

# Performance Trade-off and System Evolution Analysis of Wireless Power Supply and Signal Transmission Technology for Implantable Biosensor Systems

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**Abstract.** As more and more wireless battery-free implants are required in such areas as brain-computer interfaces and precision medicine, it is important to choose an adequate energy and data link. In order to meet this requirement, this research systematic compare three popular wireless technologies in the implantable bioelectronic devices: electromagnetic coupling, radio frequency radiation and ultrasound. This paper first develops a compact evaluation framework based on three fundamental dimensions: power supply efficiency and safety, communication performance and robustness, and system integration with miniaturization. Next, we perform detailed analysis of the principles behind each technology, its inherent limitations and state-of-the-art system architectures with their optimization approaches. The comparative study indicates that electromagnetic coupling is superior in terms of system integration density and intelligent power management, radio frequency radiation has excellent interference resistance as a dedicated communication link in hybrid systems, and ultrasound technology has great potential in deep-tissue safety and receiver miniaturization. This work not only presents a clear performance matrix for technology selection for different implantation scenarios but also gives directions towards dust-sized integration, heterogeneous fusion and adaptive networking.

**Keywords:** Implantable devices; Wireless power delivery; Electromagnetic coupling; Ultrasound; Radio frequency communication.

## 1. Introduction

In recent years, implantable bioelectronic devices have become increasingly important in neuroscience, brain-computer interfaces and precision medicine as it has allowed long-term and continuous sensing and modulation of physiological signals. But conventional implant systems are based on wired connections or internal batteries. The former is susceptible to infections and limits patient movement whereas the latter requires repeated surgical replacements because of limited battery life, which makes clinical risks and costs higher. Wireless and battery-free designs have become an inevitable trend for next-generation implantable devices with the advancement of microelectronics technology. The main goal is to supply power continuously to micro-implants through external wireless links without compromising biosafety protocols so that high-fidelity biological signal acquisition and transmission can be achieved. This transformation is expected to greatly reduce the size of implants and prolong their service life and drive the development of distributed sensing and closed-loop diagnostics.

Despite the fact that wireless power delivery and communication technologies have made major advances in laboratory conditions, there are several fundamental issues that still exist when considering long-term stable and secure implantable applications. First, systems need to supply adequate power to sustain sensing, processing and communication capabilities of implants within safety limits like specific absorption rate (SAR), which is a problem of system performance optimization under energy constraints. Second, strong power carriers can easily interfere with weak bioelectrical signal acquisition and uplink communication links, so it is important to ensure the integrity and robustness of the signal chain. Lastly, to realize truly minimally invasive implants,

possible routes should be investigated to miniaturized power supply, sensing and communication circuits integrated with biocompatible tissue compatibility.

This paper is intended to give an overview of the technological development in this area and explain the trade-offs between various technologies as well as their performance. To start with, we will develop a system of categorization and simplification of the wireless power transfer systems used in the implantable field. Then we proceed to analyze three prevailing technologies which are electromagnetic coupling, radio frequency radiation, and ultrasound, and discuss their principles of operation, most recent system design, and performance. Lastly, a comparative matrix has been given where each technology has been summed up in terms of its advantages, constraints and situations in which it can be applied so that the design selection can be made based on the specific biomedical applications.

## **2. Technical Classification and Performance Evaluation System**

### **2.1. Mainstream Technical Framework for Implantable Wireless Power Supply and Communication**

The main challenge in achieving wireless implantable devices lies in selecting appropriate energy carriers to efficiently transmit energy and data through biological tissues (mediators). Based on differences in physical principles and coupling mechanisms, current technologies can be categorized into three main types, which collectively form the technical framework of this field.

#### **2.1.1. Electromagnetic Coupling Technology**

Electromagnetic coupling technology stands as one of the most widely adopted and mature methodologies in current applications. Its fundamental component consists of inductively coupled coils: The external transmitting coil is energized with high-frequency alternating current to generate an alternating magnetic field. This magnetic field penetrates tissues, inducing electromotive force in the receiving coil implanted within the device. After rectification and voltage stabilization, the generated power supplies the chip. Data transmission typically occurs through modulation of the power supply carrier wave or via independent carrier frequencies within the same coil pair [1]. However, electromagnetic coupling technology presents significant challenges. Transmission efficiency critically depends on coil alignment (both axial and angular precision) and spatial distance. The demand for miniaturized implants necessitates reduced receiver coil dimensions, which directly results in decreased inductance and captured magnetic flux posing a fundamental trade-off between miniaturization requirements and power supply capacity.

#### **2.1.2. Radio Frequency Radiation Technology**

Radio frequency radiation technology is a form of electromagnetic radiation that uses antennas. The transmitting antenna transforms the electricity into waves and the receiving antenna which is implanted in the body absorbs the wave and then converts it to electricity. It is used as an autonomous communication link in the implantable systems, which are hybrid systems. But in its use as a power supply, radio frequency radiation has very high attenuation of the electromagnetic waves with respect to frequency within the biological tissues. In order to achieve the required specific absorption rate (SAR) levels of safety, the allowable incident power density is extremely low, and this is why it is difficult to transfer energy effectively and safely to micro-implants deep inside the tissue. Also, the dimensions of the receiving antennas restricted by their operating wavelengths pose a problem on miniaturization.

#### **2.1.3. Ultrasonic Technology**

The piezoelectric effect is the principle of ultrasonic technology. The high frequency mechanical vibrations that are produced by electrical signals in the form of ultrasonic waves are created with the help of external ultrasonic transducers and they can be used to travel through tissues. This acoustic pressure (mechanical stress) captured by the implants are converted directly into alternating current

voltage by the receiving transducers which are made of piezoelectric material, then rectified as power. The energy transfer process is mechanical waves, and this means that it does not require time-varying electric fields to be induced on tissues, a physical advantage, which makes the system safe. There are several problems with the use of ultrasonic technology though. Reflection and refraction of sound waves are quite great at the interface between the tissue and different types of acoustic impedance (soft tissue-skeleton, tissue-air interface) and hence large amounts of energy are lost. This demands strict conditions on good efficiency of the so-called acoustic impedance matching and medium of coupling. It has also been found that transmission efficiency is very sensitive to the path of acoustics and thus needs to be compensated with the help of beamforming techniques. Also, there are still some difficulties in combining the materials and manufacturing processes of high-performance piezoelectric transducers (e.g., PMUTs) with low-power CMOS circuits to produce single-chip devices.

## 2.2. Performance Evaluation Indicator System

To bridge the physical differences across different technical approaches and achieve fair and systematic performance comparisons, this paper establishes a concise three-dimensional evaluation system. The system focuses on the fundamental requirements of implantable wireless systems, aiming to provide direct evidence for technology selection and design optimization.

### 2.2.1. Efficiency, Safety, and Penetration Depth

Transmission efficiency refers to the end-to-end energy conversion ratio from an external emission source to the implantable device's load, while power density denotes the power available per unit receiver area or volume ( $\mu\text{W}/\text{mm}^2$  or  $\mu\text{W}/\text{mm}^3$ ). These two parameters collectively determine the actual operational power achievable by the implantable device under given safe input conditions (limited by SAR). The core concept lies in the "series system efficiency model."

$$\eta_{\text{total}} = \eta_{\text{link}} \times \eta_{\text{transducer}} \times \eta_{\text{rectifier}} \times \eta_{\text{PMC}} \quad (1)$$

Here,  $\eta_{\text{link}}$  denotes the energy transmission efficiency of the wireless link,  $\eta_{\text{transducer}}$  represents the conversion efficiency of transducers (e.g., coils, antennas, or piezoelectric elements),  $\eta_{\text{rectifier}}$  indicates the efficiency of the rectifier circuit, and  $\eta_{\text{PMC}}$  refers to the efficiency of the power management circuit (including voltage regulation and modulation).

The DC load power  $PL$  delivered by the system to the load (analog/digital circuit) serves as a direct indicator for evaluating power supply capacity.

$$PL = V_{\text{out}} \times I_{\text{out}} \quad (2)$$

Where  $V_{\text{out}}$  and  $I_{\text{out}}$  represent the steady-state output voltage and current at the load terminal, respectively.

Power density (PD) correlates  $PL$  with the physical dimensions of the receiver (typically area  $A_{\text{rx}}$ ) to evaluate power delivery intensity at microscale levels.

$$PD = PL / A_{\text{rx}} \quad (3)$$

Here,  $A_{\text{rx}}$  denotes the effective physical area of the receiver (e.g., coil, antenna, or transducer).

SAR is a mandatory physical parameter for ensuring thermal safety, defined as the electromagnetic energy absorbed per unit mass of biological tissue per unit time ( $\text{W}/\text{kg}$ ). The basic calculation formula for SAR is:

$$SAR = \sigma |E|^2 / \rho \quad (4)$$

Where  $\sigma$  denotes tissue conductivity ( $\text{S}/\text{m}$ ),  $\rho$  represents tissue density ( $\text{kg}/\text{m}^3$ ), and  $E$  is the effective value of electric field intensity induced by external fields within the tissue ( $\text{V}/\text{m}$ ). Although the energy absorption mechanisms differ for magnetic induction or static magnetic fields, this formula serves as the core basis for evaluating the heating effect of time-varying electromagnetic fields.

Energy transmission within tissues typically follows an exponential attenuation law, where the attenuation coefficient is a function of frequency and medium characteristics. The penetration depth  $d_{eff}$  can be defined as the distance at which power attenuates to the surface value of  $1/e$  (approximately 37%).

$$P(d) = P_0 \cdot e^{-\alpha(f) \cdot d} \quad (5)$$

Here,  $P(d)$  denotes the received power at depth  $d$ ,  $P_0$  represents the surface received power (under ideal conditions), and  $\alpha(f)$  is the frequency-dependent attenuation coefficient.

### 2.2.2. Power Consumption, Data Rate and Robustness

This dimension measures the system's performance in the core task of acquiring biological signals and transmitting them wirelessly.

The total system power consumption refers to the total electrical power consumed by the implant during normal operation, which directly determines its dependence on limited wireless power supply and sustainable working duration. Communication energy efficiency specifically denotes the energy consumed per transmitted unit of data (pJ/bit) in wireless transmission links, serving as a critical metric for evaluating data transmission efficiency. The total system energy consumption typically represents the sum of all module energy consumption.

$$P_{sys} = P_{AFE} + P_{ADC} + P_{DSP} + P_{TX} + P_{other} \quad (6)$$

$P_{AFE}$  represents the analog front-end power consumption,  $P_{ADC}$  denotes the analog-to-digital converter power consumption,  $P_{DSP}$  indicates the digital signal processing power consumption,  $P_{TX}$  refers to the wireless transmitter power consumption, while  $P_{other}$  encompasses power consumption for components such as clocks and reference sources.

Communication energy efficiency is the most core index to characterize wireless communication efficiency.

$$E_b = P_{TX} / R_b \quad (7)$$

Here,  $P_{TX}$  denotes the average power consumption of the transmitter, and  $R_b$  represents the data rate (bps).  $E_b$  is measured in joules per bit (J/bit), commonly expressed in pJ/bit.

The maximum uplink data rate determines the types of biological signals and information capacity that the system can transmit. Interference resistance reflects the system's ability to maintain signal integrity and communication reliability under complex *in vivo/ex vivo* electromagnetic environments and coupling interference in energy transmission links. High data rates combined with strong interference resistance form the foundation for obtaining high-quality physiological data. Data rate requirements are determined by target physiological signals. According to the Nyquist sampling theorem, the minimum data rate required for transmitting uncompressed raw signals is:

$$R_{b,min} = N_{ch} \times f_s \times N_{bit} \quad (8)$$

Where  $N_{ch}$  denotes the number of channels,  $f_s$  represents the sampling rate ( $\geq 2$  times the signal's highest frequency), and  $N_{bit}$  indicates the ADC resolution.

### 2.2.3. System Integration and Suitability

This dimension measures the feasibility and potential of translating technical solutions into actual implantable devices.

The first two are the size of the receiving end or the total volume after packaging. The level of integration is a matter of board-level, flexible and bulky; heterogeneous, which can be reduced in size by using SiP, etc., and monolithic, which has all its functions on one process line. Monolithic integration is an important factor in the development of compatibility of processes. Biocompatibility cannot be measured as a quantitative value, but it is a standard test of validation. It starts with the *in vitro* testing of materials to determine whether they have cytotoxic effects and should continue to *in vivo* testing to measure the response of tissues to them in terms of long-term effects and inflammation,

encapsulation. A device that has any application of implantable nature must be supported by extensive biocompatibility experimental data.

### **3. Case Studies and Performance Analysis of Various Technical Approaches**

#### **3.1. Electromagnetic Coupling Technology**

Electromagnetic coupling technology is based on the near-field magnetic induction, and its transmission efficiency depends heavily on the level of coupling between the coils. This naturally brings about three basic trade-offs; miniaturization vs power delivery capacity, alignment sensitivity and robustness and interference with power carriers in terms of sensing/communication links. When it comes to a main source of power, it has serious drawbacks because of the high-frequency loss and SAR restrictions which make it difficult to deliver the power efficiently to the implants that are deep. It follows that it is currently used mainly as specialized communication links in the performance systems. The solution to this problem is the development of the latest research aimed at maximizing performance by enhancing physical design and system-level integration. In order to maximize space utilization and durability, Wang and his colleagues designed coaxial non-orthogonal dual-coil arrangement, which was specially designed to meet the bandwidth demands of the neural recording process [2]. They have optimized the analytical models and determined that the ratio of the diameter of implant data coil and power supply coil should be 0.8 in order to optimize the effective coupling of limited space. The differential pair of antennas bucked coils (external) for receiving the data can effectively cancel the strong harmonic disturbance of the power coils. This structure managed to reach a rate of 3 Mbps in reverse data at a distance of 20 mm, where the interference resistance and spatial efficiency were synergistically optimized.

The Roshan Pathitharayil Mathews team and the team of Jaeun Jang are an evolution in system power consumption optimization and communication energy efficiency, with the former being a link optimization and the latter a system coordination [3, 4]. Jaeun Jang used dual-frequency isolation architecture that had 40.68 MHz power supply clock and 915 MHz communication frequency which essentially separated power supply and communication connections to improve communication strength substantially. The novelty is that it recovers system clock directly by self-mixing of the power supply carrier envelope without high-power-phase-locked loop [3]. Based on this premise, the Roshan team applied global adaptive power control: their clock-offset generator linearly transforms recovered clock frequencies into analog front-end offset voltages, continuously tuning amplifier bandwidth so that sampling rate, data rate, and circuit power consumption exactly correspond to signal bandwidth [4]. This extensive cooperation allowed the SoC to have total power consumption of 32 W during ECG recording and transmitter energy efficiency of 280 pJ/bit, which established a standard of communication energy efficiency.

To conclude, the main benefit of electromagnetic coupling technology is that it is inherently compatible with the conventional CMOS processes, which allows the implementation of ultra-low-power and highly integrated on-chip systems. It attains state-of-the-art power management performance through intelligent collaborative design. Its major drawbacks however are near-field operation mode leading to short transmission distances, strict alignment demands and physical limitations on power delivery capacity in submicron-scale dimensions. Therefore, this technology can be applied best where extreme sensitivity to power is needed, shallow depths of implantation, and multi-parameter sensing capabilities with complex signal processing - e.g., high-performance neural recording and metabolic monitoring. It has been the solution of choice in the development of highly integrated bioelectronic microsystems in the present-day applications.

#### **3.2. Radio Frequency Radiation Technology**

The technology of radio frequency radiation uses antennas to transmit and receive far field electromagnetic waves. In implantable uses, it is important to differentiate between two essential functions, i.e. acting as the main power supply and being a specific communication channel. When

used as a source of power, it has inherent physical limitations: the attenuation coefficient  $2(f)$  of electromagnetic waves in biological tissues grows exponentially with the frequency, leading to an abrupt decrease in the effective penetration depth. At the same time, in order to SAR safety requirements, there is a severe upper limit on allowed incident power density. These two limitations, high-frequency loss and safety restrictions, present a two-fold challenge that prevents effective and secure delivery of power to deep micro-implants. This leads to the fact that the low performance of receiving antennas at GHz frequencies is especially felt in power supply situations. Considering such limitations, RF links are now universally considered the backbone of high-speed, highly reliable communication in hybrid architectures by high-performance systems. This approach is demonstrated by the system created by the team of Jaeun Jang. It uses a dual-band wireless domain isolation architecture: downlink power supply and clock transmission is done through a 40.68 MHz electromagnetic coupling link, which has excellent penetration ability and low SAR properties, whereas uplink data communication is completely provided by an independent RF link working at 915 MHz ISM frequency band.

This architecture delivers revolutionary improvements in communication performance and robustness. First, it achieves complete physical layer isolation. The 915 MHz communication link and 40.68 MHz power supply link are fully separated in both spectrum and spatial dimensions, fundamentally preventing strong power carriers and their harmonics from directly overwhelming weak uplink data signals. This stands in stark contrast to Alexander's team's design requiring complex interference suppression within the same frequency band [5]. Second, as a dedicated communication link, its transmitter design can be fully optimized for energy efficiency. Jaeun Jang's team employs highly efficient modulation techniques in their RF transmission chain, enabling operation at extremely low power consumption. Ultimately, the chip achieves an ultra-low total power consumption of 8.8 W at a 100 kHz system clock frequency, with the RF transmission chain's high efficiency playing a critical role. This design demonstrates that role specialization allows RF technology to deliver irreplaceable advantages in interference resistance and communication efficiency.

To sum up, the fundamental value of radio frequency radiation technology in implantable systems has developed into a specialized communication expert within the so-called heterogeneous collaborative systems as opposed to its initial investigation as an independent power supply solution. Its main strength is that it can offer a very strong and energy-saving independent data channel which effectively solves the most crucial issue of mutual interference between power supply and communication links. Nevertheless, it is constrained by the fact that it actively abandons competition as the key source of power and should be combined with other high-efficiency power supply technologies like electromagnetic coupling and ultrasound. This technology will therefore be best applied in those applications where there are strict requirements on data integrity, communication reliability and real-time performance and the system power budgets can accommodate the inclusion of an optimized independent link.

### **3.3. Ultrasound Technique**

According to the explanation provided in section 2.1, ultrasonic technology is based on piezoelectric effect and uses mechanical waves as a carrier of information. This basic nature gives it its inherent advantages such as low SAR safety, high penetration, wavelength-based miniaturization capability, etc. It has also some fundamental issues like acoustic impedance matching and other challenges of alignment of the acoustic path. The present studies are working in an organized manner to solve these problems of alignment and efficiency of both the receiver and transmitter sides. In the integration and miniaturization of the receivers, Zhi Cong Rong is focused on utilizing AlN PMUT arrays that can be used as the receiver with the ability to use CMOS process to fabricate the microelectromechanical ultrasonic transducer (AlN PMUT) [6]. A direct deposition of AlN films can be made on wafers where the CMOS circuits have been already completed and this will allow three-dimensional monolithic integration of sensing, power supply and circuitry. The PMUT array units

fabricated had dimensions of only hundreds of micrometers thick and a total receiving surface area of 2.55 mm<sup>2</sup> and a thickness of 7.45 micrometer indicating that it could be integrated at the level of dust particles. To mitigate the mismatching of impedances due to the presence of high capacitive impedance of PMUT, the research was done systematically by designing and comparing the on-chip integrated L-type passive LC matching network and T-type passive LC matching network. The system output power was improved several times after optimization and the problem of the low transmission efficiency of the small size receivers was eliminated.

The work of Zeinab Kashani is the peak of control at the transmitter side in improving tolerance to alignment and robustness of the system [7]. The system uses a 32-element external phased array with feedback-based self-localization algorithms to obtain intelligent closed-loop control. It starts by sending broad-beam detection signals which use the electrode interface of the implanted PMUT as acoustic reflection beacons. Once reflected echoes are received, the array solves deconvolution optimization problems in order to determine three-dimensional coordinates of the implant in real time. Through accurate emission delay of individual elements of an array, sound waves can be superimposed coherently at target points to create high-intensity focused acoustic spots. This algorithm of positioning on its own effectively corrects positional deviations due to body movement. Experimental findings show that beamforming technology enhances efficiency of power delivery by almost 700 times at 60-degree beam angles than non-focused transmission, which significantly increases the technical tolerance window [8-10]. To conclude, the main benefits of ultrasound technology are its outstanding biosafety (low SAR), excellent tissue penetration characteristics, and physical possibility of receiving end miniaturization to millimeter/submillimeter sizes. Some of its limitations include the need to have complex external phased arrays systems to achieve efficient transmission and sensitivity to effects of tissues interfaces. As such, this technology is most appropriate in situations where there is an extreme requirement of electromagnetic safety, deep locations of implants (several centimeters) and ultra-compact designs of receiving ends such as distributed neural dust sensor networks or targeted recording/stimulation of deep brain regions/organs. In these cases, ultrasonic technology provides an unbeatable combination of safety and miniaturization benefits that other solutions cannot provide.

#### 4. Comparison of Three Technical Approaches

Based on the above discussion of principles and performance aspects of the three main technical approaches, their essential features and areas of applicability have been emerging more and more clearly. In order to illustrate their differences and support design choice, in Table 1 we present a comparative analysis over the three dimensions: power supply performance, communication effectiveness and system integration.

**Table 1.** three technical approaches comparing.

Evaluative dimension	Electromagnetic Coupling Technology	Radio Frequency Radiation Technology	ultrasound technique
Energy Efficiency and Safety	High efficiency, SAR-moderate, shallow depth.	Low powering efficiency, SAR-limited.	Excellent safety (low SAR), good depth.
Communication Efficiency and Robustness	High energy efficiency, interference-sensitive.	Excellent robustness, dedicated link.	Circuit-dependent efficiency, acoustic noise.
System Integration and Miniaturization	Excellent CMOS integration, coil-size limited.	Good RF integration, antenna-size limited.	Promising CMOS integration, superior miniaturization.
Primary Application	Low-power, high-integration superficial implants.	High-reliability uplink in hybrid systems.	Deep, miniature, or EM-sensitive implants.

## 5. Conclusion

This study systematically analyzes three major technical approaches in implantable wireless systems. Comparative analysis reveals that technology selection fundamentally involves multidimensional performance trade-offs without universal solutions. Electromagnetic coupling technology leads in achieving ultra-low-power intelligent systems due to its high integration level and mature on-chip design, particularly excelling in superficial applications with high energy efficiency. However, its performance remains sensitive to coil alignment and distance. Radio frequency radiation technology has established itself as a "dedicated communication backbone," providing highly robust and energy-efficient uplink links in hybrid architectures while effectively addressing power supply and communication interference challenges. Nevertheless, it struggles to support deep tissue power delivery. Ultrasonic technology leverages its mechanical wave properties to demonstrate unique advantages in biosafety, tissue penetration capability, and receiver miniaturization potential, offering an irreplaceable solution for deep tissue implantation scenarios requiring stringent electromagnetic safety standards. However, its effective energy focusing relies on complex external transmission systems.

There will be a number of trends in the future, which are as follows: First, it will be the trend to further miniaturization at the level of particles and deep integration of the new transducer materials with the existing processes of integrated circuit production; Second, the development of intelligent single devices to multi-device networks and the adaptive interaction between them is an important step towards the creation of more robust in vivo sensing and control systems; Third, there will be no need to develop biocompatibility tests first and then the research on bio-integration can be pursued to see how to keep the efficient energy transfer and signal quality within dynamic physiological conditions.

To sum up, the design of systems should be based on the requirements of the core: Electromagnetic coupling is a good choice in case of system integration and power consumption; The hybrid type of the systems must be applied in the communication system that needs to have RF-based links in order to ensure the reliability of the communication system and the integrity of the information; The ultrasonic technology has been identified as the best option in case of deep implantation or high miniaturization or even in cases where the electromagnetic safety standards are too high. Such wireless enabling technologies will all help to drive the future of implantable bioelectronic devices into a new era of minimally invasive devices, smart ones and seamless connectivity with continuous interdisciplinary research.

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