Enabling Multi-protocol Industrial Ethernet with the Programmable Real-time Unit and Industrial Communication Subsystem (PRU-ICSS) on TI’s Sitara™ processor family

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With more than 30 different industrial Ethernet standards deployed in the factory automation market today, developers of these products have the unique challenge of choosing the perfect hardware technology/platform. Moreover, as each of the Industrial Ethernet standards often require specific functions in the media access controller (MAC), developers often use expensive FPGA and ASIC solutions to cover multiple industrial Ethernet standards with one platform.

The Programmable Real-Time Unit and Industrial Communication Subsystem (PRU-ICSS), available in the Sitara™ product family from Texas Instruments (TI), addresses this challenge by providing the capabilities to support multiple industrial Ethernet standards on one single chip. The PRU-ICSS is a peripheral that is combined with a high performance ARM Cortex™-A application processor, allowing the developer to easily change the industrial Ethernet standard by simply loading a different PRU-ICSS firmware image.

TI has PRU-ICSS firmware support for the top industrial Ethernet protocols such as EtherCAT, PROFINET, EtherNet/IP and more. In addition, the PRU-ICSS can be programmed by customers to implement any kind of proprietary Ethernet protocol.

In this webinar, we will cover:

• Multi-protocol industrial Ethernet support with Sitara™ processor portfolio
• Introduction to the PRU-ICSS peripheral
• Getting started on implementing an industrial Ethernet protocol with PRU-ICSS
• Q&A
Agenda

• Introduction to industrial Ethernet
• Challenges of industrial Ethernet
• Programmable Real-Time Unit and Industrial Communication Subsystem (PRU-ICSS)
• Sitara™ application processors with PRU-ICSS support
• Industrial Development platforms
• How to implement your own industrial Ethernet protocol
Industrial Communication in Factory Automation

• Industrial Automation System = HMI + PLC + Sensors + Motor Control
• Connectivity is the heart of automation for greater productivity
• TI is uniquely positioned to provide efficient & scalable system solutions HW (Analog & Processor) + SW (communications & applications)
Top 5 Ethernet based standards

• **Profinet RT/IRT**
  - Factory automation including drives, some stack overhead

• **EtherCAT**
  - Large IO systems and drives, gaining momentum in Asia

• **Ethernet/IP**
  - IEEE compliance, CIPSync for drives, strong in Process Automation

• **Powerlink**
  - Open source technology, based on standard Ethernet, popular with control engineering and motion control, gaining momentum in Asia.

• **Sercos III**
  - Optimized technology for drives, only one stack partner besides own stack
Definition of real-time in industrial applications

- "Real-Time" does not refer to "fast"!
- Cycle Time is equidistant and deterministic
- Latency, Jitter, Minimum, Maximum
- Worst case latency = determinism
- The term "real-time" is senseless without setting a deadline for the given system
- Soft real-time
  - Occasional violation of deadline is acceptable
- Hard real-time
  - Each single violation of deadline is equal to a software error and must be handled by an exception routine
- Industrial Ethernet requires Hard real-time for many protocols
Challenges of industrial Ethernet

• Slave devices must support 2x industrial Ethernet ports
  – Enables Ethernet line and ring topology
  – Removes need of Ethernet hubs and switches

• Frame processing
  – On-the-fly
  – Cut-through

• Master devices can have one or two Ethernet ports
  – Ring topology
  – Redundancy

• Standard Ethernet Media Access Control (MAC) does not support the requirements for industrial Ethernet

• Most industrial Ethernet standards require specific MAC implementation
TI solves the complex slave communications problem by integrating multi-protocol support in the ARM SoCs

**Typical Solution – Today**
- MCU/MPU for application
- External ASIC/FPGA for industrial communications (especially for slave)

**TI’s ARM + PRU-ICSS solution offers 5 Benefits**
- System BOM savings (>40%) by eliminating the external ASIC
- Supports multiple protocols using the same hardware (PRU is completely programmable)
- Lower Power
- Easily adapt to changing standards or create own (requires PRU expertise or 3P help)
- Scalable solution for HMI, PLC and I/O devices

**Programmable Real-Time Unit and Industrial Communication Subsystem (PRU-ICSS)**
Sitara AM335x with PRU-ICSS

Key Features

- ARM Cortex A8 up to 1 GHz
- Flexible Industrial Communication Protocols
- Open IP for own/legacy protocol implementation
- 32 bit – 200 MHz Crossbar connection
- 64k Shared RAM
- Gigabit Ethernet switch
- Extensive peripheral set
- Guaranteed long-term supply

* 800 MHz / 1 GHz only available on 15x15 package. 13x13 supports up to 600 MHz.
(1) Use of TSC will limit available ADC channels.
PRU optimized for low latency and jitter

- Non pipelined CPU is 100% deterministic – **no jitter** in real-time execution
- Broadside interface with 1000 bit wide data bus supports **lowest latency** transfers
- Register mapped IOs and bit-wise addressing provide **max interface flexibility**

Example:

Count number of 1s in byte

```
1001'1010
```

takes 8 instructions

=> 40ns
Industrial Communication Subsystem (ICSS)

- Industrial Ethernet
- Serial Fieldbus
- Encoder Feedback
- Backplane Communication
- Sigma Delta filter
- Custom interfaces
- Signal Processing
- Application Synchronization
Media Independent Interface (MII) with Real-time (RT)

Two MII_RT ports

- Each MII port has:
  - 32-byte RX L1 FIFO
  - 64-byte RX L2 buffer
  - 64/96-byte TX L1 FIFO

- Rate decoupling on TX L1 FIFO

- Configurable pre-amble removal on RX L1 FIFO and insertion on TX L1 FIFO

- Configurable TX L1 FIFO trigger (10 bits with 40 ns ticks)

- MII port multiplexer per direction to support line/ring structure
  - Link detection through RX_ERR and RX_LINK

- Cyclic redundancy check (CRC)
  - CRC32 generation on TX path
  - CRC32 checker on RX path
TI Design Multi-protocol Industrial Ethernet: TIDEP0032

- PRU-ICSS firmware example on how to determine industrial Ethernet protocols
- PRU-ICSS firmware analyzes Ethernet header (Ethertype field) and loads appropriate industrial Ethernet I/O application
- Shown at Electronica and SPS/IPC/Drives – Link to video

.. seamless connection to market leading PLCs
Typical Software architecture

Customer Software
- Industrial Application for end product (customer value add)
- BSP for customer boards / RTOS / HLOS

Third Party Software
- Free Evaluation version of protocol stack
- For production, customers license stack from 3P, or develop/use own stack

TI Software
- Protocol firmware, protocol and peripheral drivers, example slave application, RTOS/HLOS, bootloader, tools
- Some customers use these as is for production, some use as reference for their port

Diagram:
- Layer 7 - Application
  - Industrial Application
  - API
  - Protocol Stack
- Layer 2 – Data Link
  - API
  - Protocol Driver
- Layer 1 - Physical
  - Ethernet Phy

Notes:
- RTOS or HLOS
- Bootstrap & Tools
- PRU-ICSS
- ARM
Sitara ARM SoCs with Industrial Communication

**Dual Core**

AM572x
- 2x A15, 1.5 GHz
- 2x C66x, 750 MHz
- HD, 2x 3D, 2D, USB3
- 23x23mm

AM571x
- 1x A15, 1.5 GHz
- 1x C66x, 750 MHz
- HD, 3D, 2D, USB3
- 23x23mm

**Single Core**

AM437x
- 1x A9, 1 GHz
- QSPI
- GbE Switch, 3D
- 17x17mm

AM335x
- 1x A8, 1 GHz
- GbE Switch, 3D
- 16-bit DDR3
- 13x13, 15x15mm

**2015**

66AK2G02
- 1x A15, 600 MHz
- 1x C66x, 600 MHz
- 2MB RAM, PCIe
- 21x21mm

**2016**

Pin Compatible
- Production
- Sampling

**PRU-ICSS**
- Multiprotocol Industrial Ethernet
- Serial Fieldbus
- PRU serial + parallel register

- Multiprotocol Position Feedback
- Multi-channel Delta Sigma Filter
- More PRU instruction memory

- 2nd Industrial Ethernet Protocol
- Enhanced Time Synchronization
- Enhanced Ethernet Phy interface
- More PRU data memory

Texas Instruments
## PRU-ICSS feature comparison

<table>
<thead>
<tr>
<th>Features</th>
<th>AM335x</th>
<th>AM437x</th>
<th>AM57x</th>
<th>66AK2G02</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>PRU-ICSS1</td>
<td>PRU-ICSS-1</td>
<td>PRU-ICSS-0</td>
<td>PRU-ICSS1</td>
</tr>
<tr>
<td>Number of PRU cores</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Max frequency</td>
<td>200 MHz</td>
<td>200 MHz</td>
<td>200 MHz</td>
<td>200 MHz</td>
</tr>
<tr>
<td>IRAM size (per PRU core)</td>
<td>8 KB</td>
<td>12 KB</td>
<td>4 KB</td>
<td>12 KB</td>
</tr>
<tr>
<td>DRAM size (per PRU core)</td>
<td>8 KB</td>
<td>8 KB</td>
<td>4 KB</td>
<td>8 KB</td>
</tr>
<tr>
<td>Shared DRAM size</td>
<td>12 KB</td>
<td>32 KB</td>
<td>--</td>
<td>32KB</td>
</tr>
<tr>
<td>General purpose input (per PRU core)</td>
<td>Direct; or 16-bit parallel capture; or 28-bit shift</td>
<td>Direct; or 16-bit parallel capture; or 28-bit shift; or 3ch EnDat 2.2; or 9ch Sigma Delta</td>
<td>Direct; or 16-bit parallel capture; or 28-bit shift; or 3ch EnDat 2.2; or 9ch Sigma Delta</td>
<td>Direct; or 16-bit parallel capture; or 28-bit shift; or 3ch EnDat 2.2; or 9ch Sigma Delta</td>
</tr>
<tr>
<td>Simultaneous protocols</td>
<td>1</td>
<td>2*</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

*2nd protocol limited to EnDat 2.2, Profibus, BiSS C, Hiperface DSL or serial based protocol.
# Industrial Development Platforms for Industrial Ethernet

<table>
<thead>
<tr>
<th>Platform</th>
<th>Processor Summary</th>
<th>Memory</th>
<th>Special Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>TMDSICE3359</td>
<td>AM3359 ARM Cortex A8 up to 1GHz</td>
<td>256MB DDR3</td>
<td>Industrial Ethernet PROFIBUS</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Temp Sensor, USB JTAG</td>
</tr>
<tr>
<td>TMDSIDK437X</td>
<td>AM4379 Cortex A9 Up to 1GHz</td>
<td>1GB DDR3</td>
<td>Industrial Ethernet PWM &amp; ADC</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>QSPI-NOR Flash, USB JTAG</td>
</tr>
<tr>
<td>TMDXIDK5728</td>
<td>AM5728 Dual-Core A15 + C66x Up to 1.5GHz</td>
<td>1GB DDR3L / 1GB DDR3L ECC</td>
<td>2x Industrial Ethernet PROFIBUS, PCIe, Camera</td>
</tr>
</tbody>
</table>

| Price             | $189                               | $329         | $899                                          |

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*Texas Instruments*
AM572x IDK (TMDXIDK5728)
MSRP: $899

Features:
- Sitara™ AM5728 Dual-Core A15 + C66x
- 2x PRU-ICSS Eth. + 2x Gb Eth.
- Camera board included
- Optional 10.1” 10-point capacitive touch LCD screen - coming soon

Available SW:
- **RT Linux & TI-RTOS**
- **PRU-ICSS-INDUSTRIAL-SW**
  - Profinet and EtherCAT slave available today
  - Ethernet/IP, Profibus slave, Profibus multimaster, HSR, and PRP coming throughout 2Q
Implementing own protocol – Pre-requisites

• Become familiar with
  – PRU assembly programming
  – Industrial Ethernet protocol specification
  – Processor and board system architecture

• Additional Resources
  – TIDEP0061 (coming soon) – Industrial Ethernet Protocol with PRU-ICSS
  – AM572X Technical Reference Manual (TRM)
### PRU Instruction Set

<table>
<thead>
<tr>
<th>Arithmetic Operations (green)</th>
<th>Logic Operations (blue)</th>
<th>IO Operations (black)</th>
<th>Program Flow Control (red)</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADD</td>
<td>SUB</td>
<td>ADC</td>
<td>SUC</td>
</tr>
<tr>
<td>RSC</td>
<td>LSL</td>
<td>LSL</td>
<td>RSB</td>
</tr>
<tr>
<td>XOR</td>
<td>NOT</td>
<td>ADC</td>
<td>OR</td>
</tr>
<tr>
<td>SET</td>
<td>LMBD</td>
<td>SUB</td>
<td>CLR</td>
</tr>
<tr>
<td>LBBO</td>
<td>SBBO</td>
<td>MIN</td>
<td></td>
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<tr>
<td>JAL</td>
<td>JMP</td>
<td>MOV</td>
<td></td>
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<tr>
<td>QBGT</td>
<td>QBGE</td>
<td>LDI</td>
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<tr>
<td>QBNE</td>
<td>QBA</td>
<td>SBCO</td>
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<tr>
<td>WBC</td>
<td>HLT</td>
<td>QBBS</td>
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</tr>
<tr>
<td>MVID</td>
<td>ZERO</td>
<td>SLP</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>FILL</td>
<td></td>
</tr>
</tbody>
</table>

- **IO Operations (black)**: ADD, RSC, XOR, SET, LBBO, JAL, QBGT, QBNE, WBC, MVID
- **Arithmetic Operations (green)**: ADC, LSL, NOT, LMBD, SBBO, JMP, QBGE, QBA, HLT, ZERO
- **Logic Operations (blue)**: SUB, LSR, MIN, MOV, AND, MAX, LDI, SBCO, CALL, SBCO, QBLS, QBBS, SLP, QBLS, FILL
- **Program Flow Control (red)**: SUC, RSB, OR, CLR, LDI, SBCO, (RET), QBLS, QBBS, QBLS, MVIB, WBS, MVIW

- **IO Operations (black)**: ADD, RSC, XOR, SET, LBBO, JAL, QBGT, QBNE, WBC, MVID
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- **Program Flow Control (red)**: SUC, RSB, OR, CLR, LDI, SBCO, (RET), QBLS, QBBS, QBLS, MVIB, WBS, MVIW
• Receive methods supported by MII_RT module
• On-the-fly frame processing via L1 / R31
  – Example: EtherCAT, Sercos III
  – Same Ethernet frame is shared across slave devices
  – PRU firmware processes the content of Ethernet frame in between reception and transmission
  – Single byte or word processing
  – PRU updates CRC at e/o frame if frame content has changed
  – Low PHY-to-PHY latency of typically less than $1\mu$s
Ethernet Frame Receive Processing 2/2

- Cut-through frame processing via L2
  - Example: PROFINET, EtherNet/IP, Ethernet with cut-through support
  - For Ethernet frames with dedicated addressing (e.g. MAC address)
  - PRU analyzes the addressing and takes forward decision after it receives the Ethernet header information (MAC address, QoS, …)
  - 32-byte block processing
  - Low PHY-to-PHY latency of typically less than 1..3μs
Example: RX L2 reception

- Relaxed real-time servicing of MII data
- 64 byte data buffer per PRU core
  - high performance read using XFR cmd
  - Each PRU has 2 banks of 32 bytes of data and 16 bytes of status
  - simple ping/pong buffer
- 8-bit status information for every 16-bit data
- Data is packed into data array
- Status is packed into status array
- Support "short" frames, less than 64 bytes
- Status identifies EOF and number of valid bytes
Industrial Ethernet Protocol with PRU-ICSS

**Solution Features**

- Programmable Real-time Unit (PRU) and Industrial Communication Subsystem (ICSS) supported by Sitara™ processors family
- Real-time Media Independent Interface (MII_RT) support
  - Auto-forward (with PRU snooping), 8/16-bit one-the-fly processing and 32-byte ping-pong buffer operation mode support
- Practical PRU firmware programming example on how to implement Industrial Ethernet protocol with PRU-ICSS

**Solution Benefits**

- Customers with proprietary industrial Ethernet protocol support
- Removes external ASIC or FPGA support and integrates industrial Ethernet with application processor into SOC
- Reference PRU firmware for with user’s guide, application notes, software and more

**Tools & Resources**
Conclusion and Summary

- PRU-ICSS enables multi-protocol industrial Ethernet on the scalable Sitara™ processor product family

- Removes FPGA and ASIC from the board: Saves BOM, board space and cost

- Top 5 industrial Ethernet protocols certified on PRU-ICSS enabled Sitara™ processors
  - Reduces time to market

- PRU-ICSS enables implementing custom protocols and industrial Ethernet standards