

# DSPs IN MOBILE COMMUNICATION IN THE UNITED STATES

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## ABSTRACT

The mobile communication industry in the United States is undergoing major changes. Auctioning of additional spectrum will lead to more service providers and will significantly increase competition. Service providers are likely to customize the services they offer to differentiate themselves from others. We will discuss possible technologies for differentiation of services and the implications of these on the requirements for embedded digital signal processors (DSPs). In the US, supporting at least three widely used air interfaces will be a challenge to the industry.

The need for customization in the context of multiple standards will create strong pressure to significantly improve the firmware development environment for DSPs. This also implies evolution to architectures that are more friendly to developers.

## 1. INTRODUCTION

Single chip fixed point DSPs initially proved their value in the consumer market with the introduction of the digital answering machines (DAMs), which used digital speech coders for storing messages in solid state memories.

Later, the development of DSP-based low cost modems introduced these devices to the home-computing market. Since then, they have become a critical component in another consumer market -- digital mobile phones. Increasing the clock rate of existing DSP architectures, and adding very specific accelerators to existing DSPs enabled DSPs to meet the requirements of mobile phones [1].

However, developments in the wireless industry, especially in the United States, will shake up the mobile phone business, and this, in turn, is likely to put new demands on the DSP. The goal of this paper is to enumerate these trends and assess their impact on DSPs.

PCS allocations in the US In 1994 in the US, the FCC began to auction additional RF spectrum for mobile communication services [2]. The spectrum, popularly termed the licensed personal communications services (PCS) band covers 1850-1910 MHz and 1930-1990 MHz. This new allocation has increased the total spectral allocation for mobile applications from the 50 MHz (824-849 MHz and 869-894 MHz -- the so

called "cellular" band) to a total of 170 MHz. The PCS allocation consists of six subbands, labeled (in order of increasing frequency) A, D, B, E, F, and C. The A, B and C subbands are each pairs of 15 MHz bands. D, E and F are each pairs of 5 MHz. (The pairing is intended to enable frequency division duplexing -- see below.) A variety of rules and restriction have been placed on ownership of these bands. The net result of these is that in most regions of the US there are likely to be six additional service providers for mobile communication services. In the past, there were only two, who shared the cellular band. The increase in spectrum allocation and the increase in number of service providers will both lead to increased competitive pressures in the industry.

PCS air-interfaces in the US A unique feature of the PCS allocations in the US is that the FCC chose a hands-off approach to the process of standardizing the technical details of the air-interface that would be used in these bands. Instead the FCC limited its role, primarily, to ensuring that the variety of proposals can coexist in separate segments of the PCS spectrum. In the absence of a single air-interface, the TIA (Telecommunications Industry Association) has settled on specifying seven different air-interfaces -- TAG1 through TAG7 -- for the PCS bands [3]. These seven technologies are characterized by differences in multiple access methods (which allows subscribers to share the spectrum), and duplexing methods (which allow a normal conversation including brief periods of so called "double-talk").

Multiple access methods include frequency division multiple access (FDMA), time division multiple access (TDMA), code division multiple access (CDMA), or combinations thereof.

Duplexing methods include frequency division duplex FDD, time division duplex (TDD), or combinations of the two.

On examining the stated air-interfaces choices of owners of the PCS spectrum, it is clear that at least three of the air-interfaces (TAG2, TAG4 and TAG5) will see significant deployment. TAG2 is a CDMA standard that is based on the TIA IS-95 cellular band air-interface. The upbanded standard is ANSI J-STD-008. TAG4 is a TDMA standard that is an upbanded version of TIA IS-136 (which in turn has evolved from IS-54). The upbanded version is called IS-136A. TAG5 is another TDMA based air-interface that is a band-shifted variant of GSM and DCS1800. TAG5 is popularly known as PCS1900.

## 2. COMPETITIVE OPTIONS

Service providers are preparing to respond to the anticipated competitive pressure in a variety of ways. Two that come to mind are a) to drop prices and/or b) to customize service offerings in order to differentiate themselves from others. Examples of customizations are higher than average quality of service, and the addition of new services such as text or voice messaging.

Strategies for service differentiation can be hard to predict, but they are likely to span some of the approaches discussed in this section.

Improved voice quality This can be addressed by the use of a) higher complexity speech coders that provide better quality at the same bit rate and b) more complex modulation and coding techniques to permit higher payload rates per voice channel so that higher rate coders can be used. We can provide instances of both approaches in the US. IS-136 is being modified to replace the VSELP coder with IS-641, an algebraic CELP coder commonly referred to as the enhanced full rate (EFR) coder. Recent publications [4] indicate interest in incorporating higher rate speech coders into TDMA. In response to the adverse publicity received by the initial rollout of VSELP in IS-136, the CDMA standard has been modified to support a speech mode with up to 13kb/s ("Rate Set II"). These trends generally imply a higher performance -- roughly equated to millions of instructions per second (MIPS) -- and larger memory requirement on the DSP. While the carriers would like to roll these features out simultaneously both in the terminal equipment and in the infrastructure, it is not clear that this is always possible, especially since competitive issues are driving down the time period over which this can be planned. One consequence is that both infrastructure and terminal equipment may end up with a number of modes of operation to support interworking.

Another possible direction for the development of speech coders is rate reduced coders, so called "half rate coders", to increase network capacity. Although provisions exist for half-rate coders in the US standards, there is less interest in these at the moment than there is in other parts of the world.

The decreasing size and weight of phones also implies that greater acoustic coupling between transducers in phone and this can drive the inclusion of complex processing to handle acoustic imperfections such as echo, noise, and distortion.

These trends suggest the need for increasing address space. Other implications of the multi-option support on the DSP are discussed in section 3.

Automobile Specific Features Mobile telephones first appeared in the market as car mounted sets, but with the advent of miniaturization, handset phones took over the market and the car mounted units became virtually extinct. Nevertheless, a significant number of mobile conversations are made from cars. In order to respond to the specific needs of the car environment, phone manufacturers usually offer a "car-kit" accessory.

Presently, very few of the handset owners buy a car-kit, however, this situation is likely to change due to: 1) Increasing implementation of road safety regulation that prohibit the use of handsets while driving; 2) promotion of car-kits by service providers in order to increase the usage of phones in the car; and 3) car manufacturers plans to offer car-kits as a built-in feature of new cars. One may envision that future car-kits using the DSP for a speakerphone, voice based user interface, antenna diversity, integration with the automobile audio and comfort systems, or integration with navigation and traffic monitoring systems.

An interesting design question is where should the additional processing required by those features be implemented? Implementing them in the handset may overload the limited resources available. On the other hand, installing a separate DSP and peripherals in the car-kit will duplicate much of the circuitry needed in the handset. In both cases, the lack of a standard for the handset to car-kit interface severely limits the portability of handsets among different cars.

Improved coverage In offering PCS service, service providers will, in many cases, be competing with an extensively engineered analog cellular network that is already in place. They will have to do this at the higher frequencies of the PCS band, where propagation losses are somewhat higher, and where the Doppler frequency at a given speed is higher. There are a variety of technological possibilities here.

On the uplink, a variety of techniques ranging from maximal ratio combining to adaptive combining with higher orders of diversity implemented at the base stations can be used to improve performance. The adaptive techniques [5] offer greater performance improvements but require substantially greater signal processing capability in the basestations. This can be done at no increase in complexity in the mobile terminal. Solutions for improvement of the downlink place greater burdens on the phone. One possibility is to use transmit diversity at one or more base stations. In CDMA this is used in soft hand-off. Transmit diversity has also been proposed for TDMA systems [6]. The transmit diversity reduces the penalty in the link budget due to fading, but must be accompanied by combining of the signals in the phone. In CDMA this can be done using a so called "rake" in digital hardware, but in TDMA this combining will have to be done in the equalizer that is implemented primarily in a DSP in the phone.

Antenna diversity with adaptive combining in the mobile is another way to improve call reliability in the downlink however this is a less attractive option at present because it will significantly increase the radio frequency (RF) components required in the mobile, and this will impact cost and current consumption. When further advances in RF component integration make this feasible, multiple antenna techniques for interference cancellation will permit better frequency reuse in TDMA systems.

Multi-user detection and interference suppression in CDMA, implemented at the base station, can significantly improve the capacity on the uplink. However, the signal processing complexity required is currently a barrier to implementation [7].

Improved talk and standby time The standby time in digital cellular has increased significantly over that in analog mobiles because of the implementation of a time slot structure -- similar to that used in pagers -- on the digital control channel, which permits the mobile to "sleep" between slots. Further improvements in standby time will follow the general reduction in mW per MIPS that we expect as the DSPs (and other circuits) migrate to more advanced CMOS. In addition, there are possibilities for further improvement in standby times based on improving the synchronization algorithms to reduce power-up time required to prepare for a "paging" slot.

Talk time tends to be dominated by the transmit power requirement (transmit power during a transmit burst and duty cycle of the transmit burst) and this differs among the competing standards in the US. Here different standards have very different sensitivities. IS-136 requires 600mW of transmit power at the antenna during a transmit burst in maximum power mode (duty cycle is 1/3 in full-rate operation) and, as a system, does not rely heavily on power control. In contrast, CDMA has been designed for lower peak transmit power from the handset, and a very aggressive use of power control. Indeed the CDMA system relies on accurate power control to control the co-channel interference between mobiles transmitting far from and near to the base. In addition, the use of extensive channel coding, spread spectrum, and speech activity, enables a lower maximum emitted power. Thus, IS-136 faces competitive challenges. A DSP based solution to this is to increase the efficiency of the power amplifier by biasing it with a lower current (for higher efficiency) and using pre-distortion in the DSP to reduce the non-linearities associated with the lower bias current.

Incorporation of premium features Incorporation of premium features or new service options is another approach to service differentiation. A variety of such features have already been announced or are being publicized. Popular examples are voice recognition or voice controlled operation of the phone, built-in answering systems, alphanumeric messaging, email access, etc.. Some of these can be built onto the current wireless system in such a way that they only affect the higher layers of the system, i.e., the radio modem or the physical layer processing will not be affected. Even in cases where such a clean conceptual partitioning is possible, the fact that they will have to run on the same DSP which is used to implement the physical layer (and this is essential for cost reasons) implies increasing requirements (MIPS as well as memory) on the DSP as well as increasing demands on the code development environment.

In the case of certain other applications or features, such as the ability to provide localization for emergency functions [8, 9], it may not be possible to separate the application from the physical layer implementation. Many of these competitive options impose greater demands on DSPs and on the code development environment that supports the DSPs. Some of these issues are outlined in the section 3.

Multi-Standard Operation In order to allow users to use their phones in different service areas, the handset should be

able to operate in various standards. This may lead to phones with multiple capabilities in the following areas:

1) Multiple bands - operating in both the PCS and cellular bands. This also implies support for AMPS mode.

2) Multiple coders - TDMA supports more than one speech coding standards and it seems that CDMA will follow suit in the near future. Since the infrastructure may not always be upgraded to support all options, a versatile handset should be able to switch between speech coding modes.

3) Multiple air interface standards - this option is bound to make the phone more costly, but it may provide a significant advantage for some of the more "nomadic" users.

### 3. IMPLICATIONS FOR DSPs

One of the competitive options the service providers have is to drop prices. If this were the only major strategic thrust one would expect that hardware implementation of the phone will move towards using highly customized solutions which have been optimized for cost.

Evidence today however indicates that while costs are a concern, there is significant emphasis on flexibility. This is probably because the market has not yet stabilized enough to justify the investments involved in highly customized solutions. Furthermore, the need to offer a full line of products with a range of features and options encourages modular design, which in various ways prohibits highly customized solutions. This emphasis on flexibility increases the value of programmable (as opposed to fixed function) hardware in the phones and specifically promotes the implementation of function in DSP firmware.

Many DSP manufacturers offer fixed point DSPs designed specifically for the mobile handset usage. Typically those DSPs operate at 3V or less and feature various power saving modes. Recent models offer also specialized instructions to meet the peculiar needs of mobile phones, such as Viterbi decoding or codebook searches. We expect this trend to continue and that the microelectronics industry will respond to several other needs of future mobile units.

Increasing the raw computational power The need to implement more sophisticated air interface standards, as well as the desire to provide additional features will require the DSPs to have greater processing power. For instance, basic layer one functions in IS-136 with a VSELP coder can be implemented with less than 40 MIPS and 40 Kwords of ROM on a particular DSP, but once you attempt to put in an higher quality coder (the IS-641 EFR coder), a optional features such as voice recognition, and memopad features or acoustic echo cancellation, both the MIPS and the ROM requirements increase substantially. Increase in ROM will be discussed later in the context of increasing the amount of software. It is expected that in the near future DSPs used in handset will provide over 100 MIPS. The amount of available RAM will also increase, and it is expected that designers will have more flexibility in tailoring the amount of on-chip RAM to the needs of each specific model, in order to keep costs down.

Increasing The Program Space The support of multiple standards and various optional features is about to cause an explosion in the amount of software which needs to be installed in the phone. Supporting this need requires adding program ROM and, in addition, increasing the address space which is currently typically limited to 64K 16-bit words.

An alternative approach to meeting the increasing demand for program space is to store the program in low cost, slow ROM and load and run from into RAM when necessary. This "program swapping" approach may be justified by the fact that at any given instance only one of the many options and standards available is actually active. Although this approach is simple in principle, it requires that software may be loaded into program space in real time and that the software development tools would support the program swapping mode of operation.

Field Programmability Phone manufacturers are under pressure to quickly implement new standards and options. At the same time, the proliferation of access, modulation and coding schemes makes it almost impossible anticipate all the effects of coexistence of different, incompatible standards in adjacent bands or geographical areas.

Issues like this increase the value of field programmability as opposed to the traditional, masked ROM based program storage. So called "flash" memory, which allows field programming in embedded microcontrollers, are being migrated to DSPs.

Real Time Operating Systems Early consumer application of DSPs executed a single task. However, DSPs in mobile telephones, especially when optional features are implemented, need to operate in a true multi-tasking mode: The DSP is expected to run several processes at different priorities and with hard real time constraints, e.g. channel coding, speech coding, microcontroller interface, etc.

A real time executive or operating system is needed. In order to facilitate parallel, independent development of the software for each process. This, however, requires improving the capabilities of the DSP in areas such as interrupt handling, priority management, and context switching capability.

High Level Language Support Traditionally, DSP software used to be written in assembly language in order to maximize the utilization of machine resources. However, the increase in the amount of software that needs to be developed and maintained, the need for portability as DSP architectures change and the pressures of time to market necessitate the writing of software in high level languages, such as C. C lacks a fixed point data type, but one can be added in C++ as a class library. Tight, MIPS intensive loops will still be written in assembly, but the bulk of the DSP software will be written in C++. This requires futures DSP to lend themselves to efficient, optimized compilation. Particular areas of concern are stack support, offset addressing, loop support, more registers, and instruction set orthogonality.

Integrated Development Environment The DSP in a handset has to operate in tight interactions with baseband processing

hardware, the microcontroller unit (MCU) and possibly other external devices. In order to develop real time software for this environment, the development tools have to provide means for simulation or hardware emulation of the DSP as a part of the larger system. Therefore the DSP development tools need to have hooks for interconnection with the development tools or models of other system components.

Native Signal Processing Managing two processors, DSP and MCU, and their interaction, and managing two code bases would be unnecessary if a processor existed that could do the job of both. Several vendors have proposed such "native signal processors" and these are being evaluated for cellular phones of the near future.

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