Magnetic Resonant Wireless Power Delivery for Distributed Sensor and Wireless Systems

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Abstract— **In this paper we report on a resonant wireless power delivery system using magnetoquasistatic fields. The system consists of a source coil impedance matched to a function generator using a resonant circuit and one or more repeater, or relay, resonant tanks that couple energy from source coil to loads distributed in the system. We experimentally map the power distribution for one and multiple loads as a function of distance from the source and repeater. We then use this information to construct a resonant wireless power delivery system using a distributed set of 4 repeaters and 6 loads, delivering 15 mW total over a distance of 6.4 ft. We also demonstrate that the distributed system is not strongly perturbed by weakly conducting obstructions, such as the human body, enabling non-line-of-sight wireless power of sensor and wireless networks.**

I. INTRODUCTION

Distributed wireless systems are extremely useful in many sensor and monitoring applications. One method for powering distributed wireless systems is the use of energy scavenging, such as vibration or solar power [1]. Another method is radiated power transfer, where a rectenna is used to convert RF signals into dc power [2]. These techniques are extremely useful for many applications; however, they lend themselves most readily to low power and line-of-sight (LoS) applications where the available incident energy is typically low, and each sensor requires a LoS to the energy source. An alternative power delivery method is to use quasistatic magnetic fields, which do not radiate, allowing for a wide area of coverage without significant power loss due to radiation. In addition, magnetoquasistatic fields are only weakly perturbed by many obstructions, enabling non-LoS applications [3]. Furthermore, the resonant power delivery using magnetoquasistatic fields has demonstrated significant power delivery (mW-W) [4], even for small systems.

In this work we demonstrate a wireless power transfer approach for distributed systems using resonant inductive coupling. A source coil is driven to produce a large magnitude magnetoquasistatic field (a magnetic dipole) that then couples directly with one or more loads or couples to one or more repeaters or relays that then couple to additional loads, i.e. relay the power. The quasistatic fields of a magnetic dipole reduce as $1/r^3$, where r is the distance from the dipole. To deliver power at significant distances it is necessary for the magnetic field from the source to be strong enough to induce sufficient voltage in the load coil. This is accomplished by generating large magnetoquasistatic fields at the source, such that even with the $1/r^3$ reduction in magnitude, the field is able to induce sufficient voltage to power the load.

Resonance is used in the source and repeaters to generate the large fields necessary to supply power at distances of a several feet. Since the coils are much smaller than a wavelength (410 ft at 2.4 MHz), the radiation resistance [5] is very small, enabling large quasistatic fields to be developed with little radiated loss. Resonance is also used to impedance match the source coil to the function generator and the load resistance to the load coils.

II. MAGNETIC RESONANT POWER DELIVERY

The general principle of resonant wireless power transfer is shown in Fig. 1, left. A source coil, or inductor, is driven by a source through an impedance matching network that matches the reactive load of the inductor and source referred impedances to the source impedance for maximum power transfer. The current in the source coil generates a quasistatic magnetic field that then couples to a receiving coil. The coupling is quantified by the coupling coefficient, k, and the mutual inductance, $M = k\sqrt{L_S L_R}$. A voltage is induced on the receiver coil due to the coupled field from the source coil, which then drives a load. A resonating capacitor, C_R, can be placed in the receiver circuit to resonate out the self-inductance of the receiver coil, resulting in a real impedance being seen by the source coil, through the mutual coupling of the two coils. The load resistance can be referred back to the source coil using the mutual inductance, M, and is given as [6]

$$R_{eff} = \frac{\omega^2 M^2}{R_{Load}}. \tag{1}$$

Thus, one can represent the weakly coupled receiver as an equivalent resistance at the source. The source reactance can also be resonated out, using C_S, reducing the source to the real impedance, R_{eff}, which can then be impedance transformed to match the source impedance for maximum power.

Figure 1, right, shows our system. An Agilent 33250A function generator is used as the sinusoidal source with a source impedance of 50 Ω. We use an MFJ-900 antenna tuner, which is a tunable T-network, to impedance match the reactive source coil to the real source impedance of the function generator. The T-network allows for both matching of the source coil to the source impedance as well as tuning the quality factor, Q of the source tank [7].

The source coil is 8 turns of 12 American Wire Gage (AWG) stranded and tinned wire from Anchor Marine, wound

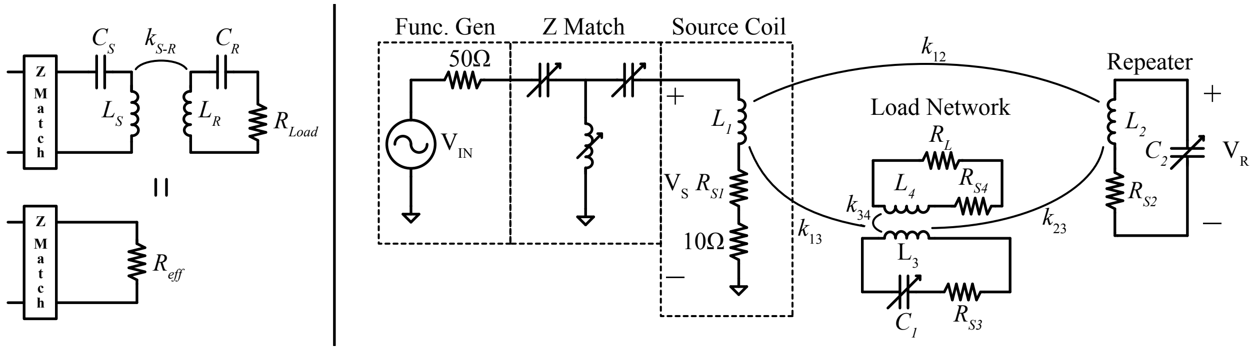
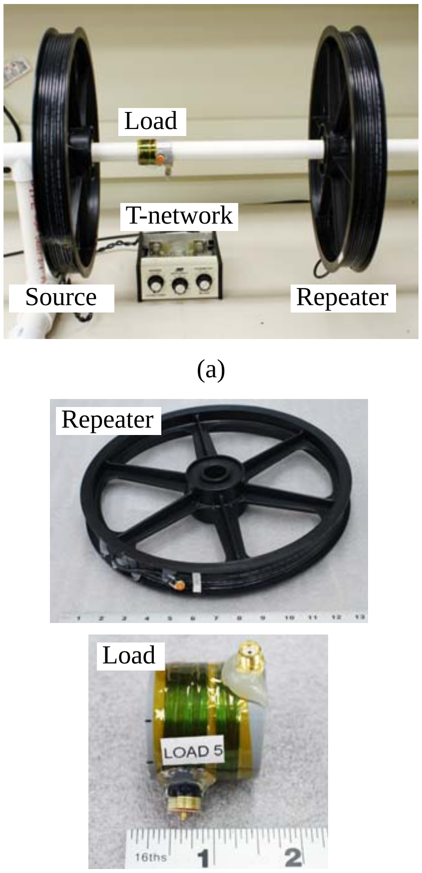


Fig. 1. Left: General analysis of resonant coupled coils. Right: Our experiential setup. We use one source coil and multiple load networks and repeaters, each of which identical to the circuit shown. The coupling lines ignore coupling between L_4 and the source and repeater(s) to simplify the qualitative analysis of the system.

around an 12.5 in diameter plastic wheel, Fig. 2b. The source coil inductance was measured to be 42.5 μH. A 10 Ω resistor is placed in series with the source coil to measure the coil current. The Q of the source coil is significantly degraded by the large value of the sense resistor, but a large value was necessary to achieve sufficient SNR in the presence of large magnetoquasistatic fields, as significant voltages ($\sim$ 50mV RMS) were seen on the loop formed by the oscilloscope probe and sense resistor, depending on orientation. The repeater coils are identical to the source coil, however without the 10 Ω resistor. A tunable capacitor (10 pF to 180 pF, $Q = 200$ at 1 MHz) and a scope probe with capacitance of $\sim$9 pF was placed in parallel with the resonator coil to form a resonant tank. These components significantly reduced the possible Q of the repeater, resulting in an approximate Q of 167, which is well below the Q necessary for high efficiency [4]. Optimization of the coil implementation should achieve much higher Q and efficiency [4].

The loads are constructed of a two coil transformer, with a variable capacitor (10 pF to 180 pF, $Q = 200$ at 1 MHz) in parallel with the larger coil and a load resistance of 50 Ω in parallel with the smaller coil. The load resistance was realized via an SMA connector to a 50 Ω termination or an Agilent N1913A power meter via an Agilent 8482H sensor with a 50 Ω input impedance. The two coils are fabricated by winding 20 turns and 40 turns of 30 AWG wire on a 1.375 in diameter plastic tube approximately 1.37 cm apart (center to center), Fig. 2b. While both coils of the load couple to the source and repeaters, the coupling of the 40 turn coil to the source dominates due to its closer proximity and turns ratio. If we make a simplifying assumption that only the 40 turn coil couples, we can then view the load as a 50 Ω resistor that is impedance transformed via transformer L3–L4 to an impedance in series with L_3, C_1 and R_{S3}, where R_{S3} is the wire resistance. This series network then couples to the source coil and repeater as explained in Fig. 1, left. The exact solution can be found by using the mutual coupling of all coils, [8], however our simplification provides an intuitive understanding, albeit less accurate.

We can describe distributed resonant power transfer as follows. When the load is close to the source coil, the 50 Ω resistor is transformed to an equivalent resistance in the source, which accounts for the power transferred from the source to the load. When the load is close to the repeater, the 50 Ω resistor is transformed to an equivalent resistance in the repeater coil, which is then transformed back to the source via the source-repeater coupling. When the load is in between



(a)

(b)

Fig. 2. (a) Source coil, left, load, center, and repeater, right. (b) Close-up view of repeater and load.

the source and repeater, it couples to the source directly and also to the source via the repeater. The amount of power delivered can be determined simply from the transformed impedances seen by the source coil. It is important to note that the repeater also contains the series resistance of the coil itself. This resistance is also transformed to the source and represents a static power loss, along with the static power loss in the source coil itself, regardless of the number of loads. Finally, it should be noted that in our simplified picture we ignore the de-tuning of the resonant circuits in the source, repeater and loads due to one another [8]. In our experiment we determined that this is valid assumption when the source and repeater are separated by at least 35 cm. When they are closer, a significant de-tuning of the coils is observed.

III. DESCRIPTION OF EXPERIMENT

To determine the ability to deliver distributed power over several meters, we conducted three experiments. In the first, we mount the source coil and one repeater coil on a tubular support such that the surface normal of both coils is in the same direction, Fig. 2a. We then place a load between the source and repeater coil and terminate the load with a power meter. The repeater is placed 37 cm, 47 cm, 57 cm and 67 cm from the source coil, measured center to center, and the load moved in 2.5 cm steps from the source to the repeater. To tune the system, we placed the repeater at the desired position and connected the input of the source T-network to an Agilent E8358A network analyzer and tune the T-network to provide an S_{11} below -20 dB at 2.4 MHz with a narrow bandwidth, i.e. high Q. We then tuned the variable capacitor in the repeater so that its voltage was at a maximum. The variable capacitor in the load was then tuned for maximum power at a distance of 2 cm from the source coil.

Figure 3 shows the power distribution as the load is moved. The power increases in the load as it approaches either the source or the repeater. When the repeater is close to the source, it is able to deliver power to the load at a similar power level as when the load is next to the source. As the distance between source and repeater increase, the power delivered to the load near the repeater decreases owing to the reduced coupling between the repeater and source.

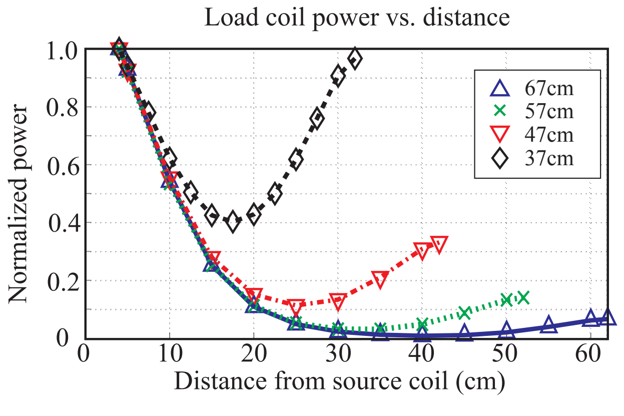


Fig. 3. Load power as a function of distance from source coil for repeater-source distances of 37 cm, 47 cm, 57 cm and 67 cm. Distance from source was increased in 2.5 cm steps. Peak power for each repeater-source distance is: 15 mW (37 cm separation), 19.1 mW (47 cm separation), 19.6 mW (57 cm separation) and 18.3 mW (67 cm separation).

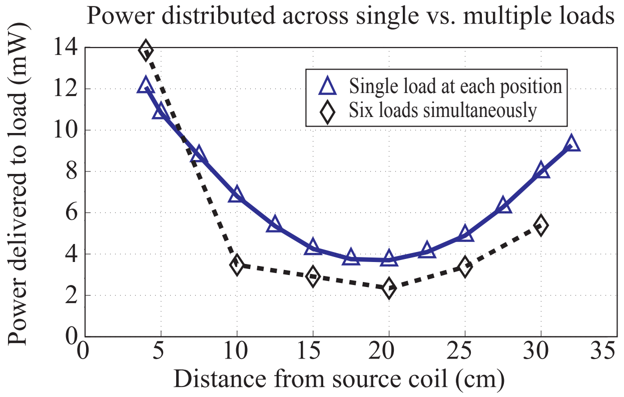


Fig. 4. Power transferred into 6 loads distributed evenly between a source coil and repeater located 37 cm from source coil. Also shown is data from Fig. 3 for a single load that is moved in 2.5 cm increments from source to repeater. The power delivered has the same spatial trend for simultaneous loading and a single load.

In the second experiment, we choose a source-repeater separation of 37 cm and placed six evenly distributed loads between the source and repeater in order to measure the power delivered to multiple loads simultaneously. We measured the power at each load with the power meter with all other loads terminated with 50 Ω terminations. Figure 4 plots the data of 6 loads as a function of distance from the source. Also plotted is the power delivered to single load at distances from 4 to 32 cm from the source coil. The spatial power distribution trend is the same for both the simultaneous load and single load case, with the simultaneous load case showing a lower power delivered to each load, as would be expected. The higher peak power in the simultaneous load case at 4 cm is believed to be due to the high sensitivity to placement of the loads near the source and also the variance of power received from load to load.

In our final experiment, we fabricated 4 repeaters and setup a distributed power system spanning 6.4 ft. The repeaters were adjusted to deliver approximately 2.5 mW to the outer most loads. An additional 4 loads where then dispersed between repeaters at locations that also produced approximately 2.5 mW. Figure 5 shows the setup and the power delivered to each load. Adjustment of loads throughout the system produced power profiles detailed in Table I.

In addition to the three quantitative experiments, we performed two qualitative experiments to test the robustness of our approach. In order to test the system's ability to operate in non-LoS environments, the authors moved about the test apparatus extensively to determine sensitivity to non-LoS conditions. When a human body was close to a repeater, a slight de-tuning would occur due to the presence of a weakly conducting obstruction (e.g. a human body). For a

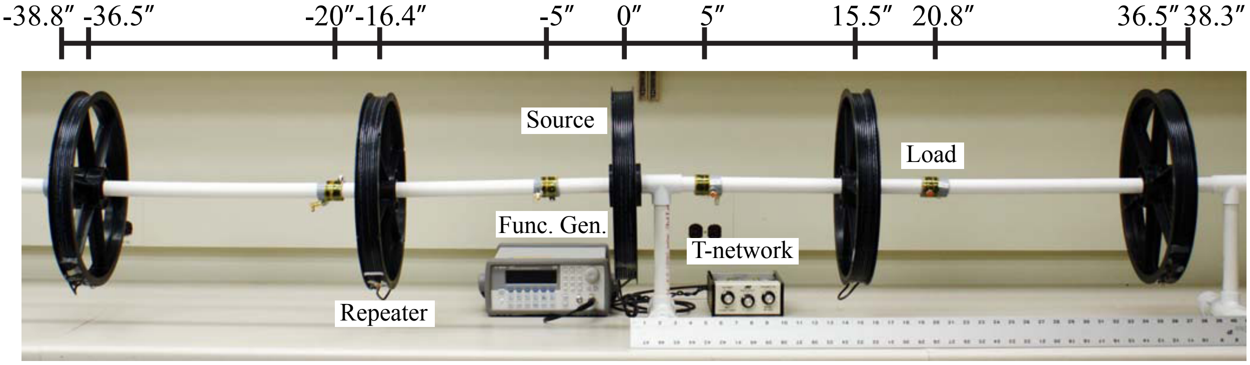


Fig. 5. Distributed wireless power delivery. The center coil is the source coil and two repeaters are placed on either side of the source coil. Locations were chosen to maximize power transferred to the outer most loads at 38 in. Four additional loads were placed between the repeaters as shown. Their locations were chosen to supply $\sim$ 2.5 mW each, or 15 mW total for 6 loads. Power transfer was not strongly affected by the presence of weakly conducting obstructions, e.g. the human body.

TABLE I

POWER DELIVERED TO DISTRIBUTED LOADS.

Component	Distance (in)	Power (mW)
Load 6	-38.8	2.32
Repeater 2	-36.5	n/a
Load 5	-20.0	2.51
Repeater 1	-16.4	n/a
Load 4	-5.0	2.74
Load 3	5.0	2.67
Repeater 3	15.5	n/a
Load 2	20.8	2.77
Repeater 1	36.6	n/a
Load 1	38.3	2.62

fixed obstruction the repeater could be re-tuned to give the same power as when the obstruction was not present. This demonstrated that the system is not strongly affected by weakly conducting obstructions and power reductions due to obstructions can be mitigated by re-tuning the system. When the repeater coils were touched directly, a significant reduction in power was seen and the system could not be re-tuned. It is not known if this reduction in power was due to a significant de-tuning that could not be compensated within our system parameters, or was the result of other phenomena.

To test the sensitivity of power transfer to the axial symmetry of the system. Loads were moved, by hand, along the surface of the repeater coils, from the center to outer radius. Power transfer was comparable for a given distance from the repeater along the entire radius, suggesting co-axial alignment is not required. In addition, loads were rotated so that the surface normal of the load coils were not parallel to the source or repeaters. Power was still transferred but reduced as the angle varied. While qualitative, these experiments show that perfect co-axial symmetry is not necessary for power delivery. A quantitative analysis of possible orientations and power delivery is beyond the scope of this brief paper.

IV. CONCLUSION

In this paper we presented magnetic resonant wireless power delivery for distributed sensor and wireless networks. We presented experimental measurements of resonant power delivery over varying distances for a single and multiple loads. We also demonstrated a distributed system that delivered 15 mW to 6 loads (2.5 mW per load), over a distance of 6.4 ft. We also showed that the system is not perturbed by weakly conducting bodies and is suitable for some non-LoS applications.

V. ACKNOWLEDGEMENTS

This work was partially supported by QNRF under grant NPRP 09-667-1-100.

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