Simultaneously Tuning and Powering Multiple Wirelessly Powered Devices

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***Abstract*—Wireless charging standards for consumer devices include specifications for charging multiple receive devices simultaneously. However if the devices are not all the same size or if they require different amounts of power, these existing standards may be incapable of charging multiple devices efficiently. This paper provides an overview of a complete wireless power transfer system that is capable of automatically tuning, communicating with, and efficiently powering multiple single-cell battery charging receive devices. Frequency tracking, power tracking, and adaptive impedance matching are used to dynamically tune each receiver and the transmitted signal for optimal power delivery to each receiver. Additionally, these same tuning techniques are used to demonstrate time-division multiplexing, where individual receive devices are powered sequentially while all other receive devices are de-tuned and do not consume any power, even in the presence of the transmit coil.**

***Index Terms*—Wireless power, magnetically coupled resonators, impedance matching, wireless communication network.**

I. Introduction

THE emergence of wearable consumer electronic devices and wireless charging standards has lead to a wide variety of devices that are wireless-power ready. These devices range from high power applications such as laptops consuming ∼100W, to mid-range power devices such as cell phones consuming ∼10W to low power devices such as smart watches and wristbands consuming less than 1W. To avoid the dilemma of requiring a unique wireless charger for each device, it is desirable to develop a universal wireless charging transmitter that is capable of charging multiple devices simultaneously at a variety of power levels.

Several wireless charging standards including the Wireless Power Consortium (WPC), Alliance for Wireless Power (A4WP) and Power Matters Alliance (PMA) all have different specifications for charging multiple receivers [1]–[3]. Each standard varies in operating frequency, achievable wireless power range and power level. However, none of these products are capable of efficiently charging more than four high power and low power devices simultaneously.

Prior research has shown that automatic frequency tuning can increase the range of efficient wireless power transfer (WPT) [4]–[6]. Adaptive impedance matching has also been used to control the impedance of both the transmitter (TX) and receiver (RX) coils to improve efficiency across a wide distance range at a single frequency [7]. However, these automatic-tuning systems only demonstrate WPT from a single TX to a single RX. Other work has shown WPT to multiple RXs, however these articles do not present methods that can optimize efficiency to each RX operating at different load power levels [8], [9].

In this work, we present the hardware, software and communication protocols associated with a novel wireless power system capable of powering and communicating with multiple RXs across a wide range of load power levels. The system performs three types of automatic tuning: frequency tracking, power tracking, and adaptive impedance matching. The system also utilizes a 2.4GHz radio communication link between the wireless power TX and RX. Frequency tracking does not require the radio link because it relies on data collected on the TX side only. A directional coupler and RF detector measure the magnitude and phase of the forward and reflected signals between the output of the power amplifier (PA) and the TX coil. Power tracking is performed by varying the gain of the PA to transmit more or less power based on the receive power measured at each RX. Adaptive impedance matching is controlled on the RX side. When multiple RXs are present, each RX automatically tunes its matching network to achieve a targeted receive power level.

We outline the TX and RX hardware in Section II. In Section III, we outline the software for each component. We present the experimental results of the system in Section IV. Five RX devices at various charge current levels are all powered simultaneously. We show that multiple RX devices operating at different power levels can only be sufficiently powered using our adaptive tuning techniques. We also demonstrate time-division multiplexing (TDM). This feature allows for one or more RX devices to be wirelessly powered while all other devices are de-tuned, even when multiple RXs are placed on the TX coil. To our knowledge, this is the first time TDM has been shown for multiple RXs in a near-field wireless power system.

II. Hardware

The WPT system requires two primary components: a transmitter that generates and amplifies the RF signal, and an RX that converts the RF signal into a DC voltage for the given device. In the most simplified configuration, the TX could use a fixed frequency source, and a fixed gain PA to deliver the RF signal to the RX. However, for applications in which the RX(s) will be moving relative to the TX coil, the efficiency of the system will decrease significantly if a static TX is used. Therefore, it is necessary to add more complexity to both the TX and RX to maintain high efficiency for a dynamic system. In this Section, we will highlight the hardware components that enable a fully programmable WPT system capable of powering multiple RXs. Figure 1 shows a schematic diagram of the full WPT system.

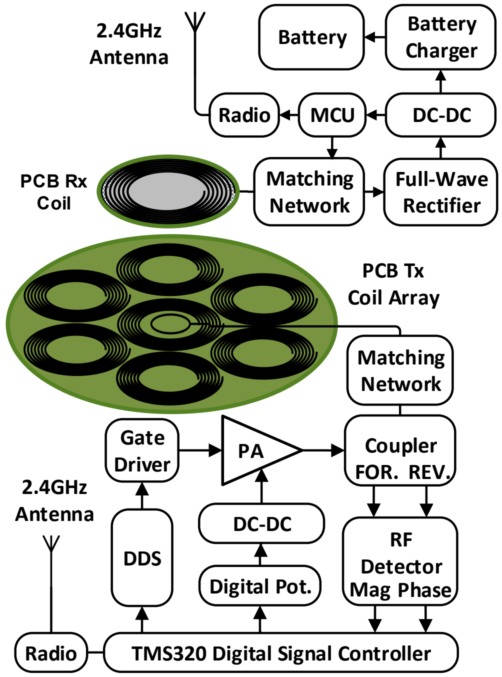

Fig. 1. Schematic diagram of the proposed wireless power system.

A. Transmitter Hardware

On the TX side, the TMS320 Digital Signal Processor (DSP) is the primary controller for the entire wireless power system. All measurements, commands, enable and disable functions are generated by or terminated at the the DSP.

The AD9850 direct digital synthesizer (DDS) generates the RF signal that drives the PA. The amplitude, frequency and phase of the DDS can all be set by the DSP. The PA consists of a gate driver that is used to drive an IRF510 Mosfet in a single-ended class-E amplifier. Although class-E amplifiers can achieve high efficiency, the downside is that they are typically designed to be most efficient at a single operating point in terms of power level, load impedance and operating frequency. In a WPT system where the load impedance changes as a function of load power and distance between the coils, a class-E amplifier will rarely operate at the fixed operating point that it was initially designed for. Therefore, the class-E amplifier used in this system has a programmable supply voltage and a programmable output matching network that can optimize the efficiency of the amplifier over a wide range of load conditions. The programmable supply voltage is realized by using a digital potentiometer to control the feedback voltage of a buck-boost DC-DC converter. The adjustable output matching network consists of a low-pass π-match network with switchable capacitor banks [5], [7]. Figure 2 shows the TX PCB.

The TX coil consists of seven separate coils on a single PCB. The center coil also has a drive loop, which is the only element of the entire coil array that is directly connected to the output of the TX PCB. Each coil is identical with an inductance L=1.11μH, tuning capacitor C=120pF and parasitic

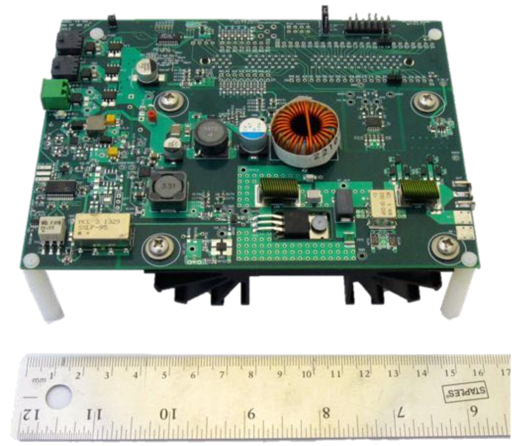

Fig. 2. Transmit controller and power amplifier PCB.

resistance R=0.79Ω with a quality factor Q=125 at a resonant frequency of 13.56MHz. Each TX coil surrounding the center coil acts like a relay resonator to extend power to each RX.

B. Receiver Hardware

The RX coil is also designed into a PCB as in Figure 3. A sheet of 0.25mm thick ferrite placed directly above the RX coil isolates the leakage fields generated by the RX coil from the RX PCB. Using the LTC4065 battery charger with a bank of digitally controlled switchable resistors, various charge currents can be set for each RX by the MSP430 MCU. An ADC measures the received voltage and current and can send this information back to the TX via a 2.4GHz radio link. To communicate with multiple RXs simultaneously, a star network wireless communication system has been implemented in which the TX is the primary access point (AP), and each RX is an end-device (ED).

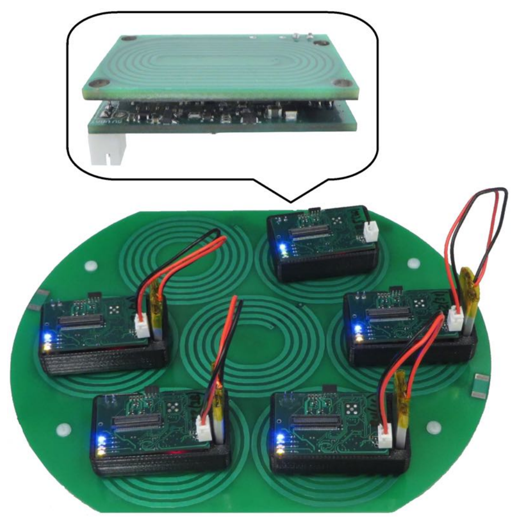

Fig. 3. Transmit coil array powering five receivers simultaneously

III. Software

When powering multiple RXs with a single TX, there is a tendency for one RX to hog all of the transmitted power, starving other devices of power. Our WPT system avoids this problem by using a combination of sensor measurements made on both the TX and RX sides to dynamically tune the WPT system. The various tuning algorithms rely on either in-band measurements (forward and reflected signals measured by an RF detector on the TX side) or out-of-band (OOB) voltage and current measurements sent across the 2.4GHz radio link. Each ED reports its wireless power consumption (rectified voltage times rectified current) back to the AP. Conversely, the AP may send commands to the individual EDs to control the adaptive matching network on each RX. This closes the feedback loop and provides the fine-grained control needed to regulate the amount of power that each ED receives. Therefore, if any given RX hogs too much power, it can be dynamically de-tuned so that another underpowered RX can be optimally tuned, enabling all RXs to have sufficient power delivery.

A. *Frequency Tracking*

Prior research has shown that frequency tracking can maintain efficient power transfer between a TX and a single RX [5]. We implement frequency tracking by using a directional coupler and RF detector to sense the magnitude and phase relationship between the forward and reflected signals from the PA to the TX coil. The operating frequency is dynamically tuned to the frequency that maximizes the forward signal and minimizes the reflected signal.

With multiple RXs, the optimal frequency for one RX may not be ideal for a different RX. Consequently, the frequency tracking algorithm typically selects the frequency corresponding to the receiver that is most strongly coupled to the TX coil. Therefore frequency tracking can be counter-productive with multiple RXs if not used in conjunction with power tracking and adaptive impedance matching.

B. *Power Tracking*

Power tracking uses the OOB radio link to create an additional feedback loop with the TX. Each ED communicates its received power measurements back to the AP, over the OOB radio link. The TX uses this information to adjust the gain of the PA by increasing or decreasing the DC voltage supplied to the PA. If any device receives too much power (i.e. rectified voltage exceeds 20V), then the transmit power level decreases. Otherwise, if any device receives too little power (i.e. rectified voltage falls below 6V), the transmit power level increases. In multiple-receiver systems, this algorithm effectively keeps all RXs sufficiently powered. However, power tracking alone cannot regulate how power is split between RXs, and certain RXs may be significantly overpowered if they have lower load power requirements or are more strongly coupled to the TX coil than adjacent RXs.

C. *Adaptive Impedance Matching*

Adaptive impedance matching allows for each RX to regulate the amount of wireless power it consumes. By adjusting a π-match network with a serial inductor and shunt switchable capacitors, various impedance settings can be set for each individual RX. The adaptive impedance matching networks and component selection techniques used in this system are based on [7].

Unlike power tracking, this algorithm can operate independently from the TX, and therefore does not necessarily require the OOB radio link. Each RX monitors its rectified voltage, and periodically checks whether it lies within an acceptable range (the same range as power tracking, 6-20V). If outside the range, then that RX performs a sweep of all possible impedance matching settings and selects the configuration that achieves a rectified voltage within the acceptable range. In some cases, the chosen impedance setting may intentionally de-tune the RX that would otherwise be prohibitively overpowered. Therefore this algorithm optimizes power delivery to the entire set of RXs, rather than maximize power delivered to a single RX. This algorithm ensures that each RX presents a similar impedance from the perspective of the TX coils, even if the coupling and power level of the RXs are different. In our system, each ED has only five possible impedance settings. We used the algorithms shown in [7] to minimize the search space of capacitor combinations, which significantly reduces the time it takes for adaptive impedance matching to optimize power delivery to the entire set of RXs.

D. *Time Division Multiplexing*

Using a combination of frequency tracking, power tracking and adaptive impedance matching, the system can optimize power delivery to a subset of devices, and subsequently ignore the remaining RXs. A practical scenario where this mode could be useful is RX prioritization: the most critical RX could be prioritized and rapidly charged while other RXs could either trickle charge or not charge at all until the critical device is fully charged. The system can also optimize multiple devices at once, so that an arbitrary subset of RXs charges simultaneously while others remain unpowered, even while they are in range of the TX coils.

TDM modes can be arbitrated in one of two ways. First, the TX can control the impedance settings on all RXs by sending commands across the OOB radio link. Second, each RX can independently control its own impedance settings. If the second mode is used, then the OOB radio link can be removed from the system, saving cost and PCB area, while still enabling frequency tracking on the TX side and adaptive impedance matching on each RX.

IV. Experimental Results

Using the setup shown in Figure 3 we charged five single cell batteries at different power levels simultaneously. The

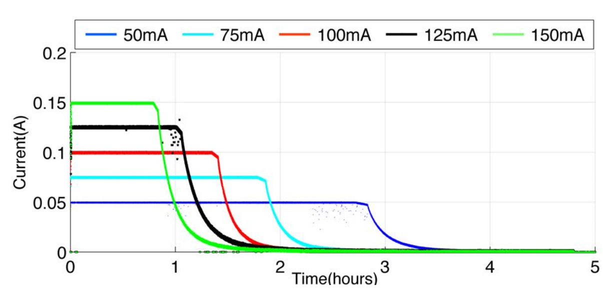

Fig. 4. Charge current for five wirelessly powered battery chargers.

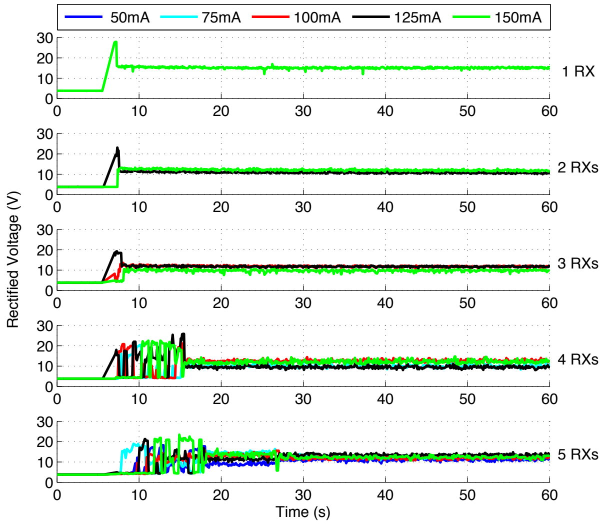

Fig. 5. Rectified voltage for 1-5 receivers using adaptive tuning techniques.

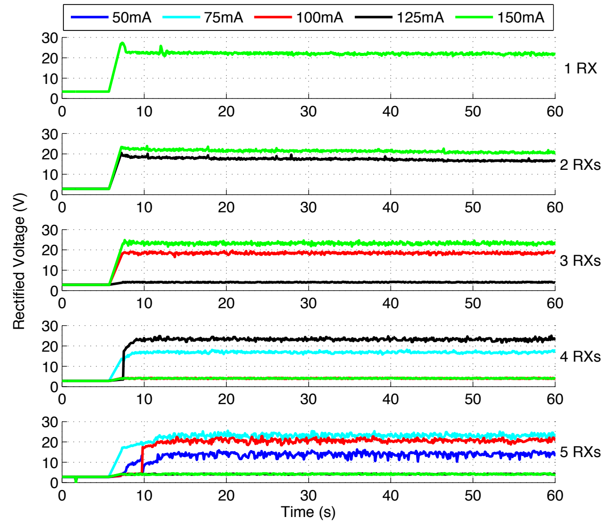

Fig. 6. Rectified voltage for 1-5 receivers without adaptive tuning.

battery charger on each receiver was programmatically set for a different charge current of 50mA, 75mA, 100mA, 125mA, and 150mA respectively. Figure 4 shows a plot of charge current versus time for each receiver.

To highlight the benefits of using frequency tracking, power tracking, and adaptive impedance matching, we compare the system performance with these dynamic tracking modes enabled (Figure 5) to the performance when the tracking modes are disabled (Figure 6. The rectified voltage reflects the equality of power distributed to each receiver. If the rectified voltage is less than 6V, then the respective receiver is not wirelessly powered, but rather powered by the battery. If the rectified voltage is high (i.e. above 20V) then the given receiver is overpowered and may hog power from adjacent receivers. With only one or two receivers present, both systems can provide sufficient power to each receiver. However when three or more receivers are present, only the adaptive system provides sufficient power to all receivers. The non-adaptive system suffers from uneven power distribution to the various receivers: the low charge current receivers are sufficiently powered while the high charge current receivers are underpowered.

Finally, we demonstrate the TDM capability of the system. The transmitter commands the matching networks on each receiver to sequentially optimize power delivery to one receiver while pessimizing power delivery to all other receivers. After holding this state for approximately 30 seconds, the next receiver gets optimized and those remaining are pessimized. It should be noted that two RXs were set for 75mA charge current and the other three RXs were set at 100mA. Figure 7 shows one complete sequence of optimizing power delivery to each receiver sequentially.

V. Conclusion

We have presented a complete WPT system capable of charging up five receive devices at various power levels. Without using the adaptive tuning techniques presented in this work, wireless power delivery to more than two receivers operating at a different power level cannot be achieved. We have shown the capability to prioritize and isolate specific

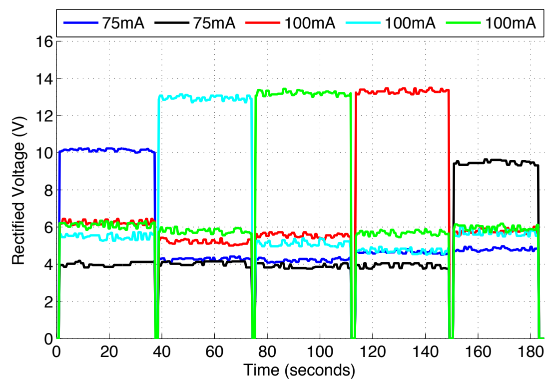

Fig. 7. Sequential charging using time division multiplexing.

receivers by demonstrating time-division multiplexing for the first time in a near-field WPT system.

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