Creating Autonomous Sensors with Integrated Power Sources

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Abstract - *The great challenge for both sensor and SOC designers is providing a reliable power source. This usually involves a battery which often exceeds in bulk and size the sensor die itself .The alternative is to integrate the battery with the sensor on a single die. This approach has two major limitations; 1) a requirement for very low power consumption and 2) a finite sensor lifetime. The latter requirement can be mitigated by energy scavenging if the environment allows. Associated with this is the need for "wireless" sensors freed from the tether. The major architectural implication is design for extremely low power (order of 1 microwatt) and with a strict energy budget*

Introduction

A fast growing chip marketplace is autonomous chips. So far these devices have little processing power or memory but have RF communications and some type of self contained power source or power management system. The more elaborate autonomous chips also include or are built around a type of sensor. The simple versions include RFID chips [RFI], smart cards and chip implanted credit cards. The simplest is the passively power RFID. The chip simply reflects the source RF carrier and modulates it (using carrier power) to indicate its ID. More complex examples include patient monitoring alarm [GHANT] and the Smart Dust DARPA research program [DUST1, DUST2] of the '90s. Both of these used battery powered RF to broadcast an ID on a detected sensor input (Table1).

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System	*Passive id*	*Active id*	*RF sensor*
Example	RFID, Smart Card {simple)	Smart card, Active RFID	Smart Dust; RFID + sensor
Power source	None	Short term battery	Battery
Maximum Memory	ROM ID (1KB)	R/W ID + parameters (2 KB)	
RF range (meters)	Passive; order of cm	Active 1-10	10 - 20
Compute	None	FSM	FSM

Table 1: Some autonomous chip examples (FSM represents a simple finite state machine or micro controller)

The various Smart Cards and Money Cards include VISA cards and Hong Kong's Octopus Card. All (except those that require contact) use a form of RFID. The simplest cards are passive without on-card writeable memory. Records are updated centrally. Implementation is frequently based on Java Card [JAV].

The Smart Dust [DUST1] project started in the early '90s and pioneered significant work in the sensor and RF areas. That project targeted sensor plus RF integrated into a form factor of the order of 1 mm^3 called motes. As a power source it relied on AA type batteries. That project was targeted at sensing an "event"; a moving object, a thermal signal, etc.

In this paper we consider tradeoffs in silicon technology, limits on batteries and energy, RF communications for sensor applications.

Technology

The main problem for useful an autonomous sensor is battery power or stored energy. In dealing with this issue recall two general relationships, relating silicon area, A, algorithmic execution time, T, and power consumption, P (in these expressions k is a constant):

1) $AT^2 = k$

This well known result [ULL] simply related area (the number of transistors) to the execution time required to complete an operation. The more area (transistors) used the faster (smaller) the execution time.

2) $P^3T = k$

This result [FLY] applies to dynamic power only and is based on voltage scaling augments. It's easy to see that as voltage is decreased power is reduced by the square but speed is reduced linearly. But the transistor charging current (representing delay) and voltage have a non linear relationship. This gives the cubic result. We can rearrange this as:

3) $P_2 / P_1 = (F_2 / F_1)^3$

So if we want to double the frequency we should expect the design to use 8 times more power. While the range of applicability of expression (2) is not precise, suppose we use it to project the frequency of a processor design that operates at a microwatt. The best power-performance design of today might consume one watt and achieve one Gigahertz (corresponding perhaps to 1,000 MIPS); this may be optimistic. Reducing the power by a factor of 10^6 should reduce frequency by a factor of 100 or 10 Megahertz.. Within the past two years a sensor processor has been built that achieves almost 0.5 MIPS per microwatt [ZHA]. While this is an order of magnitude away from our target of 10 Megahertz per microwatt, silicon scaling projections should compensate for the difference.

Powering the sensor

The key problems in forming robust sensors are energy and lifetime. Both relate to the power source, i.e. the battery. Batteries can be charged once or rechargeable (with varying recharge cycles). Rechargeable batteries can use scavenged energy from the environment. The capacity of the battery is usually measured in milliamp-hours; which we convert to Joules (watt-seconds) at 1.5 volt. Both capacity and recharagability depend on size which we assume is generally consistent with the size and weight of the sensor die (about 1 cm^2 surface area).

In table 2 we list 3 common battery types; the printed [POW, PUS] and thin film batteries [CYM] can be directly integrated into the sensor die (usually the reverse side); button batteries are external and are less than 1 cm in diameter.

Type	*Energy (J)*	*Recharge Y/N*	*Thickness (micron)*
Printed	2 / cm2	N	20
Thin film	10 /cm2	Y	100
Button	200	Y	500 stand alone

Table 2: Battery technology

Printed batteries are formed by printing with special inks in a flat surface; thin film batteries are deposited on silicon much as the sensor dies itself.

Energy may be scavenged from many sources (some are illustrated in table 3); usually the larger the battery format the more the charge. Much depends on the system environment as to which, if any, scavenging is suitable.

Source	*Charge rate*	*Comment*
Solar	65 (milliwatts)/ cm^2	
Ambient light	2 (milliwatts)/ cm^2	
Strain and acoustic	A force (sound) changes alignment of crystal structure, creating voltage	Piezoelectric effect
RF	An electric field of 10V/m yields 16uW/cm^2 of antenna	See [YEA]
Temperature difference (Peltier effect)	40 (microwatts/5^0 C difference)	Needs temperature differential.

Table 3 Some energy scavenging sources [MEN, ROU, PAR]

Assuming consumption of 1 uw (when active); the operational lifetime between charges is plotted in figure 1. Duty cycle can play an important role in expending the sensor serviceability. The assumption is that a passive sensor can detect an event and power up the system for analysis.

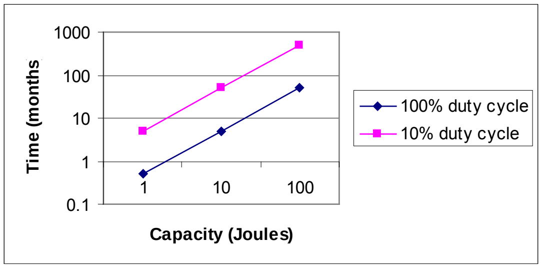

Figure 1: Maximum time between recharge for 1microwatt of continuous power consumption.

If we can configure the sensor to use of the order of 1 microwatt we should be able to incorporate a suitable battery technology especially if we have the ability to scavenge some addition energy.

RF Communications

The work of the Smart Dust program seems to the most pertinent [DUST1, DUST2]. That program demonstrated the integration of low power RF into an sensor chip. To summarize some of their many finding:

1) A feasibility study realized a transceiver achieving 100 Kbps over a 20 meter distance with an energy budget of 25 nJoules/bit. This corresponds to about 10^{11} bits / Joule/ Meter. One Joule of battery energy allows 100 Gbits to be transferred across one meter.
2) Communications with less than 1 milliwatt was not only feasible but likely to be commercialized. With typical duty cycle of less than 1% the average power consumption was between 1 and 10 microwatts.
3) There is a large data packet overhead (including startup and synchronization, start symbol, address, packet length, encryption and error correction). Short messages can have as little as 3% payload packet efficiency. It is better to create fewer longer messages.
4) As a result of (2) and (3) the system designer will want to minimize the number of transmission and maximize the data packet payload.

Conclusions

There's a whole new field to be explored based on the next generation of autonomously sensors and SOC chips. Transistor density improvements will enable close to a billion transistors per cm^2. This enormous computational potential has a major limitation: limited electrical energy. There is a new direction opening in computer architecture, *nano computing*, to contrast with historical efforts in supercomputing. The target of this field is to produce the algorithms and architectural approaches for high performance at less than one millionth current levels of power dissipation; freeing the chip from external power coupling.

For untethered operation a form of wireless communication is required. This is another significant challenge for RF especially with a power budget also in the order of microwatts; but careful budgeting of messages to limit transmissions could be helpful

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