure that the response along two sides of the path is the same, the number of coils and the coupling between coils on each side of the symmetric structure need to be identical. The illustrations in Figure 2d-2f represent some example arrangements which meet these criteria.

Thus, to compare the middle-driven and edge driven, we design the test platform as a hexagonal tessellated sheet of identical planar coils on a PCB (Figure 1d). The TX relay sheet has a total of sixteen coils, each designed based on the work from [3] where each coil is tuned at 13.56 MHz. Each tuning capacitor is connected through a mechanical switch for the purpose of experimentation, though this could be replaced by a digitally controlled switch in a real deployment.

A. Performance metric

We develop a metric for comparison of power delivery coverage for the different relay coil configurations. We note that, due to regulations, a wireless power system will be constrained to operation at a single frequency. Therefore, simple comparison of S21 maximums (which shift as a function of receiver position) are not effective as a metric. However, we also note that any relay coil configuration can be tuned to operate in a desired frequency band, and therefore that the absolute frequency values observed in these results are of little importance.

The metric we propose below addresses these observations by first identifying the optimal frequency of operation for each configuration based on a threshold for acceptable power transfer efficiency, then comparing across configurations (assuming that the optimal frequency would be used for each, but that frequency cannot be allowed to change between receiver positions):

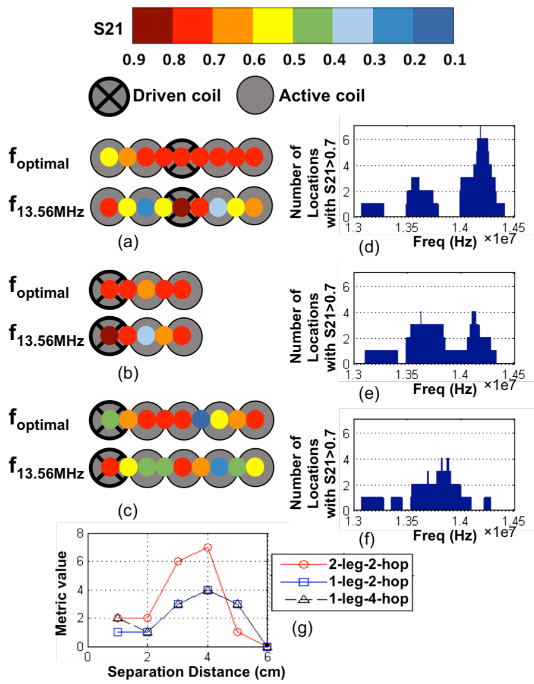

Fig. 4. Comparing the 2-leg-2-hop a), 1-leg-2-hop b) and 1-leg-4-hop c) using the metric defined in Section II. Figure d) e) and f) show the results of configuration a)-c) with 4cm separation distance (critical coupled) based on the metric. The color map of the top figures of a), b) and c) illustrates the S21 values at the optimal frequency based on result d)-f); the bottom figures of a)-c) shows the S21 at the natural frequency 13.56MHz based on result d)-f). The optimal frequencies used for these three configurations are 14.2MHz, 14.1MHz and 13.8MHz,respectively. e) compares the best metric value at separation distance 1cm to 6cm with 1cm increment for the three configurations.

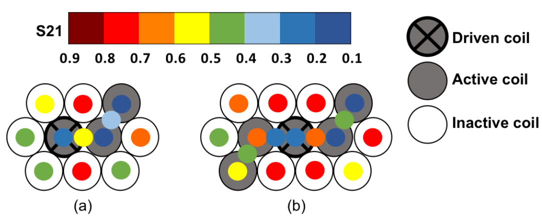

Fig. 5. Compare the S21 at locations that are not directly above the relay path when the receiver has 1cm separation distance from the transmitter plane.

- **Metric:** To evaluate a particular relay coil configuration at a particular separation distance: for each test frequency, count the number of equally-spaced locations across the test volume where the power efficiency exceeds 50% (S21 value is greater than approximately 0.7). Then, find the peak value of this count across all frequencies. This peak represents the *best possible single-frequency coverage for each relay coil configuration*.

The efficiency threshold of 50% was selected as a reasonably acceptable efficiency for many applications.

III. Experiments and Results

Three sets of experiments are performed to characterize the proposed middle-driven symmetric relay array:

1) Frequency response across position for various relay configurations: First, the proposed relay configuration (middle-driven) is compared to existing techniques (edge-driven and always-on) in terms of performance at various receiver positions along the relay path. Experiments are performed for both middle-driven and edge-driven configurations with 1-hop, 2-hop, and 3-hop relays (Figure 2a-2f). In addition, Figure 2g and 2h show the symmetric and asymmetric always-on configurations, respectively. The receiver is placed above the relay path at locations as marked in each plot, with a fixed separation between the receiver and the plane of the relay coil array. The fixed distance is 37mm, which is the critical coupling range. From Figure 2, the isolated path configurations (Figure 2a-2f) are better than the all-active-relay case (Figure 2g-2h) with higher transmission gain and a more constant resonant band. Because the relay geometry in Figure 2g is symmetric, the resonant modes at different locations do not change as chaotically as in the asymmetric case (Figure 2h). But due to inter-coupling between each connected relay, the shared optimal passband in Figure 2g is narrower compared to either the edge-driven or the middle-driven case.

Figure 3 shows the advantage of using single optimal frequency mode compared to the natural frequency mode. Frequency tracking mode, which picks the peak S21 across the entire test frequency spectrum, is used as a comparison reference. Optimal frequency mode uses the optimal frequency based on the results obtained. Natural frequency mode operates at the frequency at which each coil would resonate if it were independently tested.

2) Performance across separation distance, with comparison to single driven coil: Next, the performance of the proposed middle-driven relay coil system is studied in the over-coupled region and under-coupled region by changing the separation distance between the receiver and the plane of the relay array. Distance is varied from 1cm to 6cm, in 1cm increments. The relay configurations chosen for this test are 2-leg-2-hop, 1-leg-2-hop and 1-leg-4-hop (Figure 4a-4c).

Figure 4d-4f compare the performance of the three configurations based on the computed results from the metric defined in section II-A at the critical coupled region 4cm. The bar plot shows that the 2-leg-2-hop has better coverage than the other two configurations. Figure 4a-4c compare the coverage between the optimal frequency mode (top) and the natural frequency mode (bottom). For the optimal frequency mode, the high efficiency locations are those near the primary driven coil. On the other hand, for the natural frequency mode, there is always a null spot after the good coupling locations. The pattern of high followed by low repeats with a decaying envelope as the location is increasingly distant from the driven coil.

When the separation distance between the receiver and the transmitter plane is very small, only locations that are directly above or very close to the driven coil have good coupling, though these resonant modes are pushed further away from the natural frequency. As a result, the number of locations that has S21 greater than 0.7 is much less than those in the critical coupled region (Figure 4g). When the receiver is in the under coupled region, the edge-driven configuration decays slower

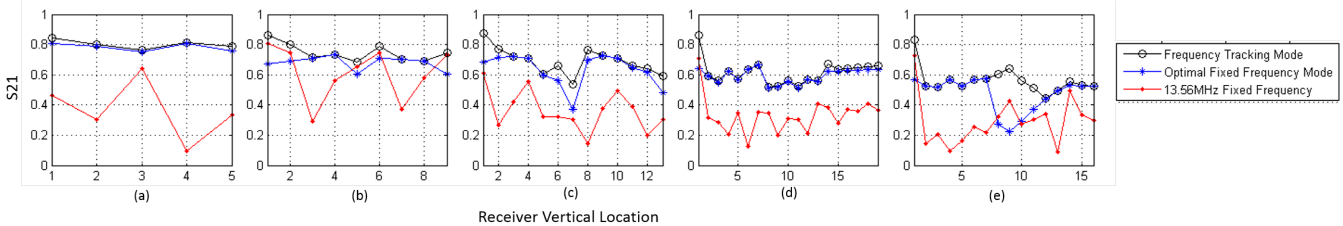

Fig. 3. Comparing optimal fixed frequency mode with frequency tracking and default synchronously tuned frequency modes. a), b) and c) are results for 2-leg-1-hop, 2-leg-2-hop and 2-leg-3-hop, respectively (configurations are shown in Figure 2d-2f). d) and e) are from the sheet relay configuration from Figure 2g and Figure 2h, respectively. The optimal fixed frequency mode is the proposed one in this work.

comparing to the middle-driven setup.

3) Receiver in the over-coupled region: In the conventional single transmitter-receiver system, improving transmission efficiency when the receiver is in the sensitive over-coupled region can only be done through frequency tracking and active impedance matching [8]. In the multi-relay system, we can bypass this by selecting a relay coil path which produces the desired amount of coupling, avoiding the sensitive over-coupled region in favor of critical coupling and thereby eliminating the need for frequency tracking and active impedance matching. Figure 5 shows that the S21 is better when the receiver is not directly above the active relay path with a separation distance. The frequencies chosen for these two plots are the optimal frequencies based on the 4cm separation case for the 2-leg-2-hop (Figure 4d) and 1-leg-2-hop (Figure 4e) configurations, respectively.

IV. Analysis and Proposal

The middle-driven relay geometry in the single optimal frequency mode has better coverage area compared to the edge-driven case with the same number of active relay coils. For a typical transmission range, by the performance metric defined in Section II-A a five-coil middle-driven relay geometry provides a 43% coverage improvement over a five-coil edge-driven geometry.

When there is need to use the natural frequency as the operating frequency, one should be prepared to work around the periodic nulls which occur between locations that have good coupling. In addition, because the edge-driven configuration has a passband with wider bandwidth and decent transmission gain at the end hop location, it may be preferred given certain design requirements.

When the receiver is very close to the relay plane, we recommend altering the active relay path so it is not directly under the receiver, in order to reduce the extra coupling and achieve the best efficiency as described in Section III-3 .

To utilize the characteristics of the relay system, one can choose to rotate the middle-driven configuration through time multiplexing. Examples of rotation patterns are shown in Figure 6.

V. Conclusions and Future Work

In this work, we have proposed a method for enabling wireless power transmission in a large area with an array of coupled resonator relays. We presented and analyzed the

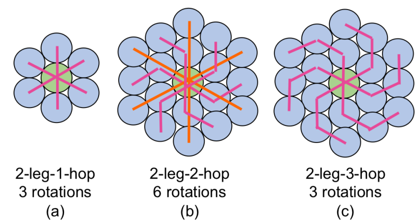

Fig. 6. The proposed time-multiplexing configurations. Each setup uses the middle-driven mode. Through rotation, the entire area is covered. a), b) and c) are 1-hop, 2-hop, and 3-hop, respectively.

experimental results of the three modes of relay configurations for best power delivery when mobile receiver operates at different vertical separation distance. Future work includes integrating all the modes for the different relay setup into an automatic switching system.

VI. Acknowledgements

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