Introduction to DSP with the ARM Cortex-M4 Microcontroller

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ARM Cortex Processor Families

Cortex-A

servers

set top boxes

netbooks

mobile applications

Cortex-R

disk drives

digital cameras

mobile baseband

Cortex-M

appliances

motors

audio

ARM Cortex-M4: Efficient Blend

MCU

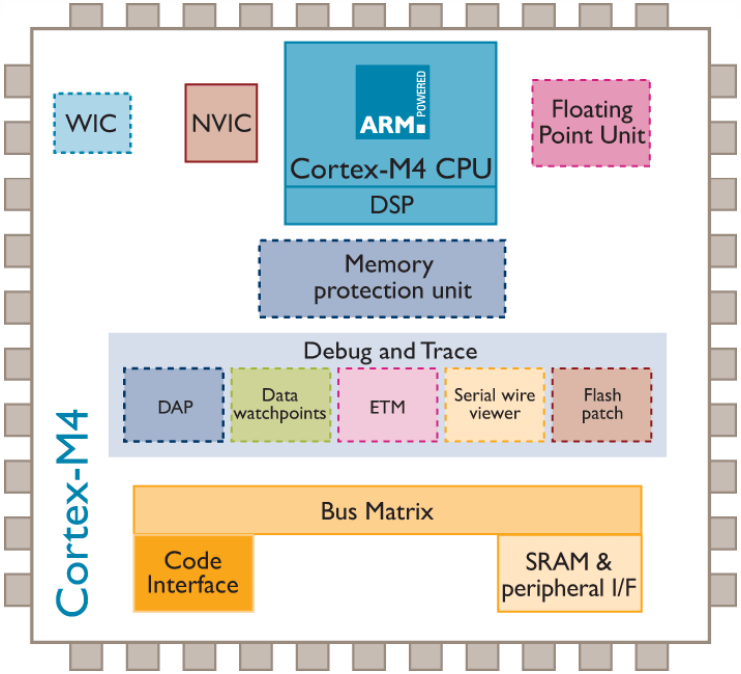
Ease of use
C Programming
Interrupt handling
Ultra low power

DSP

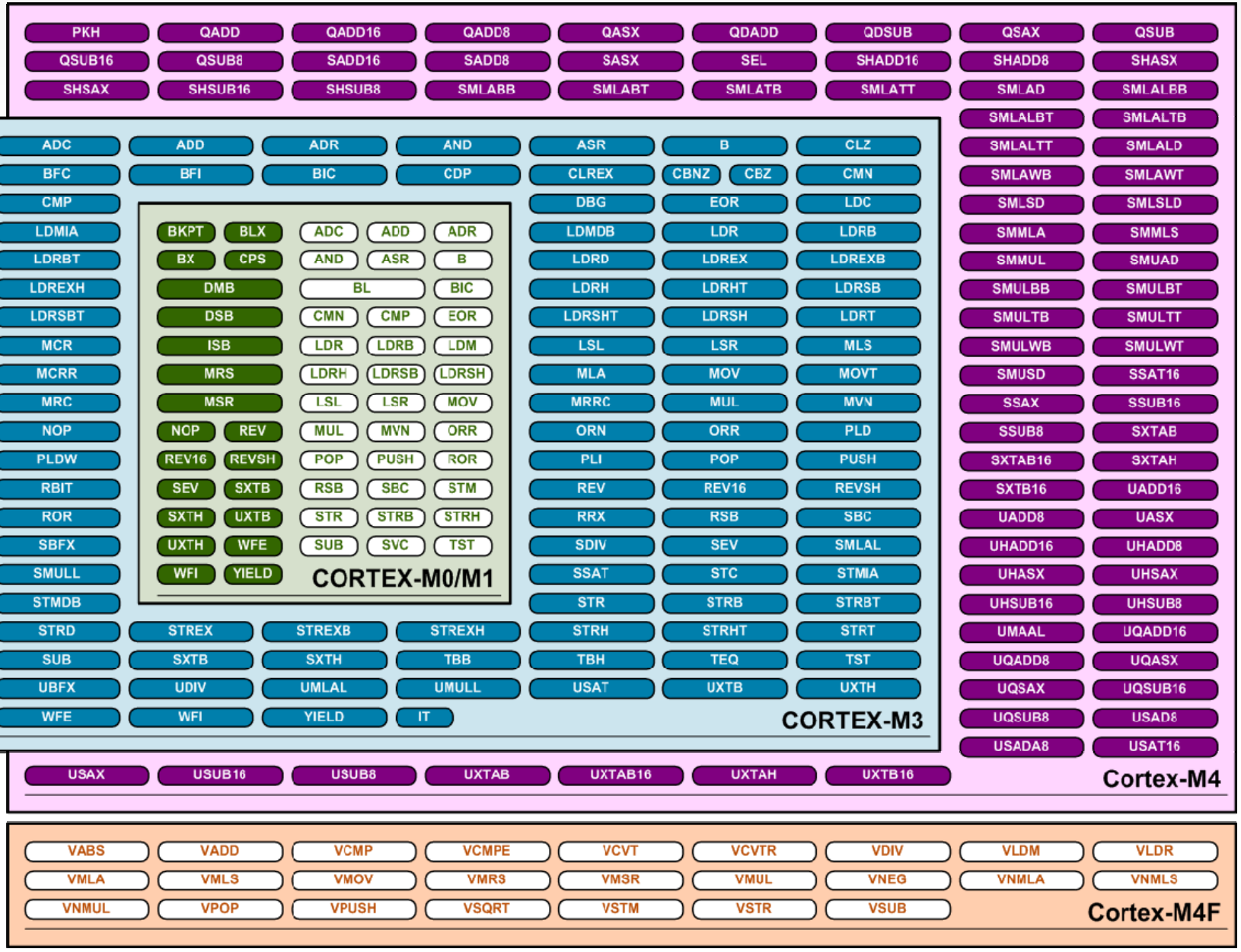
Harvard architecture
Single cycle MAC
Floating Point
Barrel shifter

ARM Cortex-M4 Microarchitecture

- **ARMv7ME Architecture**
  - Thumb-2 Technology, 1.25 DMIPS/MHz
  - Integrated NVIC and optional MPU
  - Low cost debug and trace
  - Integrated DSP and SIMD instructions
  - Single cycle MAC (Up to 32 x 32 + 64 -> 64)
  - Optional single precision FPU
- **Microarchitecture**
  - 3-stage pipeline
  - 3x AHB-Lite Bus Interfaces
- **Configurable for ultra low power**
  - Deep Sleep Mode, Wakeup Interrupt Controller
  - Power down features for Floating Point Unit
- **Flexible configurations for wider applicability**
  - Configurable NVIC and Debug & Trace. Optional MPU,WIC and FPU.



ARM Cortex-M Family Instruction Set



ARM Cortex-M4 DSP Instructions Compared

		Cycle counts		
CLASS	INSTRUCTION	ARM9E-S	CORTEX-M3	Cortex-M4
Arithmetic	ALU operation (not PC)	1 - 2	1	1
	ALU operation to PC	3 - 4	3	3
	CLZ	1	1	1
	QADD, QDADD, QSUB, QDSUB	1 - 2	n/a	1
	QADD8, QADD16, QSUB8, QSUB16	n/a	n/a	1
	QDADD, QDSUB	n/a	n/a	1
	QASX, QSAX, SASX, SSAX	n/a	n/a	1
	SHASX, SHSAX, UHASX, UHSAX	n/a	n/a	1
	SADD8, SADD16, SSUB8, SSUB16	n/a	n/a	1
	SHADD8, SHADD16, SHSUB8, SHSUB16	n/a	n/a	1
	UQADD8, UQADD16, UQSUB8, UQSUB16	n/a	n/a	1
	UHADD8, UHADD16, UHSUB8, UHSUB16	n/a	n/a	1
	UADD8, UADD16, USUB8, USUB16	n/a	n/a	1
	UQASX, UQSAX, USAX, UASX	n/a	n/a	1
	UXTAB, UXTAB16, UXTAH	n/a	n/a	1
	USAD8, USADA8	n/a	n/a	1
Multiplication	MUL, MLA	2 - 3	1 - 2	1
	MULS, MLAS	4	1 - 2	1
	SMULL, UMULL, SMLAL, UMLAL	3 - 4	5 - 7	1
	SMULBB, SMULBT, SMULTB, SMULTT	1 - 2	n/a	1
	SMLABB, SMLBT, SMLATB, SMLATT	1 - 2	n/a	1
	SMULWB, SMULWT, SMLAWB, SMLAWT	1 - 2	n/a	1
	SMLALBB, SMLALBT, SMLALTB, SMLALTT	2 - 3	n/a	1
	SMLAD, SMLADX, SMLALD, SMLALDX	n/a	n/a	1
	SMLSD, SMLSDX	n/a	n/a	1
	SMLSLD, SMLSLD	n/a	n/a	1
	SMMLA, SMMLAR, SMMLS, SMMLSR	n/a	n/a	1
	SMMUL, SMMULR	n/a	n/a	1
	SMUAD, SMUADX, SMUSD, SMUSDX	n/a	n/a	1
	UMAAL	n/a	n/a	1
Division	SDIV, UDIV	n/a	2 - 12	2 – 12

Single cycle MAC

ARM Cortex-M4 Single Cycle MAC Instructions

OPERATION	INSTRUCTIONS
16 x 16 = 32	SMULBB, SMULBT, SMULTB, SMULTT
16 x 16 + 32 = 32	SMLABB, SMLABT, SMLATB, SMLATT
16 x 16 + 64 = 64	SMLALBB, SMLALBT, SMLALTB, SMLALTT
16 x 32 = 32	SMULWB, SMULWT
(16 x 32) + 32 = 32	SMLAWB, SMLAWT
(16 x 16) ± (16 x 16) = 32	SMUAD, SMUADX, SMUSD, SMUSDX
(16 x 16) ± (16 x 16) + 32 = 32	SMLAD, SMLADX, SMLSD, SMLSDX
(16 x 16) ± (16 x 16) + 64 = 64	SMLALD, SMLALDX, SMLSLD, SMLSLDX
32 x 32 = 32	MUL
32 ± (32 x 32) = 32	MLA, MLS
32 x 32 = 64	SMULL, UMULL
(32 x 32) + 64 = 64	SMLAL, UMLAL
(32 x 32) + 32 + 32 = 64	UMAAL
32 ± (32 x 32) = 32 (upper)	SMMLA, SMMLAR, SMMLS, SMMLSR
(32 x 32) = 32 (upper)	SMMUL, SMMULR

All the above operations are single cycle on the Cortex-M4 processor

ARM Cortex-M4 Floating Point Unit

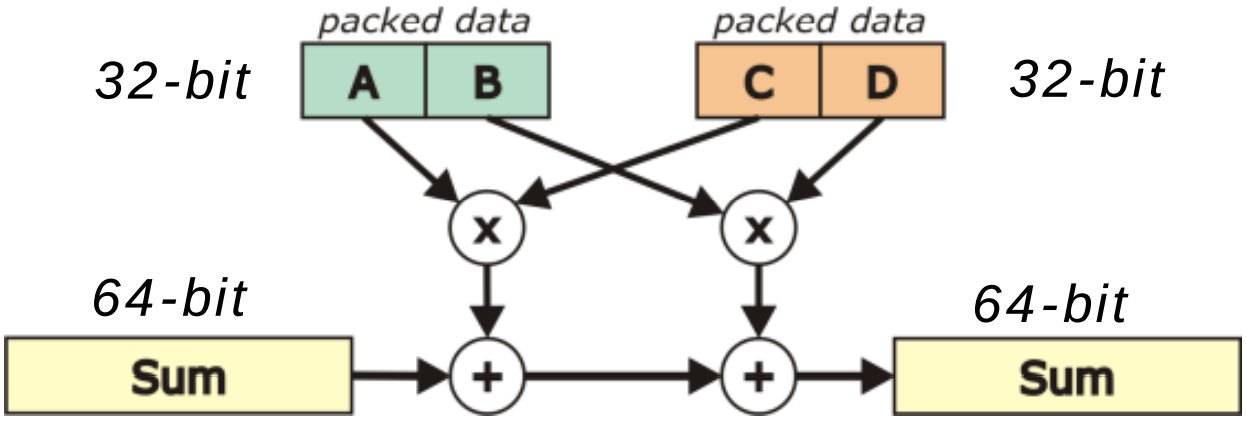
- Single precision floating point unit
- IEEE 754 standard compliant
- Single-precision floating point math
  - Add, subtract, multiply, divide, MAC and square root
  - Fused MAC – higher precision

OPERATION	CYCLE COUNT
Add/Subtract	1
Divide	14
Multiply	1
Multiply Accumulate (MAC)	3
Fused MAC	3
Square Root	14

ARM Cortex-M4 SIMD Instructions

SIMD extensions perform multiple operations in one cycle

$$Sum = Sum + (A \times C) + (B \times D)$$



SIMD techniques operate with packed data

ARM Cortex-M4 8 and 16-bit SIMD Instructions

Prefix / Instr	S Signed	Q Signed Saturating	SH Signed Halving	U Unsigned	UQ Unsigned Saturating	UH Unsigned Halving
ADD8	SADD8	QADD8	SHADD8	USADD8	UQADD8	UHADD8
SUB8	SSUB8	QSUB8	SHSUB8	USUB8	UQSUB8	UHSUB8
ADD16	SADD16	QADD16	SHADD16	UADD16	UQADD16	UHADD16
SUB16	SSUB16	QSUB16	SHSUB16	USUB16	UQSUB16	UHSUB16
ASX	SASX	QASX	SHASX	UASX	UQASX	UHASX
SAX	SSAX	QSAX	SHSAX	USAX	UQSAX	UHSAX
USAD8	Unsigned Sum of Absolute Difference (8 bits)					
USADA8	Unsigned Sum of Absolute Difference and Accumulate (8 bits)					

ASX
1. Exchanges halfwords of the second operand register
2. Adds top halfwords and subtracts bottom halfwords

SAX
1. Exchanges halfwords of the second operand register
2. Subtracts top halfwords and adds bottom halfwords

Characteristics of DSP Processors

- Harvard architecture
- High performance MAC
- Saturating math
- SIMD instructions for parallel computation
- Barrel shifters
- Floating point hardware
- ***Circular and bit-reversed addressing***
- ***Zero overhead loops***
- ***Load and store operations in parallel with math operations***

Text in ***bold*** indicates DSP processor advantage over Cortex-M4

Cortex-M4 DSP Code Optimization Strategies

- Circular addressing alternatives
- Loop unrolling
- Caching of intermediate variables
- Extensive use of SIMD and intrinsics

ARM Cortex-M4 FIR Performance

- DSP assembly code = 1 cycle
- Cortex-M4 standard C code takes 12 cycles
  - ✓ Using circular addressing alternative = 8 cycles
  - ✓ After loop unrolling < 6 cycles
  - ✓ After using SIMD instructions < 2.5 cycles [note: 16-bit data]
  - ✓ After caching intermediate values ~ 1.6 cycles

Cortex-M4 C code now comparable in performance

Cortex Microcontroller Standard (CMSIS)

- Cortex Microcontroller Software Interface Standard
  - Abstraction layer for all Cortex-M processor based devices
  - Developed in conjunction with silicon, tools and middleware partners

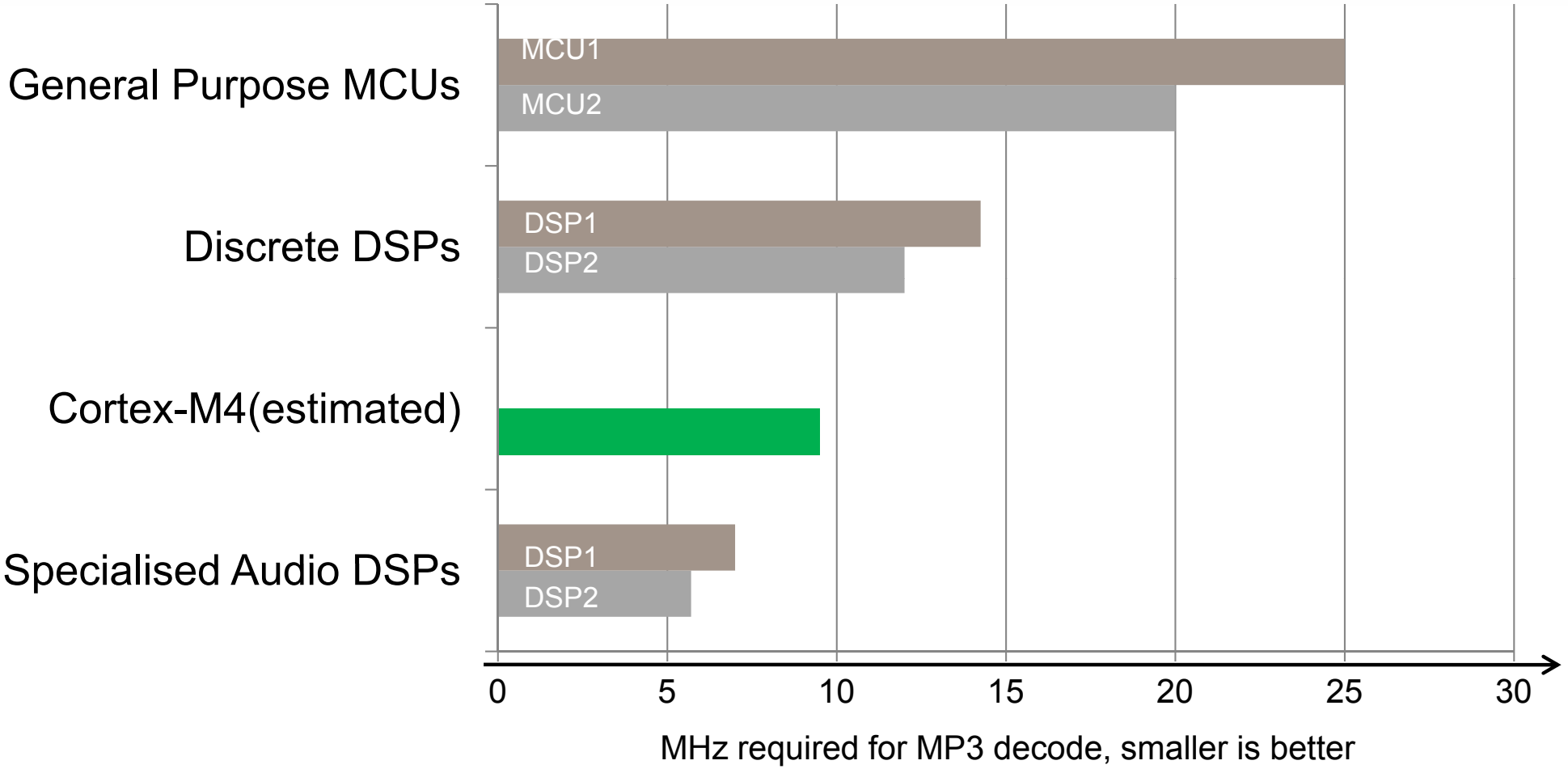
- Benefits to the embedded developer
  - Consistent software interfaces for silicon and middleware vendors
  - Simplifies re-use across Cortex-M processor-based devices
  - Reduces software development cost and time-to-market
  - Reduces learning curve for new Cortex microcontroller developers

ARM CMSIS DSP Library Snapshot

- Basic math – vector mathematics
- Fast math – sin, cos, sqrt, etc.
- Interpolation – linear, bilinear
- Complex math
- Statistics – max, min, RMS, etc.
- Filtering – IIR, FIR, LMS, etc.
- Transforms – FFT(real and complex), Cosine transform, etc.
- Matrix functions
- PID Controller, Clarke and Park transforms
- Support functions – copy/fill arrays, data type conversions, etc
- Available at http://www.onARM.com

Variants for functions across q7,q15,q31 and f32 data types

ARM Cortex-M4: MP3 Decoder Performance

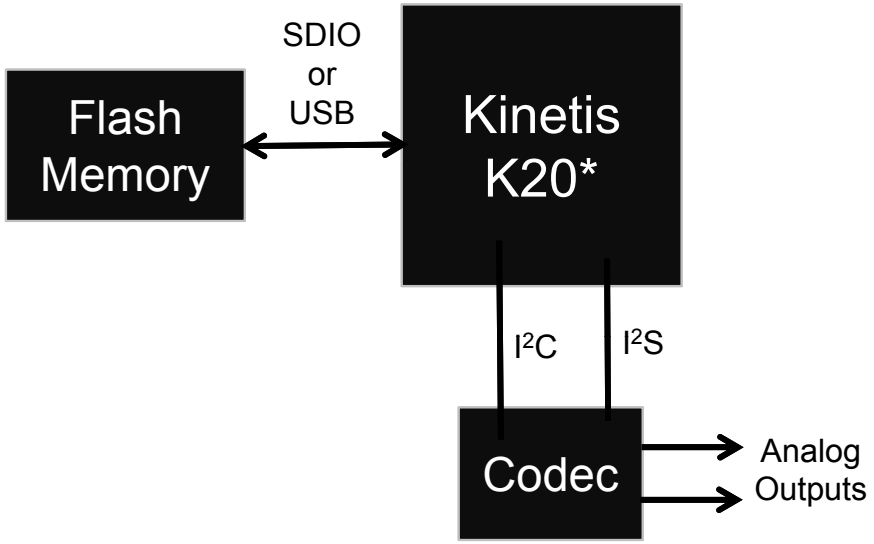


Kinetis Cortex-M4 Audio Player

Audio Input:
- WAV files
- MP3 files
- AAC files

Functions:
- File decode

Output:
- Stereo analog audio

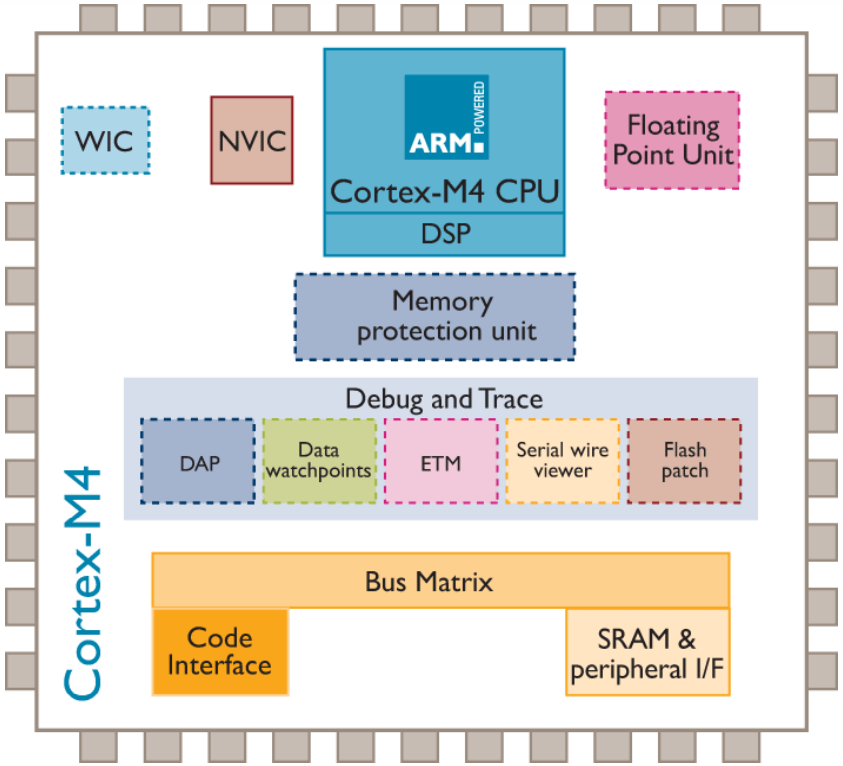


* Could also use K40, K50, K60, or K70

Freescale Kinetis Cortex-M4 Microcontroller Family

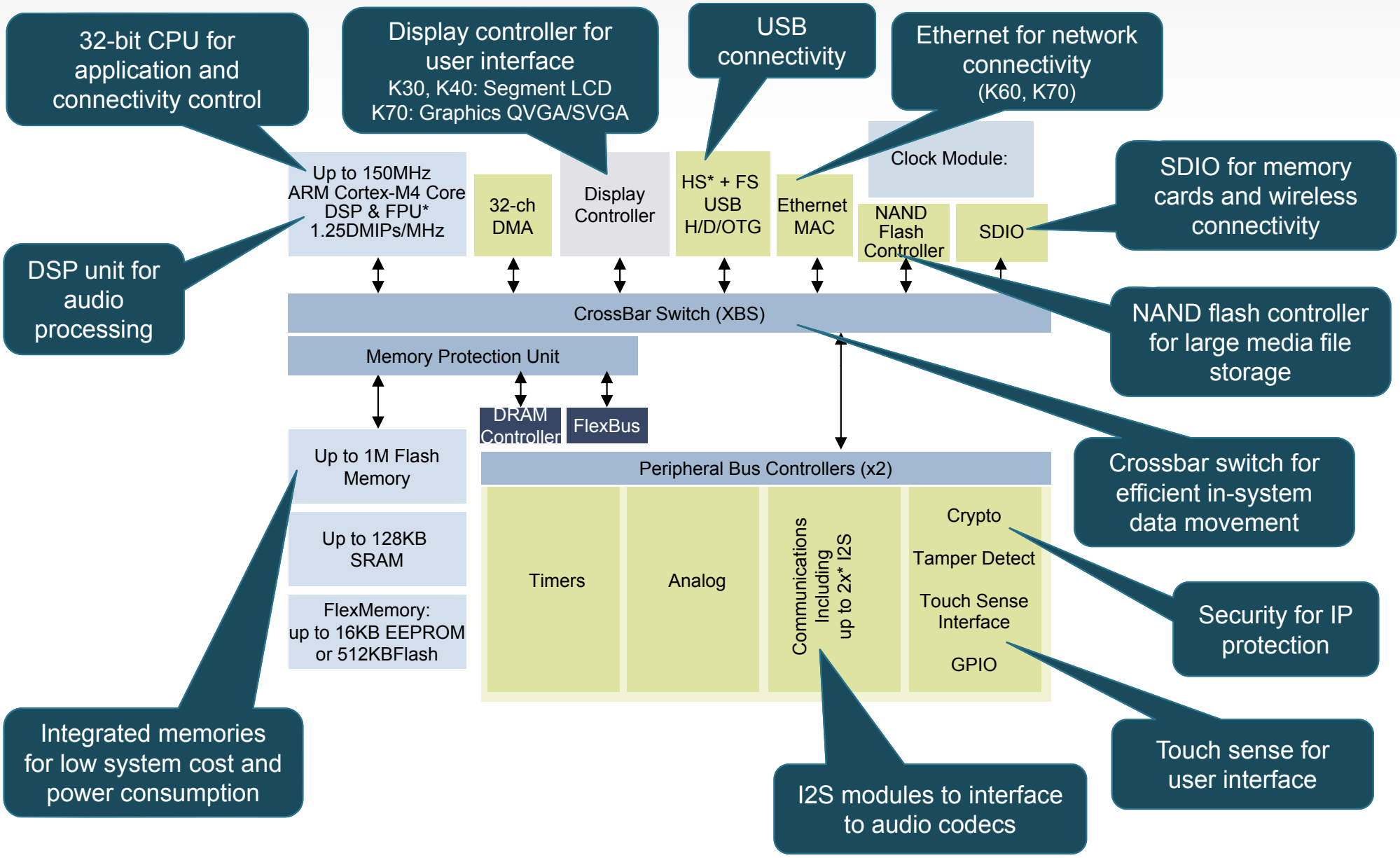
Kinetis Cortex-M4 Processor Microarchitecture

- Backwards compatible with ARM Cortex-M3
- New features
  - DSP extensions
  - Single precision floating point unit
- Freescale IP and innovation
  - Available on-chip cache for instructions and data enhanced performance reaching zero wait states
  - Crossbar switch for concurrent multi-master/slave accessing improves system throughput
  - MPU with multi-master protection enhances system safety and security
  - Low-leakage wake-up unit adds flexibility for low-power operation
- Architected for digital signal processing
  - **Motor Control** – advanced algorithms, longer lifespan, power efficiency
  - **Automation** – high calculation and algorithm bandwidth at a low cost
  - **Power Management** – designed for low/battery-powered systems
  - **Audio and Video** – 5x performance improvement over software, helping batteries last longer



http://www.freescale.com/kinetis

Kinetis MCU



Kinetis Product Families

NOTE: Floating point unit and NAND flash controller are only offered on 120/150MHz K10/20/60/70 devices.

Sample availability:

144pin now , 80-121pin now, <80pin now

144pin now, 80-121pin now, <80pin now

144-256pin now, 196pin now

MCU Family	USB OTG (FS & HS) + Device Charger Detect	Dual CAN	Ethernet (IEEE 1588)	Hardware Encryption	LCD (Segment/Graphics)	NAND Flash Controller (120MHz/150MHz only)	Floating Point Unit (120MHz/150MHz only)	Hardware Tamper Detect	DRAM Controller (256MAPBGA only)
K70 120-150MHz 512KB-1MB 196-256pin	● ●	●	●	●	●	●	●	●	●
K60 100-150MHz 256KB-1MB 100-256pin	● ●	●	●	●		●	●	●	●
K50 72-100MHz 128-512KB 64-144pin	●		●	●	●				
K40 72-100MHz 64-512KB 64-144pin	●	●			●				
K30 72-100MHz 64-512KB 64-144pin		●			●				
K20 50-120MHz 32KB-1MB 32-144pin	● ●	●				●	●		
K10 50-120MHz 32KB-1MB 32-144pin		●				●	●		

Common System IP	Common Analog IP	Common Digital IP	Development Tools
32-bit ARM Cortex-M4 Core w/ DSP Instructions	16-bit ADC	CRC	Bundled IDE w/ Processor Expert
Next Generation Flash Memory High Reliability, Fast Access	Programmable Gain Amplifiers	I²C	Bundled OS USB, TCP/IP, Security
FlexMemory w/ EEPROM capability	12-bit DAC	SAI (I²S)	Modular Tower H/ware Development System
SRAM	High-speed Comparators	UART/SPI	Application Software Stacks, Peripheral Drivers & App. Libraries (Motor Control, HMI, USB)
Memory Protection Unit	Low-power Touch Sensing	Programmable Delay Block	
Low Voltage, Low Power Multiple Operating Modes, Clock Gating (1.71V-3.6V with 5V tolerant I/O)		External Bus Interface	
DMA		Motor Control Timers	
-40 to 105C		eSDHC	Broad 3rd party ecosystem
		RTC	

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Kinetis: Freescale Enablement Bundle

Freescale Tower System

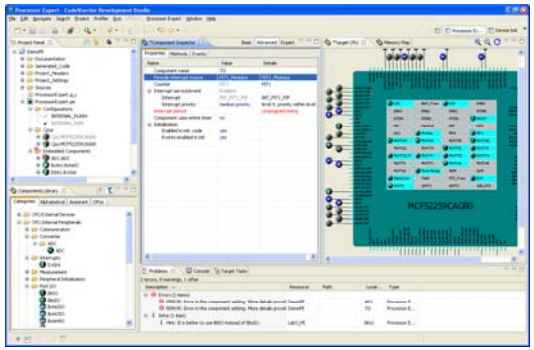
Kinetis MCU modules from $69

- Modular, expandable, open-source h/ware development platform for 8/16/32-bit MCUs/MPUs
- Rapid evaluation and prototyping with maximum h/ware reuse
- Supported by a growing range of peripheral plug-in boards (WiFi, Sensing, Graphics LCD, Audio,...)
- www.freescale.com/tower

Open source, reusable hardware platform

Freescale CodeWarrior IDE

Free of charge up to 128KB

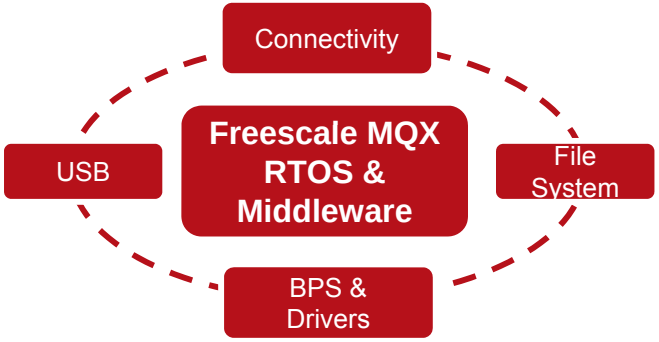


- Eclipse environment
- Includes **Processor Expert code generation wizard**
- Creates MQX-aware drivers
- Build, debug and flash tools
- Software analysis
- Kernel-aware debug
- Special Edition $0 up to 128KB
- www.freescale.com/codewarrior

Powerful IDE with code generation wizard for $0!

Freescale MQX RTOS

Free of charge ($95K est. value)



- Full-featured, scalable, proven RTOS with TCP/IP, USB, Graphics, Security and File Systems plug-ins
- Makes application code more stable, more maintainable and easier to upgrade – reduces time-to-market!
- Compatible with CodeWarrior, IAR, Keil & Green Hills IDEs
- www.freescale.com/mqx

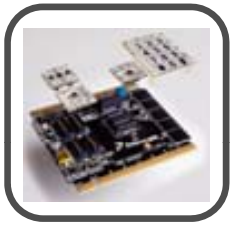
Bundled RTOS for $0!

One Stop Shop for Silicon, IDE & RTOS

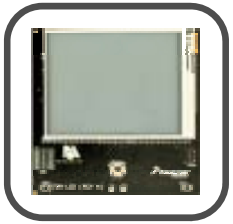
Kinetis Tower System: Reusable, modular development platform

www.freescale.com/tower www.towergeeks/org

MCU Families Supported	TWR Part Number	Contents	Price (SRP)
K30/40	TWR-K40X256	TWR-K40X256 (144MGA), TWRPI-SLCD	$69
	TWR-K40X256-KIT	TWR-K40X256 (144MBGA), TWRPI-SLCD TWR-SER, TWR-ELEV	$139
K50	TWR-K53N512	TWR-K53N512 (144MBGA), TWRPI-SLCD	$109
	TWR-K53N512-KIT	TWR-K53N512 (144MBGA), TWRPI-SLCD, TWR-SER, TWR-ELEV	$179
K10/20/60	TWR-K60N512	TWR-K60N512 (144MBGA)	$69
	TWR-K60N512-KIT	TWR-K60N512 (144MBGA), TWR-SER, TWR-ELEV	$139
	TWR-K60N512-IAR	TWR-K60N512-KIT (144MBGA), TWR-PROTO, Segger J-Link Lite Debug Probe, IAR EWARM IDE (eval. version)	$239
	TWR-K60N512-KEIL	TWR-K60N512-KIT (144MBGA), UNLINK-ME Debug Probe, KEIL MDK IDE (eval. version)	$199



TWR-SENSOR-PAK



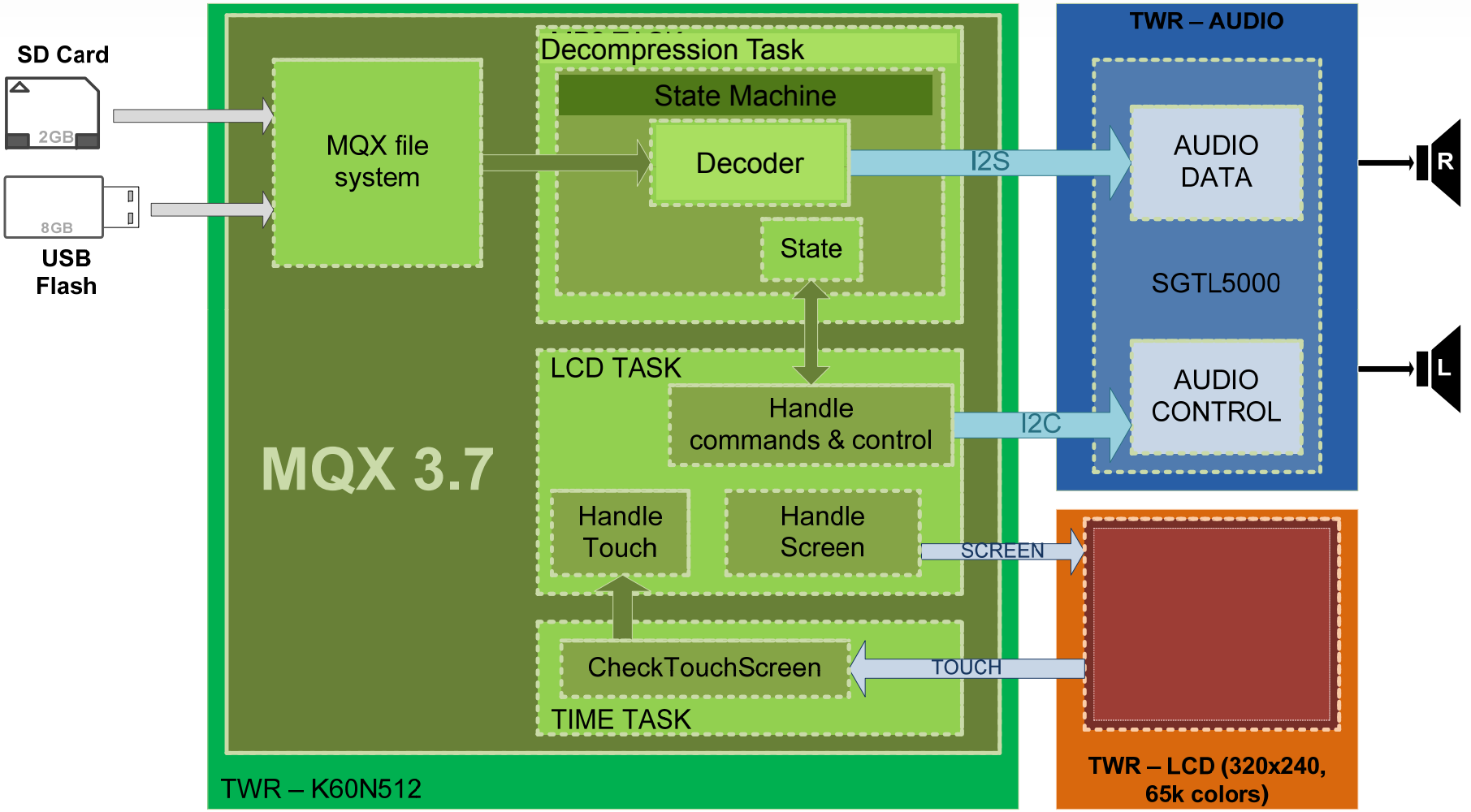
TWR-LCD

TWR-WIFI-RS2101

- IDEs: FSL CodeWarrior, IAR Embedded Workbench, Keil MDK, ...
- Freescale MQX RTOS
- OSJTAG Debug circuitry – program & debug with USB cable
- Low power touch sensing & plug-in socket for expansion: Sensors, Radio, etc…
- Fully compatible with all Tower peripheral modules

Kinetis K60 Audio Player Demo: Block Diagram

S/W MP3 decoding and playback under MQX with touch screen LCD using Kinetis K60 MCU



Kinetis K60 Audio Player Demo:
Screen Features of Audio Player demo

Main features:
- basic control features (play, stop, pause, play next, play previous)
- basic song information display (title, artist, album, year, name of file)
- plotting of both channels samples in a time domain
- display of actual time and current position of song
- current position change possible using slide bar moving
- volume and balance control

Spectrum Analyser:
- whole frequency spectrum (~40Hz - 20kHz) is divided into16 frequency sub-bands
- display 16 frequency sub-band lines with 10 pixel resolution
- spectrum analyser is based on sub-bands data hidden in every mp3 frame
- each of sub-band line includes average value of both channels in a specific frequency band

Other:
- equalizer setting
- select from playlist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