Processors for Mobile Applications

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Abstract:

Mobile processors form a large and very fast growing segment of semiconductor market. Although they are used in a great variety of embedded systems such as personal digital organizers (PDAs), smart cards, internet appliances, laptops, smart badges, cellular phones, wearable computers, and sensor networks, they share the common need for low power, code density, security, cost sensitivity and multimedia and communication processing.

The goal of this paper is to review the field of processors for mobile applications. We survey a spectrum of processors, their system software, and the accompanying hardware components. The emphasis is on classification and identification of major technology and architecture trends. Companion to this paper is a WWW page [Mob00], which provides comprehensive additional material about mobile processors.

1 Introduction

1.1 Motivation

In 1970, Intel introduced the first single chip microprocessor, the Intel 4004. It had 2,600 manually placed transistors and clocking frequency of 100 KHz. Since then, the consistent progress in semiconductor integrated circuits technology, the introduction of new architectures, and new synthesis tools has enabled a spectacular growth in performance. For example, the computational power of general-purpose processors has increased by more than 50% in the last 15 years. Today's state-of-the-art workstation microprocessors feature tens of millions of transistors, and run at GHz clock frequencies. In addition to these quantitative changes, we have also witnessed a major product diversification. Microprocessor technology is used for the manufacturing of microcontrollers, digital signal processors, graphic processors, and video processors.

In the last several years, the communication processor has emerged as one of the fastest growing processor markets. Both network processors for broadband optical communication and a variety of processors for wireless applications have been attracting a great deal of research and development, as well as market interest. Furthermore, the emergence of the next generation of distributed, ubiquitous computation, as embodied in sensor networks, ensures the long-term importance of mobile processors.

Our goal in this paper is to survey mobile processors. More specifically we summarize the main types of processors for mobile applications, their system software, and the related system hardware components. We classify mobile processors in four main groups: computation-oriented (e.g. laptops, handhelds, PDA, and calculators), communication-oriented (e.g. wireless phones), media-oriented (e.g. MP-3 players and digital cameras) and devices for emerging applications (e.g. smart cards and sensor networks). The emphasis is on identifying major trade-offs and trends. We also explore the relationship between the mobile processors, technology and applications.

1.2 What defines a Processor for Mobile Applications

The processors under discussion are used in a wide spectrum of embedded systems, including laptops, personal digital organizers, calculators, wearable computers, cellular phones, mobile internet terminals, MP-3 players, digital cameras, digital cam-coders, smart cards, and sensor networks nodes. These systems differ considerably in terms of their computational and communication requirements, and the types of real-time constraints. Nevertheless mobile processors share a number of common characteristics. Most importantly, processors that are used in mobile applications are subject to design metrics, that emphasize *cost, time-to-market, and low power.* In contrast to desktop processor, just-in-time computing takes precedence over the traditional maximum performance metric.

Because of the constrained resources of power and cost, and the real-time computation requirements, the processors for use in mobile applications posses a number of distinct characteristics. Examples of such characteristics are:

- *Limited Programmability.* Almost all mobile systems have a limited functionality and require a smaller number of operation modes than their wired counterparts. In many cases, the application is very well defined, and does not change much over the life of the mobile product. Therefore, limited programmability often provides the best trade-off.
- *High I/O to Computation Ratio.* In many mobile processors, communication is the primary feature. Even when data processing is needed, most often it requires relatively simple computations, at least in comparison with typical desktop programs.
- *Stream data processing.* Most mobile applications include some form of multimedia processing. Initially this was restricted to voice, but newer devices feature a richer media content.

1.3 Paper Organization

The reminder of the paper is organized in the following way. In the next section we survey and categorize mobile processor according to domains of their applications. After that we discuss major trends in mobile embedded processors. Next, we cover most relevant technologies, including power sources. Section 5 presents an overview of system software for mobile processors. Before concluding, we outline some of the most exciting (and most likely) future trends.

2 Mobile Processor Survey

In this section, we classify embedded mobile processors into four groups according to their targeted applications. Next, we review the most popular embedded processors used in mobile applications today, and explain the technical specifications of these processors.

2.1 Mobile Computers

Historically, mobile processors have been used mostly as computers. While initially the focus was on calculators, recently it has shifted to notebooks and PDAs. The emphasis in today's laptops is to provide complete workstation functionality, with no more than 25% reduction in performance. PDAs are on the other

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side of the mobile computer spectrum, providing a limited functionality under strict cost and power constraints.

- ***Laptops:*** Laptops usually use a lower power version of desktop microprocessors. To reduce power consumption, most of current mobile processors operate at a lower voltage and frequencies than the corresponding desktop versions. As of today, the highest clock rate for laptops is 700Mhz compared to 1 GHz. Intel's low end processors such as Tillamook, Celeron, and Deschutes operate at 300 to 400 MHz, and consume between 6 and 10 W. The PowerPC 750-400 operates at 440 MHz and consumes 8 W. This compares to the desktop PIII that operates at 1GHz, consumes 23 W, and is considered a power-efficient workstation processor. Battery life for a laptop today ranges between 3 and 6 hours. The market has been dominated for years by AMD's and Intel's Pentium mobile processors. Recently, Transmeta announced the Crusoe [Cme00], a VLIW processor that uses binary translation (code morphing) to run Intel-compatible code, while reducing processor complexity and hence improving power efficiency with little performance reduction. Unfortunately, technical details of the processor are not available in the open literature.
- ***Hand-held PCs and palm PCs:*** Hand-held PCs deliver PC functionality in super-portable form, while offering more computing power than a palm-sized PC. They cannot run full versions of the application software, and lack internal hard disks. They use static memory rather than a hard disk for internal storage. Thereby offering a longer battery life. A crucial design feature of the Palm PC is the users' ability to input and retrieve information in a variety of formats. The Palm PC allows users to quickly access and input information by voice, ink, a soft keyboard, or handwriting recognition, using natural and simplified characters. The MIPS RISC processor in one of its many varieties is the favored processor. For example, Compaq uses PR31700 in PC Companion, NEC uses VR4102 in Mobile Pro, Philips, Samsung, and Sharp use PR31700 in Velo, Infomobile, and Mobilon respectively, and Toshiba uses TX 3900 in Genio.
- ***Personal Digital Assistants (PDAs):*** The PDA was pioneered by Apple Computer, which introduced the Newton MessagePad in 1993. Shortly thereafter, several other manufacturers offered similar products. Initially, PDAs had only modest success in the marketplace. Now, PDAs are common gadgets. A typical high-end PDA can function as a cellular phone, fax, and personal organizer. Unlike portable computers, most PDAs are pen-based, using a stylus rather than a keyboard for input. Some PDAs can also react to voice input by using voice recognition technologies. Palm OS is by far the most popular operating system for PDAs. The primary processor architecture for both Palm and all its licensees is the Motorola's Dragonball chip.

2.2 Wireless Communication Devices

- ***Wireless phones: The*** wireless (mobile) phone market is one of the largest and fastest growing high tech markets. In 1996 there were less than 100 million subscribers, in 2000 more than 250 million, and it is expected that by 2008, there will be more than 1 billion. The wireless phone processor market is currently dominated by the ARM microcontroller - TI DSP processor combination. TI has more than 50% and Lucent more than 25% of this DSP market. Two other larger players are Motorola and Analog Devices, each with approximately 10% of the market. The details on the TI DSP processor in mobile phones are discussed in section 4.
- ***Pagers:*** Charles Neergard invented paging in 1949 while he was in the hospital and needed assistance. Today, more than 20 million people in US have pagers. A recently developed paging unit, i.e. the 8-bit mobile data receiver, is spurring the growth of mobile data computer applications. They connect directly to a computer serial port or plug into a PC Card expansion slot, and allow any type of data to be sent directly to a roaming computer, Thus providing applications such as spreadsheet and calendar updates, faxes, and graphics. Pagers mainly use 8-bit microcontrollers as their computational engine.

2.3 Media Electronics - Information Appliances

The next step in the Internet revolution, in addition to wireless Internet, are Internet Appliances. This is one of the fastest evolving mobile markets. We only survey a few of them. .

- ***MP3 Players:*** The MP3 players available on the market today are positioned as PC companion pieces, rather than standalone consumer devices. The most recent product is the Cirrus Logic EP7209, which replaces the three to five ICs used in current MP3 players. Such devices include a fixed-function DSP, an external 8- or 16-bit microcontroller, and programmable logic devices for storage, display and parallel ports. While more than half of the EP7209's available processing power is devoted to the decompression of audio algorithms and copy-protection schemes, the chip, operating at 74 MHz, still can devote 25 MHz to other unique features.
- ***Digital Cameras:*** The worldwide market for digital cameras is expected to reach $5.4 billion by 2002. Today, digital cameras provide the major functions needed to preview, capture, compress, store, transfer and display digital images. A typical processor for this domain is represented by the Cirrus-IBM-Polaroid. The three-chip set includes a Sierra Imaging's DSP ASIC, a SparcLiteRISC processor (MB86831) and an 8-bit micro-controller (MB89165) from Fujitsu Microelectronics. An ARM core has recently displaced the SparcLite device as the central controller.

2.4 Emerging Applications

- ***Smart Cards:*** Smart cards are credit card-like devices with some processing capability. A smart cards main limitation is memory size - typically 512 bytes of RAM, 16 Kbytes of masked ROM, and 8 Kbytes of EEPROM. The chip manufactures are mainly European: Siemens, Philips, Thomson, Motorola UK, Hitachi, and Oki. All major smart card manufacturers have either developed or are developing these advanced smart-card chips in their products (Philips 83C852, Motorola 68HC05SC29, Siemens SLE44C200, Thomson ST16CF54, European Cascade EP8670, Crisp 20847).
- ***Smart Badges:*** A badge is an identification and access control system. Badges recently started to evolve and acquired images, names, bar codes, magnetic stripes, and finally microprocessors and various types of transponders. The architecture of an intelligent badge system was first proposed in Olivetti Research Labs, and was later used by XEROX Parc and called an active badge. Implementations of badge system to support context-aware computing, were the Intelligent Badge and Smart Badge systems, developed at KTH in Stockholm and Wollongong University in Australia.

3 Major Technological Trends

The single most important and most influential semiconductor trend has been a three-decade long sequence of technological improvements. This progress enabled very-large scale of integration of a single chip, and the realization of remarkably powerful processors. It is interesting and instructive to take a closer look at key technological data and trends in embedded mobile processors. To put things in perspective, Table 1.A shows data for state-of-the-art workstation and embedded processors that are widely used in the mid of 2000. Table 1.B shows the same information for three types of processors in 1996. The internal organizations of the tables are identical.

The first column shows the design feature. The next four columns shows minimal, average, maximal and representative values for the features in the workstation processors. This is followed by the same data for embedded and eventually mobile processors. Representative processors in Table 1.A are Intel Pentium PIII, AMD 486DX5, and ARM 710. The source of all this information is the Microprocessor Report [Mpr00]. For each type of processor we used between nine and ten samples. For example, for workstation processors in 2000, we used Compaq Alpha 21264, AMD Athlon, Intel PIII, MIPS R12000, IBM Power3, PowerPC 7400 (G4), Sun Ultra-2, Sun Ultra-2i, and Hal Sparc64-III. For mobile processors, the samples consist of: SA-110, ARM710, SH7708, 401GF, 403GX, VR4121, M32R/D, CF5202, and V851.

A number of conclusions can be drawn from the two tables. Most striking is the large technological advantage of workstation processors, if only the sheer performance and integration is considered. For example, they are more than 7 times faster and 13 times larger at average. They use two more metal layers and have a 3 times larger die size. But, they cost 6 times more, and also consume 100 times more power than mobile processors. The differences between embedded and mobile processors are also significant, but of a lesser scale. Obviously, low power is a prime design objective. However, this has to be achieved with moderate technology due to high cost sensitivity. It is also interesting to follow the historical evolution of the three types of processors by comparing the data in Tables 1 and 2. For example, we see that the technology used by a workstation processor in 1996 is superior to the one used by mobile processors in 2000 in terms of feature size and number of metal layers. Furthermore, we see a small reduction in power for mobile processors. The main change is that size went up by more than three times. It is apparent that the need posed by the more complex applications is answered mainly through additional parallelism, with only a moderate increase in frequency.

An interesting trend can be seen in configurable or programmable CPUs. They form a new class of embedded processors that allow designers to customize on-chip resources of processor architecture to their application yet use standardized software and development tools that conform to existing ASIC SoC design methodologies. RISC/DSP type configurable and synthesizable cores from Tensilica, ARC Cores and Improv Systems' configurable Superscalar/VLIW cores, belong to this class of processors. Tensilica's Xtensa processor [Gon00] allows extensibility of the instruction set architecture using Tensilica Instruction Extension (TIE) Compiler with DSP rich coprocessor options [Gon00]. ARC Cores offer an architecture that can accept plug-ins to extend a core's instruction set, register set and bus configuration. Improv Systems provides a programmable platform for a multi-processor implementation of a configurable datapath. Alternate approaches have been to introduce reconfigurable processors by including programmable logic elements in the fabric of the processor as shown by Chameleon Systems CS2000 family and the Manta processor from BOPS. Clearly, configurable processors are giving the flexibility to customize processors for networking and mobile applications without increasing the design cycle time.

Table 1.A	*Workstation processor*				*Embedded processor*				*Mobile processor*			
	Min	Avg	Max	PentiumPro	Min	Avg	Max	AMD2940	Min	Avg	Max	ARM 710
Freq(MHz)	110	214	500	200	25	63	133	50	20	52	200	40
Cache(I/D)	8K/8K	32K/32K	64K/64K	8K/8K	1K	4K/4K	16K/8K	8K/8K	512/0K	4K	16K/16K	8K
IC process	0.29u 5M	0.4u 4M	0.5u 4M	0.35u 4M	0.35u 3M	0.65u 3M	0.8u 3M	0.7u 3M	0.35u 3M	0.6u 2M	1.0u 2M	0.6u 2M
Voltage(V)	3.3	4	5	3.3	3.3	4	5	3.3	2.0/3.3	3.6	5	5
# of xtors	2.3M	6.4M	15M	5.5M	0.35M	1.43M	2.53M	1.2M	0.256M	0.695M	2.1M	0.57M
Die (mm^2)	84	226	335	196	25	100	217	119	25	44	82	25
Power (W)	9	25	40	35	0.5	2.1	4.5	1.7	0.12	0.54	1.1	0.424
mfg cost	$25	$150	$375	$175	$8	$25	$75	$20	$4	$10	$18	$9

Table 1.B	*Workstation processor*				*Embedded processor*				*Mobile processor*			
	Min	Avg	Max	Intel PIII	Min	Avg	Max	AMD486DX5	Min	Avg	Max	ARM 710
Freq(MHz)	296	550	1000	1000	25	125	400	133	25	75	233	25
Cache(I/D)	16K/16K	64K/64K	512K/1M	16/16/256	1K	16K/16K	32K/32K	16K	2K	8K	16K/16K	8K
IC process	0.18u 6M	0.25u 5M	0.29u 4M	0.18u 6M	0.18u	0.35u 3M	0.7u 3M	0.35u 3M	0.25u 3M	0.5 3M	0.8u 2M	0.8u 2M
Voltage(V)	2.5	3	3.3	2.5	1.35/3.3	3.3	5	3.3	2.0/3.3	5	3.3	3.3
# of xtors	3.8M	26M	130M	24M	0.35M	2M	28M	1.2M	0.341M	2 M	7M	0.341M
Die (mm^2)	83	185	477	106	27	62	119	43	22	55	154	40
Power (W)	13	40	75	23	0.4	2.6	10	2.75	0.12	0.29	0.42	0.12
Mfg cost	$40	$130	$330	$40	$8	$16	$39	$11	$4	$18	$65	$9

Table 1 State-of-the-art of Different Processors: Table 1.A (1996), Table 1.B (2000)

Power sources are among the most crucial components when designing mobile embedded systems. Batteries are currently widely used as the power supply of choice for mobile embedded systems. Portability constrains the size and weight of the batteries. In addition, frequent battery replacements and frequent and long battery recharging are also undesirable. Figure 2 shows a simplified view of the growth in the battery technology vs. the microprocessors technology. As can be seen from the chart, Moore's law is not applicable to batteries. However, as new applications emerges on embedded processors, the power requirements for mobile processors increase. Figure 3 illustrates the trends in total processor's power consumption as the area and the frequency of the die increases.

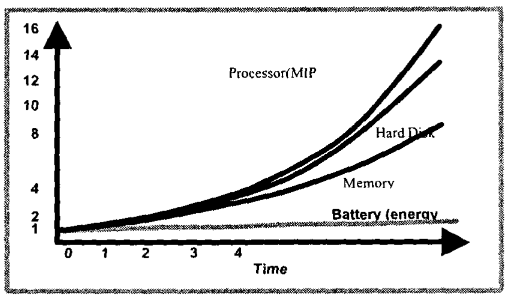

Figure2 Improvement compared to year 0

Table 4 provides information about where power is spend in laptops. Backlight and video are two major sources of power consumption. Hard disks, processors, and displays are also consuming high portions of the power. Wireless network interface card (NIC) is also a significant source of power consumption. The limited power nature of the batteries compounded with their slow growth, implies a serious need to explicitly design the mobile embedded system for low power. This system level low power optimization should include the entire synthesis at all levels including circuit, logic, software, protocols, and algorithms. The primary is to optimize the energy metric while meeting QoS constraints. Recently a number of alternatives were proposed in order to overcome the limitations of batteries. An example of such methods was discussed in [Ami97].

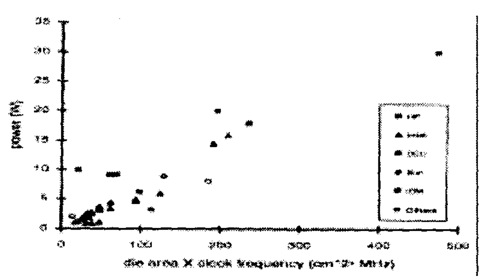

Figure 3 Power consumption vs. clock freq. x die area

Comp.	Hyp. 386	Duo 230	Duo 270c	Duo 280c	Avg
Processor	4%	17%	9%	25%	14%
Hard disk	12%	9%	4%	8%	8%
Backlight	157%	25%	26%	25%	23%
Display	4%	4%	17%	10%	9%
Modem	N/A	1%	0%	5%	2%
FPU	1%	N/A	3%	N/A	2%
Video	26%	8%	10%	6%	13%
Memory	3%	1%	1%	1%	2%
Other	33%	35%	28%	22%	30%
Total	6W	5W	4W	8W	6W

Table 4 - Power Consumption in Laptops

4 Case study – DSP processors

DSP processors form one of the most important classes of mobile embedded processors. DSP hardware sales generated over $3 billion of revenue last year and they have one of the highest CAGRs (Compound Annual Growth Rate) in the semiconductor industry. In particular, DSP processors are a mandatory component in today's mobile phones.

It is very instructive constructive to analyze the trends in DSPs in the last two decades. The DSP architecture has been strongly impacted by both the evolution in technology and the targeted applications. One of major architectural novelties of the DSP processor was the special multiply-accumulate (MAC) unit. In 1980, a general-purpose programmable DSP had more than 10 times MAC performance advantage over the microprocessor. [Ack98]. In 1985, the MAC performance advantage of DSPs over microprocessors shrank to 5. By 1995, the MAC performance of DSPs and microprocessors became comparable. DSPs have seen a slow performance improvement so that today's microprocessors are outperforming DSPs in MAC dominated applications [Ack98]. On the other hand, DSPs developed several alternative advantages over microprocessors. They have significantly lower-power lower-cost signal processing engines that have MOP/mm^2 and MOP/mW ratings that are an order of magnitude better than microprocessors. The area and power efficiency of DSP processors is optimized at several design levels: at the architecture and algorithmic level by modification of arithmetic modules through optimized memory organization, by use of special logic families, and through using more efficient and power-sensitive CAD tools [Ver00].

Advances in digital communications and pervasive computing, is putting new and even more aggressive demands for low power, low cost, and programmable DSPs. Examples of the growing mobile embedded applications include cellular terminals, smart phones, real-time video communications, 3D graphics and wireless base-stations. The DSPs in use today are not promising candidates for the applications mentioned above. A new generation of DSP processors with support for complex, multi-threaded, real-time synchronous applications is required. Parallel architectures are required to meet the desired performance. The new applications will have much larger memory and bandwidth requirements than before. The limited time to market frame implies a need for a compiler-driven programming environment that supports parallel programming and debugging. Portability requires an even further reduced power consumption, which is rapidly becoming the most critical design issue. Hence, New power-saving techniques have to be introduced. For instance, dynamic voltage scaling is an attractive option to maintain the performance at worst-case conditions while minimizing the power under normal conditions.

Among the latest attempts toward realizing the next generation DSP core is TI's TMS320C55x core. The C55x DSP core has 2 MAC and 4 ALU units. It has a variable instruction length, from 8 to 48 bits. It runs on frequencies up to 400 Megahertz (MHz), delivering the raw processing power (up to 900 MIPS and 800 MMACS) needed to bring graphics-intensive Internet applications, digital still imaging and digital audio, as well as real -time video conferencing to wireless handsets. The C55x DSP core delivers ultra-low power consumption of 0.05 milliWatts per MIPS. Also, it uses automatic power management mode and configurable idle domains to father reduce power. Additionally, in the next generation voice-only handsets, the C55x DSP core will enable a phone's battery life to operate at least a half-day to one week longer than today's leading C54x DSP-driven devices. In order to facilitate debugging it provides special emulation features.

5 Beyond Processors - System Software

In this section, we discuss the impact of system software, and in particular operating systems, on mobile processor markets and architectural trends. In addition, we briefly mention compilers and software utility tools for mobile processors.

5.1 RTOS for mobile processors

Operating system is a program that provides an interface between application programs (and often a user) and the computer hardware resources. The four main tasks of both general-purpose computing and embedded systems operating systems are: 1) process management; 2) interprocess communication and synchronization; 3) memory management; 4) input/output (I/O) management [Sil88, Tan97]. In the general-purpose microprocessor market, the operating system (OS) has been of great importance. For example, the most popular general-purpose operating systems are MS-DOS and Windows, and with this comes the implication that the Intel's x86 architecture is the dominating hardware platform for both personal computers and workstations. Similarly, the next two most popular architectures are the PowerPC due to the Mac OS used in Apple's computers, and RISC processor that run UNIX (e.g. Sun) used in scientific and engineering workstations [Com98]. More recently, Linux has been attracting a high level of interest and has been ported to numerous platforms.

Following this parallel, there is a growing consensus that operating systems for mobile embedded processors are also of ultimate importance for market success of processors. While there are numerous similarities between general purpose OSs and embedded systems OSs, there are also significant differences. For example, in embedded systems, the operating system not only provides the interface between application and hardware, but often also enables the handling of tasks with real-time requirements. Real-time systems are systems where proper functionality requires both functional correctness as well as the correct timing behavior of the system [Sli99]. The main properties that make a mobile embedded system different from a general-purpose desktop system include:

- Hardware constraints in terms of working memory, nonvolatile storage and power consumption are significantly stricter;
- User interfaces with significantly limited capabilities compared to the one found in a general-purpose desktop systems;
- Often application specific software and hardware is used rather than the traditional general purpose hardware and software, employed in desktop systems;
- Streaming media applications (e.g. voice, audio, video) which requires specific real-time requirements are often the dominant type of application;

These features of mobile processors have numerous ramifications. For example, although computational performances of general-purpose processors highly outperform the performances of DSP processors, the latter have I/O characteristics that are much better suited for media applications [Bru96] and therefore often imply better overall system performance. Furthermore, because use of mobile embedded systems is not restricted to a fixed point, security and privacy are of significantly higher importance. Finally, note that modern mobile processors most often target a soft real-time operating system (RTOS) rather than a hard RTOS. For hard RTOS, the most important requirement is that throughput and computational requirements latencies are deterministic and that all deadlines are always met. In contrast, for soft RTOS, the main issue is tailoring the operating system to the strict hardware and power requirements, while the deadlines for real-time tasks occasionally may not be met. Comprehensive survey of embedded and real-time systems trends and issues is given in [Li97].

5.2 Compilers

In addition to the OS, utility programs play an important role in the acceptance and use of mobile processors. Utility tools are usually organized in integrated development environments, which include tools such as project builders, source level debuggers, event analyzers, performance profilers, run-time error checking tools, graphical code browsers, specialized text editors, and version control systems. The most important utility tools for mobile processors are compilers, linkers and loaders [Lev99]. Development of power and memory utilization sensitive compilers is still mainly in the research phase.

6 Beyond Processors -Emerging Mobile Applications

6.1 Towards wireless networking

The current generation of mobile applications ranges widely from palm-sized, stylus-based class of PDA applications such as personal organizers, (e.g. phone/address book), wireless links to web applications, (such as email and web browsing) to keyboard-based desktop type of applications (such as word processing and spreadsheets). The Global Positioning System (GPS) has improved the positioning of mobile systems. In all these applications, the capability to transfer and synchronize data between PDAs and desktop systems has played an equally important role in the acceptance of mobile applications. Current portable devices use infrared links (IrDA, Infra-red Data Association) to communicate with each other. Although infrared transceivers are inexpensive, then have a limited range (typically one or two meters), are sensitive to direction and require direct line-of-sight and can in principle only be used between two devices.

Radios, on the other hand, have much greater ranges, can propagate around objects and through various materials and connect many devices simultaneously. The availability of a low-cost ad-hoc radio link between mobile computers, mobile phones and other portable hand-held devices along with connectivity to the Internet is expected to revolutionize the world of mobile computing and communications. Bluetooth [Har98] and HomeRF [Hom00] aim at providing ubiquitous computing by eliminating wired channels, calling for interoperability between various portable devices with the flexibility of a wireless solution.

6.2 *Sensor Networks*

The availability of cheap wireless connectivity is bound to create exciting new opportunities. Examples of this is distributed, large-scale sensor networks. This has been the focus of some research projects such as the PicoNode project [Rab00] and [Mob00]. These networks require versatile, self-organizing, multi-functional and adaptive elements for communication and computation, yet have minimal form factor, energy and cost to make them feasible for large-scale coverage. This has led to the idea of a highly energy-efficient singe-chip nodal architecture that has a sensing device and its conversion into a digital representation integrated with local computation and communication capabilities. Support for the network architecture and the accompanying protocols is also a requirement for the single node. Figure 6 shows a possible architecture. Flexibility and energy-efficiency are at the core in the design of the PicoNode processor. It is an emerging belief that this is best accomplished though the use of reconfigurable co-processors that use a programming-in-space approach rather than the programming-in-time approach of the current mobile processors.

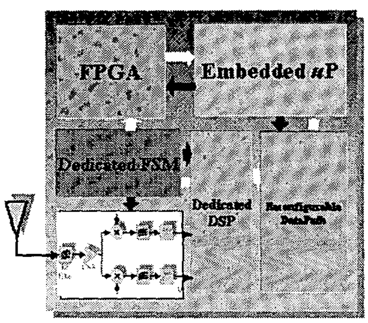

Figure 5 PicoNode's conceptual architecture

7 Conclusion

Recently, mobile applications and mobile programmable processors have attracted a great deal of attention. We surveyed embedded mobile processors, and presented their most important characteristics, their system software, and related technology. The emphasis was on classification and identification of major technology and architecture trends. Companion to this paper is a WWW page [Mob00] with additional comprehensive information.

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