Revisiting the Frontiers of Analog and Mixed-Signal Integrated Circuits Architectures and Techniques towards the future Internet of Everything (IoE) Applications

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Contents

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ABSTRACT

People-to-people (P2P) technology-assisted interconnections, embedded in a global environment, will be at the core of 21st century communications and will command the technological development of the future. The Internet-of-Things (IoT) comprises only machine-to-machine (M2M) communications handling only data and things. Expanding itself beyond IoT, the Internet-of-Everything (IoE) also incorporates intelligently the interaction of people and process (providing

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at a precise moment the correct knowledge to the exact person/machine).

In general, IoT comprises all physical or cyber objects (things) with an address that can transmit information without human-to-machine interactions (data), while the IoE also involves communications (processing) among the users (people) and the whole universe of electronic gadgets. Further, they both operate with data acquired from analog sources, thus connecting two different realities, the analog (physical/real) and the digital (cyber/virtual) worlds. Since the interface between the two realms deals with analog signals, its mandatory functions involve sensing, measuring, filtering, converting, processing, and connecting, with the accuracy and precision of the analog layer ruling the entire system. Such interface integrates several analog and mixed-signal subsystems that include signal sensing, transmission and reception, frequency generation, energy harvesting (EH), in-memory processing, and data and power conversion.

This paper presents state-of-the-art designs of the most critical building blocks of the analog/digital interface highlighting new and innovative circuit architectures and techniques. It addresses capacitive sensor interfaces, ultra-low-power wireless transceivers, key technologies for wireline transceivers, oscillators and frequency generators, integrated energy harvesting (EH) interfaces, in-memory processing, as well as, data and power converters, all exhibiting high-quality performance with low power consumption, high energy-efficiency and high speed, thus enabling a reliable and consistent development of the IoE while enlarging its frontiers.

1

Introduction

At first sight, most people think that the Internet-of-things (IoT) and the Internet-of-everything (IoE) are just distinct definitions of the same technology and they use both designations indistinguishably. However, although they share similar characteristics, the two conceptualizations are quite different.

1.1 The Internet-of-Things

In the history of IoT, an important reference in its origins is Kevin Ashton who worked at Procter & Gamble when he stamped the term for the first time in 1999 during a presentation where he analyzed the higher efficiency in the management of supply chains when controlled by a network-connection of RFID-enabled devices. Initially, his idea was just to incorporate "Internet" in the title to stimulate the attention of the audience, but afterward the designation of IoT spread to everything that had internet connection among devices that sensed and shared data without human intervention, interaction also known as machine-to-machine (M2M) communication [8, 9, 10] (Figure 1.1).

Human behavior toward technology forced a frantic development of IoT that explored the great advances in hardware and software,

Figure 1.1: Internet-of-Things — Visualization concept by Ashton [10].

constantly evolving with plummeting costs. The continuous emerging of new state-of-the-art elements led to the transfiguration of the marketing and delivery of products, goods, and services, with an enormous impact in all aspects of our daily social and economic life. With the utilization of IoT, the users can enjoy a more sophisticated and systematic analysis with larger integration and complete automation, only possible with the access to current and emerging technology for sensing, networking and robotics. Besides, it also significantly enlarges the accuracy and outstretch to all areas.

The IoT links the backbone of connectivity (Internet) with the physical or cyber objects (Things) that gather and swap data across wireless networks, empowering the internet virtual world, the handling and systematic analysis of data, plus the decision-making process, with the real world of physical objects. The most important components/characteristics of IoT include sensors, connectivity, artificial intelligence, active engagement, and small devices. Without sensors, the IoT loses its significance because they are the meaningful tools transforming a normal passive grid of devices into an active network accomplishing real-world integration. In addition, new technologies enable innovative, practical, and efficient networking in a smaller and cheaper scale than the usual exclusive web provided by major suppliers. On the other hand, artificial intelligence can convert everything virtually into a smart gadget strengthening our daily activity with the power of databases, artificial intelligence algorithms, and networks. Furthermore, the usual interaction with connected technology involves mainly passive engagement of the objects while IoT allows a paradigm shift with the introduction of active contents derived from the product or the service commitment. Finally, since the devices become smaller, cheaper, and more powerful, the IoT can constantly explore innovations like, for example, purpose-built small devices that can lead to more precise, highly scalable, and extra flexible networks.

1.2 The Internet-of-Everything

Apparently, the designation of IoE materialized in 2013 and was coined by CISCO, although the company claims that other technology companies, for example Gartner and Qualcomm, started to use such a term simultaneously (Figure 1.2). Independently of that, their definition clearly states: "*The IoE is bringing together people, process, data, and things to make networked connections more relevant and valuable than ever before — turning information into actions that create new capabilities, richer experiences, and unprecedented economic opportunity for businesses, individuals, and countries.*"[1]

Ordinary people, but also technical experts, in academia and industry, consider IoE as the subsequent development stage of IoT, classified as a complete ecosystem that interconnects through the Internet, devices, consumers and products with extended digital intelligence and versatility. Then, IoE constitutes a broader concept that accentuates, besides the

[1] Cisco, 2013; https://www.cisco.com/c/dam/en_us/about/ac79/docs/innov/IoE_Economy_FAQ.pdf.

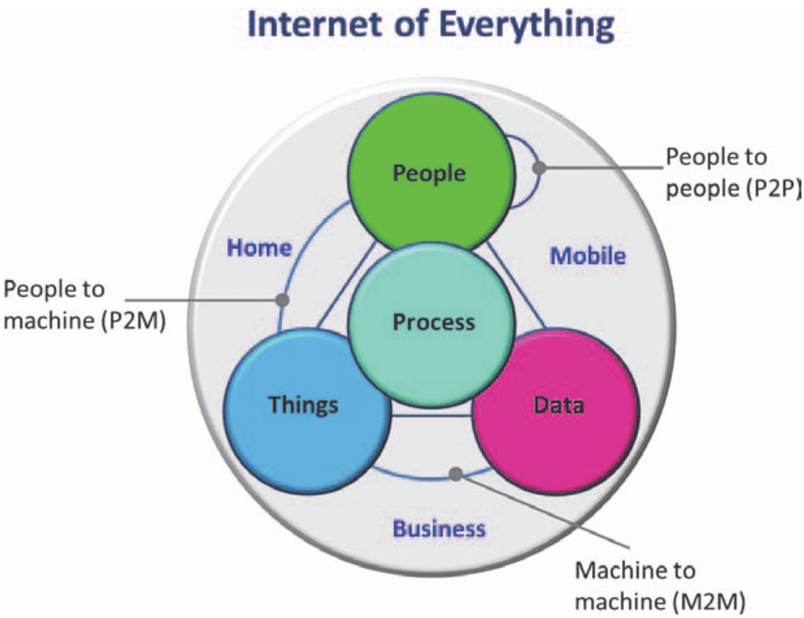

Figure 1.2: Internet-of-everything.
Source: Cisco (https://www.cisco.com/c/dam/en_us/about/ac79/docs/innov/IoE_Economy_FAQ.pdf).

important M2M, also the technological communication of people-to-machine (P2M) and people-to-people (P2P). Such a worldwide network notion that encompasses everything exhibits large benefits and has a great impact in the intelligent online connection of four crucial components: people, process, data, and things.

People, are the fundamental element of IoE because they add the intelligence to the connection by using the devices all the time, through the constant analysis and manipulation of data. Besides, people are key in P2P and P2M communications and can even possess sensors allowing them to serve as nodes in M2M communications. Process, determines how the elements of the network (Internet, either wired or wireless) operate with everything adding high value to the cyber/digital world, then, the success of the overall operation lies in the correct collection of data and transferring it to the right people at a precise moment.

Data, is a very sophisticated element of IoE that alone is purposeless, however, its rigorous analysis and efficient management leads to swift and intelligent decision-making. Finally, things equipped with sensors and linking people or networks are the building blocks of IoE, allowing the connection of devices that convene and share information among each other through the Internet. The number of connected devices already embedding some electronic intelligence in 1984 was 1 thousand, in 1992 jumped to 1 million, skyrocketed in 2010 to 10 billion, and currently, it is estimated at more than 50 billion! This ultra-complex infrastructure with ubiquitous sensing and control capability over a broad number of devices provided by the IoE significantly simplifies our daily life and increases productivity, although it requires a constant update in terms of performance of state-of-the-art electronics, with a high pressure for the development of computer chips or integrated circuits (ICs). Current developments of portable wireless IoE systems are able to keep efficiently trillions of gadgets constantly online and urgently call for more advanced ICs, at the core of information and communication technology. Besides the low-power and low-cost requirements, it is necessary to self-power such chips through energy harvesting (EH) that dictate highly efficient fully integrated power solutions to relieve the efforts of battery replacement. Furthermore, new solutions should eliminate off-chip components allowing multifaceted structures composed of small-scale devices.

1.3 IoE/IoT Major Areas of Applications

In this new era of ubiquitous communications, many companies worldwide use IoE/IoT technology for automation and simplification of their business processes. Their application in major areas of the economy relies on the capability of adaptation to any type of environment able to supply the appropriate data about its operation and performance, thus allowing remote observation and control. Here, we briefly highlight a few practical areas of IoE/IoT applications.

Wearables and Health: When referring to "smart" IoE/IoT devices, the first area that comes to mind **is** the wearable technologies normally designated only as "wearables". These are electronic gadgets used physically by people that allow tracking, analysis, and transmission of personal biometric data, like the fitness bands that trace the heart rate, calories spending or the sleep patterns. Besides, nowadays, we also see underutilization in our daily lives, such as with virtual glasses, smart watches, fit bits, smart jackets, and GPS tracking belts, just to name a few. Usually, these electronic systems are small, energy-efficient, and already include sensors, namely, they embed the required hardware and software necessary to measure, read, collect, and organize all the data related with the particular body metrics of an individual. Another important wearable is the glucose-monitoring device for people with diabetes. A glucose sensor with a tiny electrode placed under the skin detects glucose levels and transfers the information via RF to a mobile phone, for example. Wearables are still a hot topic in the market, serving a wide range of activities such as medical, wellness or fitness; then we can consider them as symbolic components of industries serviced by IoE/IoT applications. Since they include sensors, in the medical industry they already allow doctors to monitor the health status of the patients in real-time, even outside the hospital. The IoE/IoT system of communications, together with the specific data archived for each patient, allows the continuous monitoring of the precise metrics and detects automatic alerts of the patient's vital signs, enhancing the level of attention and care of high-risk patients while averting fatal incidents.

IoE/IoT applications can transform reactive medical-based systems into proactive wellness-based systems. For example, embedding the technology into hospital beds allows the emergence of smart beds provided with special sensors to keep track of lively signals, like the heart rate and pulse, the blood pressure, the level of oxygen in the blood, the body temperature, etc. Besides, IoE/IoT allows the access to an immense quantity of data with inestimable value obtained from archiving, focused analysis, real-time field information, examination, and trial. It also enlarges the capability of the existing equipment in terms of power, performance, precision, and availability, focusing on the creation of overall integrated systems instead of just independent equipment. Subsequently, areas like E-health, telehealth or telemedicine, although not yet completely developed, already present a growing future potential, with the possibility of offering health information online for consumers and professionals, as well as health education and training courses, the digital transference of medical images through the Internet, remote medical diagnosis, video-conference consultations with doctors and specialists, and even the emerging area of remote medical surgery.

Smart City (Traffic Monitoring, Fleet Management and Self-Driven Cars): One of the most important components composing a smart city is the intelligent control and optimization of its overall traffic system. Other crucial aspects comprise, for example, the smart-grid leading to energy saving, the monitoring of clean drinking water and air quality, increasing urban density, and they differ in intensity across cities, affecting each city in a diverse way. The municipal governments, urban planners, engineers, and architects can utilize IoE/IoT to analyze, design, and manage the often-complex factors of town planning specific to each city aiding in many areas like water and electricity distribution management, waste management, and emergencies, allowing the access by Internet to people and devices throughout the city, eliminating challenges and adding convenience. An interesting example, usually in many cities around the world most cars drive around looking for parking spaces leading to traffic congestion, then; one solution consists in the installation of sensors in all the parking spots in the city. The sensors pass the information about the occupancy status of each spot to the Internet *Cloud* that then shares it with any type of application available in a mobile phone guiding the drivers to find the shortest route to a vacant place. Another case is the management of the different urban service fleets that have their vehicles installed with sensors, like the buses, the taxis or the garbage collectors. The IoE/IoT networks allow constant interconnectivity between drivers and the corresponding managers of the service provider permitting an efficient management of the fleet with continuous monitoring of the status and operation of all vehicles. Another future urban equipment is the self-driven car already tried by Tesla and Google, which need to ensure increased safety for passengers and people on the roads. They use several sensors and embedded systems connected again to the *Cloud* continuously generating and analyzing data that assists conscious decision-making. Although it will take a few more years for the technology to evolve completely and for countries to amend their national regulations publishing new laws and policies, what is happening already is one of the remarkable applications of IoE/IoT.

Smart-Grid/Energy Saving and Water Supply: An important component of the electrical distribution grid is the energy meter in each consumer's place, and it becomes intelligent when it embeds sensors that allow bidirectional communication between the service provider and the user. Furthermore, the installation of sensors in the production plants and the distribution centers allows closer monitoring and control of the electrical network. Information of significant value usually obtained through the previous referred communication leads to informed knowledge about consumption patterns allowing energy saving with its eventual cost reduction, wise decision-making, detection of faults, and the necessary repairs. On the other hand, the installation of a smart-grid will enhance operation efficiency, network reliability, and intelligent management of electricity costs. The same strategy applied to the water supply network with sensors embedded in water meters, connected to the Internet and managed by the adequate software, allows the acquisition of information, the processing and analysis of data, understanding and aiding again the consumer behavior, detecting faults in the service supply, and subsequently leading to repairs by the company provider. The complete information available in real-time in the Internet helps to monitor the consumption according to the average record and even detect possible failures and leaks of the water network.

Smart-Home: Another interesting and practical application of IoE/IoT is the Smart-Home, combining into a higher-level of comfort both satisfaction and security, and blending in intelligent utility systems with home management and entertainment. Some examples include the intelligent electricity and water meters, a control box for the automatic remote management of illumination, advanced locking, and connected surveillance. In the future, more innovative devices will enable a further integrated environment with enlarged security.

The key subsystems in the IoE/IoT with energy-autonomous chips are the sensor, the wireless transceiver, the clock and frequency generator, plus the power management for harvesting energy. Furthermore, in wireline and wireless communications, one of the main components is the high-speed/wide-band analog-to-digital converter (ADC). Besides, the requirements and challenges of wide-band ADCs become more critical especially when they operate at low power. Then, high-efficiency fully integrated power solutions need advanced and adaptable switched-capacitor (SC) DC–DC converters, or when extremely small solutions not requiring energy storage are necessary the low-dropout (LDO) linear regulator becomes the most appropriate choice for providing power.

This paper presents various innovative architectures and circuits for the different subsystems described above, namely, the capacitive sensor interfaces (Section 2), ultra-low-power wireless transceivers (Section 3), key technologies for wireline transceivers (Section 4), oscillators and frequency generators (Section 5), integrated energy harvesting (EH) interfaces (Section 6), in-memory processing (Section 7), data converters (Section 8), and power converters (Section 9), consuming low power, but leading to solutions that reveal record performances in energy-efficiency and/or high-speed among the state-of-the-art. Finally, Section 10 draws the conclusions.

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