

An Intelligent Resonant Wireless Energy Distribution System for IoT Sensor Networks

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Abstract—Wireless power transmission (WPT) is a key enabling technology for autonomous Internet of Things (IoT) sensor networks deployed in remote or hard-to-access environments. This paper presents an intelligent resonant wireless energy distribution system that integrates power transfer, sensing, communication, and adaptive control within a unified Wireless Sensor Network (WSN) architecture. The proposed system introduces multi-role nodes capable of operating as transmitters, relays, or receivers, enabling scalable and battery-free network deployment. A parameterized analytical and simulation framework is developed to model power transfer behavior, and a functional prototype is implemented and experimentally validated. The system incorporates a rule-based adaptive control mechanism and IoT communication (MQTT/HTTP) for real-time monitoring and dynamic power regulation. Experimental results demonstrate wireless energy transfer over distances up to 35 meters under controlled conditions, supporting continuous operation of distributed sensor nodes. The proposed approach advances WPT-enabled IoT systems by providing a scalable, energy-autonomous architecture for distributed sensing applications.

Index Terms— Wireless power transfer (WPT), Wireless sensor networks (WSN), Resonant systems, Electromagnetic fields, Internet of Things (IoT)

I. INTRODUCTION

Wireless power transmission (WPT) enables devices to be powered without cables, making it particularly useful in locations where wiring installation is challenging [1]. This system transfers power through the air using inductive, capacitive, or resonant couplings, enabling multiple devices to operate continuously without relying on batteries or physical connections. WPT has become an efficient solution in multiple domains, including IoT sensing in remote areas, contactless electric vehicle charging, implantable and wearable medical devices, and industrial automation systems. By eliminating cables and reducing maintenance, this technology helps

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increase the efficiency and reliability of electrical systems [2].

Wireless power transmission is divided into two categories based on operating distance: near-field and far-field. In the near-field environment, inductive and resonant coupling are commonly used in applications such as wireless mobile chargers, electric vehicle charging, and medical devices. They have limitations, such as a limited range and the need for precise alignment of the elements. On the other hand, far-field transmission uses radio waves and emerges as a solution for powering remote sensors, IoT devices, and drones without being close to the transmitter. In this case, energy harvesting collects energy from the environment, and wide-beam systems stand out, allowing small amounts of energy to be sent over longer distances without requiring precise alignment. This is very useful in harsh environments or with moving devices [3].

Integrating IoT technologies into wireless power transmission systems is essential for ensuring efficient, secure, real-time energy transfer process monitoring. Power levels, transmission efficiency, alignment between devices, temperature, and electromagnetic interference are collected using distributed sensors and intelligent nodes. This information allows fault detection, optimization of system performance, and dynamic adaptation of operating modes based on environmental conditions. Furthermore, IoT connectivity facilitates remote monitoring and the implementation of automatic control algorithms, significantly improving system reliability, energy efficiency, and scalability, especially in critical applications such as sensor networks in remote areas, medical devices, or electric vehicles [4].

Wireless power transmission using resonant coupling presents several technical challenges that hinder its large-scale implementation. One of the main challenges is low efficiency over long distances, as the transferred power decreases significantly with increasing separation between the transmitting and receiving coils. Furthermore, both coils must be tuned to the same resonant frequency; any mismatch causes significant efficiency losses. Misalignment between coils also has a negative impact, weakening mutual inductance and increasing the stray magnetic field. Likewise, nearby metallic objects or dielectric materials can interfere with magnetic coupling, reducing efficiency. These factors underscore the need for optimized system design and precise control to ensure stable and secure performance [5].

This work focuses on the modeling, design, and implementation of a functional prototype capable of wirelessly transmitting power over distances of several meters while

always maintaining user control and monitoring. The system includes an automatic computing algorithm integrated into the transmitting nodes to analyze whether environmental conditions affect transmission performance. To this end, the nodes can act as power transmitters or weather stations. Preliminary modeling allows for the establishment of design patterns using programming tools, and a communication architecture is implemented to process, visualize, and store the data obtained by the network. Nodes can operate as transmitters, relays, or receivers, and their role can be reconfigured according to deployment requirements and operating conditions.

In our previous work on cooperative autonomic computing for energy-efficient sensor networks [6], we developed a distributed architecture in which each node was capable of self-management and collaborative operation based on the MAPE-K (Monitor, Analyze, Plan, Execute, Knowledge) model. That approach demonstrated that cooperative behavior among nodes can significantly reduce overall energy consumption and improve resource allocation in environmental monitoring applications. Building upon that foundation, the present study integrates Wireless Power Transmission (WPT) technology into the cooperative WSN framework to enable energy self-sufficiency and autonomous operation of sensor nodes in remote areas. This integration transforms the network from being energy-optimized to being energy-autonomous, combining intelligent computing, wireless energy transfer, and IoT-based communication to extend the network lifetime and reduce maintenance requirements.

The main contributions of this work are summarized as follows. First, we propose a system-level WPT-IoT architecture for wireless sensor networks in which wireless power transfer, sensing, communication, and monitoring layers are jointly designed rather than treated as independent subsystems. Second, the architecture introduces a multi-role node model, where nodes can operate as transmitter, receiver, or relay within the same framework, enabling cooperative energy extension in distributed WSN deployments. Third, we develop a parameterized analytical and simulation framework to predict received power and system behavior from electrical and geometric design parameters and validate it with experimental measurements from a functional prototype. Fourth, the system integrates adaptive rule-based transmission control and IoT monitoring via MQTT/HTTP, enabling remote supervision and dynamic power adjustment. Finally, we provide a system-level comparison with related WPT-IoT approaches, highlighting architectural and functional differences. The system is therefore evaluated not only at electromagnetic link level but also at IoT network level in terms of adaptive control, distributed node roles, and scalable WSN deployment.

The remainder of this paper is organized as follows. Section II reviews related work in the field of wireless power transmission and its applications to IoT networks. Section III introduces the proposed system architecture, including the design principles and operational details of the transmitter and receiver nodes. Section IV presents the simulation and

experimental results, discussing power transfer efficiency, system performance, and validation against real measurements. Finally, Section V concludes the paper and outlines directions for future research.

II. RELATED WORK

This section reviews representative prior work on wireless power transmission (WPT) systems with emphasis on resonant inductive approaches, relay-assisted architectures, and IoT-oriented energy delivery solutions for sensor networks. The goal is not to provide an exhaustive survey, but to position the proposed architecture with respect to the most relevant contributions in resonant WPT modeling, efficiency optimization, coil design sensitivity, distributed power delivery, and WPT-enabled IoT deployments. These references establish the technical and architectural context used later for comparison with the proposed multi-stage, IoT-integrated WPT-WSN system.

A. Efficiency Optimization in Wireless Power Transmission

In 2007, André Kurs of MIT experimented with self-resonant coils in a strongly coupled regime [7]. He experimentally demonstrated that non-radiative power transfer is efficient at distances of up to eight times the radius of the coils. With this, it managed to transmit 60 watts with an efficiency of approximately 40% at distances greater than two meters. He also presented a model describing the transfer of experimental measurements at 5% pressure. This is an improvement over the Tesla system because, with weak coupling, energy is efficiently transferred thanks to resonance.

In 2015, Minfan Fu conducted a detailed analysis to optimize the efficiency of WPT systems, highlighting that under realistic uncertainties, a feedback mechanism is required to improve the performance and efficiency of these systems [8]. The load resistance is optimally valued for a specific mutual induction between the coils and maximizes system efficiency. A DC-DC boost-buck converter is used to dynamically adjust the equivalent load resistance and maintain optimal efficiency under changing conditions. Its use over impedance matching networks is justified, as the latter can introduce additional losses and increase system complexity. A perturbation-and-observe algorithm is implemented to adjust the equivalent load resistance. This algorithm measures system efficiency in real time. It modifies the equivalent load resistance by controlling the DC-DC converter. It corrects the resistance if efficiency decreases, thus achieving the optimal point. Finally, they performed an experimental validation of a 13.56 MHz, 40 W WPT system by varying the load and relative position between the coils while maintaining a high efficiency of 70%.

In 2023, Xin Jin researched to improve the efficiency of single-wire power transmission using a multilayer Tesla coil [5]. He analyzed the equivalent circuit model of the Tesla coil and the Single-Wire Power Transmission (SWPT) system to validate the system with experimental tests at different transmission distances. The proposed multilayer Tesla coil reduces energy losses in air and improves efficiency. Grounding is used to concentrate energy and improve

transmission. The high-voltage coil is wound in multiple layers with minimal gaps to increase the coupling coefficient. The low-voltage coil is tightly wound around the outer layer of the high-voltage coil. The advantages are lower energy loss to the air, higher transmission efficiency, and greater power transmission capacity, 5 kW at 5 km with 87% efficiency.

In 2016, Pusparini Dewi Abd Aziz explored wireless power transfer using a Tesla coil through inductive coupling [9]. He analyzed the effects of the number of windings turns on power transmission efficiency. He also tested the system's ability to power electrical loads remotely without physical contact. Current wireless power transmission methods include direct inductive coupling and resonant inductive coupling. The main challenge is achieving high magnetic flux density at an optimal frequency to maximize power transfer efficiency. An 84 mm diameter coil with 900 turns offered the best efficiency up to 9-10 cm distance. A 48 mm coil with fewer turns showed lower efficiency. Therefore, the higher the number of turns, the greater the power transfer.

Recent post-2024 work has extended resonant WPT efficiency optimization toward IoT-oriented and sensor-layer deployments, including magnetically coupled resonant approaches and high-efficiency inductive designs with integrated DC-DC conditioning for smart sensor nodes [10], [11].

B Impact of Misalignment and Stability on Power Transfer

In 2017, Fuxin Liu modeled wireless power transfer based on coupled magnetic resonance [12]. He focused on analyzing the effects of spatial misalignments on system efficiency and stability and optimizing coil designs to maximize power transfer with high stability. The challenges are that lateral and angular misalignments affect mutual inductance, causing fluctuations in output power and transmission efficiency. Variation in mutual inductance changes efficiency and transmitted power. It is shown that increased misalignment drastically reduces mutual inductance and, consequently, transmission efficiency.

In 2014, Yiming Zhang presented the basic principles of wireless power transfer using magnetic resonance [13]. He designed resonant coils and magnetic field distribution methods to improve efficiency, reduce electromagnetic noise, and define consumer applications and OLEV transportation systems. Maximum power transfer occurs when the load impedance matches the circuit impedance, the greater the distance between coils, the less magnetic coupling, and the lower the efficiency. For $k > 0.1$, the efficiency remains constant. For $k < 0.01$, the efficiency drops dramatically.

Recent resonant inductive WPT implementations for smart sensing platforms have also emphasized practical robustness and stable operation under non-ideal coupling and deployment conditions, reinforcing the need for compensation and tuning strategies at receiver side [11].

C. Distributed Architectures for Wireless Power Transmission

In 2018, Kae Won Choi explored distributed wireless power transfer using electromagnetic waves [14]. He designed a

distributed antenna system to maximize energy efficiency and eliminate dead zones to achieve this. The distributed power transfer system uses multiple antennas and beamforming techniques. It is optimal with phase and frequency synchronization, static without phase synchronization, and random phase synchronization. The system includes an IoT device with a receiving antenna to convert the RF signal into usable energy. Beamforming algorithms are implemented to improve energy transfer efficiency. Distributed power transmission architectures are proposed, including centralized, semi-distributed, and fully distributed. Experimental validation demonstrates that optimal beamforming provides the best energy efficiency.

In 2013, Jiseong Kim classified the electromagnetic field near a source. It is divided into three regions based on distance [2]: quasi-static field (very close to the source), reactive field (greater inductive interaction), and radiative field (energy transmission by electromagnetic radiation). It is detailed that magnetic energy transfer link architectures can be classified into various categories based on their configuration. First, two-terminal (dual-terminal) topologies include links with a single transmitter and receiver, which can be direct-feed, where the coils are physically connected to the source and load circuits, or indirect-feed, based on magnetic resonance with physically decoupled resonant coils. On the other hand, multi-terminal links involve multiple transmitters and receivers, classified as SIMO (Single-Input Multiple Output), with one transmitter and numerous receivers; MISO (Multiple-Input Single-Output), with multiple transmitters and a single receiver; and MIMO (Multiple-Input Multiple-Output), where both transmitters and receivers are numerous. Finally, relay links use intermediate coils to extend the energy transfer distance, improving the system's efficiency and range.

Recent multi-relay resonant WPT systems have demonstrated efficiency enhancement through switched compensation networks and dynamically maintained resonance across multiple intermediate coils, validating scalable relay-assisted energy transfer architectures [2].

D. WPT Applications in IoT and Sensor Networks

In 2018, Janne Janhunen investigated the feasibility of an IoT system powered solely by wireless power transfer via radio frequency (RF) [16]. The traditional wireless sensor network (WSN) design methodology was adapted for energy harvesting applications. The case study chosen was temperature and acceleration measurement on rotating mechanical structures. A Solmu Technologies node optimized for energy harvesting was used. The directional antennas delivered 10.7 mW at 1 m, compared to 0.10 mW using dipole antennas. Initial tests showed that the combination of the WPT transmitter and directional antennas provided sufficient power for the continuous operation of the sensor. The system measured and transmitted temperature and acceleration twice per second. At distances greater than 1 meter, the operation became intermittent. The results confirmed the validity of the proposed development methodology. Applying WPT in IoT is viable for dynamic industrial environments, such as rotating systems.

Directional antennas dramatically improve power transfer efficiency.

Very recent studies have further analyzed RF energy harvesting and wireless power transfer integration for IoT devices and sensor networks, highlighting architectural tradeoffs and deployment constraints in practical IoT scenarios [17], [9].

To better position the proposed approach with respect to prior WPT and WPT-IoT systems, Table I provides a system-level architectural comparison including IoT integration, relay capability, adaptive control, and prototype validation aspects.

TABLE I
ARCHITECTURAL COMPARISON OF WPT-IoT SYSTEMS

Work	WPT Method	IoT Layer	Relay Multi-hop	Adaptive Control	WSN Architecture	Prototype
Kurs et al., 2007	Resonant	No	No	No	No	Yes
Fu et al., 2015	Resonant	No	No	Converter-based	No	Yes
Choi et al., 2018	RF WPT	Partial	Distributed	No	Partial	Yes
Janhunen et al., 2018	RF EH	Yes	No	No	Partial	Yes
This work	Resonant	Yes	Yes	Yes	Yes	Yes

The reviewed studies provide a relevant theoretical basis for designing a wireless power transmission system in IoT networks. Energy efficiency optimization, addressed by Fu [8] and Jin [5], supports using resonant inductive modeling to maximize system efficiency. Likewise, research by Liu [12] and Zhang [13] on the effects of misalignment highlights the importance of compensating for spatial variations to maintain transmission stability. In distributed architectures, Choi's [10] work on beamforming and multi-transmitter networks is relevant for implementing a collaborative wireless power link. Finally, Janhunen's approach to WPT in IoT using RF reinforces the integration of communication technologies such as MQTT and HTTP, which are essential in the architecture of the proposed system.

This document and proposal explore the links and elements of wireless transmission systems, whether transmitters, intermediate devices, or receivers, forming an intelligent collaborative network using IoT devices. These devices perform other functions through automatic computing, and their operating status is monitored to achieve maximum energy efficiency. We also seek to optimize the design and architecture to achieve the most significant possible distance and performance.

III. PROPOSAL

This section proposes the designs and calculations used in the wireless transmission system.

A. Deployment Scenario.

Fig. 1 illustrates the deployment scenario of the proposed Wireless Power Transmission (WPT)-based Wireless Sensor

Network (WSN) designed for environmental monitoring applications [18]. The network is composed of multiple intelligent nodes with differentiated roles: transmitter nodes, responsible for wirelessly supplying energy through resonant inductive coupling; relay nodes, which act as intermediate elements capable of rectifying, regulating, and re-emitting power to extend coverage; and receiver nodes, which harvest the transmitted energy to power sensing and communication subsystems [19]. Each node integrates a microcontroller unit (MCU) that manages both power and data processes, enabling autonomous operation and energy-aware control. The IoT gateway aggregates and preprocesses sensor data using protocols such as LoRa and MQTT, while the IoT server provides centralized monitoring, adaptive power management, and data visualization. Yellow arrows in the figure represent the wireless energy flow, and blue arrows indicate the bidirectional data transmission path. This deployment scenario demonstrates how the proposed architecture supports long-range, self-sustaining IoT networks by combining wireless energy transfer and distributed intelligence across all nodes.

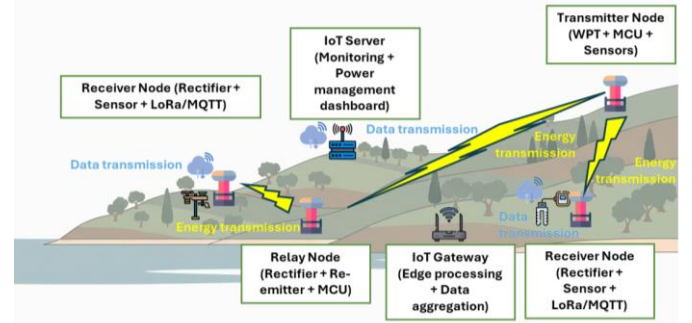


Fig. 1 WPT-powered WSN deployment architecture illustrating wireless power transfer and data flow between transmitter, relay, and receiver nodes.

B. Functional Architecture of the WPT-WSN System

The proposed system integrates wireless power transmission and intelligent sensor networking within a unified architecture designed for autonomous operation and efficient energy management. The functional block diagram is shown in Fig. 2. Power is supplied by a DC source that feeds an oscillator, generating an alternating current used to excite the resonant coupling stage and the transmitter coil. Through magnetic resonance, energy is wirelessly transferred to the receiver coil, which induces a current that is subsequently rectified and stabilized by the voltage regulator. This regulated power is then used to operate the IoT sensor node, enabling continuous sensing and data acquisition without the need for batteries or physical cabling.

The intelligent control module supervises the energy transfer process, incorporating three key functions: (1) power adjustment, which dynamically regulates transmission power according to the load and distance between coils; (2) system monitoring, which tracks efficiency, temperature, and alignment parameters; and (3) MQTT/HTTP communication, which provides connectivity between the nodes and the remote management platform.

overhead rather than by the WPT process. Since power transfer is continuous and not time-multiplexed with data packets, energy delivery does not consume communication bandwidth.

At system level, scalability is therefore determined by three main bounds: (i) relay-stage efficiency accumulation, (ii) minimum coupling distance per stage, and (iii) available IoT network capacity. These constraints define practical scaling limits while still allowing flexible incremental deployment for distributed sensing scenarios.

E. Model Validity Domains and Hybrid Propagation Approach.

The proposed analytical framework combines near-field resonant inductive coupling models with complementary far-field radiative attenuation formulations, each applied within its corresponding electromagnetic validity domain.

Near-field operation dominates when the transmission distance is small relative to the electromagnetic wavelength and when strong magnetic coupling exists between coils. In this regime, power transfer is governed by mutual inductance, coupling coefficient, and resonant circuit behavior. All primary design equations for efficiency, coupling, and resonance used in this work are derived from the inductive near-field model.

Far-field formulations, including Friis-type transmission expressions, are introduced only as auxiliary reference models to estimate radiative attenuation trends at extended distances where magnetic coupling becomes weak. These expressions are not used to replace the inductive coupling formulation but rather to provide an upper-bound attenuation reference outside the strong-coupling region.

The model separates inductive-dominant and radiative-dominant regimes and does not assume simultaneous validity. Although the system is primarily designed for near-field resonant inductive transfer, the extended-distance behavior may include a radiative coupling component due to coil geometry and operating frequency. For this reason, the hybrid model incorporates both inductive and radiative terms under clearly differentiated validity conditions. The GHz-range resonance values obtained from certain analytical formulations correspond to the radiative-equivalent resonance mode of the structure and are associated with the electromagnetic propagation component, not with the dominant inductive transfer mechanism. Therefore, Friis-based expressions are applied only to the radiative component and not to the near-field inductive regime. The practical operating frequency of the inductive transfer stage is in the kHz–MHz region; GHz values correspond only to analytical radiative-mode estimation.

F. Calculations and Simulated Parameterization of the Wireless Transmission System.

This section details the equations and concepts used to model the system.

The system's objective is to be efficient when transmitting over long distances; therefore, its design characteristics must be well-optimized based on operational requirements. These characteristics are crucial for optimal received power, based on the distance between the nodes, and for the system to function

correctly. The system's performance is influenced by several key characteristics, including the input voltage and current per transmitting node, which determine the initial energy supplied. Transmission and cable resistance affect energy losses during transmission, while the distance between nodes plays a crucial role in signal attenuation. Table II shows the notations used in theoretical development.

TABLE II
NOTATION TABLE

Symbol	Unit	Description
P_{tx}	W (watts)	Power transmitted by the transmitter
V	V (volts)	Voltage of the transmitter
I	A (amperes)	Current transmitted by the transmitter
L	H (henries)	Inductance of the coil
μ	H/m	Magnetic permeability of the medium
N	—	Number of coil turns.
A	m^2	Cross-sectional area of the coil
l	m	Length of the solenoid
r	m	Radius of the coil or toroid
ϵ	F/m	Vacuum permittivity
P_r	W (watts)	Resistive power loss
R	Ω (ohms)	Cable or internal resistance
C	F (farads)	Capacitance of the coil
D_p	W/m^2	Power density
M	H (henries)	Mutual inductance
k	—	Coupling coefficient
M_k	H (henries)	Shared mutual inductance
B	T (teslas)	Magnetic field of the solenoid
f_r	Hz	Resonant frequency
Z	Ω (ohms)	Impedance
ω	rad/s	Angular frequency
Q	—	Quality factor
μ_t	—	Transmission efficiency
λ	m	Wavelength

Physical properties such as coil radius, the number of coils turns, solenoid length, and cross-sectional area impact the efficiency of electromagnetic transmission. Additionally, the sphere radius and antenna diameter influence signal reception and propagation. Ultimately, these parameters collectively determine how much power can be effectively transmitted through the system. Table II shows a summary of the parameters used in mathematical expressions.

Once these data are detailed, characteristics such as the transmitted power P_t and the resistive losses P_r of the transmitting nodes are obtained.

A crucial factor in the system is that the resonant frequencies of the transmitting and receiving nodes are the same. Therefore, inductance L and capacitance C must be the same at the

transmitting and receiving nodes for the system to be based on resonant coupling.

The system can also behave as an inductively coupled system at very short distances as a non-resonant inductively coupled system like a classical transformer, where we can obtain its power density D_p .

The coupling coefficient of the coils indicates how strongly the two coils are coupled. To do this, we calculate the area of the coils, their inductance L , and an estimate of their mutual inductance M (1). With this, we estimate the system nodes' coupling coefficient k (2) [21]. Once the coupling coefficient is obtained, we calculate Mk to determine the coils shared magnetic field and the coils' mutual inductance coefficient.

$$M = \frac{\mu N_1 N_2 \sqrt{A_1 A_2}}{l} \quad (1)$$

$$k = \frac{M}{\sqrt{L_1 L_2}} \quad (2)$$

The magnetic field of the transmitter solenoid is given by the following equation B. The resonant frequency of the nodes, so that the resonant coupling of the power transmission system works, must be the same F_r (3) at all nodes.

$$F_r = \frac{1}{2\pi\sqrt{LC}} \quad (3)$$

Another vital aspect is that the impedances of the two systems, whether transmitters or receivers, must be equal to achieve the highest possible transmission quality factor Z . To achieve this, the optimal resistance of the receiver's load must be calculated to optimize the transfer. We calculate the angular frequency ω , create a range of resistance values $R = [1, 1000000]$, and calculate the quality factor for each resistance Q (4). We then calculate the transfer efficiency for all transfer efficiency values μ_t (5) and find the value of R that maximizes power transfer efficiency.

$$Q = \frac{\omega L}{R_t + R} \quad (4)$$

$$\mu_t = \frac{RQ}{R_t + R} \quad (5)$$

The Friis transmission model and resonant coupling are used to calculate the received power as a function of distance. First, the wavelength λ , the coupling coefficient k , the quality factors of the transmitting and receiving nodes Q (4), the node gain G_t and G_r (6), the gain in decibels G_{dB} , the dispersion factor F_d (7), and η (H) (8) are calculated. The propagation losses are then obtained from the Friis equation F_{Friis} (9), and finally, the received power P_r (10) is determined for each distance.

$$G = 4\pi\mu A \quad (6)$$

$$F_d = \frac{1}{1 + (\frac{d}{10})^2} \quad (7)$$

$$H = \frac{k^2 Q_1 Q_2}{(1 + k^2 Q_1 Q_2)^2 F_d} \quad (8)$$

$$F_{Friis} = \left(\frac{G_t G_r \lambda}{4\pi d} \right)^2 \quad (9)$$

$$P_r = H F_{Friis} P_t \quad (10)$$

The other power the receiver receives is the parasitic power between the nodes. To do this, we calculate the coil area, the estimated residual mutual inductance $M_{parasitic}$ (11), the parasitic coupling coefficient $k_{parasitic}$ (12), and the parasitic capacitance as a cylindrical capacitor $C_{parasitic}$ (13). With all this, we calculate the parasitic power of the system $P_{parasitic}$ (14) and the residual capacitive power due to capacitive coupling $P_{capacitive}$ (15).

$$M_{parasitic} = \frac{\mu A}{d^3} \quad (11)$$

$$k_{parasitic} = \frac{M_{parasitic}}{\sqrt{L_1 L_2}} \quad (12)$$

$$C_{parasitic} = \frac{2\pi\epsilon r}{\log_{10}(\frac{d}{r})} \quad (13)$$

$$P_{parasitic} = k_{parasitic} P_t e^{\frac{-d}{10}} \quad (14)$$

$$P_{capacitive} = \frac{C_{parasitic} P_t \omega}{1 + (C_{parasitic} \omega)^2} \quad (15)$$

In this model, the attenuation of the residual power due to atmospheric absorption is estimated by calculating the attenuation coefficient α , as defined in (16), where $\text{imag}(\cdot)$ denotes the imaginary part of the complex propagation constant. The imaginary component is used to estimate the electromagnetic attenuation coefficient, which characterizes the exponential decay of the transmitted electromagnetic field as a function of propagation distance. The value 1.0006 corresponds to the relative permittivity adopted in the atmospheric propagation model under standard environmental conditions. This value was selected to represent the dielectric properties of air in the proposed attenuation model. The attenuated reflected power, $P_{reflexive}$, is then calculated using (17). Finally, the overall transmission losses are estimated using the standard power-loss model described in (18).

$$\alpha = \frac{4\pi}{\lambda} \text{imag}(\sqrt{1.0006}) \quad (16)$$

$$P_{reflexive} = P_t e^{-\alpha d} \quad (17)$$

$$P_{losses} = R_t + R_r \left(\frac{P_t^2}{R_t R_r} \right) \quad (18)$$

Therefore, at each point in the distance-based model, the total received power is $P_{total \text{ received}}$ (19).

$$P_{total \text{ received}} = P_t + P_{parasitic} + P_{capacitive} + P_{reflexive} - P_{losses} \quad (19)$$

G. Transmitter Node Operation

The transmitter node is based on the principle of a double-layer oscillator, as shown in Fig. 4. A DC power supply feeds the two parallel oscillating circuits, where the SRC5200 power transistors generate an oscillating signal to the primary coils coupled to the secondary coil.

The transistors T1 and T2 bases are directly connected to one end of the secondary coil L1. As a result, the transistors automatically operate at the resonant frequency of coil L1. The primary coils (Lp1, Lp2) and the secondary coil L1 are wound in the same direction. They are wound parallel in a 3" (7.5 cm) diameter PVC tube. Each has five turns of 9 AWG (2.9 mm) wire. The secondary coil L1 has approximately 800 turns of 25

AWG (0.45 mm) magnet wire in a 2" (3 cm) diameter PVC tube.

The transistors must have approximately the same characteristics to prevent excessive heating of one of the transistors.

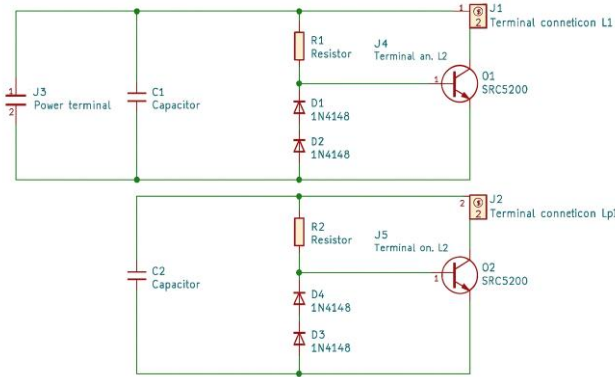


Fig. 4 Circuit diagram of the WPT transmitter node, including the power driver stage, resonant coupling network, and control circuitry.

The characteristics of the transmitter system. The diameter of the PVC pipe is 0.3 cm, the secondary coil has 733 turns, the length of the secondary coil is 44 cm, and the diameter of the toroid is 10 cm, regarding the physical characteristics. What encompasses the transmission characteristics is an inductance and capacitance of 0.001085 H and $5.56 \cdot 10^{-12}$ F, respectively. Finally, say that its resonant frequency is 2.049 GHz (radiative-equivalent analytical value).

H. Receiver Node Operation

The receiver node first acquires the field through a 10 cm diameter toroid in series with a 44 cm long coil with 733 turns and a tube diameter of 3 cm. It has the same transmission characteristics as the transmitter node, as its dimensions are the same.

This toroid and coil are connected to a rectification, filtering, and regulation stage using a Buck-Boost as shown in Fig. 5. During these stages, the energy received by the transmitter can be used to power devices such as those in a wireless sensor network, to charge a device, or to store it. In the rectification stage, the AC signal is converted to DC; in the filtering stage, the signal is made almost continuously using a capacitor; finally, in the regulation stage, the exact voltage values required by the device connected to the system are obtained.

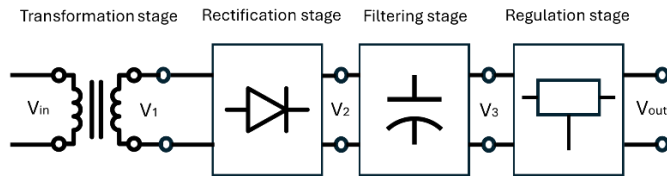


Fig. 5. Receiver rectification stages for the incoming WPT signal.

The receiver node circuit without the rectification stage is shown on Fig. 6. It shows that a diode bridge connects the coil

to a full-wave rectifier. After the diode bridge outputs, the filtering stage capacitor is connected in parallel to the system's load, which is, in this case, a resistor.

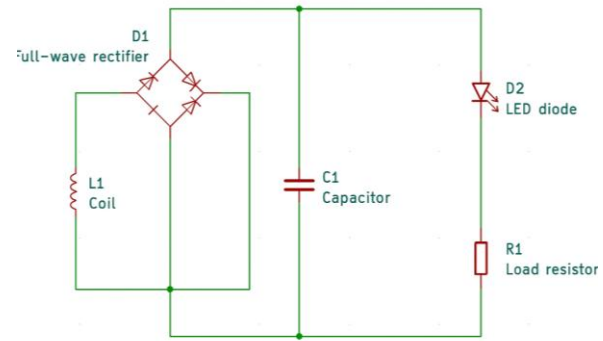


Fig. 6 Circuit diagram of the WPT receiver node, including the rectification, filtering, and load interface stages.

I. Software Developed for the Simulation of WPT in the Wireless Transmission System

This subsection proposes the design of the software used to simulate the behavior of the wireless transmission system based on its design parameters.

The simulator consists of a system of cascaded functions where the intrinsic characteristics are obtained using design parameters.

The algorithm aims to reduce the input parameters to a minimum, thus automating the process as much as possible. Therefore, once the design parameters are set, cascaded functions are called where the previous one and known data are the input parameters for the next one until the function that models the received power versus distance based on the Friis model is reached, as shown in Fig. 7.

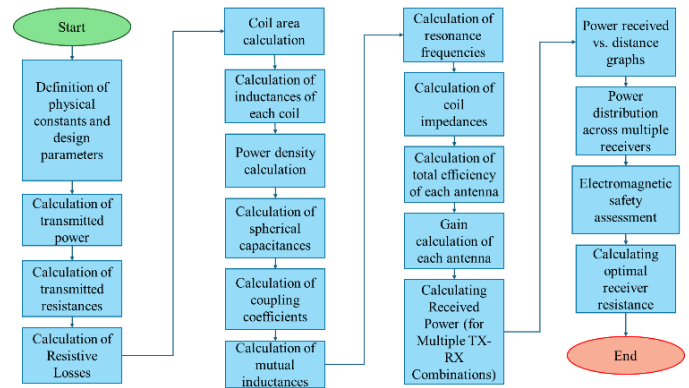


Fig. 7 Simulation software flowchart for the WPT-WSN system modeling and performance evaluation process.

J. Development of the Transmitter Node

Fig. 8 presents the structural architecture of the transmitter node and its main subsystems. The node integrates the resonant wireless power transmission stage, adaptive control logic, IoT communication subsystem, and environmental sensing components within a unified WPT-WSN platform.

The power transmission subsystem consists of the DC power source, oscillator, resonant matching stage, power amplifier,

and transmitter coil. The control and communication subsystem incorporates the MCU, MQTT/HTTP communication interface, local storage, and adaptive rule-based control mechanism used to regulate transmission power and system operation.

The environmental sensing subsystem integrates multiple sensors, including temperature, humidity, pressure, ambient light, air quality, and current monitoring sensors, enabling real-time environmental and operational monitoring.

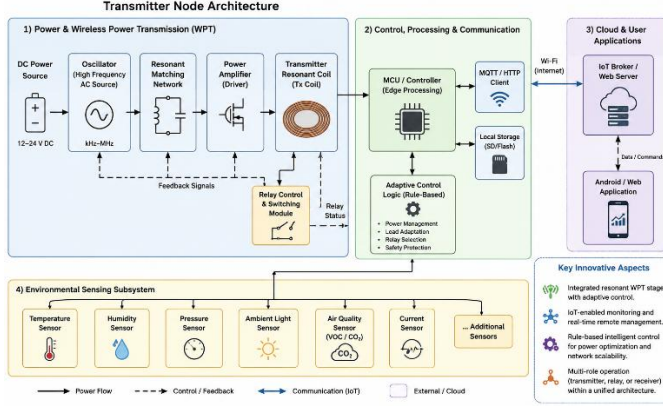


Fig. 8 Structural diagram of the transmitter node showing the integration of the resonant WPT stage, adaptive control module, IoT communication subsystem, and environmental sensing components.

IV. RESULTS

A. Simulation Results of the Wireless Transmission System

In this section, we will analyze the results obtained from the system simulation, including characterization and parameterization, simulations with different designs, and validation of the simulator with real measurements.

Validation of the simulation on real measurements

Fig. 9 shows the relationship between the power received at the receiving node and the distances obtained. The graph shows that the function has two sections. The first is at short distances, where transmission behaves as inductive coupling. This has an asymptotic trend concerning very short distances. On the other hand, in the second section, the power value remains constant over the distance.

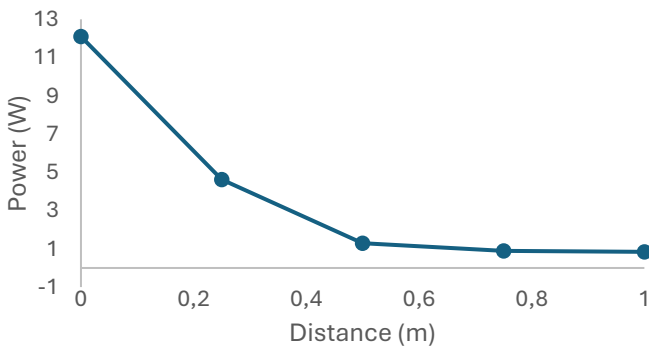


Fig. 9 Measured received power at the receiver node as a function of distance.

Fig. 10 shows the simulated ratio of received power to distance. As we can see, the actual measurements in Fig. 9 and the simulated measurements in Fig. 10 give the same result in both sections of the received power versus distance function. This means that the simulator obtains the exact WPT measurements as in the real environment using only the system design parameters. This is very useful for analyzing system behavior with different design parameters.

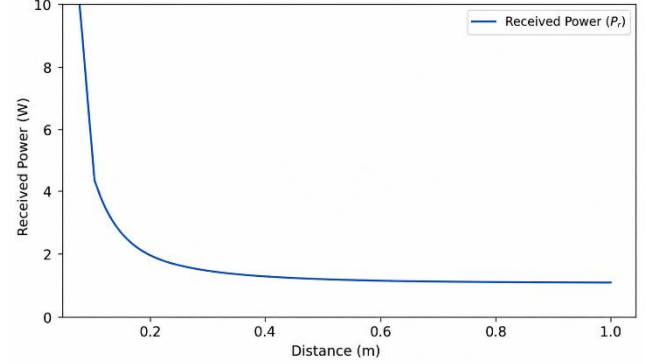


Fig. 10 Simulated received power at the receiver node as a function of distance.

System parameterization and modeling

Fig. 11 shows how the different characteristics of the transmitter system correlate with each other. All system power parameters, such as current, voltage, power, and transmission resistance, correlate 1. The magnetic field, optimal resistance, and quality factor correlate significantly with the power parameters. We can then see that design parameters such as the number of turns, solenoid length, sphere radius, and coil radius are all related. Design parameters significantly correlate with resonant frequency, gain, magnetic field, capacitance, mutual inductance, and quality factor.

Some of the intrinsic characteristics of the system are correlated. Capacitance and inductance are significantly correlated, while the quality factor is highly correlated with inductance, optimal resistance, gain, and resonant frequency.

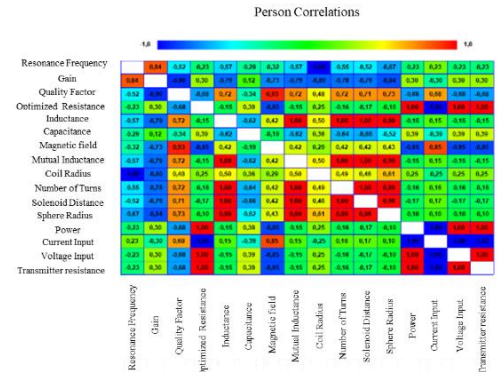


Fig. 11 Pearson correlation heatmap of transmitter node system parameters.

Transmission Through Relay and Optimal-Load Conditions

Fig. 12 compares the received power as a function of distance under three operating conditions: relay inductive operation,

relay resonant operation, and optimal-load operation. In the relay inductive case, the receiving node acts as an intermediate node that retransmits the energy received from the transmitter toward a second receiver under strong inductive coupling conditions. This configuration provides the highest received power in the short-distance region.

In the relay resonant case, the intermediate node retransmits the energy associated with the reactive/resonant component of the received signal. As shown in Fig. 12, this configuration presents lower received power than the inductive relay case, especially at short distances. This confirms that the transmission mode of the intermediate node has a significant impact on the energy available at the final receiver.

The optimal-load condition corresponds to the receiver's resistance that maximizes the quality factor and improves power transfer performance. In this case, the optimal resistance is 32.47 Ω , resulting in improved received power compared with the resonant relay case. Overall, the curves show a rapid variation at short distances followed by a horizontal asymptotic trend as distance increases. This behavior indicates that most of the useful variation occurs in the short-distance region, while the received power tends to stabilize at longer distances.

These results demonstrate that network-level wireless energy transmission is feasible using transmitter, relay, and receiver nodes. Therefore, the design of the relay operation mode and load conditions is essential to regulate the available power at the final node. In a larger WPT-WSN deployment, this behavior supports the need for adaptive control and monitoring interfaces capable of selecting the most suitable transmission mode according to the energy requirements of the receiving nodes.

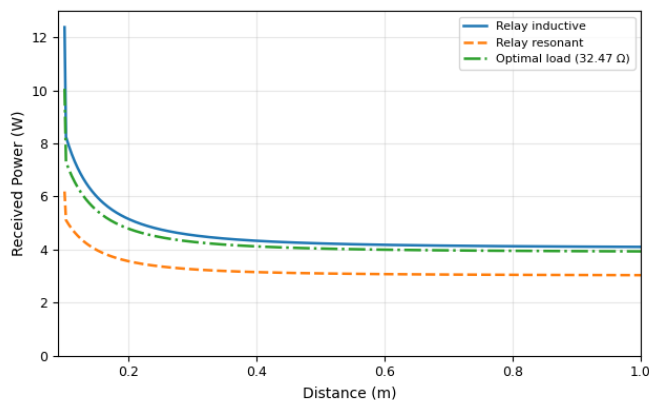


Fig. 12 Comparative received power under relay inductive, relay resonant, and optimal-load operating conditions in the short-distance region.

Fig. 13 shows the relationship between the optimal resistance of 32.47 ohms in the receiver load and the quality factor. It shows that at an optimal resistance of 32.47 ohms, the quality factor is 215. This graph on a logarithmic scale shows that finding optimal resistance with the highest possible transmission quality factor is crucial to increasing system

efficiency.

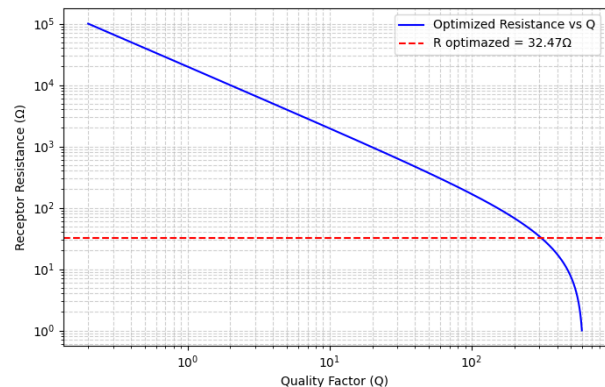


Fig. 13 Relationship between optimal resistance and system quality factors.

Safety assessment of the system's exposure to EMF fields

According to the International Telecommunication Union regulations, a threshold is established regarding the power density absorption caused by electromagnetic fields [22]. This threshold is set between 2 and 10 W/m², with 10 for specialized users and 2 for ordinary citizens. Table III shows the behavior of the transmitter in terms of power density versus distance. It shows that starting at 0.5 m, it is safe not to absorb too much power.

Electromagnetic exposure and safety limits were considered when defining the practical operating range of the proposed system. It is important to note that the electromagnetic exposure levels discussed in this section correspond to the practical operating regime of the system, which lies in the kHz–MHz frequency range for inductive coupling, as previously clarified in subsection E. The GHz-range values derived in the analytical model are associated only with radiative-equivalent modes and do not represent the dominant operating frequency of the implemented system. This distinction ensures consistency between the safety analysis and the physical operation of the proposed WPT architecture. The experimental tests were conducted at controlled power levels and distances consistent with low-power WPT laboratory operation. The architecture includes adaptive transmission control that allows reduction of transmitted power when required by operating conditions. The intended deployment scenarios correspond to remote sensing and infrastructure monitoring environments, where controlled positioning and regulated power levels can be ensured. These constraints define the practical operating envelope of the system under electromagnetic exposure and regulatory compatibility considerations.

TABLE III
POWER DENSITY IS RELATIVE TO THE DISTANCE FROM THE TRANSMITTING NODE WITH A POWER OF 12 W.

Distance (m)	Power Density (W/m ²)
0.01	5172.54
0.5	2.07
1	0.52

B. WPT Measurements of the Nodes

This section analyzes the results obtained from the transmission measurements at the receiving node.

Experimental Setup and Measurement Methodology

To ensure reproducibility and measurement rigor, the experimental validation of the proposed WPT-WSN system was conducted under controlled conditions with explicitly defined geometric, electrical, and instrumentation parameters.

The transmitter and receiver coils were constructed using enameled copper wire with an average winding tolerance below $\pm 3\%$ in the number of turns and coil diameter. Coil separation distance was measured using a laser distance meter with ± 2 mm accuracy. During measurements, coils were positioned in fixed coaxial alignment, with angular misalignment kept below approximately 3 degrees using a mechanical support structure.

Electrical measurements were performed using calibrated digital multimeters and a digital oscilloscope for waveform verification and RMS estimation. The input electrical power was measured directly at the input terminals of the buck-boost converter stage, allowing consistent estimation of the effective transmitted power. The received power was computed from measured load voltage and load resistance values at the receiver side.

All instruments used were factory calibrated. Measurement uncertainty for reported power values is estimated to be below 5% based on instrument specifications and measurement dispersion.

Efficiency in this work is defined as end-to-end power efficiency, computed as the ratio between received load power and measured input power at the buck-boost input terminals. Voltage trends are shown in some figures only to illustrate distance behavior, while efficiency values are always derived from power measurements to avoid misinterpretation in WPT evaluation.

Received voltage results concerning distance.

As shown in Fig. 14, the received voltage at the receiver was measured at different distances above the transmitter with and without floating masses between the transmitter and receiver. It shows a higher received voltage without floating masses, with a difference in the constant measurement step of 0.7 volts compared to those with floating masses. The measurements remain constant beyond 3 meters. The voltage concerning distance was measured from the most significant distance to the smallest and vice versa, with no changes in the results.

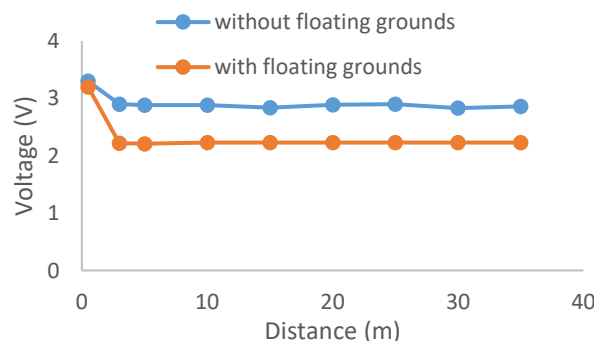


Fig. 14 Received voltage versus distance at the receiving node.

Magnetic and electric field density versus distance

Fig. 15 shows the electric and magnetic field density produced by the transmitting node versus distance. It can be seen that at distances greater than one meter, the density is almost minimal. This suggests that the inductive coupling phase ends at distances of 1 meter. At greater distances, the received voltage is already resonant coupling of the reactive portion of the electromagnetic field.

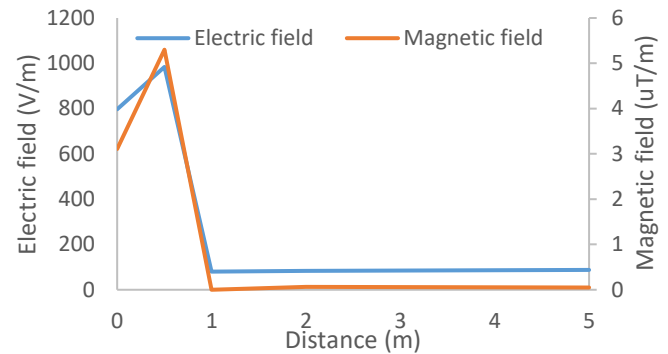


Fig. 15 Measured electric and magnetic field strength versus distance.

Effect of using an omnidirectional antenna: received voltage relative to the receiver's height relative to the transmitter.

Fig. 16 shows that when using an omnidirectional antenna, the voltage behavior relative to height is parabolic. The effect of the function at the parabolic level has an $R^2 = 0.96$, which is significant. Therefore, properly orienting the antennas or nodes is necessary to improve system efficiency.

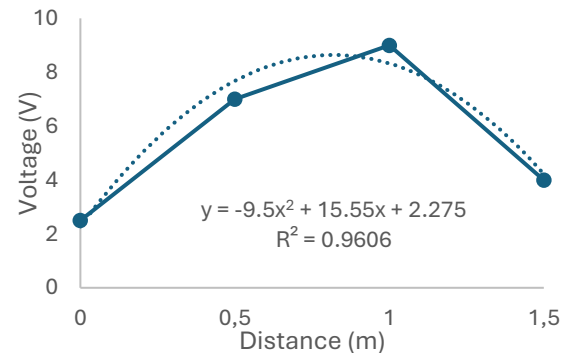


Fig. 16 Received voltage relative to height with an omnidirectional antenna.

Distance-Efficiency Behavior and Operating Regimes

Fig. 17 shows the system behavior with distance using the ratio between received and transmitted voltages as an indicator of transfer degradation. This voltage ratio is used only as a trend metric to illustrate how the received signal level evolves with distance under different grounding conditions (with and without floating masses).

It is important to clarify that this voltage-based ratio does not represent the true end-to-end power efficiency of the WPT system. The actual efficiency values reported in this work are computed from measured input and output power, as defined in the experimental methodology section.

The results show that at distances around 0.5 m, the voltage ratio indicator is approximately 20%. At larger distances, the indicator remains around 20% without floating masses and about 15% with floating masses, reflecting additional parasitic coupling and grounding effects rather than constant power-transfer efficiency. These curves therefore illustrate relative attenuation behavior rather than absolute efficiency.

These performance values were obtained under controlled alignment and load conditions under laboratory alignment conditions and fixed load impedance, with coaxial coil positioning and fixed load parameters as described in the experimental methodology subsection. Variations in angular alignment, coil displacement, or load impedance produce measurable efficiency deviations, as expected in resonant inductive WPT systems. Therefore, the reported distance and efficiency values represent validated reference conditions rather than worst-case deployment scenarios.

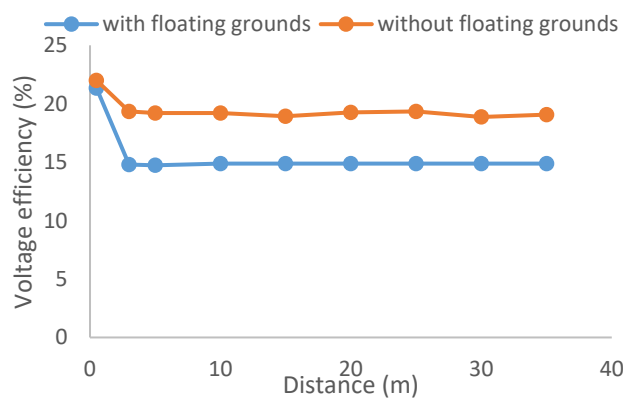


Fig. 17 Voltage ratio indicator versus distance under different grounding conditions.

C. Comparative Analysis of Existing WPT Systems

To properly position the proposed system with respect to prior work, it is important to note that wireless power transmission (WPT) solutions operate under different physical principles, power levels, and application domains. For this reason, comparisons must be interpreted within their corresponding technological and operational class rather than as a direct performance ranking.

Table IV summarizes representative WPT approaches from the literature and classifies them according to technology, scale, and application domain. It includes resonant inductive systems, RF-based distributed powering approaches, and high-voltage Tesla-coil-based transmission systems [23].

Classical resonant inductive WPT systems such as Kurs et al. [7] demonstrated efficient short-range transfer, while Minfan Fu [8] introduced adaptive load matching to improve efficiency. Other works focus on coil optimization, misalignment sensitivity, and weak-coupling efficiency modeling [9][13]. RF-based distributed and beamforming-powered IoT approaches have also been explored for low-power sensor operation [14], [16]. High-power Tesla-coil-based systems such as [9] represent a different operating class oriented toward very long distances and high voltages.

As shown in Table IV, these systems address different

objectives and constraints. Therefore, comparisons are made at technology and application-domain level rather than as uniform numerical benchmarks. In contrast to high-voltage or RF-harvesting approaches, our work targets IoT-oriented WSN deployment using resonant inductive multi-stage coupling, with integrated monitoring, adaptive control, and multi-role nodes. The proposed system is positioned within the class of medium-power resonant WPT architectures for sensor networks rather than extreme-range or high-voltage transmission systems.

TABLE IV
REPRESENTATIVE WPT SYSTEMS ACROSS DIFFERENT OPERATING DOMAINS

Author / Year	Technology	Power	Distance (m)	Efficiency (%)	Application Domain
Kurs et al. (MIT, 2007)	Strong MRI (2 large coils)	60 W	~2.0	~40%	Laboratory resonant WPT demonstration
Minfan Fu (2015)	Resonant WPT with DC-DC buck/boost control	40 W	Variable	Up to 70%	Regulated resonant charger systems
Xin Jin (2023)	Multilayer Tesla coil SWPT	5,000 W	5,000 m	~87%	High-voltage long-range transmission
Pusparini D. Aziz (2016)	Tesla coil inductive coupling study	Not reported	0.1	comparative	Coil design optimization study
Fuxin Liu (2017)	Magnetically coupled resonance imaging (modeling)	Simulated	—	—	Misalignment and coupling modeling
Yiming Zhang (2014)	MRI, efficiency theory vs. k	Simulated	—	—	Weak-coupling efficiency theory
K.W. Choi (2018)	RF, Distributed Architecture (Antennas)	mW	~1.0	—	RF-powered IoT distribution
J. Janhunen (2018)	RF, Harvesting + directional antennas Inductive	10.7 mW	~1.0	Enough for the sensor	RF-powered sensor nodes
This article (2025)	Multi-stage resonant coupling	15 watts	35 m	~25 %	IoT WSN WPT

V. CONCLUSION AND FUTURE WORK

The development of an intelligent wireless power transmission (WPT) system demonstrates the viability of wirelessly supplying energy to IoT devices in remote or hard-to-access environments [24]. The proposed network achieves efficient energy transfer across considerable distances through resonant inductive coupling and system optimization without relying on traditional wired infrastructures or batteries [25]. The experimental results, validated against real measurements, confirm that the designed simulator accurately predicts system behavior, providing a powerful tool for future design iterations

and system scaling. Specifically, the system can transmit energy up to 35 meters with an efficiency of 25%. The proposed system advances autonomous WSN infrastructures powered by WPT and enables future research in adaptive energy routing and scalable IoT deployment [26].

As future work, we want to study the possibility of using systems like the transmitter in its inductive coupling phase to study the behavior of marine phenomena in response to the electromagnetic fields produced. More specifically, the possibility of removing biological fouling from surfaces in contact with the sea was discussed [27].

Another interesting aspect is the generation of alternating fields in the transmitter due to the device's rotation. This phenomenon would be studied using a rotating surface, such as a potter's wheel, to see if any alternating effects would occur in the rotating receiver [28].

Finally, it is interesting to test the scalability of transmission links over very long distances and to be able to create more powerful prototypes to transmit over greater distances and thus offer power coverage over very long distances.

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