Attachment 1

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A Practical Wireless Charging System based on Ultra-Wideband Retro-Reflective Beamforming

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Introduction

Numerous portable electronic devices (such as laptops, cell phones, digital cameras, and electric shavers) rely on rechargeable batteries and must be routinely charged by the line power. A wireless charging technique capable of delivering electromagnetic energy to these portable devices would make them tether free and “truly portable.” Wireless charging is especially valuable for devices with which wired connections are intractable, e.g., unattended radio frequency identification tags and implanted sensors. In recent years, enormous research efforts have been devoted to wireless charging. In 1990s, a case study is reported in [1] to construct a point-to-point wireless electricity transmission to a small isolated village called Grand-Bassin in France. In 2007, an inductive resonance coupling scheme, which makes use of near-field coupling between two magnetic resonators, was demonstrated able to power a 60-Watt light bulb over two meters by a team of Massachusetts Institute of Technology [2]. In addition, several companies (PowerCast, WildCharge, WiPower, etc.) have developed products targeting specific applications. Nevertheless, several technical challenges remain to be resolved in order to accomplish practical wireless charging. Specifically, (i) to achieve efficient charging over long distance, severe power loss due to electromagnetic wave propagation must be remedied; (ii) humans’ exposure to electromagnetic radiation should always be kept below safety level while sufficient power is delivered to devices; and (iii) some existing systems are unsuitable for ubiquitous deployment due to high cost, large size, and/or heavy weight. In this paper, an innovative wireless charging system based on ultra-wideband retro-reflective beamforming is proposed to address the above challenges. The proposed charger consists of multiple antenna elements distributed in space. According to pilot signals (which are short impulses) they receive from the target device, the antenna elements jointly construct a focused electromagnetic beam onto the device (i.e., beamforming). Beamforming enables spatially focused/dedicated power delivery to devices while keeping power level in all the other locations minimal. As a result, the proposed system attains high charging efficiency and leads to little hazard/interference to other objects. Performance of the proposed wireless charging system is demonstrated by some simulation results obtained by a full-wave Maxwell’s equations solver.

Wireless Charging based on Ultra-Wideband Retro-Reflective Beamforming

The proposed wireless charging system aims for both indoor and outdoor applications. As illustrated in Fig. 1, the charger consists of a central station and multiple base stations mounted around the region of concern. The central station and base stations are connected through wires. The multiple base stations collaboratively radiate wireless power to devices residing in the region as a beamformer. In other words, the base stations jointly establish focused beams onto the devices. Beamforming results in dedicated power delivery channels to devices while keeping power levels in all the other locations minimal.
minimal, which ensures high efficiency and human safety at the same time. In this paper, retro-reflective antenna array is exploited to achieve beamforming, which involves three steps. First, all the array elements receive *pilot signals* from the target device. Second, all the array elements analyze the pilot signals’ magnitudes and phases. And finally, once all the array elements transmit complex-conjugate versions of the pilot signals they receive, the resulting beam is spatially focused onto the target device. The retro-reflective array takes advantage of channel reciprocity and acts as a matched filter [3]. As a result of channel reciprocity, the waves “retro-reflected” by the retro-reflective array are constructive at the target device and destructive elsewhere. Since retro-reflective beamforming responds to the pilot signal and traces back to the origin of the pilot signal, tracking of multiple mobile/portable devices is straightforward. Furthermore, beam focusing due to retro-reflection does not suffer from multi-path in complex environments [3]. Retro-reflective arrays have been investigated for radar tracking applications for many years [4]. Nevertheless, it has never been attempted for constructive wireless charging channels, to the best of the authors’ knowledge. In addition, existing retro-reflective technologies (which are based on continuous waves) are unable to satisfy all the practical requirements of wireless charging; thus here, a more sophisticated retro-reflective array is proposed. First, in the proposed retro-reflective array, antenna elements are distributed over multiple base stations and there is no strict restriction on the base stations’ spatial locations, which offers construction flexibility as well as reliability and safety. If the line-of-sight path between the device and a certain base station is blocked by an object (a person for instance), the base station is deactivated such that the object is not under direct illumination (Fig. 1). Second, the proposed retro-reflective array incorporates multiple discrete frequencies in a wide frequency band and the frequencies are programmable to avoid possible electromagnetic interference. Third, the pilot signal is designed to be short impulses that are able to carry information of all the multiple frequencies [5]. In summary, the proposed wireless charging system integrates three technological elements: charging, communication, and radar tracking. To be specific, it relies on radar tracking to localize the target device and dynamically reconfigure focused beams onto the device; and, coordination of radar tracking and charging is made possible by the communication functionality. As a result, the proposed system is expected to exhibit the following specifications required by practical wireless charging.

- It can be deployed in complex environments and in all weather conditions.
- It is capable of tracking and charging multiple portable devices at the same time.
- Its high efficiency and safety to human are assured by retro-reflective beamforming.
- It has low cost, compact size, and low weight.

**Numerical Modeling Results**

Feasibility of the wireless charging system proposed in the previous section is demonstrated through a numerical model in Fig. 2. Eight base stations are assumed to be deployed over a circle with radius 3 m in the *x*-y plane. Each base station comprises of an antenna array with 5 by 5 elements equal-spaced by 12 cm. Two devices reside in the region. The antennas of both base stations and devices are *z*-oriented dipoles in this study. The devices transmit short impulses as pilot signals, which cover frequency band [4 GHz, 6 GHz]. Charging power is allocated to *N* discrete frequencies in this band. To represent more realistic scenarios, a metallic plate with length 1 m and height 0.6 m is placed to block line-of-sight path between the devices and one base station (Base Station B in Fig. 2). The model in Fig. 2 is simulated by the Method of Moments. Simulated *E* field distributions in a 2 m by 2 m region around the two devices are presented in Fig. 3. When
one device (the one at the center) sends pilot signals to the charger with the absence of obstacle, all the eight base stations are active. If the charger only transmits charging power at one frequency 4.09 GHz (i.e., $N = 1$), the field distribution is shown in Fig. 3(a). Apparently, field is focused at many locations other than the device (the undesired focal points resemble side lobes of regular phased arrays). When $N$ is chosen to be 30, only one focal point is left, which coincides with the device’s location, as shown in Fig. 3(b). When both devices send pilot signals, the field is automatically focused onto the two devices (Fig. 3(c)). It is noted that wireless charging produces strong fields in certain regions around both devices, termed red zones from which humans should stay away. In Fig. 3(c), the red zones are roughly spherical regions with radii 20 cm. Out of the red zones, field strength is at least 15 dB weaker than those at the devices. Our numerical simulations show that, with more antenna elements in the beamforming array, spatial focusing improves and the red zones shrink. In Fig. 3(d), the obstacle is assumed to be present, and Base Station B is blocked and turned off (the remaining seven base stations are active). Field focusing does not rely on the obstacle’s presence and the number of base stations, as shown in Fig. 3(d). With the presence of obstacle, which base stations should be deactivated can be easily determined through processing the pilot signals. Two base stations, Base Station A and Base Station B, are used as examples. After these two base stations receive pilot signals from one device, phase differences between two local antenna elements are plotted in Fig. 4; one of the two local elements is at the center and the other at the corner in the 5 by 5 array. As expected, since Base Station A has line-of-sight interaction with the device, its phase difference follows a straight line proportional to the frequency (a time delay); while such a pattern does not appear at Base Station B.

References


Fig. 3: Simulated field distribution plots of the proposed wireless charging system (with $|E_z|$ represented by colors)

Fig. 4: Simulated phase difference of pilot signals received at two base stations