Principles, Current Status, and Optimization of Multi-Device Wireless Charging Systems

Jianing Hao*

Electronic and Electrical Engineering, University College London, London WC1E 6BT, UK

*jianing.hao.25@ucl.ac.uk

Abstract. With the rapid proliferation of mobile electronic devices such as smartphones, earphones, and smartwatches, users are demanding more efficient and convenient charging methods. Traditional wired charging in public scenarios is hampered by incompatible connectors, inconvenience, and potential safety hazards. In contrast, wireless charging technology has gradually become a research and application hotspot due to its flexibility and safety. Existing wireless charging systems primarily focus on single-device-to-single-coil energy transfer models. However, when serving multiple devices simultaneously in public spaces, the systems face challenges such as magnetic field interference, uneven power distribution, and reduced efficiency. This paper reviews multi-zone and multi-device wireless charging systems. It outlines the fundamental principles of wireless charging and mainstream technical approaches. Particular emphasis is placed on multi-coil array structure design, regional circuit models, and management modules, as well as interference suppression and power regulation mechanisms. Furthermore, the paper examines the effects of device quantity and spacing on system coupling performance and energy transfer efficiency, and summarizes the major optimization methods based on representative research results. Additionally, it highlights the practical challenges faced in public applications, including electromagnetic compatibility and safety, system cost and complexity, and issues of standardization and interoperability. In conclusion, through a systematic review and comparative analysis of existing studies, this paper summarizes the current status and problems of multi-zone wireless charging systems. It also points out that future development will move toward smarter, more efficient, and standardized system implementations, providing useful references for large-scale applications in public environments.

Keywords: Wireless charging; Multi-coil array; Regional management; Public applications.

1. Introduction

With the rapid proliferation and widespread use of mobile electronic devices such as smartphones, Bluetooth earphones, and smartwatches, users have placed higher demands on charging methods. They now desire greater convenience, flexibility, and efficiency. In public places, traditional wired charging is often hampered by connector incompatibility. This forces users to carry multiple cables for different devices, which leads to a poor user experience. Moreover, wired charging poses potential safety risks. These risks include connector wear and electrical faults during use. In contrast, wireless charging technology has emerged as a new power delivery method. It is structurally simple, easy to operate, and offers higher safety. The reason for this is that Wireless Power Transfer (WPT) technology makes it possible to use electricity anytime and anywhere [1]. Therefore, it has become a major research focus in recent years within electrical engineering and power electronics.

In fact, the concept of WPT can be traced back to the 19th century. In 1831, the British scientist Michael Faraday first proposed and experimentally verified the law of electromagnetic induction. This laid the theoretical foundation for wireless energy transfer and the subsequent development of wireless charging technology. In the early 20th century, the American researcher and inventor Nikola Tesla conducted pioneering experiments in WPT. Tesla pioneered non-radiative WPT via near-field magnetically coupled coils. He also developed radiative WPT using high-tension Tesla coils [2]. Although his vision could not be fully realized at that time, his groundbreaking foresight has become an important source of modern wireless charging technology.

In recent years, with the gradual popularization of standards such as Qi, existing research and commercial applications have primarily focused on single-device to single-coil energy transfer models. For example, Laha et al. reviewed compensation topologies, coil geometry optimization, and efficiency improvement strategies. Their work provided reliable design references for existing single-zone charging systems [3]. However, there remains a lack of exploration on the challenges of multi-device simultaneous charging. These challenges include magnetic field interference between coils and uneven power distribution. Such issues may reduce operational efficiency and compromise safety. They are particularly critical in public scenarios with dense user traffic, such as airports, libraries, and cafés.

Based on this research gap, this paper focuses on multi-device, multi-zone wireless charging systems for public scenarios. It reviews and compares the current literature to analyze existing WPT technological routes and system architectures. Particular emphasis is placed on the advantages and challenges of multi-zone structures. These structures can enhance charging flexibility and meet the diverse needs of multiple users.

2. Fundamental Principles and Theoretical Basis of Multi-Device Wireless Charging Systems

2.1. Basic Principles of Wireless Charging Systems

The core of wireless charging technology is founded on the principle of electromagnetic induction proposed by Faraday in 1831. When a conductor is exposed to a varying magnetic field, an induced electromotive force (EMF) is generated within it. Faraday's law of electromagnetic induction states that the induced EMF in a closed circuit is equal to the negative rate of change of the magnetic flux through the circuit (1). This enables non-contact energy transfer. This principle forms the fundamental framework of modern wireless charging systems. Typically, these systems consist of a transmitter and a receiver. The transmitter generates a varying magnetic field by supplying alternating current to the transmitting coil. The receiving coil captures the induced EMF through magnetic coupling. In this way, energy transfer and conversion are achieved. As shown in Fig.1, the transmitter coil (Tx) generates a time-varying magnetic field when supplied with alternating current. The receiver (Rx) captures the varying flux through electromagnetic induction, thereby producing an induced EMF and enabling wireless energy transfer. The formula of induced EMF is as follows:

$$\varepsilon = -N\frac{d\Phi_B}{dt} \tag{1}$$

where ε is the induced EMF, N is the number of turns of the coil, and Φ is the magnetic flux through the coil.

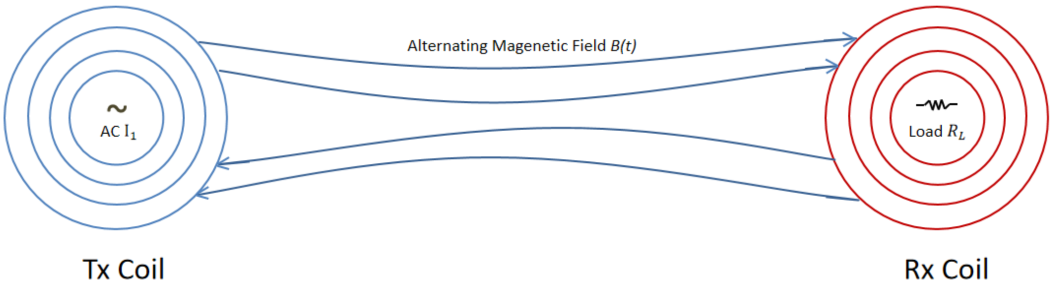

Fig.1 Schematic diagram of the basic working principle of WPT (Photo credit: Original)

With the advancement of WPT technology, three mainstream approaches have gradually been established. These include inductive coupling, magnetic resonance coupling, and capacitive coupling. Inductive coupling is characterized by its simple structure and rapid response. It is widely applied in low-power, short-range devices such as smartphones and electric toothbrushes. In this approach, an alternating current in the transmitting coil generates a time-varying magnetic field. The receiving coil captures the induced EMF to realize energy transfer. However, its effective coupling distance is generally limited to less than 10 mm. It also requires strict alignment between the transmitter and receiver. Therefore, it is not suitable for high-power or multi-device charging scenarios.

To overcome these limitations, magnetic resonance coupling has emerged as a key focus of research and practical applications. This method relies on resonance efficiency matching between the transmitter and receiver. By introducing resonance compensation circuits, both sides can operate at the same frequency. This enables efficient energy exchange and maintains high transfer efficiency over a longer distance. Magnetic resonance coupling supports simultaneous charging for multiple devices. It also offers higher tolerance to misalignment. As a result, it is particularly suitable for scenarios requiring multi-coil and multi-zone dynamic power delivery.

Capacitive coupling uses a high-frequency electric field between two electrodes for energy transfer. This method offers a compact structure and is appropriate for near-field, low-power applications in small devices. However, its conversion efficiency and spatial adaptability are generally inferior to those of the other two approaches.

Considering the respective advantages and limitations of these methods, magnetic resonance coupling has become the primary solution for designing multi-device wireless charging systems in public environments.

2.2. Theoretical Foundation of Multi-Device Wireless Charging Systems

Based on these principles, further theoretical research focuses on how to maintain efficient and stable energy transfer under multi-device charging conditions. In public scenarios, the most significant challenge of multi-device wireless charging systems is meeting the charging demands of multiple user devices on a single platform. As the number and diversity of devices continue to increase, a single transmitting coil structure is no longer sufficient. It cannot balance coverage range and power distribution efficiency. Therefore, adopting a multi-coil array for resonant coupling becomes critical. This configuration deploys multiple transmitting coils within the charging platform. The magnetic fields generated by these coils overlap and cooperate. As a result, one-to-one or one-to-many resonant couplings are formed with the receiving coils. Compared with traditional single-coil systems, the multi-coil array can effectively expand the power coverage area. Resonance tuning through frequency control also helps minimize mutual interference. This improves coupling efficiency and overall stability.

Recent studies have demonstrated promising results in this field. For example, Mirbozorgi et al. proposed a multi-resonator array structure that supports multi-device charging with stable efficiency. Their experimental results showed up to a 26% increase in efficiency for single-device charging. In multi-device environments, efficiency still improved by about 12% [4]. Moreover, the introduction of multi-input multi-output (MIMO) magnetic beamforming technology has become a research hotspot in recent years. By coordinating the phase and amplitude across multiple transmitting coils, this method generates a stronger directional magnetic flux distribution. It enables more efficient energy coupling to target receivers. This improves overall system efficiency in multi-receiver scenarios. At the same time, it reduces interference among different charging zones [5].

From a theoretical perspective, techniques such as multi-coil arrays, frequency tuning, and magnetic beamforming together form the research basis of multi-device wireless charging systems. These approaches enhance efficiency and spatial adaptability at the system level. They also provide a solid technical foundation for large-scale application of wireless charging in public environments. Among these methods, magnetic resonance coupling combined with multi-coil array configurations demonstrates the greatest potential for practical deployment.

3. Current Status of Wireless Charging System Design

3.1. Multi-Coil Array Structure Design

In the design of systems that involve simultaneous charging of multiple devices, the introduction of multi-coil arrays is a key technological approach. This method improves spatial coverage and enhances system flexibility. Through proper design and arrangement of multiple transmitting coils, the effective charging area of the platform can be significantly enlarged. At the same time, the uniformity of the magnetic field distribution is improved, and dead zones in energy transfer are reduced. As a result, the overall user experience is enhanced.

In recent years, researchers have proposed various array layouts. The arrangement of coils has been shown to directly affect system performance. For example, matrix-type arrays, as shown in Fig.2, are relatively easy to implement. However, they often create energy blind spots at the platform edges. In contrast, honeycomb-type arrays, as illustrated in Fig.3, use hexagonal tiling to achieve a more uniform magnetic field distribution. This makes them suitable for scenarios that require stable power delivery over large areas. Staggered arrays, which depicted in Fig.4, introduce phase shifts between rows and columns. This reduces coupling peaks between adjacent coils. As a result, they improve the minimum coupling coefficient and transmission efficiency in unfavorable positions. These features make staggered arrays effective when device placement is irregular. Therefore, different configurations provide multiple options for optimizing multi-zone, multi-user wireless charging applications.

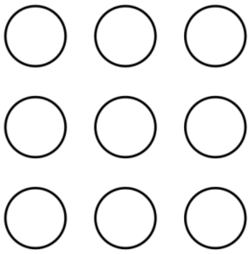

Fig.2 Schematic diagram of matrix coil arrangement (each circle represents a coil) (Photo credit: Original)

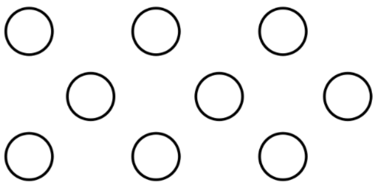

Fig.3 Schematic diagram of hexagonal(honeycomb) coil arrangement (each circle represents a coil) (Photo credit: Original)

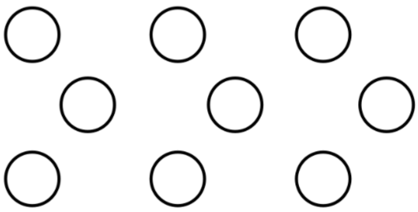

Fig.4 Schematic diagram of staggered coil arrangement (each circle represents a coil)

To meet the requirements of arbitrary placement and fault tolerance, staggered equidistant tiling has been identified as a suitable solution for multi-coil arrays. This layout introduces spacing shifts between rows to reduce the coupling peak between in-phase adjacent coils. As a result, it increases the minimum coupling coefficient and transmission efficiency in worst-case alignments. Kim et al. proposed the Shifted Resonator Coil Array (SRCA). Their study demonstrated that SRCA provides more stable efficiency and smaller dead zones than conventional planar tiling arrays in misalignment scenarios [6]. In addition, researchers have introduced magnetic beamforming technology. This technique employs cooperative control of multiple transmitters to form directional magnetic flux. It improves directional transmission performance and suppresses inter-region interference.

3.2. Regional Circuit Model and Management Module

To enable efficient control and management, systems based on multi-coil arrays are typically partitioned into regional units. Each region typically consists of three functional modules. The first is a transmitting inverter with a resonant compensation circuit (e.g., LCC-S compensation topology [7]). The second is a receiving-side rectification and voltage regulation module. The third is a management module responsible for intelligent scheduling.

Existing studies have shown clear performance advantages of advanced topologies. Under different coupling coefficient ranges, LCC, LCL, and their S-variants outperform the simple S-S structure. These topologies provide stable constant current (CC) or constant voltage (CV) output [2].

Among these modules, the management module plays a particularly critical role. It employs sensors to detect, in real time, whether a device is placed within the charging area. Based on this detection, it controls the activation of the corresponding coil as well as the power output. Its activation logic must comply with the latest Qi standard to avoid the erroneous activation of coils in regions without devices.

This modular regional management architecture meets the diverse power requirements of different devices. It supports both CC and CV charging modes. At the same time, it helps maintain system stability.

However, the integration of circuit and management modules mainly ensures high charging performance within a single region. In public scenarios where multiple devices coexist, new challenges appear. Magnetic field interference among regions becomes significant. In addition, dynamic power distribution across regions is required. These challenges necessitate the development of more advanced interference mitigation mechanisms and power regulation strategies.

3.3. System Functional Requirements: Interference Mitigation and Power Regulation Mechanisms

To meet the demands of multi-device usage in public scenarios, it is necessary to suppress magnetic field interference caused by simultaneous activation across regions. Existing research has proposed various solutions. Among them, the Time-Division Multiplexing (TDM) strategy is one of the most commonly adopted methods. It prevents multiple zones from being activated simultaneously. The system uses sensors to detect device positions, then activates the corresponding coil while temporarily disabling others.

For instance, Alvus et al. proposed a two-dimensional charging surface architecture. This system leverages multiple multihop relays to enable path-based energy routing. With this approach, users can simply place their devices on planar modules. The system then dynamically constructs a wireless charging network and automatically identifies receiver positions. Based on this, it reconfigures the energy path.

Both this reconfiguration technique and the SoftCharge energy-hopping strategy have been experimentally validated. Results show that they can restore charging efficiency close to that of single-device scenarios, even under multi-device conditions [8]. These advancements provide reliable technical support for the large-scale deployment of wireless charging systems in public environments.

4. Factors Affecting the Performance of Multi-Device Wireless Charging Systems

When multiple devices operate in parallel, the performance of wireless charging systems is restricted by several factors. This chapter discusses two main aspects: the number of devices and the spacing between devices. Their influence on coupling, power distribution, and transfer efficiency is analyzed separately.

4.1. Impact of Device Quantity on System Performance

When multiple receiving devices are placed on the same charging platform, the system evolves from a simple single-transmitter single-receiver coupling into a complex multi-transmitter multi-receiver network. As the number of connected devices increases, two typical impacts appear. First, the equivalent impedance and resonance conditions on the primary side change. This causes resonance peaks to split or shift, leading to a decline in overall transfer efficiency. Second, power distribution becomes a critical issue. Without proper power scheduling or compensation strategies, some receivers may obtain excessive energy while others receive too little. This results in low energy utilization or the inability to meet the charging demand of certain devices.

Both experimental and theoretical studies have shown that efficiency degradation exhibits a nonlinear relationship with the number of devices. It is also strongly affected by the mutual coupling strength in the coupling coefficient matrix [9]. To address this issue, two approaches have been proposed in existing research. One approach is circuit-level compensation and frequency tuning, which helps maintain operation near resonance even under multiple loads. The other approach is system-level scheduling strategies, such as selective activation, time-division multiplexing, or power allocation algorithms, which reduce severe coupling conflicts by avoiding simultaneous activation [10].

In summary, for engineering implementation in multi-device scenarios, both the robustness of compensation topologies and the fairness of scheduling strategies must be considered. Only by combining these aspects can the system maintain stability and ensure a satisfactory charging experience as the number of devices increases.

4.2. Influence of Device Spacing on the Coupling Coefficient

The coupling coefficient (κ) is a key parameter that determines the efficiency of wireless power transfer. Its value changes significantly with the relative position between the transmitting and receiving coils, including both horizontal offsets and vertical gaps. Classical theory and experimental results both confirm that κ decays with increasing distance. In coaxial alignment, κ decreases monotonically with vertical separation. When lateral misalignment occurs, κ usually shows a slow initial decline followed by a sharp drop. This nonlinear decay, which approximates a power-law behavior, often results in significant efficiency losses at certain offsets or edge positions [11].

To obtain reproducible and engineering-oriented design parameters, researchers commonly employ a combination of field simulations and analytical mutual inductance formulas. This method allows the plotting of $\kappa(d,h)$ surfaces under different spacing and misalignment conditions, which then serve as inputs for the design of compensation networks and control strategies.

Several mitigation approaches have been proposed to address distance sensitivity. The first approach is array layout optimization, which enhances the minimum κ under worst-case positions. This reduces energy nulls and improves the uniformity of overall coverage [12]. The second approach is frequency tuning or adaptive matching networks. These methods adjust the resonance conditions online so that efficiency can be quickly restored when κ varies [13]. The third approach focuses on system-level solutions, such as routing, beamforming, or selective activation. By directing energy to the target receiver or staggering power delivery over time, these methods mitigate performance degradation caused by spacing or misalignment.

In conclusion, the influence of device spacing on the coupling coefficient follows well-defined physical laws. However, through the coordinated optimization of array structures, compensation networks, and control strategies, this impact can be reduced to an acceptable range, thereby ensuring reliable performance for multi-device parallel charging.

5. Challenges and Future Prospects

Multi-zone public wireless charging systems have broad application potential. For example, in airport waiting halls or long-distance bus stations, charging tables can allow users to place devices arbitrarily. In public spaces such as cafés and libraries, charging platforms can be embedded into tables or deployed as desktop modules to provide convenient wireless charging. Office environments are also well suited, especially for meeting tables and shared workspaces, where wireless charging platforms can improve both efficiency and device management convenience.

However, despite significant theoretical and experimental progress, the large-scale deployment of multi-zone public wireless charging systems still faces several key challenges. The foremost hurdle to commercialization is addressing electromagnetic compatibility(EMC) and safety concerns. When multiple transmitting coils operate simultaneously or when cross-zone coupling occurs, the leakage magnetic field intensity may exceed safety limits, posing risks to both humans and surrounding electronic devices. Compliant designs must meet national or international regulations on electromagnetic emissions. They must also integrate proper enclosure design, shielding materials, and control strategies such as temperature monitoring and foreign object detection to respond to abnormal conditions in time.

The second challenge is cost and system complexity. The introduction of multi-coil arrays, compensation networks, management and control modules, sensors, and switching devices significantly increases both component costs and manufacturing difficulty. To ensure reliable performance, high-precision coils and premium materials are often required. However, their use may lead to high costs and energy consumption, which can become major obstacles to commercial deployment.

The third challenge is standardization and interoperability. Current wireless charging markets are dominated by multiple standards, such as Qi and AirFuel. These standards differ in frequency, communication protocol, power class, and safety regulations. Without good compatibility with existing standards or a unified interface and detection protocol, multi-zone systems will struggle to achieve large-scale deployment.

Looking ahead, there are several promising directions for both technology and industry. First, in terms of materials and coil design, the use of new magnetic materials, flexible coils, or deformable coils may enhance adaptability and efficiency. Second, in control and scheduling algorithms, the application of artificial intelligence or machine learning to dynamic power allocation, interference prediction, and energy path reconfiguration could significantly enhance system intelligence. Third, in standardization and policy support, industry and standardization bodies need to establish specific regulations for multi-zone systems, including safety standards, certification procedures, unified interfaces, and consistent communication protocols. With progress in materials, algorithms, and policies, these systems are expected to be more widely deployed in public spaces, where their portability and flexibility may become part of future public infrastructure.

6. Conclusion

This paper provides a systematic review of multi-zone public wireless charging systems. Building on the fundamental principles of wireless charging technology and current developments, it analyzes the regional partitioning of multi-coil array structures together with their circuit models and management modules. The findings confirm that well-designed compensation topologies and intelligent scheduling strategies are essential to guarantee stable charging performance across multiple zones. Literature comparison and structural analysis further demonstrate that time-division multiplexing and path reconfiguration are highly effective in mitigating interference and improving energy scheduling in multi-device scenarios.

Regarding performance factors, studies clearly show that both device quantity and device spacing are decisive in shaping the coupling coefficient and overall transfer efficiency. As the number of connected devices rises, problems of uneven power allocation and inter-zone magnetic interference escalate, which directly undermines system performance. At the same time, spacing variations exert a critical influence on coupling strength and, consequently, on the stability of power output. These findings underscore that robust power regulation mechanisms and adaptive scheduling strategies are indispensable for maintaining efficiency and stability in multi-device environments.

Furthermore, this review identifies pressing challenges for real-world deployment, including electromagnetic compatibility and safety, the balance between cost and complexity, and the lack of unified standards and interoperability. Addressing these issues demands ongoing advances in materials, control algorithms, and standardization. Ultimately, the goal is clear: to achieve smarter, more efficient, and universally standardized multi-device wireless charging platforms that can be confidently deployed at scale in public spaces.

References

[1] Park, Y. J. Next-generation wireless charging systems for mobile devices. Energies, 2022, 15(9): 3119.

[2] Hui, S. Y. Planar wireless charging technology for portable electronic products and Qi. Proceedings of the IEEE, 2013, 101(6): 1290-1301.

[3] Laha, A., Kalathy, A., Pahlevani, M., & Jain, P. A comprehensive review on wireless power transfer systems for charging portable electronics. Eng, 2023, 4(2): 1023-1057.

[4] Mirbozorgi, S. A., Maghsoudloo, E., Bahrami, H., Sawan, M., & Gosselin, B. Multi‐resonator arrays for smart wireless power distribution: comparison with experimental assessment. IET Power Electronics, 2020, 13(18): 4183-4193.

[5] Yang, G., Moghadam, M. R. V., & Zhang, R. Magnetic MIMO signal processing and optimization for wireless power transfer. IEEE Transactions on Signal Processing, 2017, 65(11): 2860-2874.

[6] Kim, J. W., Son, H. C., Kim, D. H., Yang, J. R., Kim, K. H., Lee, K. M., & Park, Y. J. (2012, May). Wireless power transfer for free positioning using compact planar multiple self-resonators. In 2012 IEEE MTT-S International Microwave Workshop Series on Innovative Wireless Power Transmission: Technologies, Systems, and Applications (pp. 127-130). IEEE.

[7] Yang, Y., Zhang, X., Guo, K., Zhang, W., & **e, S. Optimization of a Single-Switch Wireless Power Transfer Circuit Based on a Multi-Coil Array. Electronics, 2023, 12(10): 2213.

[8] Sumiya, K., Sasatani, T., Nishizawa, Y., Tsushio, K., Narusue, Y., & Kawahara, Y. Alvus: A reconfigurable 2-d wireless charging system. Proceedings of the ACM on Interactive, Mobile, Wearable and Ubiquitous Technologies, 2019, 3(2): 1-29.

[9] Kurs, A., Karalis, A., Moffatt, R., Joannopoulos, J. D., Fisher, P., & Soljacic, M. Wireless power transfer via strongly coupled magnetic resonances. science, 2007, 317(5834): 83-86.

[10] Sample, A. P., Meyer, D. T., & Smith, J. R. Analysis, experimental results, and range adaptation of magnetically coupled resonators for wireless power transfer. IEEE Transactions on industrial electronics, 2010, 58(2): 544-554.

[11] Kurs, A., Karalis, A., Moffatt, R., Joannopoulos, J. D., Fisher, P., & Soljacic, M. Wireless power transfer via strongly coupled magnetic resonances. science, 2007, 317(5834): 83-86.

[12] Imura, T., & Hori, Y. Maximizing air gap and efficiency of magnetic resonant coupling for wireless power transfer using equivalent circuit and Neumann formula. IEEE Transactions on industrial electronics, 2011, 58(10): 4746-4752.

[13] Zhang, W., & Mi, C. C. Compensation topologies of high-power wireless power transfer systems. IEEE Transactions on Vehicular Technology, 2015, 65(6): 4768-4778.