CHAPTER 1

INTRODUCTION

1.1 Introduction

One of the driving forces behind the exponential improvement in the integrated circuit design and manufacturing was the relentless pursuit of high-performance SoCs with the reduction in cost per transistor. In this regard, the prediction by Gordon E. Moore, which is now known as Moore’s law, became a strategic roadmap for the semiconductor industry. It also became a reliable source for calculating the trends and setting the pace for future growth. For decades it sets the industry on the path of innovation by doubling the number of the transistor on a chip every two years. The reduction in the device dimension resulted in exciting consequences such as increased transistor on a chip, increased speed, decreased power consumption, improved reliability, and most importantly, reduced cost. At present, Moore’s Law is staggering due to several barriers in the path of continuous technological progress [1]-[2]. The further reduction of the dimension of transistors to atomic scale is not economical. The other benefits associated with scaling transistor dimensions such as performance and energy gain showed only marginal improvement over the previous generations.

On the other hand, there has been a sharp rise in the pervasive systems supported by inexpensive, small, low-power integrated electronics that need to operate for a very long time. These systems provide a way to integrate the physical world with the digital world by connecting humans and objects in the environment. The pervasive sensing and intelligence of these systems are utilized to create a sustainable and smarter environment for humans to live a better life. There are increasing demands for these systems to reduce the human effort during routine tasks, repetitive jobs by taking a cognitive decision based on previous patterns and trends. Further, the need for real-time data monitoring and sensing is constantly increasing to track and manage the usage of various resources. These technological demands and advancements have converged to give rise to a new era called the ‘Internet of Things’ that offer unprecedented opportunities to benefit mankind. As a result, these next-generation systems emerge as new driving force for the semiconductor industry to develop technologies to match the fast pace of the evolution of the Internet of Things.

1.2 Emerging Smart Applications: Overview of Internet of Things

The concept of IoT was originated around 1999 from a network of radio frequency ID (RFID). Since then, the Internet of Things is constantly evolving, and today, it encompasses cyber-physical-social systems that seamlessly embed themselves into the everyday life of human beings. The current definition of the Internet of Things (IoT) includes any physical object embedded with sensors, actuators, software, and network connectivity to enable the exchange of information without human intervention [3]. In the IoT sense, these objects are called 'Things', where things can include people, animals, toys, vehicles, home automation appliances, buildings, heart monitoring implants, weapon assisting fire-fighters in search and rescue operation. They have the capability to sense the physical data, process and analyze it, and finally communicating it via the internet [4]. The network connectivity in smart devices also provides the benefits of remote access and control. Things in IoT are characterized by the three A's. First is awareness, i.e., they must collect information from the surrounding. The second is autonomous, i.e., they must communicate with each other without human intervention. Finally, the third is action, i.e., they can be made to act by remote user [5].

IoT is constantly trying to bridge the gap between the digital world and the physical world through its pervasiveness, networking, computing, and unprecedented real-time monitoring of the human world. The raw data collected from the IoT devices can be converted into useful information by identifying patterns and trends. The information/data collected from the different sources are combined to form knowledge. Thus, more data leads to more knowledge which helps in developing more intelligent machine learning applications. In addition, its real-time analysis will enable optimized behavior resulting in a resource-efficient network [6]. The devices or edge nodes in IoT infrastructure helps in increasing the amount of data to process. According to the International Data Corporation (IDC) estimate, the total data generated by the IoT devices in the year 2025 will be 79.4 zettabytes. Moreover, the data collected by these devices is much different from data collected by humans as it is much more accurate and detailed. It allows a better understanding of the world around us, creating opportunities to improve lifestyle, learning, and working [7].

IoT can be defined as infrastructure that enables the exchange of information over the internet between various connected physical devices. The overall architecture of the IoT can be divided into three layers. The bottom layer is made up of small physical devices with sensing and communication interfaces to monitor the physical world. These devices form the core of IoT, and they are known as ‘IoT nodes’ or ‘edge devices’ or ‘end devices’. The middle layers consist of gateways and concentrators, which collect the data from several IoT nodes and routes them to the servers for further computation. The topmost layer constitutes of server, which analyzes the data and extracts useful information. With the Internet of Things gaining popularity in monitoring environment applications, security & surveillance, resource management, and healthcare, the number of devices/edge nodes in IoT network is continuously increasing and is expected to reach more than 100 billion by 2050, as illustrated in Figure 1.1 [8]-[9]. Due to its large number and ubiquity, IoT offers numerous possibilities to build a better future.

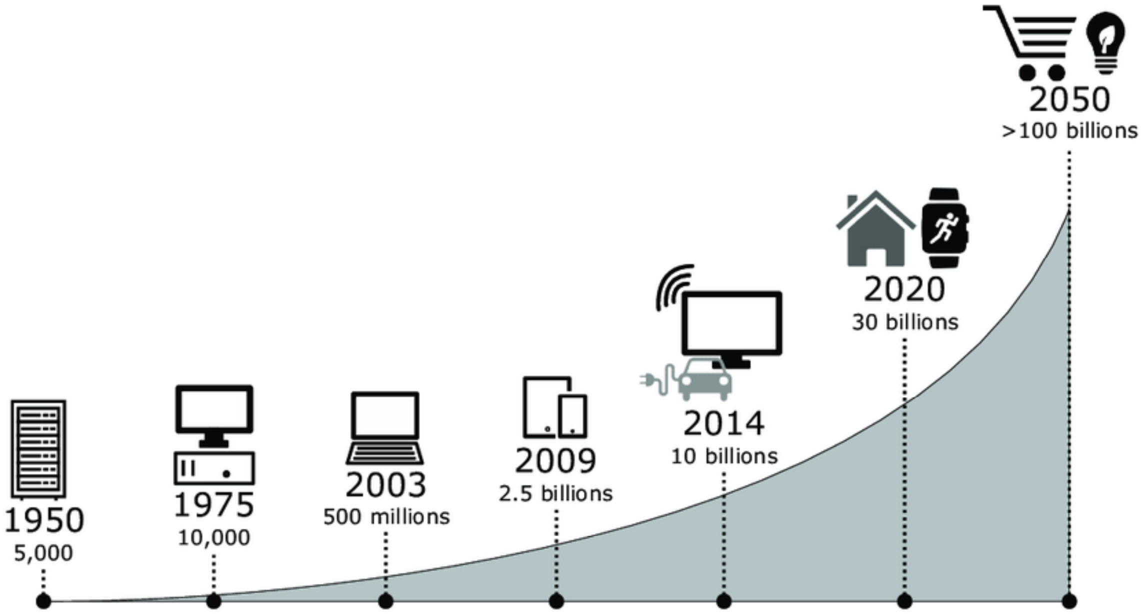

Figure 1.1: Number of connected devices in the IoT Network [9]

1.2.1 Global Market of IoT

With the technological development and rise of data analytics in the IoT, the global market of IoT is expected to reach a worth of USD 1386 billion with a compound annual growth rate of 10.53%. The wave of digital transformation flued by the IoT brings a revolution of intelligent connectivity across the whole world. The rapid growth of IoT sector is mainly due to increased demand of smart solution which aims to ease the operation and reduce the human efforts. The miniaturized devices are embedded with a smart sensor that can collect real-time monitoring data related to the surrounding environment. The data is then analyzed and transmitted through the internet for better functioning. Adopting smart and intelligent devices that offer reliable, accurate, and predictive solutions to the user is one of the key drivers for the IoT market expansion. Moreover, the solutions provided by the IoT can also help the industry in gaining larger economic profit. IoT aims to enhance the customer experience with smart and intelligent services which integrate data analysis and analytics. On the other hand, it provides useful insight into product performance and customer behaviors, which helps in predictive marketing. Additionally, smart cities, smart homes, and connected infrastructure projects enhance the penetration of smart objects into the physical world, which further helps to boost the market. Based on the survey, nearly 50% of the current population lives in the city, and this number will increase significantly by the year 2025. The proper management of the city and providing a better life to humans require a smart and intelligent solution. Due to the rising demand of smart cities, there is a shift towards projects investing in IoT-based solutions. Several companies such as IBM, Intel, and Cisco are investing heavily in IoT-based services. Recently, Cisco announced the use of 5G cellular spectrum for IoT devices which will help in improving the network connectivity of these IoT-based solutions [10]-[13].

1.2.2 Prospective Applications of IoT

The large number and ubiquitousness of the IoT have led to its inclusion into aspects of our everyday life [13]-[15]. The services provided by the IoT can be used to develop smart applications and new products for various application domains such as agriculture, industry, healthcare, consumer electronics, energy management, structural health monitoring, transportation, telecommunication, entertainment etc. which would improve the quality and productivity of the life. Some of the potential applications are summarized in the following sub-section:

- *Healthcare:* With the help of IoT-based services and applications, a deeper understanding of human health can be developed. The wearable or implantable IoT nodes provides a way to constantly monitor the vital of the person and send an alert in case of any abnormal behavior. Moreover, the data collected from patients worldwide gives an opportunity to build models and tools for early diagnosis and treatment. Additionally, the data is used for developing drugs that are efficient and effective to a large scale of patients. The IoT-based remote monitoring also contributes to the enabling of medical care for the elderly and disabled people and maintains their independent lifestyles while constantly monitoring their health status. It reduces the cost by avoiding frequent trips to the hospital and round-the-clock human supervision. Further, the medical equipments can be optimally shared among different healthcare centers, thereby increasing their reach to benefitting the entire community. The people away from the direct medical/clinical care can also be remotely supervised [14].
- *Agriculture:* The IoT-based solutions can develop an efficient framework for precision

agriculture and livestock monitoring. For example, IoT-based smart agribots can monitors the growth of the crops, assure quality, optimize the resources and avoid economic and ecological loss by using predictive management and actions. These solutions monitor the physical parameters such as soil type, humidity, temperature, and environmental parameters such as climate, rate of evaporation, rainfall using a large number of heterogeneous sensors. The collected data, and knowledge from agricultural science determine the stage of the crop and the right time to harvest. Further, weeding robots, with the help of image processing techniques, can detect the weeds and carefully remove them without harming the crop itself. It can also be used to detect any plant-based diseases which might reduce the yield of the crop. IoT-based robots with sensors and actuators for movement and control can be used to perform sowing, ploughing, and harvesting tasks. Recently, drone-based IoT services are also revolutionizing the agriculture industry. Using drones, agricultural areas can be effectively and efficiently monitored. They can be used to reduce the time required to spray pesticides over a large area. They are also used to create 3-D maps of the land, which helps us plan important tasks such as seeding. In addition to the monitoring and harvesting of crops, the IoT also helps in the efficient management of the warehouses [15].

- *Automobile Industry:* IoT is one of the biggest driving forces behind the revolutionization of the automobile industry. With the technological support from IoT-based services, the vision of driverless cars is now becoming a reality. The advanced car diagnosis, collision detection system, voice command systems are improving the quality and safety of the vehicles. The inter and intra-vehicle communication are used for real-time monitoring, which helps us determine the state of the vehicle, including locking mechanism, braking system, wipers, headlights, etc. It also reduces the chance of accidents thereby enhancing the safety of the driver by monitoring various obstacle on the road and adjusting speed of the vehicle based on the certain thresholds. Additionally, the IoT capabilities can further be utilized for car sharing services with multiple users sharing the cost. The pricing for the different pathways can be dynamically adjusted based on the real-time traffic and congestion on the road. The transportation of dangerous goods like flammable liquids and chemicals can also be optimized using the previous data and trends to find the path and time with minimum obstructions. Overall, IoT promises to enhance the existing technology by providing a low-cost solution to some advanced diagnostic and prediction management systems [16]-[19].

- *Consumer Electronics:* The increased demand for smart devices in everyday life have resulted into tremendous growth of consumer IoT. The consumer electronics rely heavily on intelligent system that offer new services such as smart health tracking, and smart home, hence improving the quality of life. The large number and ubiquity of IoT nodes allow them to sense objects and human and take the required action in case of any potential danger. For example, a smart implantable device tracks the increased blood pressure and alerts the individual to take the required steps. The devices can be used for personal care and supervision, for example, reminding a doctor's appointment, inculcating positive behavior in children. Smart refrigerators can track finished good and order by themselves. Smart clothing can suggest cleaning based on actual use. Smart toys can sense the environment and turnoff in presence of toddlers to prevent. Smart homes are equipped with more sophisticated management system to dynamically control their operation without human intervention [20]-[21].

- *Energy Management:* Energy management in smart cities can be made more effective using the IoT. IoT offers unprecedented opportunities to sense and understand the scarcity of resources. The planning of resource distribution to a large number of users can then be optimized based on the usability and requirement of the user. Additionally, IoT helps in better planning, coordination, and distribution of alternative energy sources, thereby enhancing the efficiency of overall utilization of the power [22]-[23].

1.2.3 Design Requirement of IoT

The design requirements of the IoT nodes are very different from the existing internet-connected devices such as smartphones, personal computers because of the distinctive characteristic of these devices [23]. The design requirement in terms of form factor, energy budgets, computational capability, safety and security, interoperability are discussed as follows:

- *Physical Size:* The miniaturization of the edge devices is extremely important to achieve true pervasiveness and invisibility to the end-user. The small form factor in range of a few cubic millimeters to a hundred cubic millimeters is required to achieve non-obtrusive deployment of these devices into our living environment.

- *Cost:* The future prediction regarding the IoT is that an average consumer will have thousands of IoT nodes surrounding them compare to few smartphones and personal computers. Therefore, the cost expectation of these devices is as low as 1 dollar.

- *Power budget:* The IoT edge devices are generally employed untethered because powering billion of devices with cord would populate the earth with webs of cords. They rely on battery or energy harvesting for their power source; hence their power budget is very small. For a very small IoT system with an energy harvester, the power budget could be as low as a few uW.
- *Computational ability:* The traditional IoT nodes are meant for only sensing the data and transmitting it over the internet. However, with the increasing demand for real-time surveillance applications, smartness or intelligence is bought closer to the edge devices. Additionally, pre-processing the data reduce the volume of data to be transmitted to the cloud.
- *Security:* The IoT devices are more vulnerable to attacks since the traditional cryptography algorithm used for safety in existing internet-connected systems can not be employed due to their stringent power requirements.
- *Inter-operability:* The IoT devices from different vendors should be able to work cohesively without the user worrying about interoperability. The semiconductor companies need to work in a close partnership to standardize the hardware and software design specifications.

1.3 Self-Powered IoT using Energy Harvesting

With the number of smart devices increasing exponentially, the biggest challenge faced by the IoT network is powering countless nodes. Additionally, it is essential to identify different power and lifetime requirements of the IoT devices used for various applications. Therefore, based on the power and longevity requirements, we can group IoT devices into four categories. The first group of IoT devices, also called Type-I devices, constitutes smart wearable devices such as smart watch, fitness tracker bands, etc. Based on the form factor, cost, and user requirement, various lifetime options can be provided. Since users are likely to own a few of them and can quickly recharge them, a lifetime of several weeks is suitable for these kinds of applications. The second group of IoT devices, also called Type-II devices, are smart sensor nodes deployed in homes and buildings like shopping malls for automation purposes. These devices are often called set-and-forget devices because they must operate for several years after deployment. In the case of battery-operated devices, a frequent battery replacement causes great inconvenience. The third group of devices, referred to as Type-III devices, are also sensor nodes deployed mainly for surveillance purposes in smart cities, such as parking lots, highways, and bridges. They are commonly called semi-permanent devices due to their longevity requirement of more than a decade. These devices are distributed over an area in a very large number, making the battery replacement tasks merely impossible. Finally, the fourth group of devices, known as Type-IV devices are RFID cards that extract power from the surrounding environment [7]. The majority of the IoT devices cannot be powered by a cord because that would populate the earth with web of cords. Also, it will increase the expense of employing them. Sometimes it is even infeasible to wire them due to remote locations or human inaccessible locations. With limited battery capacity, achieving longer lifetimes without frequent battery replacement becomes even more challenging [24]. In addition to the cost of new batteries, there are costs incurred during system downtime. Also, battery disposal has a hazardous effect on the environment as well as humans. More than 15 billion batteries are produced and sold all over the world every year, and many of them are discarded after a single use [25]. Environment Protection Agency reports that 3 billion of batteries are discarded every year by the USA alone, which would encircle earth six times when placed end to end. Therefore, disposal of depleted batteries is another issue for sustainable growth of IoT.

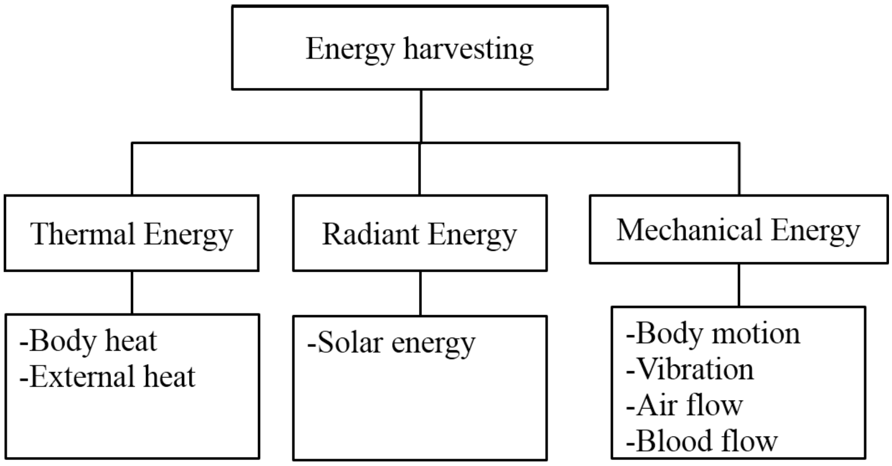

Figure 1.2: Sources of energy harvesting

Over the past decade, energy harvesting has emerged as an attractive and increasingly feasible option to address the power supply challenge in a variety of low power systems [26]. The use of energy harvesting significantly prolongs the overall system lifetime and has the potential to result in self-powered and perpetual system operation for IoT devices. Energy autonomy offers the advantage of a theoretical infinite lifetime and reduced post-deployment maintenance cost, which is mostly suitable for set-and-forget and semi-permanent devices

[27]-[32]. An energy harvester powers energy-autonomous or self-powered devices by converting thermal, radiant, mechanical energy into electrical energy, as illustrated in Figure 1.2 [27]. For example, kinetic energy harvester converts mechanical energy sources like body motion, vibration, airflow, blood flow, etc., into electrical energy [33]. They are suitable for wearable which can scavenge energy from human motion or devices attached to vibrating body. Pavegen [34] is a kinetic energy harvester that scavenges energy from the footstep. It can be installed on the sidewalk, crossover bridge, footpath, etc. Radiant energy harvester converts solar energy and RF energy into electrical energy. RF energy harvester is mainly used in an RFID system. These RF waves can be generated by a dedicated wireless charger or any RF signal used for wireless transmission like TV signals. On the other hand, solar energy is most widely used because of its higher efficiency (high power density). It is one of the more mature and well-studied harvesting techniques. Flood Beacon [35] is a solar energy harvester that can be integrated with wearable or cloths to harvest solar energy. Thermal energy harvester converts the gradient of temperature between two surfaces into electrical energy. These thermoelectric generators are more suitable for devices in contact with a hot surface. The choice of ambient sources depends upon application, operating environment and power budget. Nonetheless, the target of self-sustaining IoT node is still far away because of many challenging barriers. Some of these challenges are discussed in the following sections.

1.4 Challenges faced by the Energy-Autonomous IoT nodes

1.4.1 Increasing Static Power Consumption

Most of the sensor nodes in IoT network have burst mode of operation where they operate for only a short period of time (few ms) followed by a long period of inactivity (tens of seconds) as shown in Figure 1.3.

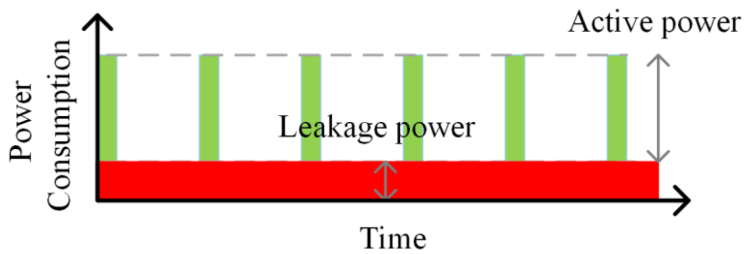

Figure 1.3: Burst mode operation characteristic of IoT devices

Since significant portion of their time is spent in idle mode, the energy consumption during the idle mode often becomes a performance bottleneck for these energy constraint devices [23]. The issue of large standby power consumption is further exacerbated due to increasing leakage current by continuous scaling of CMOS technology. For decades, dimensions of the transistor are scaled to achieve low-cost and high-performance SoCs. Moreover, to reduce the power consumption and increase reliability, supply voltages are also reduced. However, to maintain the performance gain and reasonable gate drive, the threshold voltage of the transistor needs to be scaled. As a result of lower threshold voltage, there is an exponential increase in the subthreshold leakage currents. Furthermore, a high tunneling current is observed in these short channel devices due to smaller oxide dimensions. In addition, high substrate doping is used in scaled transistors to mitigate the short channel effects, which significantly increase the leakage current through the drain-substrate and source-to-substrate junctions under high reversed biasing. The three major types of leakage current are: subthreshold current, gate-oxide tunneling current, and reverse bias junction current, which significantly impact the performance and reliability of the device [36]-[39]. In addition to these three major leakage current components, there are other leakage currents such as gate-induced drain leakage and punch-through current. However, for the sub-nanometer regime, leakage current is dominated by subthreshold leakage, gate-oxide tunneling leakage, and reverse-bias junction leakage currents.

- *Subthreshold Current:* The current between the source and drain during the weak inversion region, i.e., when the gate voltage is less than the threshold voltage, is referred to as subthreshold current. In general, the source-to-drain current has two components: drift current and diffusion current. The drift current is dominant during the strong inversion region due to the presence of a high electric field between the source and drain. On the other hand, a small longitudinal electric field between the source and drain during the weak inversion region causes carriers to diffuse between the two regions. Therefore, the sub-threshold current in the weak inversion region is dominated by the diffusion current. The sub-threshold current varies exponentially with gate-to-source voltage and threshold voltage. With shrinking transistor dimensions, the source, and drain depletion region advance significantly into the channel. As a result, the electric field and potential profile of the transistor are impacted. These effects are known as short channel effects (SCE). The short channel effect reduces the threshold voltage, thereby significantly increasing the sub-threshold current for the short channel devices.
- *Gate Oxide Tunneling Current:* Oxide thickness is reduced to control the increasing Vth roll-off and DIBL short channel effects in sub-nanometer devices. Consequently, a high electric field is formed that gives rise to a tunneling current through the gate insulator.

This tunneling current from the bulk and source/drain overlap region to the gate through the gate oxide is referred to as gate oxide-tunneling current. The tunneling of the carriers happens due to two different mechanisms: 1) Electron conduction-band tunneling: electrons in the conduction band of the substrate tunnel to the conduction band of the gate, 2) Electron/Hole valence-band tunneling: electron and holes from the valence band of the substrate tunnel to the conduction band of the gate.

- *Reverse pn-junction current:* The MOS transistor has two pn-junctions: drain-substrate and source-substrate pn junction. These pn junctions are typically reverse-biased, causing a reverse leakage current through them. The reverse bias leakage current depends upon the junction area and doping concentration of 'p' and 'n' regions. As doping concentration increases in the scaled devices, heavily doped 'p' and 'n' results in a band-to-band tunneling leakage. Moreover, a high electric field across the junction causes electrons to tunnel from the valance band of p-region to the conduction band of n-region, resulting in high reverse p-n junction current.

1.4.2 Unsteady Power Supply

The autonomous energy systems harvesting energy from the ambient sources suffer from the unsteady and uncertain power supply, which causes frequent and unpredictable power failures. As a result, devices are suddenly turned off, leading to loss of current state. Moreover, waking up is a very energy costly process that requires a boot process for re-initializing the state of the system. Since the boot process requires thousands of processor cycles, hundreds of microseconds, and hundreds of nanojoules of energy, it becomes limiting in a real-time application where quick wake-ups are required. Thus, the effective measure has to be taken to ensure reliable operation [7].

1.5 Normally-OFF Computing

Most low power systems address large standby power consumption by employing a sleep mode with lower power consumption than the active mode. During the sleep mode, on-chip memory elements are typically powered-on to retain the state, which results in significant power consumption. Addressing this challenge, in normally-off computing, the system is put into deep sleep mode, which turns off the on-chip memory component to achieve nearly zero power consumption. However, doing so requires checkpointing the current state of the system to non-volatile memory (typically flash). The following presents some of the techniques utilized to save the state before entering into deep sleep mode:

- *Periodic Checkpointing:* In this technique state of the system is periodically checkpointed to off-chip non-volatile storage. To retrieve the complete state of processor status of register file, program counter, instruction cache, data cache, and memory is required. Therefore, all of them should be preserved before power loss. More frequent checkpointing prevent rollbacks to the beginning after waking up [42]. In this technique, an instruction counter is utilized to count the number of instructions between two backup operations. A flag assisted with the instruction counter can indicate the start of backup operation. Further, to reduce the number of states to be backed up, a selective backup could be performed where backup of only changed data is performed. This data change is indicated by a flag bit which incurs additional overhead [43]. Alternatively, data compression circuits can be utilized to compress the data before backup. After a fixed number of instructions, the flag bit is raised, triggering the backup operation. This method has the advantage of simplicity, but it lacks the flexibility to adjust the backup interval according to the power profile [44].
- *On-Demand Backup:* It performs the backup operation only when it is required, thereby saving the energy wasted in unnecessary backups. This method requires early prediction of power failure, which can be done by constantly monitoring the power level, and once the power is below some threshold value, it triggers the backup operation [45]-[46]. Another alternative is an additional energy storage unit. A storage unit can have a small battery or capacitor. Since capacitor offers smaller area and unlimited charging and discharging, they are preferred over batteries [47]. When the energy harvested is more than required by the processor, the extra energy is saved in this storage unit. The probability that the energy harvested is greater than the energy required to run the processor is high when system complexity is less. In the absence of ambient sources, a signal indicating power failure starts the backup operation using energy stored in the capacitor. The decision of which element is backed up to external off-chip nonvolatile storage depends on the capacitor capacity. Not all the elements require backup, some of them can be recalculated as the energy required to store a state onto off-chip memory is large. Nevertheless, recalculating the results have energy and time penalties resulting in longer wake-up times. Thus, there is a tradeoff between the energy required to back up and wake up times. For reliable operation, there should be a gap between two successive power failures. This gap depends on the time required to charge the capacitor to be enough energy to perform the next backup operation [48]. Thus, a system holds the recovery

process so that capacitor can accumulate energy for reliable next backup operation. An ideal sleep mode should consume nearly zero power consumption and yet retain state with the ease of transitioning in and out of sleep. However, the overall energy cost of data retention when the state is saved to an external off-chip non-volatile memory (FLASH) is very high. Therefore, more efficient solutions are required to mitigate the standby leakage power consumption without the significant overhead of data retention.

1.6 Asynchronous Circuit

In recent times, increasing power consumption in synchronous systems poses a serious challenge for the IoT application to meet the strong constraints of power consumption. The drastically increasing dynamic power dissipation is attributed to the large switching activity and globally distributed clock. Moreover, the clock distribution over a large number of blocks is becoming more and more challenging to manage. The fine-tuning of clock skew and jitter to ensure timing closure and proper functionality is also difficult to achieve at lower technology nodes. Additionally, while the worst-case delay path is computing in synchronous designs, all the other paths remain active and consume static power. Since IoT systems stay idle for a long time, they suffer from large static power consumption. To address these challenges, asynchronous design is one of the most efficient solutions which provide lower power consumption due to the elimination of clock tree. They show event-based behavior and consume power only if an event needs to be processed. Therefore, the part of the circuit not active consumes almost zero static power, which lowers the total power consumption. The automatic sleep mode of the asynchronous circuit is highly beneficial for IoT applications that spend a significant portion of their time in idle mode. In addition to lower power consumption, the asynchronous circuits are robust to a wide range of variations in the temperature, process, and supply voltage, making them potentially suitable for energy-autonomous IoT applications [49]-[53].

1.7 Energy-Efficient Computing for IoT Applications

IoT-based smart devices are gaining popularity over a wide range of application domains such as monitoring environment applications, security & surveillance, resource management, and healthcare. As a result, a huge surge in the number of devices connected to the IoT network is observed in recent times. Consequently, the amount of data generated also increases exponentially. According to the International Data Corporation (IDC) estimate, the total data generated by the IoT devices in the year 2025 will be 79.4 zettabytes. The processing of such an enormous amount of data is challenging for the conventional computing system. Therefore, it is essential to find an energy-efficient solution to keep pace with the emerging loads. In recent times, approximate computing has emerged as a potential solution for low-power IoT. It is based on the fact that many real-time applications such as multimedia, wireless sensors, data mining, and search engines can produce an output of acceptable quality even though the computational accuracy is low [54], [55]. This ability to relax computational accuracy requirements is leveraged to simultaneously improve the area, delay, and power metrics. Several methodologies have been proposed to implement approximate computing either at the hardware level or software level. Techniques like early termination of algorithms and dynamic data-width are employed at the software level to realize approximate computing. On the other hand, techniques like voltage overscaling technique are employed at the hardware level to achieve a significant power saving. Researchers have recently shifted their focus on designing logic functions at the circuit level to realize approximate computation for power-constraint IoT applications. Therefore, in this work, we explore the possibility of utilizing the emerging magnetoresistive device to design an energy-efficient logic and arithmetic function to achieve low power operation for computationally intensive applications.

1.8 Thesis Contribution

In this thesis, we propose various design techniques to address the challenges of increasing standby power consumption, and unstable power supply in emerging energy-autonomous IoT applications. We exploit the low-power, fast switching, and CMOS compatibility characteristics of the emerging magnetoresistive device to develop non-volatile hybrid memory for on-chip data retention, non-volatile hybrid asynchronous circuit for low-power pipeline and non-volatile logic and arithmetic circuit for energy-efficient computing.

- **Hybrid Static Random-Access Memory:** We first develop low-power non-volatile hybrid SRAM cell (Hybrid 7T, Hybrid 8T, Hybrid 11T SRAM cells) by integrating emerging magnetoresistive device with the conventional SRAM cell. The proposed cells offer zero standby power consumption, state retention during the power-off period, and quick wakeup time.
- **Hybrid Multi-storage Memory:** We also develop multi-storage hybrid SRAM cell for multi-context applications, which can simultaneously store multiple bits of data, each corresponding to different contexts. To further reduce power consumption, we design a

write assist circuit, which is augmented with the hybrid SRAM cell to allow bit-wise monitoring and termination of write operation.

- **State Retentive Hybrid Flip-Flop:** We modify the conventional D flip-flop to design a state retentive hybrid flip-flop by using the emerging magnetoresistive device to eliminate the standby power consumption. The proposed flip-flop offers data retention before the power-off period and ensures quick wake-up by reducing restoration time.

- **Hybrid Asynchronous Circuit:** We propose to combines the asynchronous design techniques with the emerging magnetoresistive technology to overcome the challenge of large power consumption and sudden power failure faced by energy-autonomous systems. We design non-volatile hybrid c-element and half-buffer asynchronous circuits which offer ultra-low-power operation during active mode and data retention during power failure.

  Energy-Efficient Logic and Arithmetic Circuit: We develop energy-efficient logic gates and arithmetic circuit using emerging magnetoresistive device (spin transfer torque-magnetic tunnel junction), which offers the advantage of lower power consumption.

1.9 Thesis Organization

The thesis is organized as follows:

Chapter 1 gives an overview of the requirements and application areas of the emerging application. It also outlines the challenges faced by the system to meet the requirement of ultra-low-power operation.

Chapter 2 provides a detailed literature review on traditional memories such as static random-access memory, flip-flop and FLASH. It presents various existing solutions for the low power memory design, including alternative bitcell architecture, modifications to the peripherals circuits and assist circuits. It also reviews alternative computing methods to improve the energy efficiency of logic functions in energy-limited IoT applications.

Chapter 3 presents the design of hybrid SRAM cell for normally-off applications. The various operational modes of the proposed cell are discussed in detail. The exhaustive circuit analysis is performed using multiple key performance parameters including read/write energies, access times and noise margins. The comparative analysis with conventional 6T SRAM cell and the existing hybrid SRAM cell is also performed.

Chapter 4 presents the design of hybrid multi-storage SRAM cell for multi-context computing applications. The design of write assist circuit is also presented which helps in further reduction of power consumption. The proposed multi-storage SRAM cell is analyzed using key performance parameter such as energy consumption and latencies.

Chapter 5 presents the design of state-retentive hybrid D flip-flop, which offers zero standby power consumption. We analyze the proposed design with key performance parameters such as power dissipation during active and standby mode, propagation delay, and data restore time. We also perform a comparative analysis of proposed state retentive hybrid flip-flop with the existing state retentive flip-flops.

Chapter 6 explores the design of asynchronous circuit as an alternative approach to achieve ultra-low operation. We present design of power failure resilient hybrid c-element and half-buffer circuits. The proposed designs are analyzed in terms of power consumption and delay.

Chapter 7 present the design of energy-efficient logic and arithmetic gates. The design of basic logic gates such as NAND, NOR, AND & OR are presented. Further, using the proposed logic circuit, basic arithmetic function is developed to achieve energy-efficient computing in IoT systems.

Finally, Chapter 8 presents the summary of the work demonstrated in this thesis, by including key findings and important observations, and also discusses possible directions for the future work.

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