# 1 Introduction

This book focuses on sub-threshold, or weak inversion, circuit design. Digital circuits operating in sub-threshold use a supply voltage that is less than the threshold voltages of the transistors. In this region of operation, they consume less energy for active operation and dissipate less leakage power than higher voltage alternatives, but they operate more slowly. Until fairly recently, the emphasis on maximizing operational frequency in digital circuits dominated to the point that sub-threshold operation received very little attention.

A recent explosion in applications that benefit from low energy operation has carved out a significant niche for sub-threshold circuits. Gadgets that for years were tied down or wired up have severed the cords and broken loose. This trend toward portability has created two classes of applications for which sub-threshold circuits are well-suited. The first is severely energy constrained systems. For systems in this class, conserving energy is the primary constraint, and speed of operation is largely irrelevant. Instead, minimizing energy per operation becomes the primary goal. Sub-threshold circuits are ideal for these types of applications. The second class of applications consists of portable devices that require high performance for part of the time but that also spend significant fractions of their operation doing non-performance critical tasks. The mobile phone is a perfect example since it often enters periods of near-idle computation to wait for input from the user or the wireless link. For these type of applications, Ultra-Dynamic Voltage Scaling (UDVS) is a good solution. UDVS is a technique which allows the same circuit to operate at high-voltage/high-frequency for performance critical applications and at sub-threshold/low-frequency for energy-constrained applications.

Mobile technologies are enabled by wireless communication and by portable power supplies. The latter most often takes the form of a battery. Improvements in both of these categories have led to remarkable changes in portable electronics. For example, the first commercial mobile phone weighed 16 ounces and had a half-hour of talk time. Now more than 10 years later, the cell phone weighs less than 3 ounces and provides up to 4-6 hours of talk time. Many cell phones also add features including email, MP3 playback, gaming, digital TV and movies. The increase of features in portable electronics along with the decreasing form factor places a heavy burden on the battery to supply more energy from less volume. However, the energy density of batteries has only doubled every five to 20 years, depending on the battery chemistry. At the same time, prolonged refinement of any chemistry yields diminishing returns. As a result, the energy burden shifts to the circuits, which must reduce the energy consumed during each operation in order to extend the system lifetime.

This chapter briefly explores examples of energy-constrained applications and the requirements for these systems. Although best suited to these applications, sub-threshold operation can also apply to other portable devices during periods of non-performance critical operation. The remainder of the book looks in detail at sub-threshold operation as a potential approach to these applications.

## 1.1 Energy-Constrained Applications

There is an emerging set of applications for which energy consumption is the key metric. These severely energy-constrained applications generally have low activity rates and low speed requirements, but the system is required to have long battery lifetimes (e.g. $>$ 1 year). Ideally, the power consumption of these systems will decrease to the point that they can harvest energy from their environments and have theoretically unlimited lifetimes.

### 1.1.1 Micro-sensor Networks and Nodes

A micro-sensor node refers to physical hardware that provides sensing, computation, and communication functionality. A wireless micro-sensor network consists of tens to thousands of distributed nodes that sense and process data and relay the results to the end-user. Proposed applications for micro-sensor networks include habitat monitoring [4][5][6], health [7], structural monitoring [8][9][10], and automotive sensing [7].

The performance requirements for microsensor nodes in these applications are very low. The rate at which data changes for environmental or health monitoring, for example, is on the order of seconds to minutes, so the performance achieved even in sub-threshold is more than adequate. Most microsensor nodes duty cycle, or shutdown unused components whenever possible. Although duty cycling helps to extend sensor network lifetimes, it does not remove the energy constraint placed by the battery. Most microsensor node applications require very long battery lifetimes because it is not possible to recharge or replace batteries frequently. Thus, microsensor networks are a compelling platform that showcases the need for new low-energy design techniques.

### 1.1.2 Radio Frequency Identification (RFID)

Radio Frequency Identification (RFID) is another application which requires extremely low energy consumption [11]. RFID is used to automatically identify objects through RFID tags which are attached to the object. The RFID tag is able to transmit and receive information wirelessly using radio-frequencies. An RFID tag contains a limited amount of digital processing logic along with an antenna and communication circuits.

Although the concept of RFID has been in existence for many years, recently it has become more popular as a means to efficiently control large scale supply chains. Its success has spawned many more applications for RFID tags including medical implants, pet identification, smart credit cards and smart keys for automobiles.

There are two main types of RFID tags. An active RFID tag communicates with the reader by transmitting data. Active tags frequently require batteries to supply the energy for transmission, and the extra energy from the battery also allows for extended processing and longer range of communication. A passive RFID tag communicates with the reader by modulating the load that the reader sees. This indirect means of communication requires less energy, so passive tags often operate on energy that is converted from the received signal. Passive nodes are usually smaller as a result, and their lifetimes are not limited by energy.

Reducing the digital processing power would benefit both types of tags. For passive tags, the power is constrained by the ability to utilize the converted energy from the antenna. If the digital logic power dissipation can be reduced, then the distance from the reader to the tag can increase since less transmitted power has to reach the tag. For active tags, minimizing the digital logic power leads to both increased transmission range and/or longer battery lifetimes.

### 1.1.3 Low-power Digital Signal Processor (DSP) and Microcontroller Units (MCU)

Most portable electronics that are used for consumer applications require a low-power DSP or MCU. Even if the amount of processing is limited, it must be done efficiently. In a variety of applications, the Texas Instruments (TI) C5xx family of DSPs or the TI MSP430 family of MCUs have been used successfully for portable measurement, metering and instrumentation.

Also, there are portable applications that take advantage of a wide range of performance needs to reduce energy consumption and extend the system lifetime. For example, a mobile phone may be on standby for most of its lifetime but then require increased processor MIPS (Million Instructions per Second) when the user makes a call or runs an application (e.g. games, digital TV). In these applications, the DSP and MCU need a wide dynamic range of power/performance. They should both minimize energy when in standby or low activity modes and maximize performance when in high activity modes. Design considerations for both spaces are needed to optimize these devices.

## 1.2 System requirements

In this section, we motivate the need for sub-threshold circuit design based on the system requirements for severely energy-constrained systems.

### 1.2.1 Battery Lifetimes

For some micro-sensor applications, a limited lifetime is sufficient, and a non-rechargeable battery is the logical choice. The small size of the sensor nodes imply limited physical space for batteries. However, a $1\text{cm}^3$ Lithium battery can continuously supply $10\mu W$ of power for five years [12].

Since the standby power alone of most large digital systems exceeds this number, energy conservation strategies are essential for achieving the lifetimes necessary for viable applications [13]. Sub-threshold circuit design, which dissipates much less leakage power and consumes less active energy than strong inversion circuits, provides useful computation at the power levels required for extended battery lifetimes.

### 1.2.2 Energy Harvesting

Many of the applications mentioned in Section 1.1 would benefit from unbounded lifetimes in an environment where changing batteries is impractical or impossible. These types of applications require a renewable energy source. The concept of energy harvesting or energy scavenging involves converting ambient energy from the environment into electrical energy to power circuits or to recharge a battery.

**Table 1.1.** Examples of power densities for potential energy harvesting mechanisms [14] (© 2005 IEEE)

| Technology | Power Density ($\mu W/cm^2$) |
|---|---|
| Vibration - electromagnetic [15] | 4.0 |
| Vibration - piezoelectric [12] | 500 |
| Vibration - electrostatic [16] | 3.8 |
| Thermoelectric (5°C difference) [17] | 60 |
| Solar - direct sunlight [18] | 3700 |
| Solar - indoor [18] | 3.2 |

The most familiar sources of ambient energy include solar power, thermal gradients, radio-frequency (RF), and mechanical vibration. Table 1.1 gives a comparison of some energy harvesting technologies [14]. Power per area is reported because the thickness of these devices is typically dominated by the other two dimensions. The power available from these sources is highly dependent on the nodes' environment at any given time. However, these examples show that it is reasonable to expect 10's of microwatts of power to be harvested from ambient energy. Thus, researchers agree that micro-sensor nodes must keep average power consumption in the 10-100$\mu$W range to enable energy scavenging [19][20]. Coupling energy-harvesting techniques with some form of energy storage can theoretically extend system lifetimes indefinitely. Clearly, this type of system will be much more effective when coupled with the significant power and energy savings made possible by sub-threshold operation.

## 1.3 Book Summary

In this chapter we showed the motivation for sub-threshold design in future energy-constrained applications. The battery capacity of portable systems is not keeping up with the SoC requirements. Also, new wireless applications are emerging that require near infinite lifetimes. One way to extend battery lifetime is to run at microwatt power levels. If average power consumption is sufficiently low, then energy harvesting becomes possible. Sub-threshold circuit design provides a solution where a circuit can operate at the voltage supply that minimizes energy dissipation.

This book covers various aspects of sub-threshold design.

Chapter 2 is a contributed chapter by E. Vittoz, a pioneer in sub-threshold design. He gives his unique perspective on the origins of sub-threshold circuit design in which he had an important role. Then, in Chapter 3, we survey low-voltage, low-power circuit designs from as early as the 1960's. We show the trends in voltage scaling for processors, DSP's and research test chips and identify results that pushed the minimum voltage limit. Chapter 4 explores the concept of optimal energy dissipation. Minimizing energy dissipation is the primary design objective for many energy-constrained systems. We explore operating at the optimum point for minimum energy dissipation over various system parameters such as supply voltage, threshold voltage, activity factor, workload, duty cycle and temperature. A thorough discussion of sub-threshold leakage current modeling is presented in Chapter 5, which is contributed and written by E. Vittoz and C. Enz. The Enz, Krummenacher, and Vittoz (EKV) model that is presented is intended for usage in low-voltage and low-current digital and analog design. Chapter 6 discusses digital logic operation in the sub-threshold region. First the inverter in sub-threshold is analyzed, and then complex CMOS logic circuits are analyzed. In addition, different logic families are considered in a section contributed by J. Kwong. In Chapter 7, sub-threshold memories are discussed. We explore traditional SRAM designs that operate in strong inversion but fail in sub-threshold. Understanding the limitations of SRAM write and read helps us to design new bitcells and read/write circuits for sub-threshold operation. Chapter 8, which is contributed by E. Vittoz, moves on to sub-threshold analog circuit design and highlights common circuits and design techniques that take advantage of specific characteristics of weak inversion operation. The last chapter presents two system examples that incorporate ideas presented in the preceding chapters. The first system example is a Fast Fourier Transform (FFT) processor that operates down to 180mV and demonstrates optimal energy dissipation. The second system demonstrates UDVS, which allows a system to dynamically scale from strong inversion down to sub-threshold. The contributed chapters (Chapters 2, 5 and 8) use different terminology than the remainder of the book. A large portion of the content of this book comes from the Ph.D. theses of Dr. Wang and Dr. Calhoun, which were written at the Massachusetts Institute of Technology.