iSurface: Self-Powered Reconfigurable Intelligent Surfaces with Wireless Power Transfer

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Abstract

This article introduces iSurface, the first-of-its-kind self-powered reconfigurable intelligent surface (RIS) that can engineer ambient wireless propagations in the environment via a reconfigurable RF layer. Additionally, it can charge multiple devices close to the surface via power transfer enabled by a reconfigurable magnetic resonance layer. We develop a resonance coupling power distribution framework that allows flexible and on-demand power spots with power flow paths over 2D and 3D resonator surfaces to power RIS units and wirelessly charge devices. We design reconfigurable source and extender resonators and validate the iSurface prototype through simulation, experiments, and a real application demonstration. Our results demonstrate the feasibility of creating fully reconfigurable power spots with the deliverable power ranging from 0–16 W through different power flow paths and for different types of surfaces.

Introduction

The wireless community has witnessed the emergence of several transformative applications over the past few years given the rapid adoption of 5G and the pervasive Internet of Things (IoT) paradigm. "Smart infrastructure and environment" is often identified as one such example application, which will accelerate ubiquitous connectivity and pervasive sensing capability to the next generation of wireless networks. Reconfigurable intelligent surface (RIS) is a candidate technology to realize smart environments. Going beyond passively reacting to the environment, RIS will actively shape the wireless environment by engineering on-demand signal reflection and propagation characteristics. However, new installation of specialized RIS in legacy spaces is often infeasible. In this article, we propose a bold vision of transforming ordinary surfaces into such intelligent environments using low-cost and low-power hardware. Many published designs for RIS-aided systems require advanced signal processing, intelligent computation, and higher active electronic components, such as PIN diodes, RF switches, and phase shifters. These requirements result in significant power consumption, which poses a challenge to scalable deployment of RIS systems. For example, an RIS operating at 28.5 GHz frequency consumes up-to 153 W with 256 elements in [1], the RIS hardware with 16 × 16 elements that operates in the 10.7 GHz–14.5 GHz band consumes 93 W in [2], and the RIS proposed in [3] with 224 reflective elements incurs power consumption of around 40.32 W.

Battery-powered RIS operation generally has limited lifetime in many practical applications, given cost, weight, and size of deployment that impacts battery size. Additionally, RF-based energy harvesting that provides an average charging rate of 1 W at a charging distance of about 10 m is not a suitable solution for RIS in many cases. On the other hand, coupled wireless power transfer (CWPT) is emerging as a new approach for powering devices for future 5G industrial applications [4]. CWPT delivers power wirelessly to electronic devices via near-field electromagnetic coupling. Traditionally, this process involves two techniques: magnetic inductive coupling (Qi) and strong magnetic resonant coupling (A4WP). Magnetic inductive coupling is effective for power transfer only over short distances and requires perfect alignment between transmitter and receiver coils. This is due to the inherent characteristics of using low-frequency (kilohertz) and loose coupling between transmitter and receiver coils. On the other hand, A4WP enables longer power transfer distance, higher power transfer amount, and considerable spatial offset between the receiver placement and transmitter. Hence, we choose this approach in realizing the proposed surface-based wireless charging systems. Surface wireless charging creates intelligent power distribution at different points over a surface that enables a self-powered RIS system along with contactless multi-device charging of devices close to the surface. We envision this technology playing a key role in realizing practical RIS deployments.

Previous studies have reported magnetic-resonant-based surface charging systems with multiple resonators (coils) to improve the wireless power transfer performance. Popular methods for such surface charging are Multi HotSpots[5] and SoftCharge[6]. Multi Hotspots relies on theory very similar to multiple-input multiple-output (MIMO) in wireless communication. However, the cost of multiple power amplifiers limits wide use of this approach for large surfaces. Additionally, the synchronization complexity for multiple power amplifiers makes this difficult to implement. SoftCharge[6] introduces the concept of a soft-

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For a large charging surface, energy hopping is an interesting candidate solution, as a single power amplifier can be leveraged to charge a larger surface. SoftCharge introduces a software-defined surface charging architecture using energy hopping. These developments motivate us to develop our surface design and adopt magnetic resonance for the reconfigurable resonance coupling wireless power distribution over the surface.

ware-defined wireless charging surface, which utilizes energy hopping and eliminates the need for multiple amplifiers and complex synchronizations. However, SoftCharge cannot create arbitrary power spots over a large surface. Additionally, the complex analysis model of the cross-coupling between resonators increases the burden for configurable power distribution.

This article proposes the first-of-its-kind self-powered RIS architecture that can engineer the electric and magnetic fields over the surface. It introduces a resonance coupling framework that enables configurable power spots and redistribution of power in 1D, 2D, and 3D surface planes. The whole surface is reconfigurable, and the power of each resonator can be set with different adjustable variations. A coupling-factor-based framework is introduced that models power distribution over the surface based on the power change among an array of resonators, instead of complex electromagnetic field interference analysis. Given the locations of electronic devices on the surface as well as RIS units that need to be recharged, iSurface configures the power distribution and amplitude of resonators and forms the desired power spots using multiple power flows. We make the following contributions:

- We design a self-powered RIS architecture with reconfigurable source and extender resonators to enable recharging RIS units and surface-aided wireless transfer. We describe the implementation of and build the iSurface prototype based on densely placed magnetic resonators for 1D, 2D, and 3D surfaces.
- We introduce a resonance coupling power distribution framework for creating arbitrary and configurable power spots on the charging surface.
- We perform simulation studies and provide detailed analysis of the resonator's electronic parameters and the electromagnetic power distribution over a surface.
- We demonstrate through experiments wireless charging of an iPad and drone over different RIS configurations.

Related Work

Novel RIS Architectures: An RIS architecture is proposed in [7] to improve spectrum sharing in indoor environments by optimally controlling each element's phase shift, and leveraging software-defined metasurfaces [8, 9] demonstrates an RIS hardware architecture composed of 160 x 160 antenna elements for a millimeter-wave imaging system operating in the 60 GHz band using a pin diode as a single digital phase shifter. In [10], the authors use RIS for a simultaneous wireless information and power transfer (SWIPT) [11] MIMO system for enhancing the performance of both the energy and information receivers. We note that iSurface is a non-radiative magnetic resonance-based wireless power system, while RIS-assisted SWIPT is a radiative RF-based wireless power system. SWIPT creates radiative energy fields to charge devices over long distances ranging from centimeters to meters. RIS-assisted SWIPT aims to improve wireless charging performance such as energy harvesting rate, charging distance, and information transfer rate by leveraging RIS reflections in the middle. On the other hand, iSurface creates self-powered RIS and charges nearby devices with a non-radiative energy field over a maximum range of centimeters. In addition, in contrast to RIS-assisted SWIPT, iSurface does not require any additional channel estimation and feedback for wireless charging and does not add any bandwidth overhead as RF and magnetic resonance layers operate independently.

RF Wireless Power Transfer: The use of the radiated microwave for wireless power transfer has been explored and applied extensively for low-power integrated circuits, charging wireless sensor networks, and IoT applications [12]. This wireless charging approach does not require any coupling between transmitter and power receiver. Additionally, it works at frequencies higher than 100 MHz up to gigahertz bands, and is suitable for relatively lower power level (< 1 W) charging.

Magnetic Inductive Wireless Power Transfer: Magnetic inductive wireless power transfer works in the lower frequency (hundreds of kilohertz) with loose near-field coupling. The inductive-based Qi standard [13] has become the dominant commercial approach for mobile device charging. Inductive charging supports different power ranges from low-power (milliwatts) to high power (kilowatts). However, the short power transfer distance (around 1 cm) and the strict alignment condition make this approach challenging for providing spatial charging with higher freedom without perfect alignment between transmitter and receiver coils.

Magnetic Resonant Wireless Power Transfer: The typical magnetic resonant transfer operates with several MHz frequencies (6.78 MHz for A4WP). Based on the strong coupling between coils, this method delivers power over longer distances, and permits greater flexibility in spatial alignment and orientation angle between transmitter and receiver. However, magnetic resonance power transfer with one transmitter provides a limited charging area. For a large charging surface, energy hopping is an interesting candidate solution, as a single power amplifier can be leveraged to charge a larger surface. SoftCharge [6] introduces a software-defined surface charging architecture using energy hopping. These developments motivate us to develop our surface design and adopt magnetic resonance for the reconfigurable resonance coupling wireless power distribution over the surface.

Self-Powered RIS Architecture: Design and Components

Figure 1 depicts the design of the first-of-its-kind self-powered RIS architecture, which consists of two reconfigurable layers. The RF layer at the top engineers ambient wireless propagation in the environment and the power layer at the bottom recharges the RIS units and wirelessly charges multiple devices close to the surface. At the top layer, the receiver coils obtain power from the power layer and charge the battery of an RIS unit through the rectifier, DC-DC voltage converter, and battery control part. The RF layer has a patch antenna array, which jointly influences the reflected signals' phase and amplitude. We place patch antenna elements of half wavelength dimension of the carrier frequency at each grid location with a spacing of half

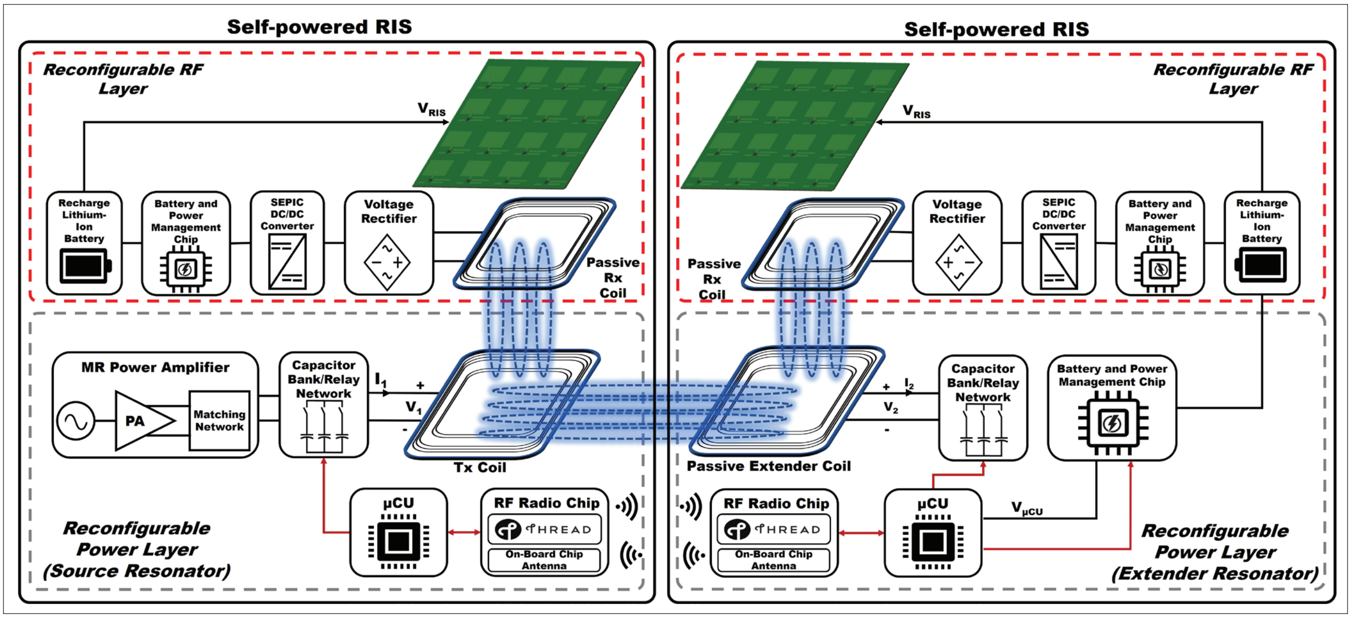

FIGURE 1. Component block diagram for self-powered RIS with reconfigurable RF and power layers.

wavelength of the carrier frequency to minimize mutual coupling effects between neighboring antenna elements. Furthermore, each element is connected to eight loss-less transmission lines [14] of different lengths that can vary the antenna element's impedance using an RF switch. By selecting the length of our transmission lines, we can alter each reflective element's impedance, which in turn changes their reflective coefficient, and consequently introduces a phase shift to the signal reflected by that particular element. The RF switch and transmission lines are placed on the top layer of the RIS PCB to tune each RIS element's dynamic response in real time based on the microcontroller commands. The RF antenna array can be designed to operate optimally at one or more sets of frequencies, including 5G operational bands.

On the other hand, the power layer is the surface-aided wireless charging system and consists of arrays of reconfigurable resonators. This layer creates arbitrary power spots over the surface, and power propagates on the bottom layer between resonators through energy hopping. Here, a portion of power that passes into each resonator recharges the RIS unit, enabling self-powered RIS operation. The rest of the power charges electrical devices close to the surface and goes into the following neighbor resonators. Note that the power layer includes only one source resonator and multiple reconfigurable extender resonators. The source resonator consists of:

- A magnetic resonance power amplifier is a Class-D amplifier operating at 6.78 MHz.
- A customized resonance PCB coil fabricated with FR-4 epoxy glass substrate is used as a two-layer PCB in which two copper coils are placed at the RF and the power layers and connected as parallel.
- A capacitor bank/relay network is used to adjust impedance for forming the power spots over the surface.
- A low-power microcontroller orchestrates the control of resonator configurations.

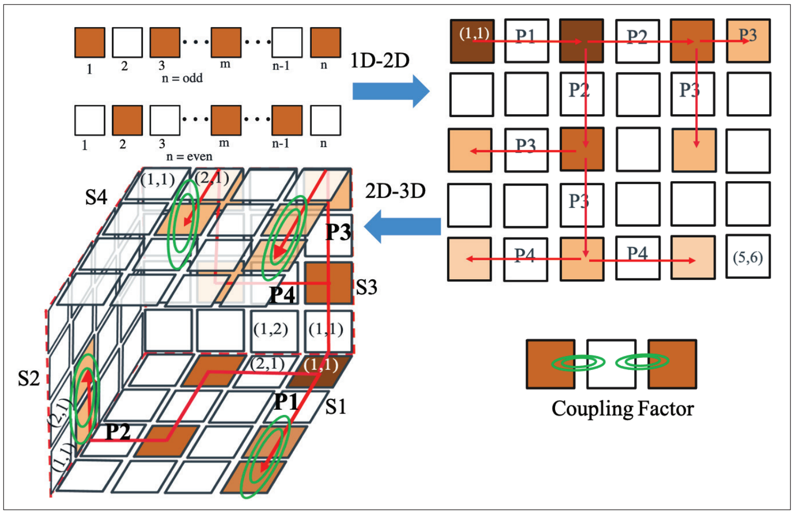

FIGURE 2. Resonator arrays for 1D, 2D, and 3D surfaces.

- An RF radio chip sends and receives messages between resonators and the power source [6]. The RF radio chip uses thread-based mesh networking to create a resilient and low-power full-mesh network among the resonators to exchange the control messages for real-time adjustment of coils impedances and coordination between RIS units. It uses 6LowPAN and IEEE 802.15.4 for communication at 2.4 GHz frequency band. There are two main hardware differences between extender and source resonator hardware design:
- A chargeable lithium-ion battery with a capacity of 34.6 Wh and a weight of 191 grams is utilized to provide the power required by components in the resonator.
- A battery and power management integrated chip consists of separate isolated DC/DC converters for the required voltage level to power up different components in the resonator with overcurrent protection and voltage and current sensing.

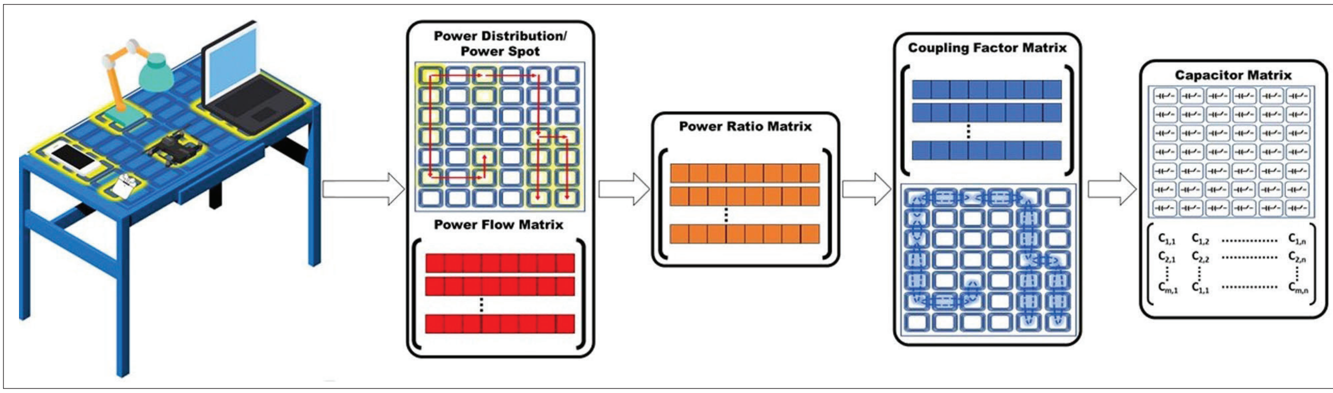

FIGURE 3. iSurface resonance coupling reconfigurable power distribution framework.

Resonance Coupling Power Distribution

In this section, we introduce a framework for a reconfigurable-surface-aided wireless charging system that models and captures arbitrary power distribution over the surface from a source of power over an array of resonators. The framework enables us to obtain optimal resonator configurations for forming configurable and desired power spots.

In Fig. 2, each square block represents a resonator with parameters such as self-inductance, resonant capacitance, and mutual inductance with neighbor resonators. Here, the 1D array consists of *n* resonators, the 2D surface consists of densely placed resonators in two dimensions, and the 3D surface has multiple 2D surfaces such as S1, S2, S3, and S4, where the resonators can be arranged vertically and horizontally together. Each surface has at least one source resonator that generates power and one or more extender resonators to hop the power. The power is generated from the source resonator and hop through extended resonators over the surface. The power is distributed between resonators when there is strong coupling between each pair of resonators in the array. On the other hand, the disconnection of strong coupling in the array of resonators blocks the power from hopping and propagation. On a surface, any given resonator is surrounded by multiple neighboring resonators. These neighbors divide power from the resonator to multiple power paths. For example, it can be observed in Fig. 2 for the 2D surface case that power path P1 can be divided to paths P1 to P2, P2 to P3, and then to P4. Similarly, for the 3D case, paths P1, P2, and P3 share the first resonator's power. The last resonator of one path becomes the first resonator of the divided path. The power exchange among resonators and the ratio of power split depends on the mutual coupling between them; that is, variation of mutual coupling significantly affects each resonator's power allocation. We define the coupling factor between any two resonators as a metric that describes the mutual coupling ratio between them and ranges from 0 to 1. Additionally, the coupling factor between a resonator and its neighbors is determined based on the capacitance of each resonator.

Figure 3 shows the resonance coupling power distribution framework that captures the process of driving the capacitance configurations for arrays of resonators to form arbitrary power spots over a 2D surface. A set of electronic devices placed on the surface and equipped with a magnetic resonance power receiver can be charged simultaneously when the generated power distribution over the surface has enough power underneath each device. Given the maximum power of the source resonator, the desired locations of power spots, and the required level of power per spot, the power flow paths from source to target devices can be determined. Red arrows in Fig. 3 show the power flow path. Accordingly, the power flow matrix presents the power density of each resonator through power hopping. In the next step, the normalized power densities are calculated and represented as a power ratio matrix, where each element shows the normalized power density of each resonator over the surface, ranging from 0 to 1. Based on Kirchhoff's Voltage Law (KVL) , we calculate the coupling factor between each pair of resonators and represent them by the coupling factor matrix. The coupling factor matrix, along KVL equations, give us the required capacitance for each resonator on the surface. The proposed iSurface reconfigurable resonator design enables changing the capacitance at each resonator. The source resonator uses the RF control channel to send the configuration commands via the mesh network to reconfigure each resonator directly. The resonator receives the source resonator's control message and uses the microcontroller to select a combination of capacitors from its capacitor bank to adjust the resonator's capacitance.

System Implementation

We implement the self-powered RIS with wireless power transfer and demonstrate it by evaluating the power distribution of the proposed RIS surface, and wirelessly charge the real devices such as a drone and an iPad with the RIS surface, while it is also powering the RIS units. Toward this aim, we build the prototype of iSurface for the 1D, 2D, and 3D surface charging scenarios by using off-the-shelf power amplifiers, a PCB transmitter coil, and electronic components (SMD capacitors with different fixed value) to change the coupling factor. Our fabricated PCB coil resonator is 15 cm × 22 cm with inductance of 4.8 μH. We use power resistors as the load to measure the power at different locations through the surface. We use 16 antenna elements at the RF layer of each RIS unit, which is composed of a patch antenna made of a metal patch on the top layer of the PCB dielectric substrate and a full metal sheet on the bottom layer.

Each RIS unit consumes around 325 mW for all 16 elements, with the RF switches and the microcontroller accounting for 320 mW and 5 mW, respectively. The total power consumption of each self-powered RIS unit, including all components of the RF and power layers, is about 0.5 W. The battery and power management chip in the RF layer ensures that we can charge a rechargeable Lithium Ion battery with up to 1 W charging rate in a reasonable time. We design the RIS PCB in two layers and fabricate it with FR-4 epoxy glass substrate with dimension of 25 cm × 25 cm × 0.16 cm, where a 1 m × 1 m area consists of 256 elements with 16 RIS units/resonators.

Additionally, we use an iPad and drone as consumer electronic devices for testing the charging performance of iSurface for different charging applications. The total cost of an RIS unit with source resonator is US$160, and the total cost of an RIS unit with relay resonator is US$122. We elaborated further in SoftCharge [6] details related to implementation of the magnetic resonance charging. Additionally, we have earlier proven that transfer at 6.78 MHz will not interfere with and impact RF signals in gigahertz bands. Thus, the RF layer operates independent from the power delivery layer.

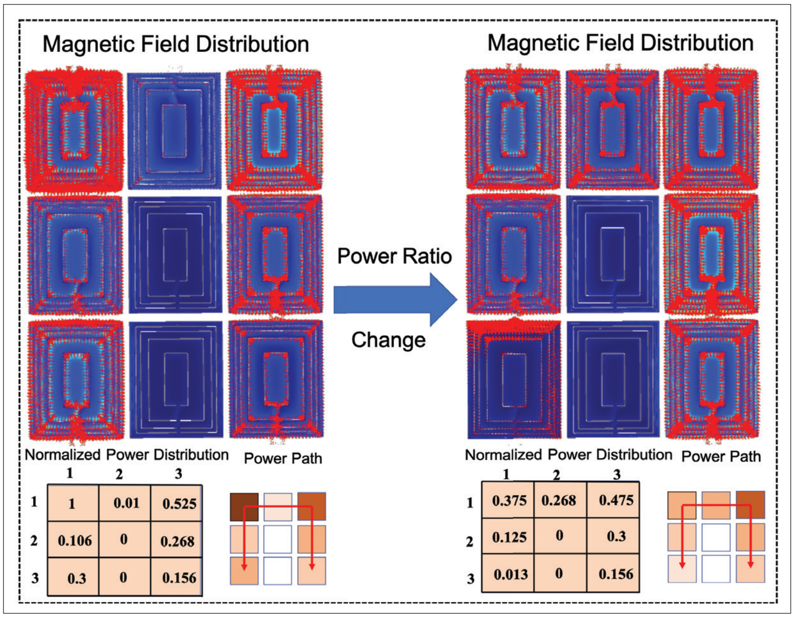

FIGURE 4. Simulation of power distribution of 2D surface for two different RIS configurations.

Results and Discussion

Power Distribution

The power distribution based on the reconfigurable resonator model is simulated using COMSOL. The model contains a two-layer PCB with FR-4 epoxy glass substrate in which two copper coils are placed at the top of the bottom layer of the PCB and connected in parallel. We specifically choose each turn's width as 2 mm and the thickness of copper as 0.14 mm for copper coils. This selection gives the calculated inductance of 4.64 μH and a quality factor of 330 at 6.78 MHz, which is high enough for efficient wireless transfer power. The overall size of each resonator is 15 cm × 22 cm × 1.5 mm. In the simulation, we select an AC source operating at 6.78 MHz with a 1A peak value.

For 2D surface simulation, nine resonators are placed with an identical gap of 1.5 cm. Figure 4 shows the magnetic resonance power distribution over the RIS-powered surface with two resonance configurations that have different coupling factors between resonators. The surface has three rows and three columns, and the resonator located at (1, 1) is the source resonator connected to the power amplifier. The red arrows around resonators depict the corresponding magnetic field. The higher the power density of a resonator, the more arrows appear over it. The resonators without any red arrows, such as (2, 2) and (3, 2) (i.e., with capacitance change of 100 pF or higher) do not pass the power flow. Additionally, Fig. 4 shows the corresponding results for normalized power distribution (i.e., power ratio matrix). It can be observed that while the power paths of these two configurations are the same, their normalized power distributions are different. The first power flow path includes resonators (1, 1)-(2, 1)-(3, 1), and the second path includes (1, 1)-(2, 1)-(1, 3)-(2, 3)-(3, 3). In the first configuration on the left, the power ratios over the first power flow are [1, 0.106, 0.3], and over the second power flow are [1, 0.01, 0.525, 0.268, 0.156]. The capacitors over these power paths are [0pF, 2pF, 5pF] and [0pF, 2pF, 0pF, 0pF, 9pF,] respectively. In the second configuration on the right, the power ratios over the first power flow are [0.375, 0.125, 0.013] and for the second power flow are [0.375, 0.268, 0.475, 0.3, 0.156]. Here, the capacitors over these two power flows are [0pF, 7pF, 2pF] and [0pF, 5pF, 0pF, 7pF, 2pF], respectively. The simulation results demonstrate the impact of different configurations on power distribution.

2D Surface Performance Results

In this section, we study the performance of the proposed RIS prototype over a 2D surface and compare it with the simulation results. For ease of comparison, the received powers are normalized by the maximum received power of 16 W; that is, the normalized power 1 represents 16 W. The experimental setup consists of nine resonators that are fabricated as described previously. The resonators are placed in three rows and three columns, and the gap between each resonator pair is 1.5 cm, same as the configuration in the simulation. Each resonator's location index pattern and coil orientation on the surface follow the same index and orientation shown in Fig. 4. The resonator located at (1, 1) connects to the power amplifier, and resonator (3, 3) is the terminal resonator. The resonators located at (2, 2) and (3, 2) are set with capacitor change higher than 100 pF to block the power, while the rest of the resonators allow energy hopping.

Figure 5 shows the experimental results of net received power for two RIS configurations. The net receiver power of each location over surface is the received power over that location after powering the RIS unit. Here, around 1 W from the total power goes to the RIS unit, and the rest is the net received power that can charge the devices close to the RIS unit surface along with energy hop to the next resonator. We use a power resistor of 22 Ω as the receiver to mea-

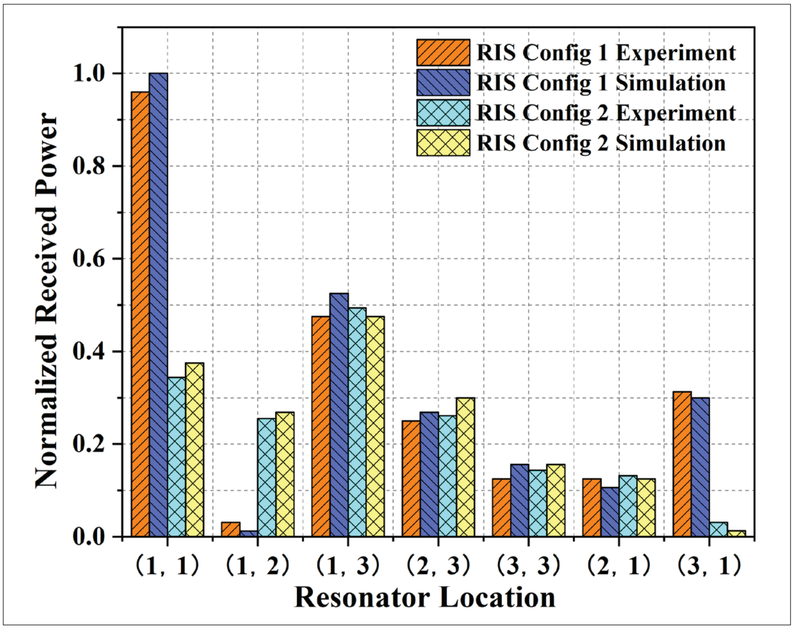

FIGURE 5. Experimental and simulation results of the normalized received power over the 2D surface for different RIS configurations.

sure the net received power. As explained in the simulation, RIS configurations 1 and 2 both create two power paths, path 1 of (1, 1)-(2, 1)-(3,1) and path 2 of (1, 1)-(1, 2)-(1, 3)-(2, 3)-(3, 3), and the deliverable power at each resonator can be observed in Fig. 5 and ranges from 0 W to 16 W over the surface. In RIS configuration 1 for path 1, the power ratio between resonators (2, 1) and (3, 1) is [0.138, 0.3125], with delivered power of 2 W and 4.5 W, respectively. For path 2, resonator (1, 2) and resonator (1, 3) can deliver 0.5 W and 7.6 W, respectively, with the power ratio of [0.03125, 0.475]. The power ratio between resonators (2, 3) and (3, 3) is [0.25, 0.125], and the received power from resonators (2, 3) and (3, 3) is 3.9 W and 1.9 W, respectively. In RIS configuration 2, the deliverable power at resonator (1, 1) has a large drop compared to case 1 due to the different surface capacitance configurations. The power of resonator (1, 1) changes from around 16 W (15.5 W to be exact) in configuration 1 to 5 W in configuration 2. In path 2 for RIS configuration 2, the power ratio between resonators (2, 3) and (3, 3) is [0.261, 0.143], with deliverable powers of 4.2 W and 2.3 W, respectively. However, path 1 in this configuration only gets 3 W, which is shared by resonators (2, 1) and (3, 1) with deliverable power of 2.2 W and 0.5 W, respectively. The normalized experimental results for the received power and the simulation results are compared in Fig. 5 for two studied surface configurations. The results demonstrate a good match with low errors.

3D Surface Performance Results

This section discusses the 3D surface performance results with drone and tablet charging. We compare the experimental results with the simulation results that are obtained for the same RIS configurations and locations of devices. We use two iPads for the tablet and one SANROCK U52 drone for the drone experiments. The experimental setup consists of four 2D surfaces (S1 to S4) with the vertical and horizontal arrangement, as shown in Fig. 2. The fabricated resonators are attached to each surface from S1 to S4. S1, S2, and S4 have six resonators with a 1.5 cm gap between them, and S3 has four resonators with a 2.2 cm gap. The index of each resonator is the same as the resonator index pattern in Fig. 2. For example, S1(1, 1) denotes resonator (1, 1) at surface S1, and S2(1,2) denotes resonator (1, 2) at S2. Here, we have one source resonator that is located at S1(1, 1). We attach magnetic resonance receivers to iPads and drone devices to get power from the surface. In our setup, the drone battery is removed, and the magnetic resonance receiver is connected to the drone engine. When the drone starts getting power from any resonator, the engine begins running in the landing state with the standard propeller's rotating speed as if the drone is running purely on a battery. The iPad does not have any hardware or software change, other than one additional magnetic receiver that is connected for charging the battery. The maximum power of the source resonator from the amplifier is 33 W. The experimental results for three different 3D surface configurations are depicted in Fig. 6. For each case, the iPads and the drone are getting power simultaneously in real time. In these three configurations drone, iPad1 and iPad2 are located at S1(1, 3), S3(2, 1), and S4(2, 2), respectively, at three different surfaces, and the net received power is normalized by the maximum received power of 7.5 W.

For RIS configuration 1, the drone gets around 7.5 W through power path 1 S1(1, 1)-S1(1, 2)-S1(1, 3), and iPad1 and iPad2 received around 5 W and 3 W through power path 2 S1(1, 1)-S3(1, 1)-S3(2, 1)-S4(2, 1)-S4(2, 2). The capacitors that play a role in power paths 1 and 2 are [0pF, 2pF, 0pF] and [0pF, 2pF, 0pF, 2pF, 5pF], respectively. At the second RIS configuration, the power ratios between the drone, iPad1, and iPad2 are [0.86, 0.53, 0.64] with received power around 6.5 W, 4 W, and 4.8 W, respectively. The capacitors that change over path 1 and path 2 are [0pF, 2pF, 0pF] and [0pF, 5pF, 2pF, 2pF, 4pF]. At the third RIS configuration, the capacitors' changes over path 1 and path 2 are reconfigured as [0pF, 2pF, 4pF] and [0pF, 5pF, 2pF, 3pF, 7pF], respectively. The received power of the drone, iPad 1, and iPad 2 become 5.2 W, 6 W, and 4.5 W, respectively.

The simulations are conducted with the same RIS configurations as the experiment, and the results of the normalized power are shown in Fig. 6. It can be observed that the experimental power ratios are lower than the simulation; this is because of the practical power loss at the power conversion between the receiver and the battery of devices. We can see the more devices receiving power simultaneously, the higher the end-to-end power efficiency [5], where this efficiency would be defined as the received power of devices divided by input power of the power amplifier. In the 2D surface experiment, the measured end-to-end efficiency for RIS configurations 1 and 2 are 63 and 67 percent., respectively. Additionally, the end-to-end efficiency for 3D surface experiment are 71, 87, and 82 percent for RIS configuration 1, 2, and 3, respectively.

Conclusion and Open Challenges

This article proposes a self-powered reconfigurable intelligent surface that can engineer electric and magnetic fields over the surface. The system operates with both 2D and 3D surfaces to create arbitrary power spots, and multiple power flows over the surface to charge RIS units and power devices simultaneously. The simulation and experimental results validate the system's performance in terms of power distribution over 2D surfaces. Additionally, the experimental results have demonstrated the charging of the drone and tablets for 3D surfaces.

The following open challenges need further investigation. The first challenge is to keep the end-to-end power transfer efficiency high over the RIS surface as the number of resonators increases. Toward this, optimizing magnetic resonance coil for higher-quality factor designs, adaptive tuning of the power amplifier for impedance matching, and real-time impedance matching of resonators based on the location of devices and power requirements are among key variables that can be investigated further. Second, the power distribution density over the surface can be enhanced by adding more than one power source. However, the impact of various harmonics from multiple power sources needs to be investigated and the interference mitigated.

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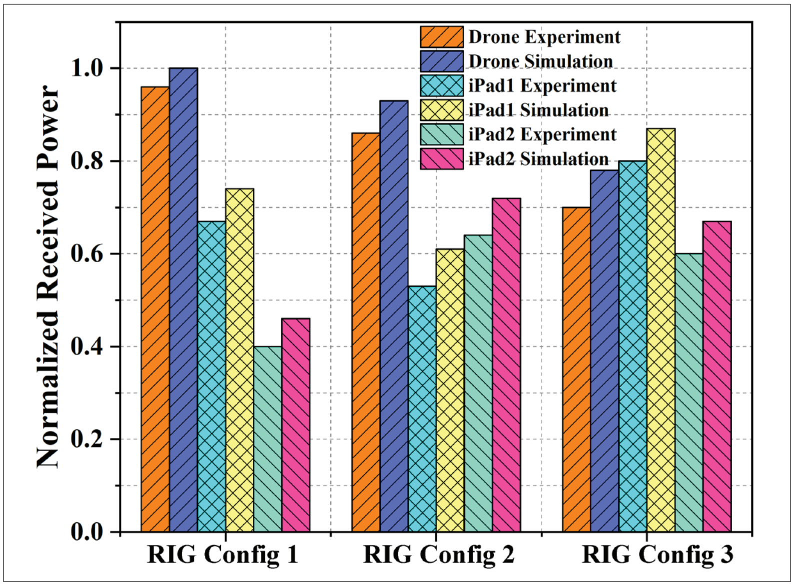

FIGURE 6. Experimental and simulation results of the normalized received power over the 3D surface for iPad and drone over three different RIS configurations.

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