論 文 の 内 容 の 要 旨

論文題目　Ubiquitous wireless power transfer in three-dimensional spaces
（三次元空間におけるユビキタスな無線電力伝送）

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Wireless power transfer has the promise to eliminate power cords and radically change how we interact with technologies involving electricity. However, existing approaches fail to embody this vision because achieving “high-power” and “wide-range” all at once in wireless power is challenging; microwave-based methods have limited power-levels due to safety concerns, and inductive systems using coils suffer from the narrow powering range.

In this thesis, I explore the fundamental physics, system design, and deployment of cavity-inspired, magnetoquasistatic wireless power technologies for drastically extending the powering range of inductive approaches, which are known to be capable of safely delivering higher power-levels. Unlike previous coil-based methods, the presented techniques leverage the widely distributed currents on conductive surfaces around the target volume for generating widely distributed 3-D magnetic field patterns while confining the troublesome electrical field within embedded circuit components. The presented approaches enable high-power, high-efficiency, and safe wireless power transfer over large areas, which would unlock device modalities that were previously inaccessible owing to limitations in power supply technologies.

Chapter 1 introduces the vision I aim to embody, describes the confronting challenges, and defines the scope of this thesis. Then, I provide a brief survey of relevant topics and research in chapter 2 to motivate the technologies developed in this thesis.

Chapter 3 presents an approach termed multimode quasistatic cavity resonance for enabling efficient wireless power throughout the full room-volume. This approach drastically extends the powering range of previous quasistatic cavity resonators, which could only cover half of the room volume, by introducing “multimode” features. By appropriately arranging conductive surfaces around the empowered volume and leveraging the nature that surface conductors can accommodate multi-directional and widely distributed current, this approach generates multiple, mutually unique, widely distributed 3-D magnetic field patterns within the room-volume. These modes used together achieved a power delivery efficiency exceeding 37.1% throughout the constructed test room (with dimensions of 3 m × 3 m × 2 m), and power exceeding 50 W could be delivered to mobile receivers, in accordance with safety guidelines.

Chapter 4 empowers IoT nodes by utilizing the room-wide channel for wireless power and low-power communication. This work reuses the room-wide wireless power transfer system as a communication channel, where nodes communicate with a centralized reader and each other via load-modulation. Because this communication system works in the near-field regimes where the source and the nodes intensely interact, and the communication signals and power inputs coexist, the incoming signals have a large dynamic range. To overcome this challenge, I develop a hardware/software-combined decoding circuit to normalize the incoming signals and read out the embedded data bits without distortion. Furthermore, I provide a theoretical analysis of the channel, followed by performance evaluations of communication and power transfer to validate this analysis. The proposed system shows that ten receiver nodes fully-equipped with custom-designed front-ends and power management units can be safely and efficiently wirelessly charged through analysis and experiments. The end node to end node communication rate can achieve from 1 kbps without occurring any errors, up to 5 kbps with a 6% bit error rate (BER), while the end node to the central unit can achieve 10 kbps without occurring any errors.

Chapter 5 tackles the challenge for powering pebble-scale (*i.e.*, a few cm) devices via room-scale transmitters. Such significantly asymmetric transmitter/receiver links suffer from a $1/\alpha^4$ degradation with increasing transmitter/receiver size ratio α; thereby, room-scale power transfer systems can barely empower pebble-scale devices. Inspired by optical lenses, I present a concept termed hierarchical resonance, which efficiently bridges significantly asymmetric transmitter/receiver links by focusing the ambient magnetic field using relay modules. General large-scale inductive transmitters can introduce this hierarchical link by placing low-cost, low-power, maintenance-free relay modules within the powering range. This approach offers a much more robust and efficient link than straightforward methods, which directly couple large transmitters with small receivers. I demonstrated the proposed concept and show that the hierarchical link increases the power efficiency by more than ten times compared to direct power transfer. Furthermore, I demonstrate a 500 mW power supply to pebble-sized (20 mm) devices, enabling driving microcontrollers and various sensing sub-systems without batteries.

Finally, chapter 6 concludes this thesis and raises future research directions.