Next-Generation Audio Engine

Robert Kennedy
Senior Software Engineering Manager

Darin Petkov
Member of Technical Staff
Moving to System on Chip (SoC)
Expanding universe of audio standards
Portable and multi-purpose devices (e.g. handsets) feature:
  • Audio
  • Multiple non-audio applications
Increasing pressure to reduce power and area
Low power and area

Low cycle consumption by codecs
  • Multiple codecs run simultaneously
  • Cycles left for effects, mixdown, non-audio applications
  • Achieved through MAC, load/store, ALU, Huffman, control performance, parallelism, etc.
  • Fewer cycles -> lower clock rate -> lower power

Flexibility / programmability

Multiple data types (16- and 24-bit signal data, sometimes even 32-bit)

Applicable to the widest range of audio products
Today’s Approaches

**General-purpose embedded CPU**
- Not optimized for high-quality real-time sound processing

**DSPs**
- General purpose DSPs use more silicon area than required for audio applications
- Not a good match for control tasks

**Hard-wired RTL**
- Requires one block per audio standard (makes the chip huge)
- No changes possible without redesigning chip

**Tensilica’s HiFi 1 Audio Engine**
- Based on Xtensa V architecture
- Runs AC-3, G.723, G.729AB, MP3, MPEG-2/4 AAC and WMA
- Designed into:
  - Cell phones
  - Portable Audio Players
- With new Xtensa LX technology we do better
Xtensa LX makes HiFi 2 possible

Xtensa: Configurable, Extensible, Synthesizable
• Extensions driven by analysis of audio codecs

Enabling Xtensa LX features
• FLIX (Flexible Length Instruction eXtensions)
  • Base has 16- and 24-bit instruction sizes
  • Custom instructions can use 24-bit and 32- or 64-bit instruction sizes
  • 32- and 64-bit sizes allow multiple independent operations per instruction
  • FLIX relaxes single-issue programming model of Xtensa V / HiFi 1
• Functional clock gating reduces power

HiFi 2 is Xtensa LX with a particular audio-specific set of instruction extensions
• More custom instructions can be added
• Extensions are first-class citizens
• Imposes a minimum configuration requirement
HiFi 2 adds more than 300 operations

- Dual multiply with 56-bit accumulate
  - Each multiplier supports 24 x 24 bits and 32 x 16 bits
  - Both multipliers operate every cycle
- Add / subtract and variable / immediate shifts
- Huffman encode / decode and bit stream support
  - Streams interleave coded / uncoded items
- Convert / round / truncate instructions
- Two special audio register files with multiple data types
  - P: 8 x 48 bits (each holds two 24-bit values)
  - Q: 4 x 56 bits (accumulator values)
- Two way SIMD arithmetic and boolean operations on 24-bit or 16-bit data
Close-up view: MAC modes supported

- Single and dual multiplication
- Fractional and integer arithmetic
- Operands:
  - 24x24 bits P x P (typical audio)
  - 16x16 bits P x P with intermediate saturation (AMR, G.7xx)
  - 32x16 bits Q x P (WMA at low bit rates)
- Accumulation: overwrite, add, subtract; with or without saturation
- Signed and unsigned:
  - signed x signed (typical)
  - signed x unsigned (multiple precision)
Example MAC Instruction Usage

```c
ae_p24x2s a, b;    /* allocated in P registers */
ea_q56s  x;        /* allocated in Q registers */
...
/* fractional real part of complex multiply:
   * x = a.H * b.H - a.L * b.L */
x = AE_MULZASFP24S_HH_LL(a, b);
```
Example MAC Instruction Mnemonic

```
x = Audio Engine instruction

x = AE_ MUL Z A S F P24S_ HH_ LL(a, b);
```

- Multiply
- Second product is L x L
- First product is H x H
- Multiply signed 24-bit P values
- Fractional arithmetic
- Subtract second product
- Add first product
- Accumulate against zero
HiFi 2 Instruction Formats

FLIX: Flexible-Length Instruction eXtensions

Dual-Issue 64-bit FLIX or Single-Issue 24/16-bit Operations

- **Operation 0**
  - 64b
  - 24b
  - 16b

- **Operation 1**
  - 64b

**Slot 0**
- Multiply and Audio ALU Operations
- Load / store, Huffman Operations

**Slot 1**
- Multiply and Audio ALU Operations
- Base / HiFi2 Audio Operations

**HiFi2 Audio Operations**
- Base LX Operations
HiFi2 Datapath and Registers

**HiFi 2 Audio Engine Hardware**

- **Q Audio Registers (4x56 bits)**
- **P Audio Registers (8x(2x24) bits)**
- **Data Multiplexer**
- **Audio ALU**
- **Add/Sub**
- **Misc Audio Functions**

**Base Registers**

- **Base ALU**
- **Load/Store**
- **Misc Audio Functions**
- **Variable Length Encode/Decode**

**Slot 0**

**Slot 1**

HiFi 2 Audio Engine Hardware

Base Xtensa LX Configuration
HiFi 2 MAC alternatives:
- 24 x 24 bits (48-bit product, 56-bit accumulation)
- 32 x 16 bits (48-bit product, 56-bit accumulation)
- 32 x 32 bits (8 product bits discarded)
- Single or dual multiplier

Memory bandwidth:
- 64- vs. 128-bit bus requirement
- One vs. two load/store units
- Bandwidth >2 GB/sec

Implemented features shown in bold green
HiFi2 extensions

- 64-bit interface to memory
- 8k icache, 8k dcache, 2-way
- MUL32 option (~5-6k gates) present in one experiment
### Example Configuration 1 Experiment: MAC Options and Hardware Cost

<table>
<thead>
<tr>
<th>Option Description</th>
<th>Maximum clock rate (MHz)*</th>
<th>Gates*</th>
<th>Area* (mm^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single 24x24-bit MAC</td>
<td>299</td>
<td>88,569</td>
<td>0.98</td>
</tr>
<tr>
<td>Dual 24x24-bit MAC</td>
<td>289</td>
<td>100,860</td>
<td>1.12</td>
</tr>
<tr>
<td>Dual MAC supporting 24x24 and 32x16</td>
<td>284</td>
<td>101,408</td>
<td>1.13</td>
</tr>
<tr>
<td>Dual MAC supporting 24x24, 32x16 and single 32x32</td>
<td>270</td>
<td>110,012</td>
<td>1.22</td>
</tr>
</tbody>
</table>

* Based on TSMC 0.13μ LV, Artisan library, includes MUL32 option
## Example Configuration 2 Experiment: Power Dissipation Estimates in Simulation

<table>
<thead>
<tr>
<th>Implementation</th>
<th>Area (mm^2)</th>
<th>Leakage power (mW)*</th>
<th>Switching power (mW/MHz)*</th>
<th>Real-time MP3 decode power (mW @ 14 MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.13(\mu) lv** synthesized to 200 MHz</td>
<td>0.94</td>
<td>0.4</td>
<td>0.09</td>
<td>1.6</td>
</tr>
<tr>
<td>0.13(\mu) g*** synthesized to 50 MHz</td>
<td>0.85</td>
<td>0.3</td>
<td>0.07</td>
<td>1.3</td>
</tr>
</tbody>
</table>

MUL32 option not present

* Power measured running MP3 decode

** Artisan SAGE-X library

*** Artisan metro library
Six weeks from concept to first customer delivery

Development guided by:
- Software and hardware optimization experiments
- Customer input

Automatic processor generation provides:
- Processor core RTL
- Complete software tools
  - C/C++ compiler
  - Debugger
  - Linker
  - Simulator
  - Assembler
  - Profiler
  - RTOS Hardware Abstraction Layer
Rapid turnaround (minutes) of tools generation and hardware estimation allows rapid assessment of
- Software performance benefit
- Hardware impact

Full RTL generation in under an hour

Software porting and optimization can (and should!) proceed concurrently with instruction set definition

Optimized code uses
- HiFi2-specific data types, register-allocated automatically by the compiler
- HiFi2-specific instructions, generated by the compiler via instruction intrinsics
- No assembly language (sure you can, but why?)
## Selected Codec Preliminary Specs

<table>
<thead>
<tr>
<th>Codec</th>
<th>Worst Case Required MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>HiFi 2 MP3 Decoder</td>
<td>15-17</td>
</tr>
<tr>
<td>HiFi 1 MP3 Decoder</td>
<td>18</td>
</tr>
<tr>
<td>HiFi 2 MP3 Encoder</td>
<td>38-40</td>
</tr>
<tr>
<td>HiFi 1 MP3 Encoder</td>
<td>65</td>
</tr>
<tr>
<td>HiFi 2 AAC-LC Decoder</td>
<td>13-14</td>
</tr>
<tr>
<td>HiFi 1 AAC-LC Decoder</td>
<td>26</td>
</tr>
<tr>
<td>HiFi 2 AAC-LC Encoder</td>
<td>40-44</td>
</tr>
<tr>
<td>HiFi 1 AAC-LC Encoder</td>
<td>85</td>
</tr>
<tr>
<td>HiFi 2 WMA Decoder</td>
<td>18-21</td>
</tr>
<tr>
<td>HiFi 1 WMA Decoder</td>
<td>30</td>
</tr>
</tbody>
</table>
Realistic configurations approaching 300 MHz, below 100k gates, below 1.5 mW for MP3 decode

Excellent performance on broad set of audio applications, including future codecs

Rich audio instruction set with complete, extension-aware software tools support

Processor remains configurable to take on additional tasks

Power, performance, and broad codec support make HiFi2 appropriate for a wide range of consumer and automotive products.