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Recent Advancements in Implantable Medical Devices: pacemakers, cardioverter-defibrillator (IDs) for Embedded systems

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***Abstract*—This survey investigates recent advances in the design, security, and optimization of implantable medical devices (IMDs), implantable cardioverter-defibrillators (ICDs) and pacemakers. A novel approach based on convolutional neural networks (CNNs) is proposed to improve arrhythmia detection while reducing energy consumption in ICDs, achieving 90% accuracy with a low parameter count. In contrast, security vulnerabilities in IMDs are critically examined, highlighting the risks of signal injection attacks (InjectICD) that can manipulate ICD therapy decisions, as well as the broader cybersecurity threats posed by wirelessly enabled pacemakers. In addition, the feasibility of ultra-low-power 32-bit RISC-V processors (Siwa) for IMDs is explored, with a power-efficient design fabricated using a 180- nm CMOS process and the introduction of a new benchmarking metric (BMIMD) for performance evaluation. Furthermore, the study looks at the electromagnetic interference (EMI) characteristics of active implantable medical devices (AIMDs) exposed to radio waves from the 4G and 5G Sub-6 frequency bands, using FEM-based simulations to analyse near-field and far-field effects on AIMDs at frequencies up to 4.5 GHz. Overall, these studies contribute to the field of medical AI, security of IMDs, etc.**

***Index Terms*—Implantable Medical Devices, AI in Healthcare, Cybersecurity in IMDs, Low-Power Processors Electromagnetic Interference.**

I. INTRODUCTION

Implantable Medical Devices (IMDs), pacemakers and implantable cardioverter-defibrillators (ICDs), have made advances in recent years, with a focus on power efficiency, security, and resistance to electromagnetic interference (EMI). As these life-saving devices become more complex, issues such as low-power processing, cybersecurity threats, and the impact of wireless communication on device functionality must be analysed. This review focuses on research from multiple studies that address these issues from various angles. One study describes Siwa, a 32-bit RISC-V processor for ultra-low-power IMDs. Siwa, which is built using a 180-nm CMOS process, prioritises high-voltage operation and low power consumption, compared to traditional 8-bit and 16-bit microcontrollers (MCUs) used in IMDs. The study provides a detailed power consumption analysis and introduces a new benchmarking metric, BMIMD, to evaluate processor efficiency.

Another study focuses on weaknesses in security in IMDs, particularly in ICDs. InjectICD, a model-based framework, formulates attack synthesis as a multi-objective optimization problem, demonstrating how adversaries can maximize an attack's effectiveness while minimizing its detectability. This raises concerns about potential signal injection attacks that could manipulate ICD therapy decisions.

A separate study looks at the use of deep learning-based arrhythmia detection in IMDs, using FPGA-based hardware acceleration by the Xilinx Zynq UltraScale+ MPSoC. The authors use a neural network optimized for real-time electrogram (EGM) signal processing, which improves accuracy while remaining energy efficient.

Another study examines the impacts of electromagnetic interference (EMI) on AIMDs because of the quick development of 5G wireless technology. It covers the gap in EMI research beyond standard low-frequency interference by measuring interference voltages generated by pacemaker circuits under radio frequency (RF) exposures at higher frequency bands (3.7 GHz and 4.5 GHz) using numerical simulations based on the finite element method (FEM).

Furthermore, a security-focused study defines two major vulnerabilities in implantable pacemakers that make them open to eavesdropping, denial-of-service (DoS) attacks, replay attacks, and man-in-the-middle attacks: the lack of authentication for wireless programming and unencrypted communication. The paper shows the urgent need for enhanced encryption and authentication systems in IMDs by citing real cybersecurity breaches.

Together, these studies address key problems in ensuring the security, efficiency, and reliability of next-generation implantable medical devices by improving the areas of low- power processor design, AI-driven arrhythmia detection, cybersecurity in IMDs, and EMI resilience.

II. LITERATURE REVIEW

The five studies' various goals on implantable medical device security, efficiency, and performance enhancement can be seen in the wide differences in their implementation techniques. InjectICD, a model-based approach aimed to optimize attack synthesis on ICDs, is shown in [1]. Using Pareto-optimal solutions, this work develops attack development as a multi-objective optimization task that combines stealth and effectiveness. The Insider, knowledgeable, and universal attackers are the attack models; each has various levels of access to patient data. The framework is tested using a major manufacturer's ICD separating algorithm for 19 different cardiac diseases. According to the tests, InjectICD can successfully create attacks under any situation, obtaining a maximum success rate of 71% for particular threat scenarios.

[2] analyzes weaknesses in communication encryption and authentication having a focus on implantable pacemakers. According to the study, the majority of pacemakers communicate without encryption, making them exposed to manipulation and eavesdropping, and they lack authentication features, enabling unwanted access. The study uses communication assaults (eavesdropping, denial-of-service, replay, and man-in-the-middle attacks) and internal attacks (battery depletion) to classify threats. Case studies involving real cybersecurity breaches in pacemakers are used in the implementation to show how prone these devices are to online attacks.

Siwa, a low-power 32-bit RISC-V processor designed for implantable medical devices (IMDs), was evaluated in [3] to assess its efficiency in power consumption, execution performance, and interrupt-driven operation. The processor architecture integrates an external boot flash memory for program execution and employs a Keithley 2400 Source Measurement Unit (SMU) for precise power supply monitoring. The study evaluates Siwa’s efficiency through various instruction types, including arithmetic, logic, control, and memory operations, ensuring a comprehensive analysis of its computational capabilities. A critical aspect of the evaluation is the processor's ability to switch between sleep and wake states, a fundamental requirement for low-energy IMDs. The research utilizes BMIMD as a benchmark to measure Siwa's power efficiency, emphasizing its effectiveness in minimizing energy consumption while maintaining real-time processing capabilities. The performance of Siwa is further assessed using the Basic Task Sets (BTS) metric, which remains unaffected by variables such as instruction set architecture, bus width, and CPU clock speed, providing an unbiased measure of processing efficiency. The results indicate that Siwa demonstrates superior energy efficiency and reliable task execution, making it a promising candidate for next-generation IMDs. The study also highlights the significance of low-power microarchitecture in extending battery life and improving the long-term functionality of medical implants. Future research directions could focus on enhancing computational efficiency, optimizing memory hierarchies, incorporating advanced security frameworks to protect patient data, and integrating AI-based health monitoring solutions to improve IMD adaptability in dynamic physiological conditions. Additionally, further investigation into real-world deployment scenarios and in vivo testing would strengthen the validation of Siwa’s effectiveness in medical applications.

[4] The study employs a phantom-based simulation model to analyze the risks of electromagnetic interference (EMI) in pacemakers, utilizing Irnich's flat torso phantom, an acrylic box filled with saline that mimics human tissue interactions with electromagnetic fields. This phantom model provides

a controlled environment for assessing EMI effects on implantable medical devices. A commercial finite element method (FEM) solver, PathWave EM Design (EMPro), is utilized to simulate and evaluate the EMI susceptibility of a ventricular lead pacemaker operating in VVI mode. The pacemaker is strategically positioned inside the phantom to ensure accurate replication of in vivo conditions. To assess the impact of radiofrequency (RF) fields on the pacemaker, a half-wavelength dipole antenna is employed to generate controlled electromagnetic exposure. The induced voltage at the pacemaker's terminating resistor is measured across various frequencies and antenna placements, allowing for a comprehensive evaluation of interference effects. The study systematically investigates how different RF field conditions influence the pacemaker's operation, providing critical insights into EMI-induced voltage variations. The results highlight the importance of considering lead positioning, antenna distance, and frequency variations when evaluating pacemaker susceptibility to external electromagnetic sources. Furthermore, the research underscores the necessity of standardized EMI testing frameworks to enhance the reliability and safety of active implantable medical devices (AIMDs).

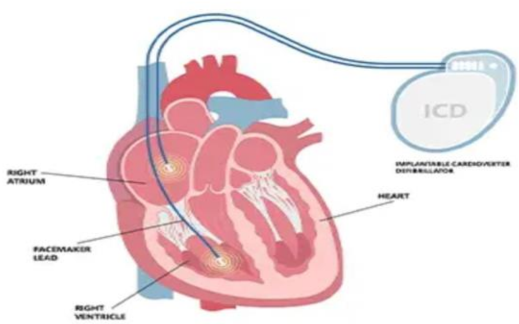

Figure 1

In [5], a convolutional neural network (CNN) which is based on deep learning methods is used to detect arrhythmias in ICDs. For exact and energy-efficient processing of electrogram (EGM) signals, the 10-layer CNN contains convolutional layers, dropout layers, max pooling, ReLU activation, and fully connected layers. By reducing the number of parameters (less than 1200), the network can be enhanced to improve processing speed and energy efficiency. The Xilinx Zynq UltraScale+ MPSoC ZCU102 evaluation kit is used to set up the CNN on FPGA hardware, using MATLAB Deep Learning HDL Toolbox to simplify good hardware acceleration. The performance of real-time arrhythmia detection in battery-operated ICDs is greatly enhanced by this technology, which allows parallel processing.

[6] investigates the electromagnetic interference (EMI) risks that vehicles pose to active implantable medical devices (AIMDs) such as pacemakers and neurostimulators. With the growing integration of electronic systems in modern vehicles, particularly in electric and hybrid models, the electromagnetic environment inside vehicles has become increasingly complex. This study analyzes the EMI susceptibility of AIMDs and evaluates the potential risks posed by vehicle components, with a particular focus on wireless charging systems.The research provides a systematic analysis of several key aspects related to EMI risks. It examines the electromagnetic compatibility (EMC) performance of AIMDs, referencing ISO 14708 and ISO 14117 standards, which define immunity levels for implantable devices. Additionally, it identifies sources of EMI in vehicles, emphasizing potential interference from electric drive components.

To assess risk levels, the authors conduct experimental analysis by measuring vehicle electromagnetic radiation and comparing the results with AIMD immunity thresholds. A key finding of the study is that while most vehicle components produce radiation levels below AIMD interference thresholds, wireless charging modules may exceed safe limits, particularly as transmission power increases. The study highlights the importance of maintaining a safe distance from wireless charging systems in vehicles for individuals with AIMDs, reinforcing the need for further research into mitigation strategies and improved safety guidelines. With the increasing adoption of electronic control systems, especially in electric and hybrid vehicles, the electromagnetic environment within vehicular compartments has become increasingly complex.

This research assesses the susceptibility of AIMDs to vehicular EMI and evaluates risk factors associated with specific automotive components, particularly wireless charging infrastructures

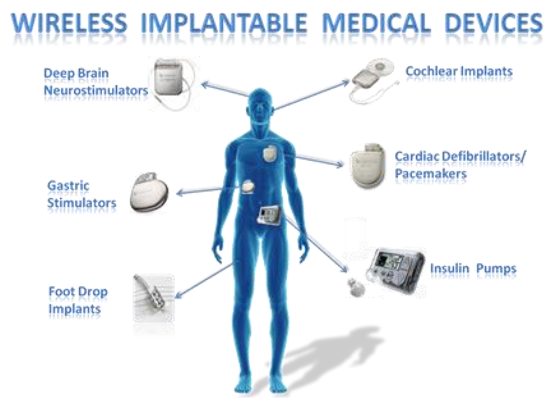

Figure 2.

The study by Li et al. [7] investigates the temperature rise mechanism in pacemakers induced by time-varying gradient magnetic fields, particularly in MRI environments. The research employs both theoretical modelling and experimental validation to analyze the effects of key parameters such as initial system temperature, gel thickness, and magnetic field waveform on temperature rise.The authors establish that initial temperature has no significant effect on temperature rise, whereas a thicker gel layer results in a smaller temperature increase due to enhanced heat dissipation. Their findings also highlight that sine wave magnetic fields cause substantially greater heating than triangular wave magnetic fields, with the highest temperature rise observed near the pacemaker battery. These insights provide critical considerations for the design, testing, and evaluation of active implantable medical devices (AIMDs).

The experimental approach in the study involves embedding a pacemaker in a conductive gel to simulate human tissue, exposing it to sine and triangular wave magnetic fields at a rate of 42 T/s, and monitoring temperature variations using a fibre optic thermometer. The study conforms to ISO and ANSI/AAMI standards, enhancing the reliability of the results. Li et al. emphasize the importance of waveform-dependent heating effects, which have been largely overlooked in previous research focusing on RF field-induced heating. Their findings stress the need for improved AIMD safety protocols in MRI environments, particularly by refining testing procedures to account for waveform-specific heating. The study suggests that future work should focus on in vivo studies, advanced numerical simulations, and further refinements in experimental methodologies to improve AIMD safety.Overall, this research significantly contributes to the field of AIMD safety in MRI environments. By integrating theoretical models with experimental validation, it provides a robust framework for assessing thermal risks associated with gradient magnetic fields. The findings are particularly valuable for medical device manufacturers, regulatory bodies, and healthcare professionals seeking to enhance MRI safety for AIMD users.

I. COMPARATIVE ANALYSIS

With a focus on different topics like energy efficiency, security, and performance under external influences, the five looked at studies all contribute to improving implantable medical devices (IMDs). Even though they deal with different issues, they all emphasize the need for technical and safety-optimized solutions.

Performance Optimization and Energy Efficiency: [1] provides a CNN-based architecture for implantable cardioverter-defibrillator (ICD) arrhythmia detection that focuses on low energy consumption by decreasing the network's parameters. It is suitable for battery-powered devices as it has a low parameter count and 90% validation accuracy. A different kind of optimization that puts on the device's performance in external environments, the fourth study deals with the problem of electromagnetic interference (EMI) from 5G and 4G signals on pacemakers and ICDs, making sure that external RF signals are not affecting the device's functionality.

[2] and [3] study addresses implantable pacemaker safety issues. Using weaknesses in the sensing and algorithms for classification, [2] discusses hidden signal injection attacks on ICDs. The study highlights the need for security like electromagnetic shielding by showing a trade-off between harm effectiveness and stealth. In opposition to the signal injection attacks discussed in the second paper, [3] focuses on unencrypted communication and lack of authentication in pacemakers, indicating eavesdropping and denial-of-service as the primary issues. Both studies highlight the need of extra precautions to stop the harmful use of these gadgets.

As an energy-efficient processor choice for ultra-low-power IMDs, [5] presents 32-bit RISC-V cores with dynamic voltage scaling and optimized sleep modes that extend battery life. In contrast, the CNN-based signal processing in

[1] favours signal processing accuracy rather than hardware processing power, although both have low-

energy consumption. As opposed to conventional 8-bit and 16-bit microcontrollers, the Siwa processor described in the fifth paper has more computational capabilities, which makes it more suitable for next-generation IMDs that need more processing power.

The impact of RF fields from current 5G networks on device functionality is directly addressed in [4], which uses FEM-based simulations to determine electromagnetic interference (EMI) in pacemakers. As wireless communication technologies grow, it analyzes the induced voltages in pacemaker circuits, bringing to light an important risk. The second and third papers' security discussions, based on communication protocol issues like unencrypted data transfer and the risk of eavesdropping, are made better by this. Through energy optimization, security changes, or external interference management, each study improves the overall aim of enhancing IMD ability. Some studies [1] and

[5] focus more on technical performance, while others [2] and [3] focus on security, and one [4] analyzes the effect of external environmental factors. When put together, they give an in-depth understanding of the problems and solutions which IMD design and operation may encounter in the future. [6] This study presents a rigorous evaluation of the EMI risks that modern vehicles pose to AIMDs. While most vehicular components operate within acceptable EMI thresholds, wireless charging systems present a potential hazard. The research effectively underscores the need for continued investigation into mitigation strategies to safeguard AIMD users against evolving electromagnetic challenges in the automotive industry.

In [7] research provides a systematic analysis of various aspects related to electromagnetic interference (EMI) risks for active implantable medical devices (AIMDs) in vehicles. It examines the electromagnetic compatibility (EMC) performance of AIMDs**,** referencing ISO 14708 and ISO 14117 standards, which define immunity levels for implantable devices. Additionally, the study identifies sources of EMI in vehicles, highlighting potential interference from electric drive components. To assess risk levels, the authors conduct experimental analy**sis** by measuring vehicle electromagnetic radiation and comparing the results with AIMD immunity thresholds.

III. CHALLENGES AND FUTURE DIRECTIONS

A. Abbreviations and Acronyms

The studies on implantable medical devices (IMDs) and related technologies highlight several challenges and areas for improvement. [1] which discusses signal injection attacks on implantable cardioverter-defibrillators (ICDs), the paper points out the weaknesses in the sensing and discrimination methods of ICDs. Even small, undetectable changes can lead to dangerous outcomes, focusing on the need for robust safeguards against such attacks. Although potential solutions like electromagnetic shielding and adaptive filtering are suggested, these measures are not widely used in current ICDs. Future research could gain from using AI-based pattern detection systems to improve real-time security and look into energy-efficient security systems to protect devices without affecting battery life, which are important limitations of IMDs.

The design of a 32-bit RISC-V processor with low power consumption for IMDs that improves energy efficiency without losing processing power is the subject in [2]. The BMIMD benchmark used in the article may be made simpler to handle many kinds of IMD workloads, like real- time telemetry and ECG processing, yet the Siwa processor shows positive results. Siwa could also be made stronger and helpful in real-world medical device scenarios through enhancing its instruction throughput, scaling it to smaller process nodes, and increasing its peripheral integration by including wireless modules. The processor's use over time in IMDs may also be increased by adding energy harvesting methods and improving data privacy and tamper-resilience features.

In [3] the scientists replicate actual scenarios using a virtual model to evaluate the electromagnetic interference (EMI) dangers to pacemakers. However, the use of phantom models and simulations has disadvantages because they may not accurately represent the variations seen in real patients. The accuracy and reliability of the results would be increased by increasing the models' scope with more RF exposure scenarios and doing field testing in real-life situations.

Also, the results could be improved by using a variety of phantom models that represent different body types and pacemaker systems.

[4] Looks at the need for measures to mitigate EMI

interference in pacemakers. Although the study discusses the issues caused by electromagnetic interference (EMI), it does not go into great detail about workable solutions that could be used to safeguard pacemakers. Designing practical EMI protection systems that work with present pacemaker technologies could be the main focus of future research. Also, more research on shielding technologies and alternative design ideas can help decrease interference in real-world use, and adaptive methods of filtering might be designed that adapt to different RF exposure levels. Future work may also focus on refining simulation models by incorporating more anatomically accurate human phantoms, expanding frequency range assessments, and validating findings through in vivo studies. Additionally, integrating advanced numerical methods and AI-driven predictive analytics could further improve EMI risk assessment methodologies, ultimately contributing to the development of more resilient medical implant technologies

[5] provides a convolutional neural network (CNN) for arrhythmia identification in ICDs, which is based on deep learning. Despite the study's favourable results, challenges with real-time processing, adaptability for different patient populations, and hardware implementation scalability remain. Future studies may focus on improving real-time processing speeds and making sure the model works with more kinds of patients and arrhythmias to improve the model's functionality. Also, using this CNN model with additional tools for diagnosis, such as ECG monitoring, could result in a more complete system for IMD arrhythmia recognition.

Security mechanisms, including encryption and authentication protocols, contribute to increased power consumption, which can have a substantial impact on the battery longevity of implantable pacemakers. With the rapid progress in artificial intelligence (AI), machine learning (ML) algorithms can be employed to anticipate and actively mitigate electromagnetic interference (EMI) risks in automotive environments. Future investigations could focus on developing real-time AI-driven monitoring frameworks that notify AIMD users when they enter high-EMI areas, ensuring proactive risk management and enhanced device safety.

In [6] one potential area for improvement is the integration of artificial intelligence (AI) in electromagnetic interference (EMI) prediction and prevention for active implantable medical devices (AIMDs). With advancements in machine learning (ML), AI models could be trained to analyze real-time electromagnetic environments inside vehicles, identifying potential EMI risks based on historical data, sensor inputs, and environmental conditions. By leveraging deep learning algorithms**,** AI-based systems could dynamically detect, classify, and predict high-EMI zones, providing real-time alerts to AIMD users through wearable devices or mobile applications**.** Additionally, AI-driven adaptive filtering techniques could help mitigate EMI effects by automatically adjusting AIMD operation parameters.

Future research should focus on developing lightweight, energy-efficient AI models that can be integrated into AIMD ecosystems while ensuring low-latency decision-making and high reliability in complex vehicular environments.

[7] provides valuable insights into the temperature rise mechanisms in pacemakers induced by time-varying gradient magnetic fields in MRI environments; however, several improvements could enhance its scientific contribution. The research relies on gel-based tissue phantoms, which do not fully replicate human bioheat transfer dynamics; incorporating models such as Pennes' Bioheat Equation would improve accuracy. The study considers sine and triangular waveforms**,** but real MRI systems generate complex, multi-frequency gradient fields; analyzing non-sinusoidal waveforms could yield more practical insights**.** Additionally, the paper highlights localized heating near the pacemaker battery but does not explore how device materials and structural designs influence thermal behavior, an aspect crucial for improving AIMD safety. The research focuses on short-term heating effects, whereas long-term exposure could impact both device performance and surrounding tissues, necessitating further investigation. Computational modeling using finite element analysis (FEA**)** and computational electromagnetics (CEM) could supplement experimental validation, enabling parametric studies under varying MRI conditions. The study would also benefit from in vivo experiments**,** as phantom-based testing may not fully represent human physiological

responses. Moreover, integrating real-time wireless temperature monitoring within AIMDs could provide an automated safety mechanism, preventing excessive heating during MRI scans. Future work should address these aspects to develop a more comprehensive safety framework for AIMD users in MRI.

IV. CONCLUSION

Every study presents diverse methodologies for improving the implementation of implantable medical devices (IMDs), ranging from low-power CPU architectures and advanced security frameworks to deep learning-based arrhythmia diagnosis and phantom-based electromagnetic interference (EMI) testing. These approaches collectively aim to enhance the performance, safety, and efficiency of IMDs, ensuring their reliability in clinical applications. The integration of artificial intelligence (AI) plays a crucial role in advancing IMDs by enabling real-time monitoring, predictive diagnostics, and adaptive learning mechanisms. AI-driven algorithms, particularly deep learning models, have demonstrated the potential to automate arrhythmia detection, improve signal processing, and optimize decision-making in pacemakers and neurostimulators. However, the computational overhead and power consumption of AI models present a challenge, necessitating hardware optimization techniques such as edge computing, neuromorphic processors, and low-power digital signal processing (DSP) units to ensure energy-efficient real-time processing. Additionally, cybersecurity measures are vital to protect IMDs from potential threats such as malware attacks, unauthorized access, and wireless interference. Modern security frameworks, including encryption protocols, blockchain-based authentication, and AI-driven anomaly detection, are being explored to safeguard patient data and device integrity. EMI testing methodologies using phantoms and simulation models also contribute to assessing the risks posed by external electromagnetic sources, particularly in environments such as MRI scans and modern vehicles with wireless charging systems. Despite these advancements, several challenges remain. Security vulnerabilities, energy efficiency constraints, real-time processing limitations, and real-world applicability are still open research areas that require further exploration. Future developments in the field of implantable medical technology will necessitate greater integration of AI, optimization for various workloads, and enhancements in hardware scalability to accommodate a wider range of medical conditions and patient needs. Multi-disciplinary research, combining biomedical engineering, embedded systems, and artificial intelligence, will be key to overcoming these challenges and paving the way for the next generation of intelligent, safe, and efficient IMDs.

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