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Original Article

Design and Implementation of a Wireless Power Transfer (WPT) System for Autonomous Power Supply to Remote Weather Stations Using Yagi Antennas at 2.45 GHz

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Abstract - *This article presents the design and implementation of a long-distance Wireless Power Transfer (WPT) system operating in the 2.45 GHz ISM band, which allows continuous or intermittent power transmission via highly directional microwave links. The transmitter subsystem consists of an ADF4351 wideband frequency synthesizer tuned to 2.45 GHz, a medium-gain amplifier (SPF5189Z), and an RF2126 power amplifier, radiating through a high-gain Yagi antenna optimized in 4nec2, with the aim of transmitting sufficient and permitted power up to a maximum of 1 km for the constant or intermittent power supply of low-power electronic devices. At the receiving end, a tuned Yagi antenna captures the RF energy and conducts it to a rectenna composed of Schottky diodes, low-pass filters, and impedance coupling. The rectified energy is stored in supercapacitors and regulated by ultra-low start-up DC-DC converters (LTC3108) to supply power to a modern embedded weather system with a maximum consumption of 15mA. This architecture demonstrates WPT's technical feasibility and sustainability in the far field for low-power applications in remote areas, reducing dependence on batteries and solar panels, minimizing maintenance, and increasing operational reliability in hostile or isolated environments.*

Keywords - *Wireless Power Transfer (WPT), Rectenna, Yagi antenna, Energy harvesting, Remote weather stations.*

1. Introduction

Environmental monitoring systems, such as autonomous weather stations, are traditionally powered by rechargeable batteries or photovoltaic systems (solar panels). Although these solutions are widely implemented, they have significant technical disadvantages: electrochemical degradation of batteries, intermittent supply in low irradiance conditions, and the need for periodic maintenance, which limits their reliability in remote or difficult-to-access environments.

Faced with these limitations, an alternative based on Wireless Power Transfer or Far Field Wireless Power Transfer (WPT) is proposed, using microwave links in the 2.45 GHz ISM band for long-distance power supply. This approach allows power to be transmitted continuously or intermittently via electromagnetic radiation, with high directivity and without physical contact, eliminating the use of accumulators such as batteries and reducing human intervention. The transmitter system consists of an ADF4351 synthesizer, configured to emit a stable carrier signal at 2.45 GHz with an adjustable output power of up to +5 dBm. Since this power is insufficient for long-range links, an amplification stage is implemented: an SPF5189Z medium-gain driver and a power amplifier, with a delivery capacity of up to +36 dBm (4 W). The signal is radiated by a high-gain Yagi antenna between 14-18 dBi, whose design was optimized using electromagnetic simulations in 4nec2, with special attention to directivity, impedance, and optimal Standing Wave Ratio (SWR) to reduce delivered power losses. At the receiving end, a Yagi antenna tuned to 2.45 GHz captures the radiated energy and conducts it to a high-frequency rectifier circuit (rectenna), based on Schottky diodes, low-pass filters, and impedance matching. The rectified energy is stored in a supercapacitor and regulated by very low start-up DC-DC converters (such as the LTC3108), capable of supplying continuous power to an embedded weather system that includes temperature, humidity, pressure, and wind speed sensors. This design approach demonstrates the technical feasibility of far-field WPT for low-power applications, enabling remote weather stations to be powered sustainably, without local electrical infrastructure, with low maintenance and high operational reliability in hostile or isolated environments.

This document is divided as follows: The Related Works are presented in Section 2. Section 3 describes the Methodology. Section IV presents the development of the system. Section V presents the tests and results obtained. Finally, Section VI presents the conclusions of the research.

2. Related Works

The growing interest in low-power autonomous devices has driven significant research into Radio Frequency (RF) energy harvesting systems, where, in [1], the rectifier plays a central role in converting ambient RF signals into usable DC power. Recent work has focused on improving rectifier topologies for 2.45 GHz applications, with the aim of optimizing both output voltage and Power Conversion Efficiency (PCE). A notable study proposes a novel rectifier architecture based on the HSMS-285C Schottky diode, showing superior performance compared to classic Dickson and Cockcroft–Walton configurations. The design was evaluated over an input power range of –20 dBm to 35 dBm, targeting compatibility with energy levels present in ambient Wi-Fi signals. Simulation and experimental validation results demonstrated that the proposed rectifier achieved up to 43% and 47% improvement in conversion efficiency compared to the Dickson and Cockcroft–Walton models. Furthermore, the manufactured prototypes confirmed the simulated results, validating the reliability of the design under real RF energy harvesting conditions. RF energy harvesting is a promising alternative for powering wireless devices, although it is limited by low power density, efficiency, and gain.

In [2], to overcome these limitations, the use of Koch snowflake-type fractal antennas with circular polarization has been proposed, combined with Jerusalem cross-type Frequency Selective Surfaces (FSS) and Schottky diode-based rectifiers, operating at 5.8 GHz. The design, optimized using the SGO algorithm and simulated in ANSYS HFSS, demonstrated high performance, with a gain of 9.96 dB, S11 of –33 dB, and VSWR of 1.01. These results position this architecture as an effective solution for improving collection efficiency in autonomous wireless energy harvesting systems. Similarly, the study conducted in [3] seeks to respond to the demand for autonomous IoT devices and has developed a dual-band rectenna with dual polarization, operating at 3.6 GHz (linear) and 5.8 GHz (circular).

The antenna achieves gains of 4.85 dBi and 6.75 dBic, with good impedance bandwidths, allowing efficient harvesting at both frequencies. The integrated rectifier achieves up to 65.5% and 44% efficiencies in their respective bands, maintaining good performance over wide input ranges. This design improves RF energy harvesting and enables sustainable, maintenance-free IoT applications. In [4], to overcome the efficiency limitations of multistage rectifiers, an RF energy harvester has been proposed that combines an optimized rectifier with a low-frequency cascade charge pump. The system operates in burst charging mode, which reduces the charging effect and improves sensitivity. An output of 1 V was achieved with a sensitivity of –31 dBm and a conversion efficiency of 31.3% at –25 dBm, using 55 nm CMOS technology. These results make it ideal for powering low-power electronics in energy-constrained environments. In [5], a high-gain rectifying antenna has been developed for wireless power transfer applications in the 1.8 and 2.1 GHz bands, using a compact butterfly dipole antenna coupled to a Frequency-Selective Surface (FSS) reflector. The inclusion of the FSS reflector significantly improved performance, achieving gains of 8.59 dBi and 6.69 dBi, with a reflection coefficient of up to –44.19 dB and a bandwidth of 0.45 GHz, representing an FBW of 23.26%. The system includes a high-efficiency rectifier that achieves a conversion of 63.2% at 1.8 GHz and 57.4% at 2.1 GHz with 10 dBm inputs, maintaining efficiencies above 50% over wide input ranges.

These results position this architecture as an effective solution for WPT systems focused on mobile or IoT networks, where high efficiency and selectivity in specific bands are required. For [6], sustainable and self-powered solutions are required to reduce environmental impact. In this context, a compact, flexible, and cost-effective rectenna made from biodegradable materials such as natural rubber with rice husk ash has been proposed. It is designed to operate in the 2.45 GHz ISM band and the low-mid 5G band, and its tree-like fractal geometry allows for size reduction without compromising performance. Both the antenna and the rectifier were integrated on flexible substrates, facilitating their implementation in portable or ultra-low-power IoT devices. The numerical results, obtained using the Finite Difference Time Domain (FDTD) method, show high agreement with experimental data, validating their applicability in ecological and autonomous energy solutions for next-generation portable electronics. In [7], a detailed numerical analysis of a full-wave bridge rectifier at 2.45 GHz for RF energy harvesting under low-power conditions, highlighting the evaluation of HSMS2850 and SMS7630 Schottky diodes, which achieved Power Conversion Efficiencies (PCE) of up to 57% and 33% at input powers of –5 dBm and –15 dBm. A guide was also proposed to establish a standardized Figure of Merit (FOM) for rectennas, supported by data science techniques, with the aim of facilitating comparisons between architectures.

In addition, rectifier variants were developed and simulated, including dual-voltage topologies and CMOS designs, which achieved PCEs of up to 66% and 69% for low-power signals. The design of a PCB for experimental measurements allows the numerical models to be validated, laying the foundations for optimized rectennas in energy-limited applications such as wireless sensors or self-powered IoT devices. This study is also compared with [8], where a miniaturized rectenna was developed to power Implantable Medical Devices (IMDs) in the 2.4 GHz ISM band, prioritizing efficiency, biocompatibility, and electromagnetic safety.

Using a human tissue phantom model, its performance and compliance with SAR limits were validated. The rectifier, designed in ADS using harmonic analysis, achieved an efficiency of 88.65% under physiological conditions. This design demonstrates the feasibility of powering IMDs wirelessly, safely, and efficiently, advancing the development of autonomous biomedical devices. Similarly, in [9], a Multi-Sector Planar Rectenna System (MLRS) was designed for efficient wireless charging of IoT nodes through microwave energy transfer. The array integrates four radially distributed EFRA antennas and a central BSRA antenna, all without the need for DC combination networks, which reduces insertion losses and allows for a compact design. The system achieves omnidirectional reception with up to 1400 mV output voltage in different orientations, which is suitable for powering low-power IoT sensors. Experimental tests validated its effectiveness, positioning it as a robust solution for WPT in smart environments.

Also in [10], a Dual-Band Reconfigurable Polarization Rectenna (DBPR) is proposed for RF Energy Harvesting (RFEH) systems, operating at 2.4 GHz and 5.8 GHz. The antenna uses short-circuit probes to activate TM10 and TM30 resonant modes, along with a branch line coupler and six PIN diodes that allow signals with linear and circular polarization (left or right) to be received by switching control. The system achieves gains of 5.71 dBi and 6.9 dBi, and maximum conversion efficiencies of 54% and 44.4% in the respective bands. This design facilitates efficient energy harvesting from multiple polarizations, improving the robustness and adaptability of the RFEH system for variable environments and multi-service IoT applications.

Similarly, in terms of antenna design in [11], a 3D cubic antenna derived from the Quasi-Yagi (QYA) structure is proposed, optimized for Radio Frequency Energy Harvesting (RFEH) and Wireless Power Transfer (WPT) at 915 MHz. Unlike traditional 2D antennas, the three-dimensional design allows multidirectional reception, increasing the efficiency of capturing both environmental and dedicated sources. Through simulations in CST Studio and validations with equipment such as the FieldFox N9912A, a gain of 11.43 dBi, a return loss of −45.61 dB, and a bandwidth of 25 MHz were obtained.

The design was improved by using Generative Adversarial Networks (GAN) to optimize parameters without requiring large volumes of experimental data. The antenna was integrated with an impedance matching network and evaluated with a 1.5 kΩ load, demonstrating practical efficiency in real-world scenarios.

This architecture represents a versatile and efficient solution for RFEH systems, adaptable to multiple IoT and ambient energy applications. Finally, it can be applied in other sectors such as medicine, as in [12], where the objective is to optimize the efficiency of Wireless Power Transfer (WPT) in Implantable Medical Devices (IMDs), presenting a hybrid architecture based on a receiving rectenna composed of a heterostructure Magnetoelectric (ME) antenna and an RF inductive coil. This configuration operates at low frequency (54 kHz) and combines a ME antenna measuring 30 × 10 × 0.456 mm³ with a 60-turn coil measuring 30 × 12 × 3 mm³, enabling efficient and compact coupling in biomedical applications. Theoretical and experimental analyses include simulation of the Specific Absorption Rate (SAR), complying with safety regulations. A PTE of 2.82% was achieved at 15mm between the transmitting coil and the receiving antenna, significantly exceeding the performance of individual configurations. This hybrid approach demonstrates feasibility for efficiently and safely powering IMDs, opening new possibilities for battery-free biomedical technologies.

3. Methodology

This article presents the design, simulation, and implementation of a Wireless Power Transfer (WPT) system focused on supplying remote power to low-consumption weather stations using directed radiation in the 2.45 GHz ISM band.

The Methodology was divided into five technical stages: design, simulation, construction, integration, and experimental validation, considering both the radio frequency link and the rectification and energy management system. In addition to the structure, some of the main features of the system and materials used for post-simulation development and implementation are shown.

- Far Field WPT wireless power transfer.
- Operating frequency at 2.45GHz.
- ADF4351 signal generator controlled with ESP32.
- Intermediate preamplification stage and power amplifier to the Tx Yagi 14-18dbi horizontal polarization transmitter antenna at 1W, and Rx Yagi receiver equal to the transmitter.
- A receiver system based on high-frequency diodes and RF filters, a low-voltage start-up controller from 20mV, and a supercapacitor for energy storage.
- Intermittent and intelligent consumption of 10mW on average with an optimized duty cycle.
- Operating distance of up to 0.75km in an open field.
- Simulations in Radio Mobile, Friis equation, and 4nec2.
- Unidirectional link type respecting maximum and minimum antenna heights according to RadioMobile.

Table 1. Components to be used

Type	Model	Quantity
Microcontroller	ESP32	2
Signal generator	ADF4351	1
Yagi antennas	14 dbi 1W	2
Medium-gain amplifier	SPF5189Z	1
Power amplifier	RF2126	1
Connectors	SMA	2
PCB with integrated circuit	LTC3108	1
Capacitors	0.01F	1

To better understand how the system works, it is divided into two stages. The first stage involves the design and development of the transmitter, which includes the equipment included in Tx for subsequent signal enablement capable of performing the respective functions. The second stage involves designing and developing the receiver Rx, such as the receiving antenna, rectenna, and energy storage for powering low-energy electronic cards in meteorological modules. For the first stage, the ADF4351 module is used in the design of the transmitter system. This is a signal generator capable of transmitting from 35 MHz to 4.4 GHz. It will be configured by an ESP32 microcontroller via an SPI interface, allowing frequency selection and transmission enablement, using the 2.45 GHz frequency within the permitted ISM band.

As for the amplification of the generated 5dbm signal, it is amplified in two stages, the first by the SPF5189Z (LNA) module, which is a driver that will provide a gain of 19 to 22db and good noise stability, being a class A device (full 360° amplification throughout the input signal cycle) with the purpose of raising the main signal from 5dbm to 15dbm without distortion. The second stage is a final power amplification, with the RF2126 module responsible for amplifying the preamplified signal to an output power of 28 to 30 dBm, equivalent to 0. 6-1W. The transmitting antenna will be a Yagi antenna of up to 14dbi designed in 4nec2. It will consist of 6 to 7 elements with horizontal polarization and will serve to concentrate the energy beam towards the remote station with a narrow directional pattern. It will be adapted using a 50-ohm RG-58 coaxial SMA connector. As for the second stage, the receiver design is similar to the transmitter's Yagi antenna, with the function of capturing the incident electromagnetic energy from the directional beam emitted by Tx. This stage also has a rectenna rectifier module that uses components such as low-threshold, high-efficiency Schottky diodes, an LC network, and a low-pass filter with inductors and capacitors, with the function of converting the received signal to a rectified voltage of 0. 3Vdc. Likewise, the LTC3108 integrated circuit acts as a low-voltage step-up converter capable of operating from 20mV and 1uW, with the function of collecting the DC energy obtained in the rectification stage and raising it to a useful voltage of 3. 3V, together with a supercapacitor, stores the energy necessary for the direct power supply of the weather station modules. A block diagram is provided to understand the development of the proposed stages, following a design and development structure for each one to achieve its function (see Figure 1).

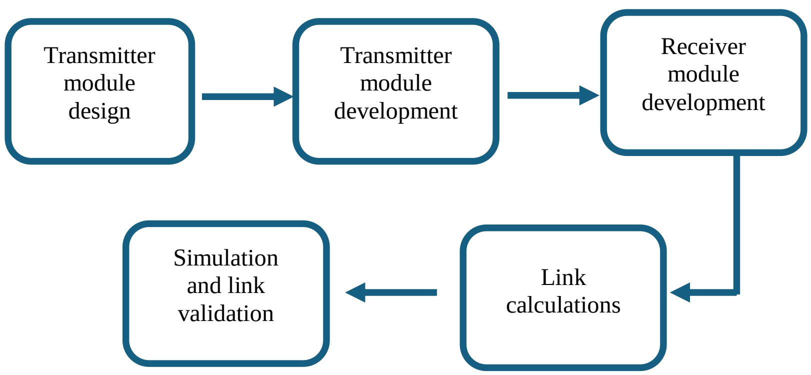


Fig. 1 System block diagram

4. Developed System

The system is based on power generation and transmission through a transmitter based on the ADF4351 synthesizer, which allows RF signals to be generated from 35 MHz to 4.4 GHz. This design was configured to operate at 2.45 GHz, within the ISM band.

The ADF4351 is controlled via a Serial Peripheral Interface (SPI) by an ESP32 microcontroller. To increase the signal power level, an SPF5189Z driver amplifier is used, with a gain of approximately 20 dB. This boosts the signal from 5 dBm (3.16 mW) to 25 dBm (316 mW). Subsequently, an RF2126 class AB power amplifier increases the signal to 30 dBm (1 W) under ideal conditions (see Figure 2). However, due to legal restrictions in Peru (EIRP ≤ 36 dBm), the output of the RF2126 is limited to +22 dBm (158 mW), in conjunction with a 14 dBi directional Yagi antenna.

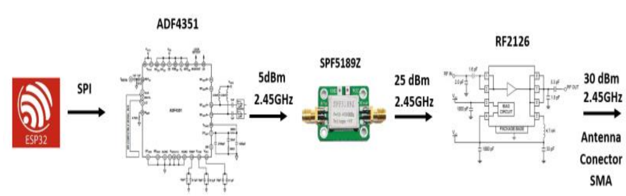


Fig. 2 Power transmission and control from Tx

According to the Equivalent Isotropic Radiated Power (EIRP), the permitted 4W in TX must not be exceeded. The transmission target is 1 km away. Depending on the terrain, propagation modeling is performed in free space, where the energy is transmitted at a free distance of 750 m, and the remainder with obstacles from the same terrain. The Friss equation is used to estimate the received power, where Pt is 22 dbm, Gt 14dBi, in Tx and Rx, in Lp at 2.45 GHz and 32.44

as a constant for the frequency used (see Figure 3). According to the rectification and conversion of energy in the rectenna, the receiver system uses a 14dBi Yagi antenna, aligned with the transmitter. The signal is directed to a Schottky diode-based rectifier circuit using SMS7630 diodes, an LC matching network, and a low-pass filter to obtain useful DC rectification.

The LTC3108 integrated circuit will be used for energy storage and management, since the rectified voltage is not sufficient to directly power the digital circuits of the weather module. This integrated circuit is used as an ultra-low voltage step-up converter, as it can operate from 20mV with a 1:100 transformer.

Depending on the energy stored in a 0.01F supercapacitor connected to the VSTORE pin, the regulated output at VOUT of 3.3V is used to power the weather module. This power supply will be intermittent, as a constant power supply would not be successful. A 1:100 transformer will be used to ensure the integrated circuit starts up properly.

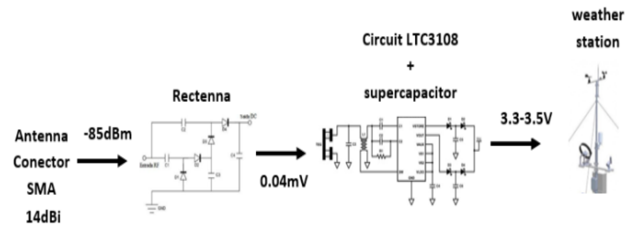


Fig. 3 Signal receiver, receiver, and voltage amplification

Regarding the antenna design, initial calculations were made that do not exceed the legal restrictions in Peru, EIRP ≤ 36 dBm. For the simulation in 4nec2, the following respective values are obtained (see Figure 4).

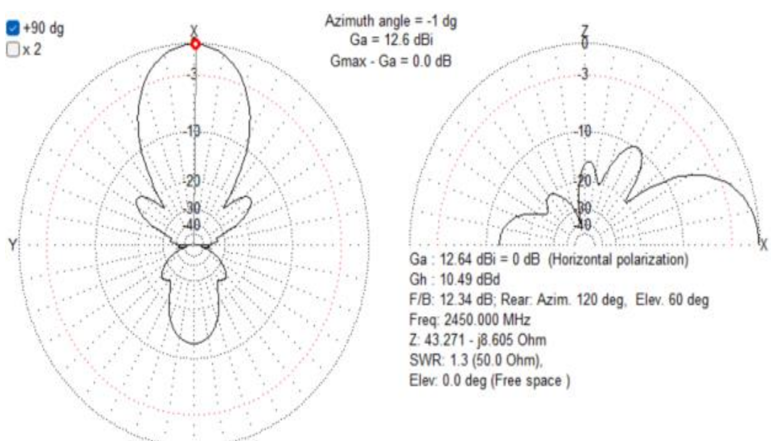
No.	X1(m)	Y1(m)	Z1(m)	X2(m)	Y2(m)	Z2(m)	R(mm)	Seg.
1	0.0	-0.028	0.2	0.0	0.028	0.2	2.0	10
2	0.032	-0.026	0.2	0.032	0.026	0.2	2.0	10
3	0.056	-0.023	0.2	0.056	0.023	0.2	2.0	10
4	0.088	-0.022	0.2	0.088	0.022	0.2	2.0	10
5	0.12	-0.022	0.2	0.12	0.022	0.2	2.0	10
6	0.152	-0.022	0.2	0.152	0.022	0.2	2.0	10
7	0.184	-0.022	0.2	0.184	0.022	0.2	2.0	10
8	0.216	-0.022	0.2	0.216	0.022	0.2	2.0	10
9	0.248	-0.022	0.2	0.248	0.022	0.2	2.0	10

Fig. 4 Data from 4nec2 regarding reflector, dipole, and director dimensions for simulation

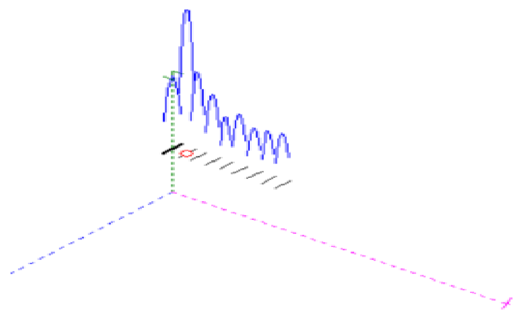
Based on the dimensions generated for the reflector, dipole, and directors, the dipole was placed in the second position to obtain an isotropic dBi and achieve a practical design with easy measurement, obtaining 12. 6 dBi of absolute gain with respect to isotropic, 10.5 dBd gain referred to a dipole in horizontal linear polarization, and an SWR50 of 1.26, which indicates that the impedance is excellent, maximizing the efficiency of power transfer from the transmitter to the receiver (see Figure 5). The field diagram shows the antenna radiation, displaying the corresponding impedance and gain values suitable for the required power transmission (see Figure 6).

F (MHz)	R (Ohm)	jX (Ohm)	SWR 50	Gh dBd	Ga dBi	F/B dB
2450.0	43.27	-8.605	1.26	10.49	12.64	12.34

Fig. 5 Impedance results, antenna gain from 4nec2



(a)



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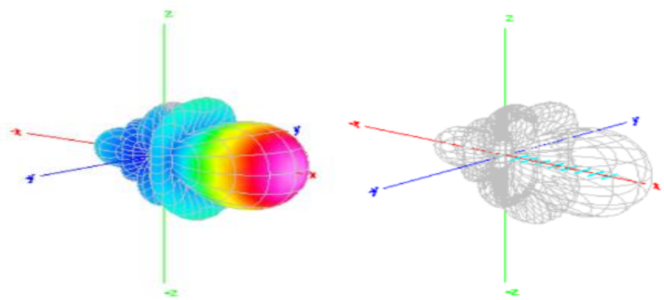

(c)

Fig. 6 Radiation field and spectrum

Based on the gain, the EIRP power for the TX antenna of 12.6dBi will use an output power of 22dBm of the RF2126, obtaining:

$$EIRP = 22dBm + 12.6\ dBi = 34.6\ dBm\ \approx 2.88W$$

This complies with the objective of not exceeding the permitted ISM bands for WPT systems of 4W = 36dBm. As for the power obtained from the receiver, dBm conversions are performed to calculate the power obtained and thus calculate the voltage obtained. For an SMA connector antenna, the signal voltage is obtained at the input.

$$P_{useful}\ =\ 13.12uW * 0.6 = 8.2uW$$

$$V =\ \sqrt{8.2 * 10^{-6} * 50} = 20.2mV_{rms}$$

$$V_{peak} = \sqrt{2} * V_{rms} = 28.6mV$$

To verify the energy stored in the supercapacitor, values such as its charging and discharging time must be taken into account in order to support modern 15mW weather modules, which can use an electronic design with microcontrollers such as an ESP32 in 5uW deep sleep mode until a new command is received.

Energy stored in a capacitor:

$$E = \frac{1}{2} * C * V^2 = \frac{1}{2} * 0.01 * 3.3^2 = 0.005 * 10.89 = 0.05445J$$

Capacitor charging time:

$$t_{charge} = \frac{E}{P} = \frac{0.05445}{8.2*10^{-6}} = 6\ 641sec \approx 1.84hours$$

This value indicates that at least 1.84 hours is required for the system to operate and initiate a continuous duty cycle as the ESP32 Deep Sleep mode standby at 15uW controls the turn-on of the 15mW maximum weather module.

With ESP32 charging at 5uW:

$$t_{discharge} = \frac{E}{P} = \frac{0.05445}{5*10^{-6}} = 10\ 890sec \approx 3.03hours$$

Approximately 3 hours of theoretical charging time for the ESP32 to be active and activate the module, for which a 15mW maximum consumption discharge is added for the activation of the meteorological module.

$$t_{discharge} = \frac{E}{P} = \frac{0.05445}{0.015} = 3.63sec$$

Suitable for quick readings of the corresponding weather conditions, to be subsequently downloaded completely, it should be noted that this system has an empirical working life of every 5 hours, since calculations show that the capacitor can be charged more quickly, reducing the reading time to every 2 hours as its working cycle. Simulations are performed in the Radio Mobile software, obtaining a stable radio link at 0.75 km in an open field to avoid interference from signals from other antennas and too many obstacles (see Figure 7).

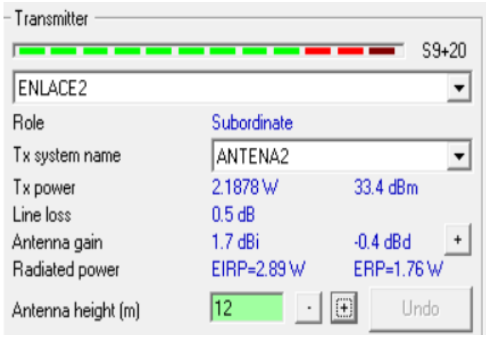

Fig. 7 TX antenna data in low condition

The TX transmitter shows EIRP values of 2.89, which do not exceed the ISM band limit. In addition, the power of the equipment was affected because a different supply voltage was used according to the previous simulation, from 10V to 12V, obtaining 2. 2W. The necessary height was considered to avoid conflicts with the terrain and other 12m antennas and to obtain a completely clear Fresnel zone. The simulation considers that both antennas have the same power, showing a stable link for the values entered compared to the theoretical values found (see Figure 8).

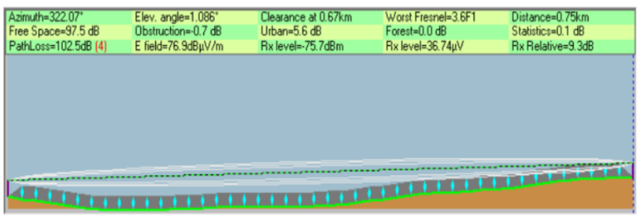

Fig. 8 Link condition between TX and RX

In addition, the correct link is shown in Google Earth software on the proposed terrain, taking advantage of some obstacles to simulate an area with forests or rocks, obtaining the results already shown (see Figure 9). After implementation, the results are corroborated in terms of the power transmitted and received by the terrain conditions. The antennas are located 10 m high in link 1 and 12.5 m high in link 2. The RMpath table shows an adequate Fresnel zone, avoiding conflicts of up to 97.5 dB for the link, allowing for even greater distance than the established 0.75 km, but with relatively low power for the study, reducing the discharge time of the capacitors, along with instability in terms of their recharge (see Figure 10).

Fig. 9 Simulated terrain in google earth

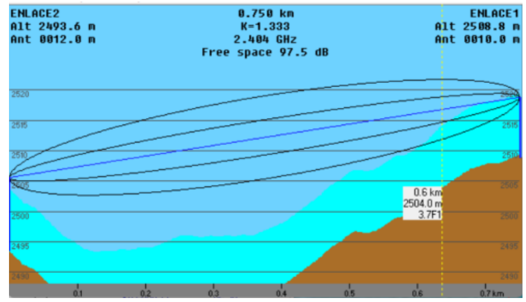

Fig. 10 Appropriate fresnel for the radio link

The system was simulated to obtain a maximum range of 1 km, as calculations were limited to a range of 0.75 km due to conditions of having a 4W limit on the ISM band. In addition, for subsequent implementation, partially free space is considered, as shown by the radio link in Google Earth. The receiver should be chosen with high-speed diodes and optimized with an LC filter designed to avoid abrupt drops due to radio link connectivity.

$$XL = 2\pi f L \quad \text{and} \quad XC = \frac{1}{2\pi f C}$$

The following formulas yield an inductance value of 2.2uH and 1.5uF after rectification, stabilizing the signal at the input of the LTC3108 for a transformation ratio of 1:100. The optimization of the system after implementation must be rigorously configured electronically, as it starts from a base frequency control of 2.45GHz and an optimal load control in the meteorological module according to the stored energy, both with ESP32, using the latter in Deep Sleep mode.

5. Tests and Results

Comparative tests were conducted between three power supply approaches for autonomous weather stations with rechargeable battery-based systems, solar panel systems, and Wireless Power Transfer (WPT) at 2.45 GHz. Metrics evaluated included power reliability, maintenance requirements, and performance in adverse conditions of irradiance, temperature, and accessibility. The data acquired were estimates as to the optimal required voltage of 3.3V using the closest wireless power systems, such as lithium batteries at 3.7V, solar panels from 1.2 to 3.6V and the proposed stable 3.3V system.

Table 2. Comparison of the absence of maintenance and errors

Metric evaluated	Batteries	Solar panels	WPT 2.45 GHz
Continuous operating time (%)	72%	84%	100%
Technical interventions required	4 visits	2 visits	0 visits
Losses due to	Not	High	Low

weather conditions	applicable	(cloudy, dusty)	
Minimum guaranteed energy level	Variable	Intermittent	Stable

In environments with high cloud cover or extreme weather conditions (jungles, mountainous areas and high plateaus), solar systems showed an average energy yield drop of 45-60%. The loss of performance in adverse conditions is calculated at 1W:

To 45%:
$Effective\ power = 1W*(1 - 0.45) = 0.55W$

To 60%:
$Effective\ power = 1W * (1 - 0.60) = 0.4W$

Thus, it deals with 0.4W of the actual charge through the solar panel under adverse conditions for a weather module.

Also, the batteries showed significant degradation after extended charge/discharge cycles, reducing their useful capacity by up to 30% typical after 18 months of continuous use or 500-1000 charge/discharge cycles, in addition to requiring periodic maintenance or replacement.

$$E_{initial} = 3.7V \times 2.6Ah = 9.62Wh$$

$$E_{degraded} = 3.7\text{V} \times 1.82\text{Ah} = 6.73\text{Wh}$$

$$Degraded\ capacity = 2600mAh \times (1 - 0.30)$$

$$Degraded\ capacity = 1820mAh$$

On the other hand, the WPT-based system delivers stable power to the receiver, even with minor beam misalignments (up to ±5°), thanks to the use of high-gain Yagi antennas and optimized alignment. In field tests with distances between 100 and 1000 meters, a continuous power supply between 5 and 17.6 mW was maintained at the receiver, sufficient to power a low-power weather system (duty cycle mode with collection and transmission every 30 minutes, values shown in dbm according to the km captured in the conflictive terrain to the RX point as shown in Figure 9, which validates the calculations made in terms of range and permitted power limits.

Table 3. Gain according to the distance between TX and RX is found

Gain (dBm)	Distance (m)	Power(mW)
14	750	17.6
17.5	500	16.2
20.8	250	94.3
25.4	150	164.2
26.8	100	172.5

From a maintenance perspective, WPT eliminates the need for physical access to the receiver node for frequent recharging or inspection. In contrast, solar systems require panel cleaning for dust pollution and charge controller verification, while battery systems require periodic visits for state-of-charge inspection and possible replacement. The estimated cumulative operating cost for annual maintenance in hard-to-reach areas is reduced by more than 70% if the WPT system is used.

6. Conclusion

This study demonstrated that far-field Wireless Power Transfer (WPT), operating in the 2.45 GHz ISM band using Yagi antennas and optimized rectennas, is a viable technical solution for powering low-power autonomous weather stations. By using an ADF4351 generator, SPF5189Z amplifiers, an efficient link was achieved that allows energy harvesting and conversion through circuits with Schottky diodes and ultra-low regulators such as the LTC3108.

Compared to batteries or solar panels, the WPT system requires less maintenance, offers greater reliability in harsh environments, and eliminates dependence on irradiance or recharge cycles. Although it presents moderate overall efficiency, its operational stability, scalability and autonomy position it as an effective and sustainable alternative for IoT deployments in remote locations without electrical infrastructure. In conclusion, the results obtained after implementation show that in distributed or hard-to-access applications, the wireless power transfer approach improves energy reliability and significantly minimizes maintenance tasks, making it a highly effective solution for autonomous environmental monitoring systems.

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