

Wireless Brain-Machine Interfaces: Key Technologies and Future Perspectives

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Abstract. Research on Brain-machine interfaces (BMIs) has reached a stage where the limited experimental work needs to be translated into real-world, practical applications. Wireless technology is one of the most crucial methods to implement the translation. This review systematically examines the core technologies enabling fully implantable wireless BMIs, with a focus on the fundamental design challenge: the trilemma involving data rate, power consumption, and device size. The paper outlines the essential system architecture, including neural signal acquisition, processing, wireless transmission, and power supply modules. It provides a comparative analysis of wireless transmission methods, such as radio frequency, optical, and ultrasonic communications. The study evaluates their bandwidth, tissue penetration, and efficiency. Furthermore, implant powering strategies are contrasted, weighing the limitations of batteries against the potential of wireless energy transfer. The review highlights transformative applications in neuro-prosthetics and neuroscience research, illustrated through notable experimental and clinical demonstrations. Ultimately, it identifies persistent challenges related to long-term bio-integration and scalability, indicating future directions for developing more robust, intelligent, and clinically adaptive wireless BMI systems.

Keywords: wireless brain-machine interface, implantable neurotechnology, neural signal acquisition, wireless energy transfer, clinical translation.

1. Introduction

The BMI technology establishes direct communication channels. It provides a revolutionary tool for restoring neurological functions, enhancing human-machine interaction, and exploring the mysteries inside the brain. However, the traditional BMI technology heavily depends on wired connections. The external signal processing devices are connected with the implantable electrode array through transcutaneous cables. This physical connection shows its limitations in long-term implant applications. The constraint of wires not only restricts the behaviors of laboratory animals or patients, but it also increases the risk of infection and tissue damage. Furthermore, long-term mechanical stress on the cable can lead to equipment failure or signal degradation. These issues collectively hinder the translation of BMIs into practical technologies for chronic clinical monitoring and daily assistive use.

The wireless BMI technology gains significant development under such a background, as it is the key direction of finding solutions to the above issue. Being wireless is not just about removing the cables. It represents the simultaneous advancement of the BMI system in integration level, biocompatibility, long-term stability, and flexibility. An ideal long-term implantable wireless BMI needs to highly integrate certain modules in a miniaturized, biocompatible packaging, such as a microelectrode array, low-energy-consumption neural signal processing chip, wireless data transceiver module, and power supply system. It involves deep interdisciplinary convergence across materials science, microelectronics engineering, neuroscience, and communications engineering.

A series of breakthroughs in wireless BMI technology has been accomplished in recent years. For instance, a bunch of prototypes integrating thousands of channels, equipped with the ability of wireless data transmission and power supply, have emerged [1]. However, the sector continues to face numerous core challenges: How to achieve reliable wireless transmission of high-bandwidth neural data under constraints of extremely small dimensions and power consumption? How to design an efficient and safe intra-body wireless energy supply solution? And how to ensure that the implant works stably within the complex intracranial environment in a long-term scheme? At present, relevant

research findings are scattered across various technology disciplines. For BMI technology, the systematic review of its full scope of the technical system, key design trade-offs, and future evolution path is insufficient.

Therefore, this review aims to offer a systematic, fundamental review of wireless BMI technology for novice researchers. Beginning with the basic architecture and core performance metrics of wireless BMIs, the paper will continue demonstrating the core design trade-offs, wireless transmission methods, and wireless power supply strategies. Application and examples will also be provided. At last, this review will explore the principal challenges currently facing wireless BMI technology. In addition, the review also looks ahead to future trends towards more channels, a long lifespan, and greater intelligence. Hopefully, the review is going to help the readers build a clear technical framework and inspire reflections on the next-generation BMIs.

2. Basic Architecture and Functional Requirements

Wireless BMIs establish a direct communication channel between the brain and external devices, which offers important technical support to neuroscience research and BMI applications. The design of wireless BMIs needs to achieve high-performance signal acquisition and wireless communication under complex biophysical constraints. This chapter elaborates on the basic architecture and functional requirements.

2.1. Basic architecture of Wireless BMIs

A complete wireless BMI system is a highly integrated microelectronic system. The implantable unit typically comprises the following four essential functional modules. They cooperate to implement the conversion from neural electrical activities to wireless data:

1) Neural signal acquisition module. This module is the physical interface between the system and the neural tissue. The core component is a microelectrode array, which is directly implanted or placed on the cortical surface. It is responsible for capturing subtle electrical signals generated by neuronal activity (typically in the microvolt range). The electrode material, geometry, and impedance characteristics will immediately affect the quality of signals and also the long-term biocompatibility.

2) Signal processing module. This module implements the preliminary conditioning and digitization of the raw neural signals acquired. Its typical process includes: (a) front-end amplification. It initially amplifies microvolt signals via low-noise amplifiers; (b) filtering. This part removes high-frequency noise and low-frequency drifts from the organism and environment, and retains the target frequency bands of neural signals; (c) Analog to Digital Conversion (A/D Conversion). The step converts an analog signal to a digital signal for subsequent processing and transmission.

3) Wireless transmission module. After the neural data is digitized, this module sends the data to the external receiver via a miniature radio frequency (RF) transceiver and antenna. The design of this module should select an appropriate carrier frequency, modulation scheme, and communication protocol. It aims to maximize the reliability and efficiency of data transmission within the constraints of limited bandwidth and power consumption budgets.

4) Power supply and energy management module. This module provides a stable power supply to the whole implant. The main strategies include wireless energy transmission and an integrated micro-battery. The energy management module is responsible for rectification, voltage regulation, and storage of the received energy. Subsequently, it dynamically allocates power according to the requirements of each module.

2.2. Functional Requirements for Wireless BMIs

To ensure the practicality, safety, and effectiveness of the system, the design of wireless BMI systems must satisfy a series of rigorous interdisciplinary requirements:

1) High fidelity and high resolution. The system must possess a sufficient number of input channels, sample rate, and quantization accuracy to accurately capture the spatiotemporal activity patterns of neural populations.

2) Ultra-low power operation. The overall power consumption must be controlled at the milliwatt or even microwatt level. This restriction can prevent tissue damage caused by heat dissipation and extend battery life, or avoid placing wireless power sources too close together.

3) Miniaturization and biocompatibility. The whole package volume should be minimized to reduce surgical risks and immune rejection reactions. All materials should meet the biocompatibility standards for long-term implantation.

4) Robust wireless connection. The wireless connection must ensure the stability and interference resistance of the data link in an environment where human tissue attenuates and scatters radiofrequency signals.

5) Long-term reliability and stability. Under complex internal conditions such as fluid erosion and mechanical stress, the system should remain stable in electrical and mechanical properties for several years.

3. Technical Principles and Design Key Points

3.1. Core Trade-off: Data Rate vs. Power vs. Size

The essence of the design of wireless BMIs is to reach the optimal compromise in the trilemma of data rate, power consumption, and size.

A higher data rate requires that the signal processing circuit functions at a higher speed, and the wireless transmitter must operate at a higher output power. Subsequently, it increases the overall power consumption dramatically. Therefore, it is often necessary to employ strategies such as data compression, feature extraction, or sparse coding to achieve a balance between reducing wireless transmission load and preserving valid information.

Increasing data rate usually requires a larger chip size. Moreover, antenna dimensions are constrained by the wavelength of electromagnetic waves. Achieving high-efficiency radiation at a lower frequency needs larger physical dimensions. Otherwise, transmission efficiency or distance might be sacrificed.

Smaller size strictly constrains the scale of the power supply module, restricting the total power consumption budget. Meanwhile, the thermal challenges arising from miniaturization further constrain permissible power dissipation levels.

Hence, any design of a specific BMI system needs to identify key operating points within the trilemma concerning the application scenario. All the wireless transmission and power delivery technologies discussed in subsequent chapters essentially explore ways to push the boundaries of this trade-off.

3.2. Neural Signal Acquisition

Neural signal acquisition is the physical front-end through which the wireless BMI system interacts with the neural tissue. Its performance immediately decides the richness and quality of the acquirable information. So far, mainstream techniques rely on implantable microelectrode arrays. The traditional material of electrodes is rigid silicon or metal (such as tungsten, platinum-iridium alloys). The academic community is currently exploring the use of flexible polymer-based electrodes (such as polyimide and Parylene C) and mesh electronic devices [2]. The design objective of the electrodes is to achieve high spatial resolution signal acquisition while minimizing tissue damage and immune response. Acquired neural electrical signals are primarily categorized into two types: Action potential and Localized field potential. The former reflects high-speed discharge of single or a few neurons, while the latter represents the synchronized activity of the neuronal population [3]. In recent years, the development of high-throughput electrode array enables the simultaneous recording of activity

across large-scale neural clusters [4]. It provides the data foundation for decoding complicated neural representations.

3.3. Signal Processing

The main task of the signal processing module is to extract the numerous raw neural data within an ultra-low power consumption budget. After amplification and filtering, the module needs to implement on-chip feature extraction and data compression. This step is the key to lowering the wireless transmission load. Directly transmitting the full-band raw data for all channels can achieve extremely high-power consumption. Therefore, modern BMI chips integrate dedicated hardware circuitry to implement online processing immediately following A/D conversion.

3.4. Wireless Transmission Methods for Neural Data

Wireless transmission is the key technology to realize the practical application of a BMI system. The mainstream method is RF communication. There are also certain promising methods, such as optical communication and ultrasonic communication. Each method has its unique advantage and application scenario that is decided by its physical characteristics.

3.4.1. RF communication

RF communication is by far the most mature and widely adopted solution. It mainly uses industrial, scientific, and medical bands (such as 2.4 GHz or 915 MHz). The design core is achieving a balance between power consumption, data rate, and transmission reliability. Narrowband communication has simple structures and low power consumption. However, its data rate is limited, and it is susceptible to interference. To satisfy the high-throughput requirement, ultra-wideband technology enables burst transmission at speeds of hundreds of megabits per second over short distances with an extremely low power spectral density. On the other hand, the propagation of RF waves through biological tissue results in attenuation and thermal effects. Its penetration depth is inversely proportional to frequency. It is one of the constraints on the selection of frequency and effective transmission power to the deep brain region.

3.4.2. Optical Communication

Optical wireless communication primarily utilizes the near-infrared spectrum. This communication technology offers the possibility to transmit data with extremely high bandwidth for cortical or superficial implantation. Its advantages lie in its immense potential bandwidth and significant electromagnetic interference resistance. The recent research showcases the potential for realizing high-speed data downlink and uplink capabilities utilizing miniaturized light-emitting diodes or laser diodes with photodetectors [5-7]. However, the scattering and absorption of light by biological tissue are intense, resulting in significant transmission path loss. Therefore, strict alignment is required, and the input optical power must be maintained within the biosafety threshold. These constraints lower the effective range and depth.

3.4.3. Ultrasonic Communication Technologies

Ultrasonic Communication Technologies utilize sonic waves as the carrier. The primary advantage is that the attenuation of sound waves in soft tissue is significantly lower than that of radiofrequency waves, and they cause virtually no thermal damage. Therefore, the technologies are highly suitable for wireless data transmission in deep brain regions (such as the hippocampus and thalamus). This system achieves electroacoustic conversion by employing a piezoelectric transducer. The main

disadvantage is that the data rate is usually lower than RF solution because of the relatively long wavelength of ultrasonic waves. Meanwhile, sonic waves undergo reflection and modal conversion at interfaces with hard tissues such as the skull, which causes signal distortion and energy loss. Efficient transmission across the skull requires complex beamforming or coding techniques for compensation.

3.5. Implant Powering Strategies

Providing a stable energy supply to implantable wireless BMI systems is the fundamental prerequisite for achieving long-term work. The choice of powering strategy immediately affects the system's dimension, lifespan, safety, and implantation depth. It is primarily centered around two pathways: batteries and wireless energy transmission.

3.5.1. Limits of Batteries

One of the most direct solutions is integrated miniature disposable batteries. But there are unignorable limitations. Firstly, the energy density is insufficient. Under millimeter-scale dimensional constraints, battery capacity is typically only in the milliampere-hour range. It is difficult to maintain long-term work with multi-channel, high data rate systems. This limitation might necessitate frequent charging or replacement, and secondary surgery carries significant risks and costs. On the other hand, the battery volume accounts for a huge part of the whole implant system. The miniaturization of the system would be severely constrained. Therefore, although the battery technology is continuously advancing, it is still not the ideal solution to pursuing a permanently implanted BMI system.

3.5.2. Wireless Charging

Wireless energy transmission powers implanted devices via an external energy transmitter. It is a key technology for breaking the limit of batteries. There are currently two main approaches: inductive coupling and RF radiation.

Inductive coupling is one of the most mature and effective solutions. Based on the principle of near-field electromagnetic induction, energy is transferred between the external primary coil and the internal secondary coil via magnetic field coupling. The advantages are relatively high transmission efficiency (achieving over 70% when closely aligned) and reliability [8]. The disadvantages are a short transmission distance and that it is extremely sensitive to coil misalignment. Inductive coupling also requires that the implant site be relatively superficial and fixed.

RF radiation utilizes RF electromagnetic waves to implement far-field radiative energy transmission. The advantages are a relatively long transmission distance and a low requirement for direction. These make it a better option to power the deep implants. However, due to the attenuation and scattering of electromagnetic waves in tissue and the safe power limit, its end-to-end transmission efficiency is generally low. In addition, RF radiation may cause thermal effects on surrounding tissues.

4. Applications and Example Systems

The development of wireless BMIs follows an evolutionary trajectory from fundamental research tools, through clinical translation exploration, to future concept prototypes. This chapter follows this line of reasoning to demonstrate its key application scenarios and representative systems.

4.1. Revolutionary Impacts as a Research Tool

The foremost contribution of wireless BMI lies in liberating paradigms of experiments, thereby becoming an important engine for neuroscience research. Traditional wired systems have a severe constraint on the natural behavior of experimental subjects, whereas wireless technology enables large-scale neural observation and intervention in freely moving animals. For instance, the wireless Neuropixels system integrates thousands of recording channels. It enables researchers to simultaneously capture neuronal activity across multiple brain regions while animals perform

complex tasks [9, 10]. This provides unprecedented data for demonstrating the neural ensemble coding mechanisms underlying cognition and behavior. Likewise, wireless closed-loop optogenetics platforms enable real-time recording-decoding-stimulation cycles [11]. This allows precise modulation of specific neural circuits during spontaneous animal behaviors [12]. It directly verifies the causal functions of the neural circuits [13]. These tools have significantly advanced our understanding of learning, memory, and the mechanisms underlying neurological disorders.

4.2. Systems and Trials for Clinical Translation

These are certain wireless BMI technologies that have entered the clinical translation phase, aimed at addressing specific medical needs. Intracortical wireless BMIs, exemplified by BrainGate, have had demonstrations in clinical trials. Paralyzed patients can wirelessly control robotic arms or computer cursors by decoding motor intentions [14]. This significantly enhances their independence in daily living. Such systems are evolving towards the goal of being fully implanted, eliminating the need for external wearable devices. On the other hand, fully implantable closed-loop stimulation systems (such as the NeuroPace RNS® system, approved for epilepsy) have been in clinical use for many years. It is capable of continuously monitoring electroencephalograms and wirelessly transmitting data [15]. When epileptiform activity is detected, the system will automatically apply electrical stimulation to block seizures [16]. This demonstrates the feasibility and efficacy of long-term implantable wireless systems for the management of neurological disorders.

4.3. Exploratory Prototypes and Concepts

Future breakthroughs hinge upon the disruptive concepts currently taking shape in laboratories. These pioneering prototypes are dedicated to overcoming the fundamental bottlenecks of existing systems.

The concept of "neural dust" aims to develop ultrasonic-powered sensing nodes. They can be widely dispersed within tissue, enabling distributed, battery-free neural monitoring [17].

Many research teams are developing customized low-power ASIC chips. These chips are designed to wirelessly transmit raw neural data from thousands of channels at a total power consumption of a milliwatt level [18].

Electrodes and circuits are fabricated using flexible, stretchable, and even biodegradable electronic materials. The aim is to minimize foreign body reactions and achieve long-term stable integration with neural tissue.

Although most of these demonstration systems remain in the preclinical research phase, they clearly indicate the technical direction for overcoming existing challenges.

5. Remaining Hurdles and Future Directions

Even though wireless BMI technology develops rapidly, there are still a series of interdisciplinary challenges if the target is achieving long-term stable, high-quality clinical application. Meanwhile, the uprising technological path points the way towards future breakthroughs.

5.1. Key Challenges

Currently, the key challenges focus on three aspects: long-term stability, system integration level, and clinical transition.

1) Chronic immune response induced by the implant leads to increased electrode interface impedance and attenuation of neuronal signals. It is the fundamental obstacle to long-term stability. The task of paramount importance is the development of novel interface materials. The ideal material should combine biocompatibility, mechanical compatibility, and long-term electrochemical stability.

2) The more complex the system functionality, the higher the power consumption tends to be. This creates a fundamental conflict with power supply capacity, thermal safety requirements, and miniaturization demands.

3) With the dramatic increase in channel numbers, demands on wireless data transmission rates and power consumption have grown exponentially. Existing RF, ultrasonic, or optical methods struggle to balance penetration depth, data rates, and safety.

5.2. Promising Trends

Future development will follow a trend of collaborative innovation across materials, devices, algorithms, and systems.

Concepts such as "neural dust" and "bioelectronic medicines" – ultra-miniature, and biodegradable devices – aim to minimize tissue damage while enabling long-term stable monitoring or instantaneous treatment [17, 19].

Leveraging proximity sensor computing and dedicated AI accelerators, feature extraction and preliminary decoding occur directly at the implanted end. Only critical information is transmitted. This significantly lowers wireless transmission load and system power consumption.

Hybrid systems combining different physical principles have a promising future. At the same time, self-powered technologies harnessing chemical or mechanical energy within the body may offer new solutions for ultra-low-power devices [20, 21].

6. Conclusion

Through systematic analysis and argumentation, this paper clarifies that the core to realizing practical wireless BMI technology lies in resolving a fundamental trilemma comprising data rate, power consumption, and size. Research indicates that all current technological pathways are fundamentally seeking optimal solutions for specific application scenarios within this constraint boundary. Therefore, the design of wireless BMIs is by no means a stacking of isolated components. It is rather an engineering endeavor that highlights systematic coordination and cross-level trade-offs. For instance, on-chip intelligent processing exemplifies this collaborative approach by substantially reducing wireless transmission loads through sacrificing some computational complexity. This review further reveals the profound significance of wireless technology, which is to drive BMI from controlled laboratory environments towards dynamic real-world scenarios.

The principal contribution of this review is providing an integrated technical evaluation framework and a systematic design perspective, especially for interdisciplinary researchers across engineering, materials science, and neuroscience. The paper integrates research advances scattered across various disciplines within the "architecture-module-trade-off" framework. Using this framework prevents the researchers from being limited by single-technology optimizations. It also assists the researchers in understanding the impact of specific local innovations on the system as a whole. This systematic review not only accelerates the rational comparison and integration of different technological approaches but also provides a conceptual foundation for establishing industry standards and clinical translation protocols.

Looking towards the future, research into wireless BMIs should have a clear goal by being demand-driven or fostering integrated innovation. First, future system designs must be more closely integrated with specific clinical scenarios, developing adaptive, flexible solutions. Secondly, technological breakthroughs will increasingly rely on cross-disciplinary convergence. Ultimately, researchers need to drive the establishment of a comprehensive evaluation system encompassing biological safety, long-term reliability, and information security. This will be a significant step in advancing wireless BMIs from innovative demonstrations to large-scale clinical applications. Only through sustained, systematic innovation and rigorous clinical validation can this technology truly serve the needs of human health and scientific exploration.

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