A DSP Powered Solid State Audio System

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ABSTRACT

New audio compression algorithms and non-volatile flash memory technology have enabled the creation of portable solid-state personal audio players. This paper presents a low-power portable audio system based on the Texas Instruments TMS320C5000 DSP family. This system is designed to play music and other audio media stored on flash memory cards that can hold over an hour of CD quality music. The flash card provides higher audio quality than a cassette tape, yet is smaller and more durable than a CD. The music or audio material downloaded to the flash is obtained from licensed distributors, either through the internet or through kiosks setup in retail outlets. All the audio decoding and watermarking required by this system is handled by the TMS320C5000 DSP. System performance characteristics are also presented.

1. INTRODUCTION

Cassette tape, Compact Disc, MiniDisc™, and the associated personal, hand held audio players have captivated consumers with the ability to carry their music everywhere. However, these systems have several limitations that fail to address consumer's needs. First, consumers experience disappointment with the short battery life. Second, the sensitivity to physical vibration and motion limits the use of these players in demanding mobile environments, such as jogging or cycling. Third, consumers' desire for comfort requires very small portable players. Fourth, consumers desire high fidelity audio and durable media storage. To address these limitations, this paper describes a low-power DSP implementation based on solid state media. This implementation utilizes new distribution and compression technologies to provide high fidelity, long battery life, and shock resistant portable audio.

2. SOLID STATE AUDIO

2.1 Description

A solid state audio player uses either volatile or non-volatile integrated circuit memory devices, instead of magnetic or optical media. This media provides a long shelf life and high resistance to vibration and motion [1]. The player is small, light and durable. Audio is output through a stereo headphone jack provided on the player. A flash card and a docking bay, or similar interface, provides the ability to exchange music between your personal computer and the solid state player. Distribution of the audio data can occur at traditional media retail stores, other retail outlets without traditional media warehousing, or internet-based retailers. This distribution concept allows consumers to download audio media at a variety of locations without necessarily requiring the ownership of a computer with internet access or other expensive hardware. The data purchased at these distribution centers can be protected from piracy with digital watermarks. This technique embeds inaudible identification information that can be recovered even from analog copies of the original source [2]. Outside of these features, the player provides the familiar human interface and functionality that is traditionally offered in a tape or CD player.

The features of a solid state audio player can also be integrated onto other systems, including personal data assistants, palm top computers, and wireless phones. By utilizing a programmable DSP, additional features, such as recording, digital radio reception and wireless communication, can be added to the player. Other possible features are the use of acoustic noise cancellation to reduce background noise, speech recognition for voice commands and speech compression for memo/dictation recording.

2.2 System Overview

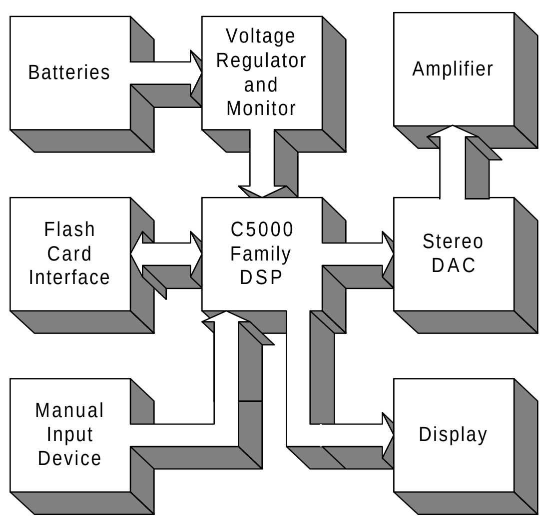

Figure 1: Solid State Audio Block Diagram.

Figure 1 illustrates one solution for the solid state audio system. This system utilizes a Texas Instruments TMS320C5000 family digital signal processor (DSP) as its processing engine and a flash card for media storage. In the system, the DSP responds to events from human input devices and updates a display to provide visual feedback to the user.

When the user plays an audio track, the DSP accesses the compressed audio samples on the flash card, decompresses the samples in its internal memory, verifies the digital watermark, and passes the uncompressed audio samples to a D/A. The analog signal is then fed through the amplifier to drive stereo headphones.

2.3 System Components

The following subsections describe the hardware and software components of the solid state audio system.

2.3.1 Algorithms

There are several audio compression algorithms that reduce the amount of data necessary to store the algorithms. If no compression techniques are utilized, enormous storage capabilities will be required. For example, CDs contain 16-bit data samples at a 44.1 kHz rate. To store one minute of a CD stereo signal would require about 10 Mbytes. Using perceptual coding techniques, music can be compressed to between 0.3 and 1.0 Mbytes per minute with almost no discernible difference in the signal quality. These compression techniques reduce the storage requirements up to an order of magnitude. Typical audio compression standards that provide CD-quality audio at high compression factors are: Dolby Digital™ (AC-3™) [3], MPEG-1 Audio Layer 3 (MP3) [4], MPEG-2 Advanced Audio Coding (AAC) [5], Adaptive Transform Coding (ATRAC) [6] and Precision Adaptive Subband Coding (PASC) [7]. Utilizing a programmable solution, these algorithms can be easily programmed into the DSP and switched at will. As future algorithms are developed, they can be downloaded to the solid state audio system as a system software upgrade.

To protect the music industry from piracy, watermarking algorithms embed identification, such as the copyright owner, distributor and consumer equipment, in the data stream. Whenever the digital stream is copied, the identification information is also copied, thus providing a trace to the original source and allowing the use of copy protection schemes. The industry has not yet standardized any one watermarking algorithm, nor are there any copy protection methods that are widely standardized in consumer equipment. A programmable engine solves this problem by being able to switch between, or upgrade to, multiple watermarking algorithms.

2.3.2 C5000 Family DSP

The Texas Instruments C5000 family of programmable, catalog DSPs are well suited for this system. The C5000 family offers a variety of peripherals and memory combinations for different system needs. For the solid state audio system, using the TMS320VC549 eliminates the need for external memory due to its large on-chip memory [32K x 16-bit RAM and 16K x 16-bit ROM] [8]. For instance, a complete 6-channel implementation of a Dolby Digital™ decoder requires less than 16K words of program memory and around 16K words of data memory. The program can be burned into ROM and the remaining 16K words can be utilized for additional proprietary features or other audio decoders. With fast external catalog SRAM consuming approximately 600mW, the overall system power is greatly reduced by eliminating the need for external memory.

Even though the TMS320VC549 is a 16-bit architecture, its large performance (100 MIPS) allows the use of double precision (32-bit) arithmetic for audio algorithms. For example, a 20-bit implementation (Class A) of a Dolby Digital™ decoder consumes less than 80 MIPS. This leaves over 20 MIPS available to perform other tasks, such as the human interface and system control. Most importantly, the TMS320VC549 consumes only 0.45 mA/MIPS (1.125 mW/MIPS at 2.5 V), making it an extremely attractive processor for battery operated systems.

Recent advances in VLSI process technology have provided increasing computational performance and lower power consumption in digital signal processors. These changes have led to the use of DSPs in power critical applications. **Table 1** shows a dramatic decrease in power in the last couple of years. This table shows that by 1999, power consumption will be half of what it was in 1997 for a device that now has 50% more performance.

Table 1: TMS320C5000: Power Efficient Performance.

Technology	**Voltage (V)**	**Performance (MIPS)**	**Power (mA/MIPS)**
0.44 µm (1996)	**3.3 V**	**50**	**0.8**
0.35µm (1997)	**3.3 V**	**66**	**0.6**
0.25 µm (1998)	**2.5 V**	**100**	**0.45**
0.18µm (1999)	**1.8 V**	**100**	**0.32**

For a more complex system, the TMS320C5410 offers twice as much on-chip RAM and lower power consumption (0.576mW/MIP) than the TMS320VC549 [9]. This allows a TMS320C5410 powered system to tackle more algorithms and provide additional battery life. In the coming years, this trend will continue, providing greater on-chip memory integration and even lower power consumption.

2.3.3 Amplifier

The DSP outputs decompressed digital audio samples that are then converted into an analog signal by a DAC before being amplified. There are several classes of amplifier circuit technology topologies available for this system. Class-A amplifiers are based on a single gain transistor circuit. These class-A amplifiers produce good signal quality but have the major drawback of large power consumption. Class-B amplifiers introduced two complementary transistors at the gain stage. By shutting off both transistors when no signal is present, class-B amplifiers offered improved power consumption. However, shutting off both transistors introduced significant distortion into the signal at the zero crossover point, thus making these amplifiers unacceptable for quality audio applications. Class-AB amplifiers improve the signal quality of a class-B design by biasing the output transistors so that a little quiescent current flows during the zero crossover. This increases power consumption from a class-B design, but offers lower power consumption than a class-A circuit [10]. A good example is the Texas Instruments TPA302 300mW stereo audio amplifier, ideal for headphone applications [11].

In the near future, class-AB amplifiers will be replaced in portable applications by class-D amplifiers because of improved power consumption efficiency offered by this circuit topology.

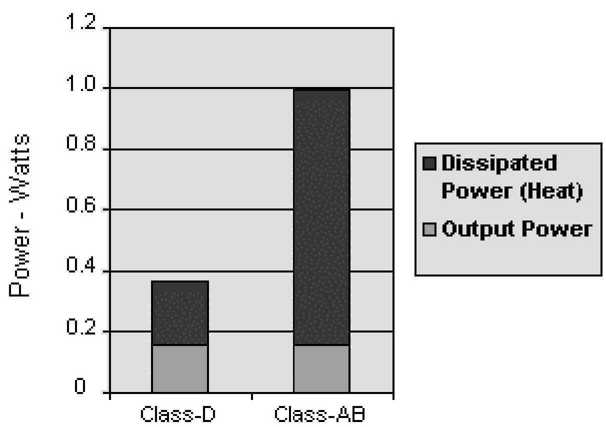

Figure 2: Class-D Amplifier Efficiency.

Class-D amplifiers use pulse-width modulation (PWM) techniques to produce the amplified analog output. The amplifier outputs high frequency square-waves of varying width that, when properly filtered, provide quality audio at the output of the speaker. Pull-up and pull-down transistors are used in completely on and completely off states. Because a bias current is not required to produce the appropriate transistor states, the class-D amplifiers have increased power efficiency. As shown in Figure 2, a class-D amplifier dissipates roughly one-fourth the power of a class-AB amplifier [12]. This allows the class-D amplifier to generate nearly three times the effective battery life as a class-AB amplifier [13].

The TPA005D02 from Texas Instruments is a fully integrated class-D amplifier well suited for portable systems. The TPA005D02, with an 8Ω load, provides up to a 2W RMS output power per channel with an 80% efficiency rating [14]. Soon these class-D amplifiers will be designed for extremely low power portable applications.

Future audio amplifiers will integrate the PWM, eliminating the need for the stereo DAC and the PWM generation in the class-D amplifier. The DSP can generate the PWM, leaving only pull-up and pull-down transistors, the H-bridge, in the amplifier. This integration will reduce system power consumption and cost.

2.3.4 Storage Medium

Non-volatile flash memory technology offers portability and ruggedness not available in disc based media. With the popularity of digital still cameras, two standards have emerged in the last few years: CompactFlash™ and SmartMedia. CompactFlash™ cards are available in capacities from 4MB to 64MB. CompactFlash™ includes an ATA controller interface as well as the flash memory. This embedded controller allows for industry-standard compatibility with many systems. SmartMedia utilizes flash memory, but has no controller functions and is based on a single flash chip solution. This reduces its cost, but limits the capacity of the card. SmartMedia cards are available in capacities of 2MB to 8MB. CompactFlash™ is a better choice for solid a state audio system due to its large capacity.

The CompactFlash™ Association has defined 5V and 3.3V cards, but there are also allowances for lower voltage cards. With the availability of flash at 1.8V, the CompactFlash™ Association could easily incorporate a 1.8V CompactFlash™ card in its standard in the near future.

2.3.5 Manual Input Device and Display

The C5000 family of DSP devices provides a general purpose I/O bus for communicating with peripherals, including external interrupts to eliminate polling loops. To get an estimate of the power consumed by a display, we examined the Densitron LM4012-TN 16x1 character LCD display. This LCD display is 85mm x 36mm x 12.8mm in volume and consumes 1mA with a single 5V supply [15]. This LCD display has the primary advantage of using an LED back-light and, therefore, does not require a voltage inverter. The back-light requires 30mA when lit.

2.3.6 Batteries

Two “AA” batteries provide the desired volume, weight, and current capacity for our player. Duracell® “AA” alkaline batteries provide 2,850mA-hours of capacity [16]. At a current loading of 50mA, Rayovac Reusable Alkaline™ “AA” batteries provide approximately 1,700mA-hours of capacity and nickel-cadmium “AA” rechargeable batteries provide approximately 800mA-hours of capacity [17].

2.4 System Performance

This solid state audio player improves on current portable players by offering longer battery life, ruggedness, large data capacity, and small size.

2.4.1 Battery Life

To compute the typical battery life of the system, some assumptions about the flash operation must be made. An uncompressed 48kHz, 16-bit data stream is equivalent to a data rate of 1.526 Mbits/s. For CD-quality audio, an MPEG-2 AAC compressed data stream requires only 128kbits/s. The MPEG-2 AAC algorithm requires a new frame of less than 688 bytes every 43ms [4]. Assuming the flash sleeps for 40ms, consuming 200µA, and is running for 3ms, consuming 45mA, the average current would be 3.3mA (or 11mW).

All of the steady-state device I/O is driven by the transfer of the audio data stream. It is possible to estimate that each sample will require an average of less than 50 pin toggles. If each pin has a capacitance of 40pF and the sample rate is 48kHz, the device I/O power is approximately a single milliwatt with 3.3V I/Os

Table 2: Power Consumption of the audio system.

SanDisk SDCFB-48-101 CompactFlash	11mW
Texas Instruments TMS320C5410 DSP	58mW
AKM AKM4350 DAC	8mW
Texas Instruments TPA152 Stereo Amplifier	32mW
Densitron LM4012-TN 16x1 LCD Display	5mW
Device I/O	1mW
Voltage Regulators (80% efficiency)	23mW
Total	138mW

Table 2 shows the power consumption for the individual components in the solid state audio system. For a 3V system, two "AA" batteries would be needed. For the 138mW system shown here, this would offer about 39 operating hours. For comparison, a typical CD player consumes 600mW and operates for approximately 9 hours on 2 "AA" batteries [18].

2.4.2 Storage Duration

With CompactFlash™ cards supporting 64MB capacity, storage is currently available in sizeable quantities. Using the previously mentioned algorithms to compress the audio signal, these cards could store between 64 to 128 minutes of CD quality music. As flash technology progresses, the storage capacity will double, offering greater storage capacity than CDs and cassette tapes.

2.4.3 Ruggedness

The solid state audio system described here does not use any moving parts, allowing the system to be much more robust and reliable than those relying on moving media. This system does not have any magnetic heads, optical components, or motors that require care and maintenance. For solid state devices, typical reliability numbers are:

- Mean Time Between Failures (MTBF) greater than 1,000,000 hours,
- Vibration resistance to 15G peak-to-peak and
- Shock resistance of 2000G (maximum).

2.4.4 Size and Weight

The availability of compact packages, such as the microstar ball grid arrays (μ*BGA) and surface mount technology, allows for a very dense system. For example, the TMS320VC549 is available in a 144-pin Microstar ball grid array package, with a volume of only 12mm long, 12mm wide and 1.4mm tall. The CompactFlash™ cards measure 36.4mm long, 42.8mm wide and 3.94mm tall with a weight of 11.4g. Due to the lack of any motors and mechanical components, the system is extremely light, with most of the weight due to the batteries.

3. CONCLUSION

This system proves the feasibility of using a TMS320C5000 DSP as the processing engine of a solid state audio system. It also demonstrates several advantages over "AA" battery powered CD and cassette tape players. First, this system provides two to four times the battery life of current players. Second, the media is durable and rugged. Third, high semiconductor integration results in a small, lightweight player. Fourth, the player provides large, high fidelity storage capacity that can be upgraded as flash technology improves. Finally, the programmable nature of the C54x allows for future compatibility with emerging standards and implementations of additional features.

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