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Introduction

1.1 Wireless Communication

The idea of using electromagnetic waves to send information over the air, without wires, dates back to the end of the 19th century. Although many scientists at that time worked on similar devices, Marconi was the first to demonstrate a working "wireless telegraph". First radio systems were large, relatively simple and only used in a handful of applications such as navigation and keeping contact with ships and, later on, planes. At first, they could only be used to transmit dots and dashes of the Morse code, the human voice followed slightly later in the beginning of the 20th century.

The evolution of wireless communication followed the technological advances in the field of electronics. The invention of the vacuum tube provided means to amplify and process the received weak signal and increase the range of communication. The first radio receivers were developed by Armstrong, who is well known for the invention of the super-regenerative receiver and the super-heterodyne receiver, and also the first to propose the use of frequency modulation. The next important step in the evolution of wireless was the invention of the transistor. This allowed for a remarkable reduction in weight and size of most electronic components, improved reliability and generally fueled the rapid development of mobile communications in the second half of the 20th century.

It was the reduction in size and cost of components that ultimately enabled the penetration of mobile devices into the consumer market and led to the huge commercial success of the mobile phone. Aside from the phone, different technologies were developed to transmit data over the air. W-LAN and Bluetooth followed quickly and provided a wireless link between all kinds of devices. Today, we have reached a point where wireless connection has become almost as pervasive as electricity. The radios have become so small that they can be seamlessly integrated into almost any object.

There are two main directions of development of modern wireless devices. The first one is toward higher speed and better performance, and is driven by technologies such as 5G, aiming to provide more data and uninterrupted connectivity to users in all corners of the world. Here, the size and energy come second, what matters most is providing high data rate and low latency to all users. The second direction is towards energy, size and cost reduction, driven by the IoT (Internet of Things). The vision of IoT is to provide worldwide network access to billions of objects surrounding us, to gather information from those objects and give them the ability to interact with their environment without human intervention. To achieve this, the performance of a radio must often be sacrificed in order to conform to the needs for miniaturization and low power consumption.

1.2 CMOS Technology and Scaling

The Complementary Metal Oxide Semiconductor (CMOS) process technology is undoubtedly the dominant IC technology used today. Initially intended for use in digital circuits, the CMOS is now used in a wide variety of analog and RF applications as well. The tremendous success of CMOS is a result of exponential technology development over more than 50 years. This exponential development is described by Moore's law [1] that states that the number of transistors on a silicon chip doubles every two years. Originally an observation, it became a principle that provided a guideline for the semiconductor industry for over 50 years.

The number of transistors on a chip increased owing to the reduction of feature sizes (transistor gate length). The increase in numbers and reduction of size also led to a drastic fall of price per transistor. Not only that, but smaller transistors make logic gates faster and are more energy efficient. With every new generation more and more digital functionality could be placed on a single chip, the speed of chips increased and the price kept dropping. This in turn enabled the revolution in computing, with ever more powerful computers becoming smaller and cheaper every year. Today, we are at a point where a hand-held device possesses more computing power than super-computers the size of a room used to. CMOS also revolutionized wireless communications, providing more power for digital signal processing, enabling more complex modulation and demodulation algorithms and fast error correction.

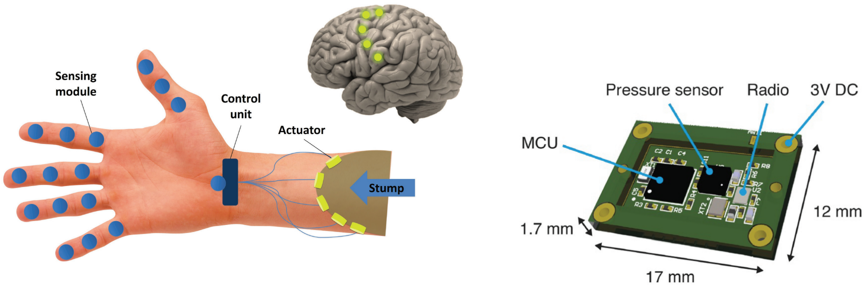
Low prices and high level of integration eventually led to the use of CMOS in analog and RF circuits. Unfortunately, the analog circuits did not benefit as much from technology scaling. One reason is that passive components simply cannot scale, as their size is governed by the laws of electromagnetism. Furthermore, the decreasing intrinsic gain of transistors and progressively lower supply voltage make analog design more challenging in modern deep sub-micron CMOS technology nodes. One parameter that improves with smaller transistor sizes is the transit frequency, i.e. the frequency where the current gain of transistor falls to 1. As a result, CMOS is now widely used in various RF applications and is slowly paving its way in the sub-THz domain, narrowing the gap between CMOS and dedicated RF and microwave technologies.

Technology scaling is one of the key enablers toward fulfilling the dream of bringing intelligence and connectivity to objects and deploying sensor networks consisting of billions of nodes. It is the exponential development of CMOS that brought the size and cost of integrated circuits down to the needed level, but innovative circuit design, novel radio architectures and clever system optimization are still necessary to provide energy efficient wireless connectivity.

1.3 IoT and WSN

Wireless Sensor Networks (WSN) and the Internet of Things (IoT) are two concepts that have been gaining traction over the past 20 years. The idea of using a distributed network of miniaturized sensing or actuating devices appeared with the advances in micro electro-mechanical systems (MEMS), digital signal processing and wireless communication [2]. Instead of using one or several sensors, a collaborative network of miniature sensor nodes is deployed near the phenomenon. These type of networks can find applications in a variety of fields, such as military, home automation, industrial automation, environmental, agricultural, construction, health care and so on. While many different types of wireless networks existed previously, their goal was mainly to provide the desired quality of service, whereas in a WSN the protocol must primarily ensure power conservation, given the limited resources available on each node and the fact that the nodes do not have access to the power grid in most cases.

An interesting subset of WSNs are the body area networks (BAN), where a network of sensors is distributed on, or inside a human body. These type of networks can provide remote patient monitoring, allowing the doctor to track all relevant physiological information without keeping the patient hospitalized, effectively improving his quality of life. A network of sensors can also be placed on a prosthetic limb and used to provide sensory information



(a) (b)

Figure 1.1 The *WiseSkin* concept (a) and a prototype sensor node (b).

to the patient, allowing him to regain the sensation of touch [3]. The tactile information is necessary to close the feedback loop and allow the amputee to control the limb and experience it as a part of his body. The concept, together with the prototype of the used sensor node is shown in Figure 1.1. As in the general case, the node itself consists of three main parts: the sensor, the processor and the radio. The processor is the brain of the node, it stores the information from the sensor and decides when to send this information using the radio. In some cases local processing of the raw data can be used to reduce the amount of data sent, reducing the overall power needed for the radio. This is an important point as the radio is typically the dominant consumer on a sensor node [4]. The main challenge today is to reduce the communication power in WSNs, either by focusing on hardware and lowering the consumption of the radio, or by focusing on software and aiming to improve efficiency at the protocol level.

The IoT can be seen as a natural expansion of the WSN concept. In its most basic form IoT is a vision wherein various objects are connected via the internet. All of these objects can either extract some information about the environment or interact with the environment using the information provided to them. This information is stored on remote servers, where it can be processed to extract the useful information. The IoT blends together the internet technologies with data science and pervasive distributed sensing, with the goal of optimizing and automating industrial and common, everyday processes. It is a commonly agreed target of the IoT to provide approximately one thousand connected devices per person [4]. Different challenges lay ahead before this vision can become a reality. Efficient cloud storage and processing must accommodate the amounts of data generated by trillions of sensor nodes. They must be able to extract knowledge from it and provide useful services to the end user. The gateways and concentrators that provide the interface between the internet and the sensor networks must provide sufficient bandwidth to allow real time response to different stimuli. The cost and energy requirements of sensor nodes must be sufficiently low to enable deployment at such a large scale. Commercially available components are still too expensive and consume too much power to realize the IoT vision, the main obstacle currently being the wireless transceivers.

Different schemes and modulations have been used, different architectures and circuits have already been examined in order to reduce consumption of radios. This work focuses on frequency modulated ultra-wideband (FM-UWB) technology as a candidate to bring down the cost, power and size of sensor nodes, but also to enable scalability and robust communication, and bring us one step closer to realizing the IoT vision.

1.4 Energy Sources

Since most nodes in a WSN do not have access to the power grid, they must be powered in some other way. Today they are mainly powered by batteries. The exact energy needs depend on the application and dictate the size and requirements on the battery. Unfortunately, the energy capacity of batteries has not scaled as fast as the CMOS technology. Although scaling improved circuit efficiency, addition of new functions actually increased consumption of electronic devices, and batteries have simply not been able to keep up with the pace.

Different batteries are available today, providing different characteristics and using different chemistries. When designing a radio, or an entire sensor node, it is important to be aware of their characteristics in order to exploit the battery in a maximally efficient manner. The lithium based batteries are by far the mostly spread today, as they have the highest energy density of all the commercially available batteries [4]. Regardless of the type, the capacity of a battery is always proportional to its size. For a given lifetime, the node consumption determines the minimum battery size and, since the battery is often the largest component of a node, the size of the node itself. The fact that the consumption of a sensor node is proportional to its size is yet another incentive to minimize the consumption of a radio. Another issue is that the battery capacity is related to the load current, and it generally diminishes as the load current increases. High pulsed currents can significantly reduce the capacity or even damage the battery. This is highly inconvenient as the radios on a sensor node nearly always use duty cycling, meaning that they are activated to transmit a packet of data during a short period of time, after which they are put to sleep to conserve energy. As a result, the peak power of the radio has an impact on battery lifetime, making radios with lower peak current more convenient. This is why the low peak current of the FM-UWB transceiver proves to be an advantage in battery powered systems.

Batteries can be non-rechargeable and rechargeable. Rechargeable batteries can be used to extend the lifetime of a system, provided that they can be charged in some way. A very appealing mean to provide more energy to IoT devices is using the energy harvesters, especially for devices that are not easily accessible. Whenever some form of energy is available in the environment, they can be used to gather it and increase the autonomy of the node. Commercially available harvesters are thermoelectric generators (TEG), microbial fuel cells (MFC), photovoltaic cells (PVC) and piezoelectric generators. In academic work, electromagnetic harvesters, that collect energy from already present electromagnetic waves, are also described. Unfortunately, the power that can be provided by these harvesters is still too small to sustain even a small sensor node. Unsurprisingly, the amount of energy they can provide is proportional to the size of the harvester.

All of these harvesters can provide different voltage and current levels, and present a different impedance to the load. To make things more difficult, all of these quantities change with time, as the environmental conditions change. Dedicated circuits must be used to provide optimal conditions for energy extraction and track the maximum power point (MPP) of a harvester. At the same time these circuits must ensure the required voltage and current profiles in order to charge the battery in an efficient way and avoid loss of capacity. Finally, they must provide different supply voltages to different parts of a sensor node while minimizing losses. This is why the power management circuits are, alongside radios, becoming an important component of the IoT node, that is becoming increasingly more challenging to design.

1.5 Work Outline

With the previous thoughts in mind, it is the aim of this work to explore another communication scheme, the FM-UWB, within the context of WSN and IoT. The work described here was originally directed toward providing short range wireless connectivity for sensor nodes on a prosthetic limb [3], however the conclusions and results can be applied to a much broader field of applications, highlighting the potential of FM-UWB in the IoT space.

The largest part of the work focuses on the hardware implementation of an FM-UWB transceiver, emphasizing architectural and circuit techniques needed to achieve the low power consumption needed for a sensor node. Since the number of nodes in sensor networks is expected to grow in the future, the issues of scalability are also addressed. Here, the multi-user capability of FM-UWB comes into play, allowing multiple devices to share the same RF band and providing an additional degree of freedom compared to systems that exploit only TDMA (Time Division Multiple Access). The growing number of connected devices also means more devices fighting for the limited spectrum resources, and more interference in the air. The inherent rejection of narrowband interferers provided by the FM-UWB ensures a robust link even in such scenarios, allowing a transceiver implementation without a separate pre-select filter. The scaling of the CMOS technology greatly reduced the cost and size of silicon devices. The trend is therefore to integrate as many components as possible on a single die, and avoid using off-chip components that would make the node bigger and more expensive. The FM-UWB has a unique potential for full transceiver integration that gives it an advantage compared to standard narrowband transceivers. This aspect is also explored as the cost and size of devices are still a barrier to arriving at more than a thousand connected devices per person.

Chapter 2 provides a survey of low power transceivers. The most important low power techniques at the architectural level are presented and briefly explained. Performance of commercially available radios and academic implementations is shown and compared focusing on data rate, sensitivity and efficiency, but also commenting on selectivity, dynamic range and relations among these metrics. The emphasis is on architectural trade-offs of transceiver implementations as well as advantages and disadvantages of different communication schemes.

Chapter 3 explains the fundamentals of FM-UWB modulation and demodulation, highlighting the potential of this technique in the WSN and IoT context. The potential directions of evolution of FM-UWB radios are given and discussed. A survey of existing FM-UWB transceiver implementations provides a glimpse into the practical capabilities of this modulation scheme.

Chapter 4 presents the two developed receiver architectures. The "approximate zero IF" (AZ-IF) receiver architecture is derived from the "uncertain IF" architecture, previously employed to reduce consumption of the narrowband wake-up radios. The principle of operation is explained, and combined with system-level simulations in order to estimate the expected performance of the two receivers.

Chapter 5 describes the first implementation of the low power, quadrature approximate zero IF receiver. First, all the circuits are explained in detail together with the most important simulation results. Then the measurement results are reported. The receiver performance is characterized in different conditions, with narrowband and wideband interferers and using different variations of FM-UWB modulation, demonstrating in that way some of the interesting features of the FM-UWB approach.

Chapter 6 describes the implementation of the fully integrated, low power FM-UWB transceiver. Aside from the quadrature AZ-IF receiver, a single-ended receiver is added, providing a mode with even lower power consumption. As in the previous case, the two receivers are characterized under different operating conditions. In this case the emphasis is on robustness to narrowband interferers (with a special focus on 2.4 GHz band), and frequency offset tolerance. The implemented receiver is proven to tolerate clock offsets large enough to make use of an external quartz reference unnecessary, making it the first FM-UWB transceiver that can truly be implemented with no external components.

Chapter 7 concludes the topic, providing a summary of achieved results and contributions, and pointing to potential research topics and development directions for future work.

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