



Key Technologies for Low-Power Iot Chip Design

Shuhan Qi

Faculty of Engineering, The Hong Kong University, Hong Kong, China

u3618160@connect.hku.hk

Abstract. The design of Internet of Things (IoT) chips revolves around achieving efficient, reliable, and low-power architectures tailored to the unique demands of IoT ecosystems. This review examines the critical components of IoT chip design, including sensing units, processing cores, memory subsystems, communication interfaces, and power management units. These components are optimized through collaborative design approaches to ensure minimal energy consumption while maintaining high performance. The article also delves into the pivotal role of advanced semiconductor processes, such as FinFET and gate-all-around (GAA) technologies, which enable higher integration and efficiency. Furthermore, innovative techniques like ultra-low-power circuit design and energy harvesting mechanisms are explored to extend the operational lifetime of IoT devices. Hardware security measures, such as lightweight cryptographic protocols and physically unclonable functions (PUFs), are highlighted as essential for protecting sensitive data in IoT applications. The adoption of System-on-Chip (SoC) solutions, integration of AI-based edge computing, and the development of emerging semiconductor materials, including 2D materials, further enhance energy efficiency and scalability. These advancements pave the way for sustainable IoT chip design, addressing both performance demands and environmental concerns.

Keywords: IoT Chip Design, Low-Power Architecture, Energy Harvesting, Hardware Security.

1 Introduction

The Internet of Things is transforming various sectors, including healthcare, smart home technology, agriculture, and industrial automation as shown in Fig. 1. At the core of IoT devices are highly efficient and reliable chips that manage sensing, computation, communication, and power management. Designing these chips presents significant challenges, particularly in achieving ultra-low power consumption, robust performance, and secure operation. These challenges are central to enabling the scalability and adoption of IoT technologies.

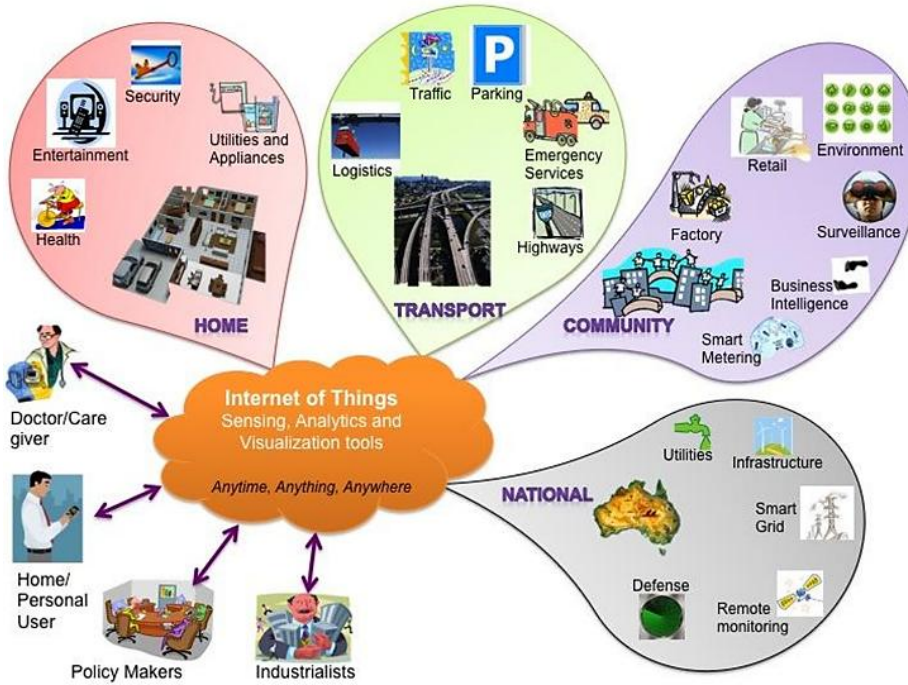


Fig. 1. IoT application [1]

Minimizing power consumption is essential for Internet of Things devices, as many of these devices depend on finite battery resources or function within energy-limited settings. The design of IoT chips employs sophisticated methodologies, including dynamic voltage and frequency scaling, subthreshold operation, and event-driven sensing, to effectively mitigate these power constraints. Furthermore, advancements in semiconductor processes, such as Fully Depleted Silicon-On-Insulator (FD-SOI), have proven essential in reducing leakage currents and improving energy efficiency. FD-SOI technology offers enhanced transistor performance and allows fine-grained control of threshold voltages through body biasing. It is particularly suitable for IoT applications that demand ultra-low power consumption.

In addition to energy efficiency, IoT chip design increasingly emphasizes integration. System-on-chip architectures that combine sensing, computation, communication, and power management functionalities reduce system complexity while enhancing reliability and scalability. This level of integration enables IoT devices to meet the growing demands of diverse applications in areas such as smart cities, remote monitoring, and wearable technologies.

IoT chip development will also be shaped by adopting FinFET processes for miniaturization and power efficiency. FinFET technologies below 28nm have shown remarkable potential for reducing leakage currents and enabling operation at lower supply voltages, contributing to energy efficiency and improved performance [1]. The advancements in technology, along with the incorporation of artificial intelligence and machine learning functionalities, are facilitating the development of intelligent Internet

of Things devices. By embedding AI-enabled processing capabilities, IoT chips can perform real-time analytics and intelligent decision-making at the edge, reducing reliance on cloud processing and enhancing privacy, responsiveness, and energy efficiency.

This paper provides an in-depth review of IoT chip architecture, focusing on its core components, key technologies, and future trends. It explores how advancements in semiconductor processes, energy harvesting, and hardware security are shaping the next generation of IoT devices to meet the ever-growing demands of a connected world.

2 The Architecture within the Realm of IoT Chip Design

The architecture of IoT chips acts an important role in deciding their efficiency, reliability, and adaptability to various application scenarios. A carefully designed low-power IoT chip combines multiple functional blocks like sensors, analog front-ends, digital processing cores, memory modules, wireless communication interfaces, and specialized power management units. Each of these components needs to be optimized both individually and collectively to attain ultra-low power consumption while keeping the functionality robust.

2.1 Sensing Units as well as Analog Interfaces

Sensing units serve as the principal connection between IoT devices and the environment in which they operate. Typical sensing elements include temperature, humidity, accelerometers, gyroscopes, pressure sensors, and biometric sensors. These sensors usually interact with analog front-end circuits, including low-noise amplifiers, analog-to-digital converters, and sensor readout circuits. These circuits transform environmental signals into digital formats appropriate for processing [2]. IoT chip architectures integrate event-driven sensor interfaces and wake-up circuitry to reduce power consumption. This enables the device to stay in low-power standby modes until a particular event or threshold is detected, thus considerably lessening the active sensing time.

2.2 The Processing Cores Alongside the Computational Units

The processing architectures utilized in Internet of Things chips predominantly incorporate low-power microcontrollers (MCUs), digital signal processors (DSPs), and application-specific instruction-set processors, which are tailored for enhanced efficiency [3]. The Cortex-M series from ARM and the open-source RISC-V architecture are two processor architectures widely adopted for IoT applications. The cores of ARM Cortex-M have a highly optimized pipeline, possess a relatively small transistor count, and come with an efficient instruction set architecture, and in this way, they can achieve the least amount of dynamic power usage. RISC-V processors present modularity and extensibility, enabling designers to implement domain-specific instructions that can enhance performance efficiency and lower power consumption. Furthermore, specialized hardware accelerators and dedicated co-processors are being

integrated into IoT chips more and more frequently to relieve the burden of computationally intensive tasks, further enhancing power efficiency.

2.3 Memory Subsystems

Memory subsystems have a crucial impact on IoT chips' power and performance characteristics. Non-volatile memory technologies, including Flash, Resistive RAM (RRAM), Ferroelectric RAM (FeRAM), and Magneto Resistive RAM (MRAM), are extensively used in IoT systems. This is because they possess low static power consumption, the ability to retain data without a continuous power supply, and quick wake-up times [4]. Among these technologies, emerging ones like RRAM and MRAM show remarkable energy efficiency, excellent endurance, and impressive scalability. These qualities make them highly suitable for future IoT applications requiring frequent power-off states and intermittent computations [5]. Moreover, memory architectures that incorporate hierarchical caching and intelligent memory management schemes can considerably reduce dynamic power consumption. They achieve this by minimizing the number of unnecessary memory accesses.

2.4 Communication Interfaces and Wireless Protocols

Wireless communication is fundamental to the functionality of Internet of Things chips. The predominant protocols employed in this domain include Bluetooth Low Energy (BLE), Zigbee, Wi-Fi, LoRa, and Narrowband IoT (NB-IoT). Protocols such as BLE and Zigbee, which are specifically designed for short-range communication, are widely adopted due to their ease of use, low power requirements, and effectiveness in environments with a high density of devices. Conversely, for long-range communication with low data rates, Low Power Wide Area Network (LPWAN) technologies like LoRa and NB-IoT have become increasingly favored. This preference is attributed to their extensive coverage capabilities, low power consumption, and their appropriateness for battery-operated IoT devices deployed in remote or challenging locations [6]. The communication interfaces of IoT chips usually incorporate adaptive power control mechanisms and duty-cycling strategies, which help reduce active radio time and extend battery life. These incorporations aim to minimize the active radio time, extending the battery life.

2.5 Power Management Units (PMUs)

Power Management Units (PMUs) are crucial in augmenting energy efficiency. They achieve this by taking charge of voltage conversion and distribution and regulating power states across the whole system. Conventional Power Management Units integrate components such as DC-DC converters, linear regulators, voltage references, and power gating circuits. Sophisticated power management techniques, including dynamic voltage and frequency scaling (DVFS), adaptive voltage scaling (AVS), and power gating, are extensively employed to reduce leakage currents and dynamic power consumption during periods of system inactivity or low activity states [7]. Moreover,

intelligent PMUs include power-aware algorithms that optimize energy usage, considering workload variations, battery states, and environmental conditions.

3 The Essential Key Technologies within the Realm of IoT Chip Design

IoT chip designs use several crucial technologies to attain ultra-low power consumption and robust performance. These encompass advanced semiconductor processes, novel circuit techniques, energy harvesting mechanisms, and hardware-based security implementations.

3.1 The Technologies of Advanced Semiconductor Processes and Devices

Advanced semiconductor manufacturing procedures, such as fully-depleted silicon-on-insulator and FinFET technologies, offer significant advantages for IoT chip design, including lower leakage currents and improved energy efficiency. The FD-SOI technology offers lower leakage currents. It also improves transistor performance. Moreover, it has a superior control over transistor threshold voltages by means of body biasing techniques. All these aspects make it especially fitting for ultra-low-power IoT applications. FinFET processes below 28nm allow designers to reduce leakage currents significantly. They also help enhance energy efficiency at scaled supply voltages [1].

3.2 Methodologies for Designing Ultra-Low-Power Circuits

Ultra-low-power circuit techniques like subthreshold and near-threshold voltage operation, along with clock gating, adaptive body biasing, and power gating, have been researched quite a lot to cut down on both active and standby power consumption as much as possible. Subthreshold operation means that circuits operate at voltages below the transistor threshold, significantly reducing power consumption. This does reduce power consumption quite a bit, though it does come at the cost of a lower operational speed. It is actually quite suitable for IoT applications that need a moderate level of performance while consuming ultra-low amounts of energy [8]. Adaptive body biasing dynamically adjusts transistor threshold voltages in response to performance requirements, thereby reducing leakage currents and improving energy efficiency. These further decrease leakage currents and also boost energy efficiency.

3.3 Integration of Energy Harvesting and Power Autonomy

Energy harvesting techniques utilize ambient energies such as photovoltaic, thermoelectric, kinetic, and radio-frequency (RF) energy to generate electrical power directly on-chip, extending battery life or even eliminating the need for batteries. They manage to generate electrical power directly on-chip. In this way, they can either extend battery life or even eliminate the need for batteries [9]. When efficient rectifiers, power conditioning circuits, and maximum power point tracking (MPPT) mechanisms are

integrated into IoT chips, sustainable energy management can be realized, particularly in energy-scarce IoT deployments. This is particularly suitable for IoT deployments where energy is scarce [10].

3.4 Mechanisms for Hardware Security and Privacy

Security and privacy have become increasingly crucial factors to consider when it comes to the design of IoT chips. This is because there are constantly growing threats and vulnerabilities related to connected devices. Hardware security solutions, such as physically unclonable functions, secure boot mechanisms, and cryptographic accelerators, provide robust security. At the same time, they maintain relatively low energy overhead, making them suitable for IoT applications, as shown in [11].

4 The Future Holds and the Prospects

The future of IoT chip development is marked by a growth in integration, the presence of AI-enabled edge computing capabilities, and the introduction of new semiconductor materials and emerging technologies. These advancements are expected to significantly improve IoT device performance, energy efficiency, security, and application diversity. The growth of integration and System-on-Chip solutions has been witnessed. There is an increase in the level of integration, and at the same time, the development of System-on-Chip solutions is also taking place. These two aspects, namely the enhanced integration and the emerging System-on-Chip solutions, are significant in the relevant field.

Integrating various functionalities like sensing, computation, communication, energy harvesting, and security into single-chip solutions continues to be a key focus in IoT chip development. This kind of integration cuts down on the system's overall complexity, boosts its reliability, lessens power consumption to a considerable extent, and brings down production costs. These aspects facilitate the extensive adoption of IoT technologies across numerous application areas. Future developments are likely to integrate heterogeneous functions, such as RF antennas, power converters, and multi-sensor arrays, onto monolithic silicon substrates to enhance system efficiency and reduce complexity. This will notably reduce the size and complexity of the system. Moreover, when advanced power management and adaptive control circuitry are integrated into IoT SoCs, it will allow for more thoughtful and more efficient use of power, especially in IoT applications powered by batteries and facing energy constraints.

Embedding AI and ML computational capabilities into IoT chips facilitates intelligent analytics and decision-making at the network edge. This, in turn, significantly reduces latency and energy consumption associated with cloud-based processing. Lightweight neural network accelerators, along with optimized DSPs, are increasingly being integrated into IoT architectures. This integration enables efficient local data processing, boosting the responsiveness and autonomy of IoT devices. Looking ahead, IoT chips will incorporate advanced AI features to a greater extent. These features include federated learning capabilities, which allow for collaborative intelligence across distributed IoT nodes without centralized data handling. This

evolution will enhance privacy to a significant degree, reduce communication overhead noticeably, and improve the robustness against network disruptions quite a bit. All of these improvements will make IoT systems more scalable and more adaptive.

Novel semiconductor materials such as gallium nitride, silicon carbide, and graphene demonstrate enhanced electrical, thermal, and mechanical characteristics. These advantages make them superior to traditional silicon-based technologies. These new materials hold the potential for further progress in terms of energy efficiency, mechanical flexibility, and performance, which in turn enables novel forms and applications of IoT devices. Advancements in printed and flexible electronics using organic semiconductors and innovative techniques will drive future IoT applications requiring ultra-thin, flexible, and low-cost devices. This will broaden the range of IoT applications to encompass wearable devices, healthcare monitoring, and ubiquitous environmental sensing. Integrating these new materials and technologies into the commercial IoT chip production processes will necessitate continuous research on manufacturability, optimization of yield, and reliability testing. Tackling these challenges will be of great significance for the widespread adoption within the industry and will ultimately result in IoT devices that are lighter, more compact, flexible, and environmentally sustainable.

In addition, future designs of IoT chips will place more and more emphasis on environmental sustainability. They will make use of eco-friendly manufacturing processes as well as recyclable semiconductor materials. The strategies for sustainably producing and disposing of IoT chips will mitigate their environmental impact. This aligns with the global endeavors towards greener electronics and circular economy models. It is anticipated that such sustainability efforts will become an essential part of the roadmaps for IoT technology in the upcoming decade.

5 Conclusion

IoT chip design lies at the intersection of innovation, integration, and efficiency, enabling the rapid expansion of IoT applications across diverse domains. The optimization of core components-sensing units, processing cores, memory subsystems, communication interfaces, and power management units-has been pivotal in achieving ultra-low power consumption and robust performance. Advanced semiconductor processes like FD-SOI and FinFET technologies have significantly contributed to energy-efficient designs. At the same time, ultra-low-power circuit techniques and energy harvesting solutions address the challenges of energy-constrained IoT environments.

The future of IoT chip development is shaped by three key trends: the growth of System-on-Chip solutions, the integration of AI and ML capabilities for edge computing, and the adoption of emerging semiconductor materials. SoC solutions reduce IoT systems' complexity and power requirements, while AI-enabled chips enhance their intelligence and autonomy. New materials like gallium nitride and silicon carbide also promise further improvements in energy efficiency and scalability. As IoT chips evolve, environmental sustainability will become an increasingly important focus. Eco-friendly manufacturing processes, recyclable materials, and strategies for reducing the environmental impact of chip production will align with global efforts

toward greener electronics. These advancements will enhance IoT device performance and contribute to a sustainable and connected future.

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