9.2. LOW POWER APPLICATIONS AT SYSTEM LEVEL

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Abstract

Microelectronics opens new perspectives by the full integration of complete systems: including sensors, actuators, digital and analog signal processing, control and wireless communication. Compactness and ease of use require portability and battery operation. This chapter describes considerations of power usage in integrated systems design, with special emphasis on the power availability in batteries and the power usage in system components not dealt with in previous chapters of this book.

1. Introduction

The microelectronics VLSI technology [14] is in a steady evolution [2, 18]. This results in ever increasing system complexities that can be integrated on a single silicon chip. This is well illustrated with the evolution in complexities in RAM's and state-of-the-art microprocessors [30]. Every 1.5 year the amount of transistors that can be put on a chip doubles. By the year 2000, state of the art microprocessors will have 100,000,000 transistors on a die. This evolution is still expected and planned for the next decades [2, 18].

This trend gives rise to a wide spread usage of microelectronics e.g. in personal computers [30] as well as in novel applications that were previously impossible: digital mobile telephones, personal digital assistants (PDA's), multimedia, digital video decompression and compression etc., high speed communication, ATM... The progress has been the most extreme with digital circuits.

CAD tools for the design of complex digital systems are mature and ease the management of high complexity design. Novel aspects required by multiple interconnect layers and deep sub-micron effects are being added to the functionalities.

Currently there is also a large evolution in the supply of new CAD support for the power efficient design, estimation, verification and synthesis of digital systems [11].

Many applications however require the interaction of electronic circuits with a physical world or human beings. These are characterized by continuous physical quantities that have to be dealt with. Examples of such physical signals are: pressure (microphone), force, optics, chemical properties, electric and magnetic fields, temperature.

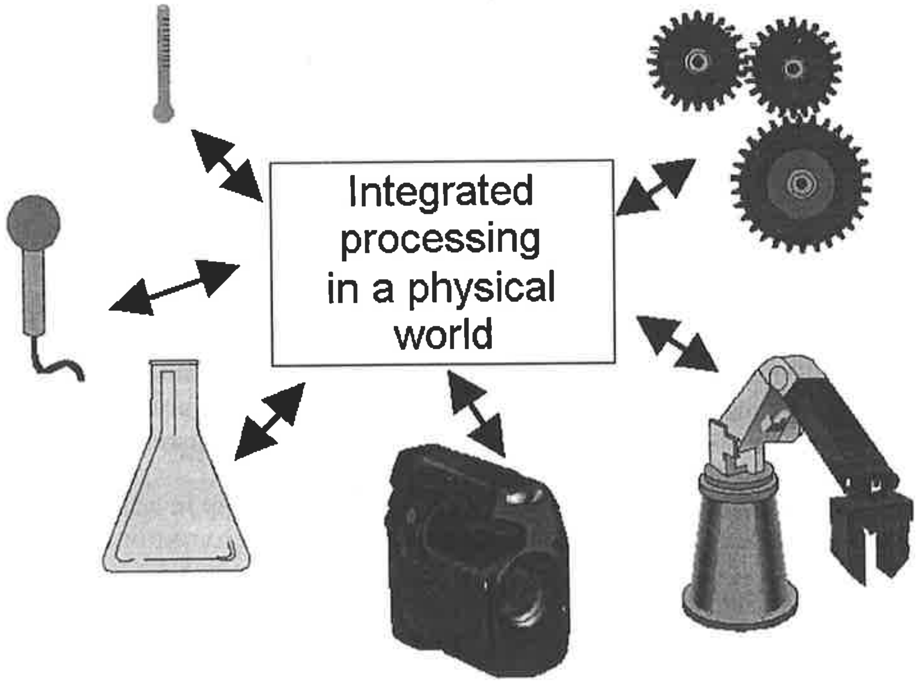

Figure 1: Interfacing in a physical world with quantities such as: pressure, force, chemical properties, electrical and magnetic fields, temperature, radiation...

These physical quantities need to be conditioned, processed and transformed in digital information for further processing in VLSI. Analog circuit design plays an important role here.

A mobile phone requires analog interfaces (Codec's) for the microphone and speaker as well as in the RF parts. In this respect there has already been a long time trend towards mixed-signal VLSI, combining digital and analog circuits. The analog part takes into account the preprocessing and conditioning of analog interface signals.

There is a continuous trend towards moving more and more of the signal processing from the analog side to the digital side with DSP (digital signal processing). DSP has interesting properties due to stability, reproducibility, calibration, programmability etc.. Analog signal processing is however very important in the front-end physical interfaces, as well as in the signal processing of RF parts (e.g. in mobile telecommunication). Usually analog signal processing is advantageous from a power consumption point of view, which is important in battery operated systems.

2. MEMS and Micro Machining

VLSI technology is not limited to the integration of digital and analog circuits as is usual in CMOS technology. The advent of MEMS (Micro Electronic and Mechanic Systems) allows the integration of sensors [26, 27] and actuators [22, 23, 25] in technologies related to VLSI. This even enables to realize circuits and sensors/actuators on the same substrate and making use of high volume production techniques as are currently in use for VLSI. This gives rise to new applications at low price or with higher quality than previously possible.

Micro machining based on selective etchants such as EDP and KOH allows to pattern 3D structures [21] in materials such as e.g. Si. This has been used already to fabricate accelerometers [24] (e.g. in airbag usage), gas sensors, temperature sensors, micro-pumps, micro-engines [22, 23] and gears [22].

In [22] a micro-engine realized in polysilicon is presented. An electrostatic comb drive actuation is used for generating a linear movement. By making use of two gear/link elements the linear movements of two perpendicular comb drive actuators can be converted in a gear rotation. The polysilicon gears have a diameter of 50 μm. With such a device, torque can be delivered for applications such as for example: optical switches, electrical switches, micro-positioners or other applications that require mechanical power. A very interesting aspect of such technology is that it allows to be completely batch processed, similar to other microelectronics technologies, without requiring piece by piece assembly as is the case in their macro counterparts. Given the appropriate applications, such micro-mechanical devices can be mass produced and be cheap in volume quantities.

In [23] a thermally actuated micro-mirror is presented as fabricated in CMOS Si technology. The mirror is suspended on two bimorph cantilever beams. The applications for such devices are in spatial light modulators for use in printers, scanners and video projection systems.

Given the possibilities of current microelectronics technology, it is becoming possible to integrate complete systems in small dimensions and even on single integrated circuit chips: including sensors, actuators, analog signal processing, digital signal processing and control.

These micro-systems allow for new applications often only limited by the imagination of designers. The miniaturization and use of VLSI technology is not only interesting when we need small dimensions (e.g. medical applications, space use, portable devices...), but also has advantages for high volume low cost production of intelligent systems.

In the following sections we will discuss aspects of the new design paradigms, called IMSD or Integrated Micro System Design, and specific aspects of low power design that are needed to the successful conception of such novel systems.

3. IMSD: Integrated Micro System Design

The design of complete systems goes far beyond the traditional design of digital circuits [14], for which the paradigms are very well established. Besides digital design [14], such micro-systems require an *integrated approach* to the conception of such complete systems called: **Integrated Micro System Design** (or IMSD). For the successful design, IMSD requires a overall approach to the system design. This is necessary because in such an integrated system most of the aspects (sensors, signal processing, packaging, testability, wireless operation, portability, low power consumption) influence one another. The traditional approach where all of the design aspects are done separately makes tradeoffs among implementation aspects more difficult.

An example of integrated system design is the Berkeley InfoPad project [4, 6, 7]. This project encompasses the design of a PDA with graphics capabilities, pen input, video decompression and wireless operation. Low power issues have got particular attention in the realization of this project.

The design and low power aspects involved in IMSD can be illustrated with portable systems such as for example the SmartPen™ [i][1]. The SmartPen™ is a novel computer input device. It is portable and operates autonomously. It includes sensors, electronics, embedded processing and wireless communication. Small dimensions and battery operation require that in this device special care is taken for an appropriate low power design.

In what follows, individual aspects related to the low power design of integrated micro-systems are discussed: choice of batteries, overall system level power reduction, power reduction in wireless communication. Low power aspects in the embedded processing and ASICs are dealt with in other chapters of this book [11] and are not repeated here.

System level optimizations for low power should be done before proceeding to electrical level optimizations for low power, as in the initial system concept a large amount of power can be gained (or wasted) when making overall system implementation decisions.

4. Batteries

Autonomous integrated systems require powering by means of batteries. Especially hand held electronic devices are often battery operated. Customers do not want to be bothered by having to replace batteries too often. Most lap-top computers only operate autonomously during a few hours, which is still a major bottleneck in their flexible use. For other equipment, users do not want to be bothered at all with battery power. Replacing batteries is an activity that should only be done every half a year for most electronic devices. To help achieve this autonomy several applications (e.g. pagers, mobile phones...) etc. rely on the use of rechargeable batteries. The recharging can then be performed during times of inactivity in docking stations.

Besides the autonomous usage time, also the size and/or weight of portable electronic systems is constrained. A good balance between autonomous usage time, dimensions and the weight of equipment has to be made. The power use of the system will be the main factor determining the range in which these characteristics can be traded off..

Table 1 gives an overview of a number of battery characteristics (including packaging overhead) for use in small sized electronic systems. Applications could be in pagers, calculators, thermometers, digital payment terminals, photographic equipment, game tools etc...

The information on batteries in this chapter has been derived from [15,16,36]. In table 1, we have characterized the weight factor by Energy/unit mass (in J/g). The size characteristic of batteries is given by Energy/unit volume (in J/mm^3). The higher these numbers, the more preferable for light weight, small size portable electronic devices. The ranges in energy densities are caused by the overall overheads in specific packages in which the batteries are available.

Table 1.
Comparison of battery characteristics (diameters < 16 mm and length < 30 mm).

Battery	Voltage	Charge-able?	Energy/ Mass J/g	Energy/ Volume J/cm*3
NiCd	1.20	yes	40 .. 90	150 .. 270
Ni/MH	1.20	yes	40 .. 90	150 .. 270
Lithium/R	3.00	yes	50..100	210 .. 310
Lithium	3.00	no	500 .. 1000	1100 .. 2600
Alkaline	1.50	no	50 .. 300	570 .. 1000
Mercury	1.35	no	300 .. 500	1000 .. 2200
Zinc-Air	1.40	no	800 .. 1800	2400 .. 5000
Silver	1.55	no	200 .. 450	850 .. 1700

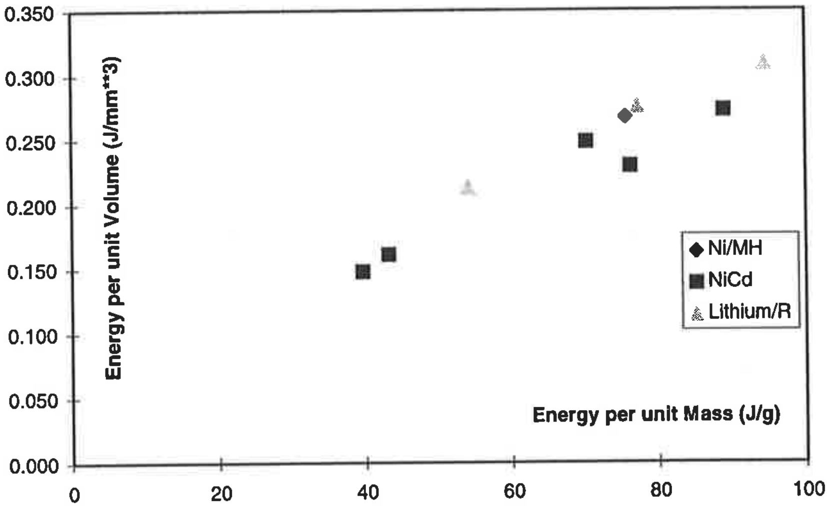

Figure 2: Energy density characteristics of rechargeable batteries.

In the density characteristics, the properties of the Zinc-Carbon batteries are not taken up as they are usually not available in the size range for which we did the survey. The characteristics are comparable and in the same range as the NiCd or Ni/MH batteries.

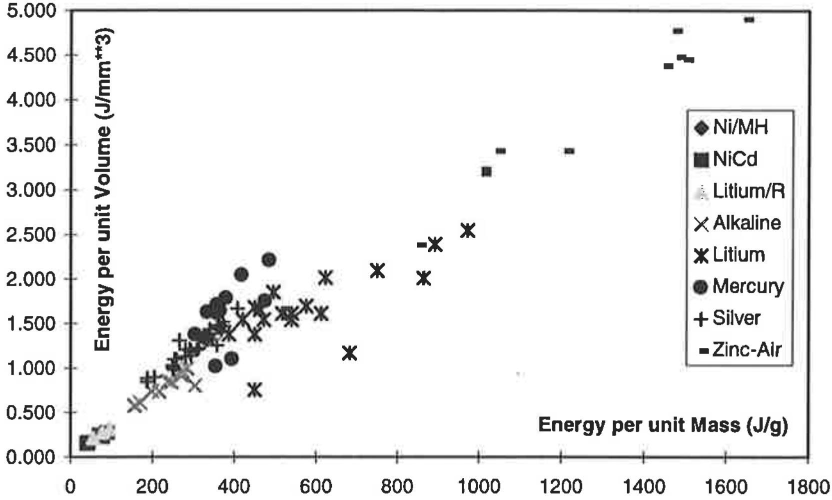

Figure 3: Density characteristics of several battery technologies.

A first major characteristic is the rechargeability of batteries. NiCd, Ni/MH and Lithium are industrial technologies for producing rechargeable batteries. As can be seen from the comparison in Table 1 and figure 3, the energy density for rechargeable batteries is a factor of 3..20 lower than the densities in battery technologies for single use (Alkaline, Silver, Mercury, Lithium and Zinc-Air). This means that the autonomous time between charges or battery replacements can be 3 to 20 times longer for single use batteries than for rechargeable batteries.

Besides the energy density of batteries, the cell voltage differentiates technologies. The power consumption is proportional to the square of the overall power supply voltage.

$$P \sim V_{dd}^2$$

When not relying on DC-DC converters, the voltages available from the battery cells can be exploited to achieve lower power. Power efficiencies of DC-DC converters are currently in the range 70 .. 90 %. The switching power supply versions require the addition of an external inductance coil, that can not be integrated on a chip. This adds to the system cost.

Higher voltages can of course always be obtained by cascading a number of battery cells. Also switched capacitor charge pump based DC-DC voltage up converters can be used. If the current required by the electronics is too high, the switched capacitors of the charge pumps can not be integrated on the chip. External capacitors add to the system cost.

Applications that demand higher speeds or accurate analog electronics will often not allow the usage of the lowest voltages. Lithium batteries with cell voltage of 3 Volts or cascades of other batteries can be used. Power losses due to DC-DC converters can be avoided.

If possible however, it is advantages to operate electronic circuits at voltages of one cell in the range of 1.2 volt up to 1.55 volt, as the resulting power consumption will be lower by a factor of 4 .. 6. The resulting battery usage time will also increase by that factor (e.g. from 1 week to over a month).

4.1. DESIGN EXAMPLE

Suppose we want to design a portable application with an expected autonomy of 40 hours effective use. The electronics operate at 3 volt and the shape factor of the system allows space for 2 cm^3 of batteries. What is the current that is available for the electronics?

We can choose e.g. for the high energy Lithium or two ZincAir batteries and can expect around 2500 J/cm^3. For 2 cm^3 of batteries we have an energy of 5000 Joule. With a supply voltage of 3 volt (Lithium) the current capacity available is: 5000 J/ 3 volt = 1667 A.s = 5000 * 1000/(3.3600) mAh = 462 mAh. For a duration of 40 hours effective use, this leaves: 462 mAh/ 40 h = 11.55 mA.

5. Overall power management strategies at the system level

Most portable systems are not constantly in operation or in a similar level of activity. Mobile phones can be off, can be in attentive modes for incoming calls or can be communicating with base stations. Laptop computers usually have several modes of power operation (hard disk not spinning, screen blank to avoid back light power, DRAM memory powering only, cooling fan on/off depending on temperature, processor slow down...).

Therefor it is beneficial to exploit several modes of operation and power usage. Similar strategies can also be exploited in integrated micro systems [1]. The highest gains in system power usage can be obtained here.

6. Power use in system communication

6.1. WIRED COMMUNICATION

Portable integrated systems need to communicate with other systems. Depending on the application, this could be done with a wired coupling (e.g. a serial interface RS232, RS244, I^2C-bus, SPI-bus etc.) with wires, connectors or contacts such as e.g. SmartCards.

6.2. COMMUNICATION BY MEANS OF INDUCTIVE COUPLING.

If the distance between the base terminal and the device can be narrow during required communications, magnetic coupling is possible. This also allows that energy can be transferred from the base terminal to the integrated micro-system during the communication. Applications are e.g. in inductive cards as can be used for tickets on busses, charging of cars on highways etc... No physical contacts need to be made. It is evident that these integrated micro-systems need to operate at low power, as all of the power has to be transferred by the magnetic coupling. The power consumption of the device determines the required distance between the base terminal and the integrated micro-system. Larger distances are more user friendly.

More flexible communication can be arranged by means of infrared (IR) or radio frequency transmission.

6.3. RF COMMUNICATION

For RF transmission there are a number of frequency bands available for civil applications. (e.g. 27 MHz, 418 MHz, 900 MHz, 2.4 GHz...). The range of transmission is mainly determined by the transmission power. Official standards can be used for wireless transmission with standard equipment such as e.g. DECT.

RF transmission is rather flexible as sender and receiver do not need to be in each others field of sight. They can be in different rooms or buildings. The sharing of the same frequency spectrum by different users at the same time requires a careful coordination and are addressed in RF wireless LAN's. RF devices need to be in regular contact with each other and RF equipment can not be switched on and off at will: they require setup times. This makes power management more difficult than e.g. in the case of IR transmission. Modulation techniques such as e.g. TDMA or CDMA address the simultaneous communication of different devices.

6.4. IR COMMUNICATION

Wireless communication in the same room can be organized by means of infrared communication. Figure 4 shows the principle of infrared communication.

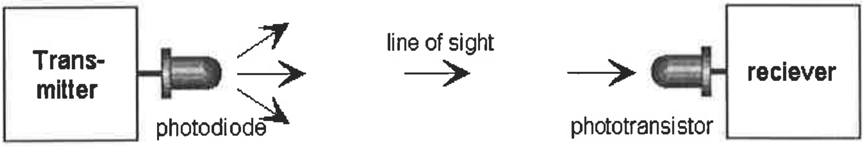

Figure 4 **Principle of infrared data transmission.**

A photo diode radiates infrared light. This infrared light is received by an IR sensitive photo-transistor. Both sender and receiver need to be within visible distance. Most systems require a line of sight that is not obstructed. Current research addresses IR transmission systems where there is no direct requirement of "line of sight", but where also the reflected infrared light on walls, floors, ceilings and furniture is used.

With IR communication continuous, as well as discrete modulation schemes can be used.

In the case of continuous infrared communication AM, FSK, PSK can be used as modulation schemes as illustrated in figure 5.

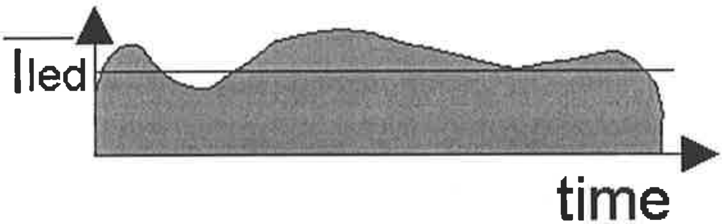

Figure 5 **Current usage in continuous IR modulation schemes.**

The drawback of continuous modulation is that there is an average current drain I_{led} during the transmission and that the data transmission rates are limited to a few kbits/second. The power consumption $P = I_{led} \cdot V_{dd}$ can be rather high. For example with I_{led}= 50 mA and V_{dd}= 3 Volt the power consumption for IR transmission is 150 mW. These kind of modulation schemes are used in portable equipment such as remote control systems for TV sets.

Discrete modulation schemes (PCM) where the data information is represented by IR light pulses are more performant in data rate as well as from a power consumption point of view.

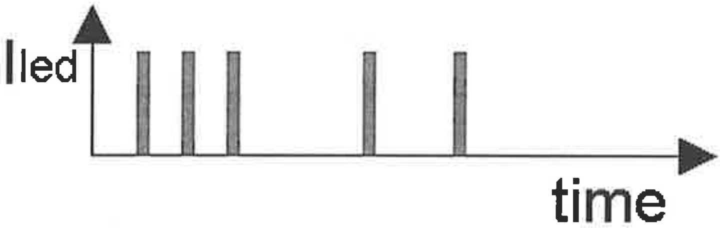

Figure 6. LED current in pulsed infrared radiation for data transmission.

Figure 6 represents the current flow in an IR LED when used with pulsed infrared radiation. Pulses can occur at specific time intervals. The presence or absence of a pulse determines if a "1" or a "0" is being transmitted. Such modulation schemes can be used for data rates up to 4 Mbit/sec, as is the case in the new IrDA standard.

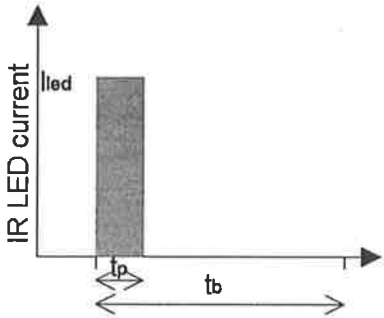

Figure 7. Infrared LED current pulse in bit-cycle.

As illustrated in figure 7 the power of an infrared pulse to represent a "1" bit is given by:

$$P_p = \alpha_p \cdot I_{led} \cdot V_{dd}$$

where:

P_p : power per bit pulse
$\alpha_p = t_p/t_b$: pulse duty cycle
I_{led} : IR led current

In the IrDA infrared communication standard the pulse duty cycle is 1/16.

Data words can be transmitted in a serial protocol as indicated in figure 8.

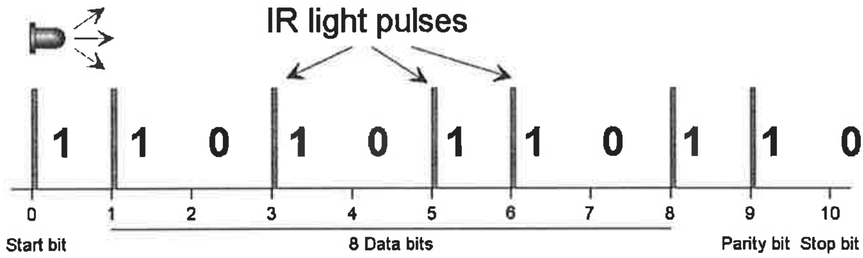

Figure 8. Example of serial word transmission with infrared communication.

This example serial protocol transmits 8-bit data words. The word frame begins with a start bit, followed by 8 data bits, a parity bit and a stop bit. With a special receiver this protocol can be easily converted into the usual UART protocols.

The IR word power consumption P_w is given by:

$$P_w = \alpha_w \,.\, n_{bit} \,.\, P_p$$

where:

P_w	: IR word power consumption
α_w	: bit probability
n_{bit}	: number of bits per word frame
P_p	: IR pulse power

For random data the bit probability $\alpha_w = 0.5$. The number of bits per word frame as in the example of figure 8 is $n_{bit} = 11$.

The overall infrared transmission power P is given by:

$$\begin{aligned} P &= (r_d / r_{max}) \,.\, (n_{bit} / 8) \,.\, Pw \\ &= \alpha_p \,.\, \alpha_w \,.\, (r_d / r_{max}) \,.\, (n_{bit} / 8) \,.\, I_{led} \,.\, V_{dd} \\ &= k \,.\, I_{led} \,.\, V_{dd} \end{aligned}$$

with $\quad k = \alpha_p \,.\, \alpha_w \,.\, (r_d / r_{max}) \,.\, (n_{bit} / 8)$

where:

r_d : required data rate (bits/sec)
r_{max} : maximum data rate (bits/sec)
k : IR power usage factor

For the pulse based transmission method a specific transmission rate has to be used. In the case of the first IrDA standard this rate is r_{max} = 115000 bits/sec. The required data rate is determined by the amount of information that a specific device wants to communicate at a specific time. According to the above equation for power it is seen that the infrared communication power is directly proportional to the amount of data that needs to be transmitted per time unit.

Let us take an example with an IR LED current of 50 mA, power supply of 3 Volt, a data transmission requirement for our application of 10 kbit/sec. Assume that we use a maximum transmission speed of 115 kbit/sec and a pulse duty cycle of 1/16 = 0.0625 as is often used in the IrDA infrared data transmission standard.

In this case the IR power usage factor k is given by:

$$\begin{aligned} k &= \alpha_p \,.\, \alpha_w \,.\, (r_d / r_{max}) \,.\, (n_{bit} / 8) \\ &= 0.06256 \,.\, 0.5 \,.\, (10000/115000) \,.\, (11/8) \\ &= 0.00373 \end{aligned}$$

Which means that we have a power reduction of nearly 3 orders of magnitude in comparison to a continuous modulation scheme (that operates at lower data rates). Our overall IR transmission power in the case of this example is:

$$\begin{aligned} P &= k \,.\, I_{led} \,.\, V_{dd} \\ &= 0.00373 \,.\, 0.05 \,.\, 3 \\ &= 559.5\ \mu W \end{aligned}$$

This example shows that pulse modulated IR schemes are very favorable for power reduction. Even if larger LED currents are used, for larger communication ranges, power usage is determined by the instant data transmission rate required by the application. Higher transmission rates (r_{max}) are also more favorable for consuming less power.

Standardization efforts such as IrDA (infrared data association) exploit this concept of low power usage and define infrared communication protocols from the physical level up to higher levels enabling up to 128 devices to communicate simultaneously with one another. This standard is currently adapted by most palmtop and laptop computers as well as peripheral devices.

7. Application example

The application example of IMSD illustrates the integrated design of a new computer input device. The SmartPen™ [1] is a stand-alone pen that can communicate the written gestures to a computer via an RF link. The operation of the pen is based 1) on measuring the friction forces in three dimensions of the pen tip on the paper while writing and 2) on measuring accelerations in three dimensions while moving in the air. Forces and accelerations are corrected by means of a two-axis tilt sensor. There is no need for extra support devices such as tablets. The whole system has been integrated in a pen [1], including sensors, mixed analog/digital electronics, embedded processing and an RF transmitter. Application specific IC's have been designed for the pen.

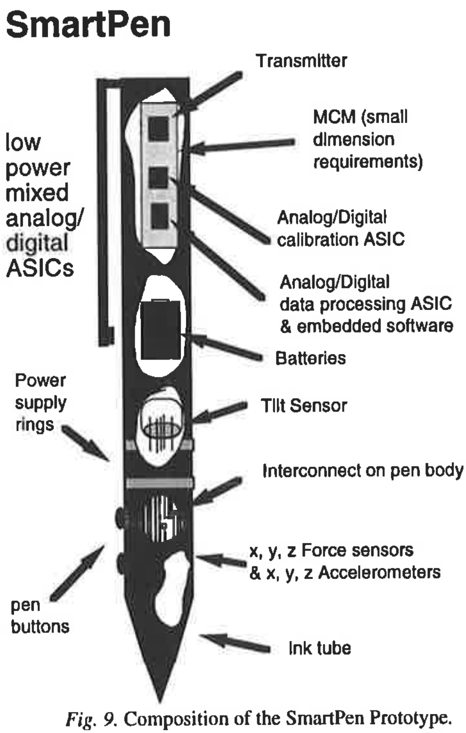

Fig. 9. Composition of the SmartPen Prototype.

7.1. COMPOSITION OF THE PEN

The composition of the pen is illustrated in figure 9.

In the front, the SmartPen™ uses a standard ink-tube, that can be replaced when empty. This ink-tube is supported in a mechanical structure that is used to measure the friction forces as imposed on the pen-tip.

The tilt sensor consists of a small glass tube that has five electrodes of which four are positioned in the form of a cross, with one electrode in the center. The tube is filled with a resistive fluid. Such tilt sensors are also used for example in airplane navigation systems. In this case, a dual axis tilt sensor is used. The angle of the tilt sensor (and consequently the pen axis) with respect to the z-axis of the paper coordinate system can be measured, as the fluid surface remains horizontal in the tube, thereby making that certain electrodes are more and others less covered by the fluid in the tube. By measuring the difference in resistance of the different electrodes, the angle can be determined. In this measurement no DC currents can be used as the fluid tends to ionize near the electrodes and gives rise to a polarization of the fluid and results in wrong measurements.

The signals resulting from the four strain-gauge Wheatstone bridges and the two-axis tilt sensor are digitized by means of an A/D convertor. The choice of the values of strain-gauge resistances is a trade-off between the power consumption (higher resistances are better) and between accuracy (higher resistances generate more noise).

The pen houses rechargeable Ni/MH batteries. They can be recharged via two power supply rings on the outer pen body. These rings touch a so-called "SmartInkWell" which includes a receiver and a charger. Special attention for the charging of the batteries has to be taken care of to obtain a good battery lifetime. Overloading must be avoided and appropriate drip charging is foreseen depending on the battery status.

In the front of the pen are two pen buttons, that can be used in conjunction with the application software. They can be used in the same way as buttons on a normal computer mouse. An example of this would be that a button could be used to indicate that a signature is going to be started.

The mixed analog digital electronics, capturing of the analog signals from the sensors, the conditioning of the tilt sensor and the software calibration of the sensors and the capture of the pen button information is performed by an embedded controller. This processor converts the captured data into a serial protocol together with error detecting coding for wireless transmission.

The transmission of the information is done via an RF transmitter at a frequency of 418 MHz. This is a band available for domestic applications.

A receiver which is embedded in the SmartInkWell captures the information and includes the interface circuitry for the connection to a standard IBM compatible PC. On the PC the application software can determine the specific use of the pen.

7.2. ASIC DESIGN

Application specific ASIC design [1], taking into account considerations of low power usage and compactness has been performed. Two mixed-mode analog/digital ASICs have been developed. A first ASIC [1] implements the front end-electronics to condition and capture the analog information from the sensors and the pen buttons. It emcompasses the formatting, error detecting coding and serial conversion of the information for the transmitter.

A second ASIC [2] implements the control and software calibration of the offsets of the measurements from the Wheatstone bridges.

Special considerations have been taken for achieving low power:

- Use of lower supply voltage (3.3 volt).
- Switching off Wheatstone bridges during periods of inactivity. This reduces power consumption considerably as they are major power consumers.
- Use of one-hot encoding in implementing the control logic.

Both of the chips have been made scan testable.

The electronics is mounted on an MCM (multi chip module) carrier for obtaining compactness.

8. Challenges for Low Power Integrated Micro System Design

8.1. INTEGRATED AND COMPLEMENTARY EXPERTISE

Integrated systems require the combination of a diversity of engineering disciplines: microelectronics, micro-mechanical, chemical and computer science. Systems that are designed and integrated as a whole will become more important in the future. This will allow to make tradeoffs between different disciplines more easily: e.g. sensor accuracy and the required signal processing can be traded off..

8.2. POWER CONSUMPTION

In portable applications the power consumption is very important and is determined by a combination of power users: sensors, actuators, wireless communication system, analog circuits (and accuracy) and digital processing. An easy switch between domains is required to make good balances. Tradeoffs can be made between the power usage in different parts of a design like:

- power consumed in sensors and power consumed in analog interface
- power consumed in analog versus power consumed in digital signal processing.
- power consumed in the wireless data communication and power consumed in signal processing to compress the data content.

8.3. LOW-POWER LOW-VOLTAGE ANALOG CIRCUITS.

In today's applications, the major part of the signal processing occurs by means of DSP (digital signal processing). But the signals to and from I/O devices remain analog. Therefor the use of analog processing will continue in future portable equipment, even with the use of complicated digital processing.

A very effective method to reduce the total power consumption is the lowering of the supply voltage. Analog circuits however show some fundamental difficulties at very low supply voltages. These difficulties will be a major issue for decreasing the total power consumption of some mixed analog/digital systems used in portable equipment [31].

Due to the wide variety of analog circuit functions (opamps, comparators, A/D-convertors, filters, oscillators,...) together with the many specifications (bandwidth, noise, stability, offset, distortion, settling time,...) and the large number of possible topologies for a given function, a general approach to the low-voltage problem seems to be very difficult [31].

When the supply voltage is reduced, the dynamic range decreases as well. As the noise level remains at a constant level, this results in a lower signal-to-noise ratio. Therefor it is important that low-voltage analog building blocks provide a maximum input/output-range, going from the lower supply line (Vss) to the upper supply line (Vdd). Special circuits will be needed to assure this rail-to-rail input/output-range [32][34]. Another way to increase the dynamic range is the use of fully-differential building blocks which have two separated and opposite moving signal paths [35].

This technique provides a two times larger signal-to-noise ratio (compared to the equivalent single-ended circuits) at the expense of a large area overhead.

A low supply voltage also limits the number of transistors in the current path between Vdd and Vss. Through this, some useful circuit techniques for increasing the bandwidth and reducing the distortion cannot be used [31]. To minimize the minimum required voltage over a certain device, one can choose for transistors operating in weak inversion (sub-threshold region). In this region however, very large transistors are needed for the same amount of current. Only low currents can be used in order to limit the parasitic capacitances and to guarantee a sufficient stability. In case of an operational amplifier [32][33], a low current will result in low gain and low slew-rate.

Mixed analog/digital circuits play a key role in integrated micro systems and portable applications. From the discussion above, one can see that the analog circuit part will probably be the bottle-neck in lowering the supply voltages. The power consumption and minimum supply voltage in analog circuits will not decrease as rapidly as in the digital circuits. One practical way to overcome the problem is the use of multiple supply voltage. Low-power low-voltage analog circuit design will be strongly needed for future battery-powered mixed analog/digital circuits [33].

8.4. CAD

Microelectronics CAD, especially in the digital domain, has matured very well in the last decades. Cell and module libraries as provided by many silicon foundries and synthesis tools starting from HDL's (VHDL and Verilog) have eased the design trajectory. It made possible that rather complex designs can be done in a reasonable time.

The behavior of global systems can be studied by means of algorithmic models built in algorithmic modeling tools such as MathCAD or MathLab.

3-D microstructures need to be designed in a 3-D CAD system (e.g. like AutoCAD). They have to be simulated for their performance (force, temperature, magnetic fields, electrical fields, humidity...) by means of FEM (Finite Element Model) simulators such as Systus, Ansys or Nastran. The integration with electronics CAD tools is non-existing or weak.

When these 3-D microstructures are realized by means of anisotropic etching [21] e.g. with EDP or KOH, it is not trivial how the structures will be etched starting from the original gdsII mask drawings. This is because these etchants have a different etching behavior depending of the christal directions of the material. Etching modeling [21] and simulators need to be used here, to enable the appropriate design of compensation structures in the original mask drawings.

8.5. DESIGN QUALITY: VERIFICATION

Design quality is very important, as design iterations are too lengthy and as in some cases human lives can be in danger due to malfunctioning of systems. Verification of the global system behavior is done in either custom made software models or in algorithmic modeling systems such as MathCAD or MathLab.

The behavior of the digital electronics [19, 20] and the software in embedded processors [29] will more and more require the help of formal verification. This verification method is much more thorough than simulation. By using symbolic values, it is possible to describe and verify global system behaviors. Currently first steps are made in the formal verification of mixed mode analog digital systems [28].

8.6. PRODUCTION QUALITY: TESTABILITY

Systems can be malfunctioning due to design errors as described in the previous paragraph. They can also fail due to errors in the production process. It is the goal of testing methods to determine appropriate strategies to allow for the testing of systems after production (and in operation). Design for Testability has gained good understanding in the area of digital electronic circuits and are very well adopted in digital design for testability (DfT) strategies such as scan-paths, built-in self test (BIST) and Iddq testing. In IMSD we not only have digital circuits, but also analog circuits as well as sensors and actuators. When they are integrated on micro-level or on one chip, it is not trivial to test the global systems anymore. Special strategies will have to be worked out to enable cost-effective testing of such integrated systems.

9. Conclusions

In this chapter design and low-power aspects in Integrated Micro Systems Design have been discussed. The technology evolution allows that complete systems can currently be integrated. This opens up a lot of new possibilities for novel applications employing microelectronics. Critical in IMSD is a global design approach combining several engineering disciplines: microelectronics, mechanical, computer science, chemical ...

CAD support for IMSD is still in its infancy. Much needs to be done for integrating different aspects: electronic, mechanical, etching. In order to get reliable and cost effective systems sufficient attention has to be paid to system verification and integrated test methodologies.

A global design approach avoids a waste of efforts in point-optimizations which often neglect the global optimization problem. This is especially true for the global power budgeting and power optimization of systems, which needs to take into account the available power sources (batteries) and power users (sensors, actuators, mixed-analog digital electronics, embedded processors and wireless interface).

10. References

1. L. Claesen, D. Beullens, R. Martens, R. Mertens, S. De Schrijver, W. De Jong: "SmartPen: An Application of Integrated Microsystem and Embedded Hardware/Software CoDesign", Proceedings ED&TC'96 Electronic Design and Test Conference'96, IEEE Computer Society Press, February 1996.

2. SIA Roadmap.

3. L."J." Svensson, J.G. Koller, "Adiabatic charging without inductors", Proceedings 1994 International Workshop on Low Power Design, ACM-SIGDA, Napa California, April 24-27, 1994, pp.159-164.

4. A.P. Chandrakasan, S. Sheng, R.W. Brodersen, "Low-Power CMOS Digital Design", In IEEE JSSC, Journal of Solid State Circuits, Vol. 27, no. 4, April 1992, pp. 473-484.

5. E.A. Vittoz, "Low-Power Design: Ways to Approach the Limits", Proceedings, IEEE International Solid State Circuits Conference, ISSCC'94, pp.14-18.

6. A. Chandrakasan, A. Burstein, R.W. Brodersen, "A Low Power Chipset for Portable Multimedia Applications", 1994 IEEE International Solid-State Circuits Conference, pp. 82-83.

7. J.B. Burr, J. Shott, "A 200mV Self-Testing Encoder/Decoder using Stanford Ultra-Low-Power CMOS", 1994 IEEE International Solid-State Circuits Conference, pp. 84-85.

8. E. A. Vittoz, "Micropower Techniques", in "Design of VLSI Circuits for Telecommunication and Signal Processing", Ed. J. Franca and Y. Tsividis, Prentice Hall, 1993, pp. 53-96.

9. J. Yuan, Christer Svensson, "High-Speed CMOS Circuit Technique", IEEE Journal of Solid State Circuits, Vol. 24, no. 1, February 1989.

10. D. Liu, C. Svensson, "Trading Speed for Low Power by Choice of Supply and Threshold Voltages", IEEE Journal of Solid State Circuits, Vol. 28, No. 1, January 1993, pp. 10-17.

11. W. Nebel, J. Mermet, (editors), "Low Power Design for Deep Submicron Electronics", Kluwer Academic Publishers, 1996.

12. A. Bellaouar, M.I. Elmasry, "Low-Power Digital VLSI Design - Circuits and Systems", Kluwer Academic Publishers, 1995.

13. J.P. Colinge, "SOI Technology: Materials to VLSI", Kluwer Academic Publishers, 1991.

14. N. J. E. Weste, K. Eshraghian, "Principles of CMOS VLSI Design: A Systems Perspective", second edition, Addison-Wesley, Reading, MA, 1993. ISBN 0-201-53376-6.

15. Varta, Portable and Micro Batteries, document nr. 40 107[e]/0693.

16. Panasonic Batteries, document nr. BSG-SF-3-95/10.

17. T. Kobayashi, T. Sakurai, "Self-Adjusting Threshold-Voltage Scheme (SATS) for Low-Voltage High-Speed Operation", In Proc. IEEE 1994 CICC, Custom Integrated Circuits Conference, May 1994, pp. 271-274.

18. J.D. Meindl, "Evolution of Solid-State Circuits: 1958-1992-20?? (As reflected in the ISSCC Digest), IEEE 1993 ISSCC International Solid State Circuits Conference, Commemorative Supplement, pp. 23-26.

19. L. Claesen, F. Proesmans, E. Verlind, H. De Man, "SFG-Tracing: a Methodology for the Automatic Verification of MOS Transistor Level Implementations from High Level Behaviroal Specifications", Proceedings ACM-SIGDA International Workshop on Formal Methods in VLSI Design, ed. P.A. Subrahmanyam, January 9-11, 1991.

20. L. Claesen, D. Borrione, H. Eveking, G. Milne, J.L. Paillet, P. Prinetto, "CHARME: Towards Formal Design and Verification of Provable Correct VLSI Hardware", in Correct Hardware Design Methodologies, ed. P. Prinetto, P. Camurati, 1992 Elsevier Science Publishers (North-Holland), pp. 3-25.

21. I. Barycka, I. Zubel, "Silicon anisotropic etching in KOH-isopropanol etchant", Elsevier, Sensors and Actuators A 48 (1995) pp. 229-238.

22. E.J. Garcia, J.J. Sniegowski, "Surface micromachined microengine", Elsevier Sensors and Actuators A 48 (1995) pp. 203-214.

23. J. Buehler, J. Funk, O. Paul, F.P.-Steiner, H. Baltes, "Thermally actuated CMOS micromirrors", Elsevier Sensors and Actuators A46-47 (1995) pp. 572-575.

24. W. Kuehnel, "Modelling of the mechanical behavior of a differential capacitor acceleration sensor", Elsevier Sensors and Actuators A 48 (1995) pp. 101-108.

25. V. Temesvary, S. Wu, W.H. Hsieh, Y-C. Tai, D.K. Miu, "Design, Fabrication, and Testing of Silicon Microgimbals for Super-Compact Rigid Disk Drives", Journal of Micromechanical systems, Vol. 4, No. 1, March 1995.

26. A. Sartori, F. Maloberti, A. Simoni, G. Torelli, "A 2D photosensor array with integrated charge amplifier", Elsevier Sensors and Actuators A 46-47 (1995), pp 247-250.

27. A. Simoni, A. Sartori, M. Gottardi, A. Zorat, "A digital vision sensor", Elsevier Sensors and Actuators A 46-47 (1995) pp. 439-443.

28. S. Hendricx, L. Claesen, "Symbolic modeling of mixed-mode systems", in proceedings of DCC'96, Designing Correct Ciruits, Editors: S. Singh, M. Sheeran, Stockholm, September 1996.

29. O. Thiry, L. Claesen, "A Formal Verification Technique for Embedded Software", Proceedings of the IEEE International Conference on Computer Design ICCD'96, October 7-9, 1996, Austin Texas.

30. R.P. Colwell, R. L. Steck, "A 0.6μm BiCMOS Processor with Dynamic Execution", Proceedings of the IEEE International Solid State Circuits Conference, ISSCC'95, pp. 136-137 and p. 176.

31. A. Matsuzawa, "Low-Voltage and Low-Power Circuit Design for Mixed Analog/Digital Systems in Portable Equipment," IEEE J. Solid-State Circuits, vol 29, pp.470-480, April 1994.

32. J.H. Huijsing, K.J. de Langen, R. Hogervorst and R.G.H. Eschauzier, "Low-Voltage Low-Power Opamp Based Amplifiers," Analog Integrated Circuits and Signal Processing, 8, pp 49-67, 1995.

33. M. Ismail, T. Fiez, "Low-Voltage Signal Processing," in 'Analog VLSI Signal and Information Processing', McGraw-Hill, pp 135-183, 1994

34. J.N. Babanezhad, "A Rail-to-Rail CMOS OpAmp," IEEE J. Solid-State Circuits, vol SC-23, pp 1414-1417, Dec. 1988.

35. S.M. Mallya, J.H. Nevin, "Design Procedures for a Fully-Differential Folded-Cascode CMOS Operational Amplifier," IEEE J. Solid-State Circuits, vol SWC-24, pp 1737-1740, Dec. 1989.

36. -, Battery Engineering Inc., "Custom Designed and Standard High-Energy Density Lithium/Thionyl Chloride Batteries".

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