PROFINET® on TI's Sitara™ processors

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Executive summary

Texas Instruments (TI) has successfully integrated the **PROFINET® industrial Ethernet standard** into its Sitara™ Arm®-based processors, leveraging the Siemens ERTEC® stack as the foundation for its PROFINET implementation. This integration enables the creation of high-performance, reliable, and efficient industrial automation systems.

The Sitara processor's industrial communication sub-system (ICSS) is built upon TI's programmable real-time unit (PRU) technology, which provides a dedicated platform for handling the real-time processing requirements of PROFINET. The ICSS features a two-port PROFINET cut-through switch, which offloads the processing demands of PROFINET from the Arm core, thereby optimizing the utilization of the processor's resources. This architectural approach ensures that the majority of the Arm core's processing power is available for executing industrial applications, resulting in improved system performance and efficiency.

Introduction to PROFINET

Overview

PROFINET is a real-time Ethernet standard for the high-speed, deterministic communications required for a wide range of industrial applications including factory automation, process automation, and building automation. Originally developed under the leadership of Siemens AG as a network extension to the popular PROFIBUS® fieldbus technology, PROFINET is now supported by PROFIBUS & PROFINET International. In 2003, PROFINET was integrated into the IEC 61158 and IEC 61784 standards. Its architecture was developed by 30 working groups whose members represented more than 70 different companies.

Adapting Ethernet to support industrial applications creates a technology bridge between the worlds of corporate IT and the factory floor by using familiar technologies such as TCP/IP and XML. Although standard Ethernet provides excellent solutions in an IT-centric corporate environment, it falls short on several counts for factory automation. Standard Ethernet is not efficient for the small amounts of data exchange that are typical in factory automation, for example, and lack of determinism means it cannot support the real-time operation necessary for motor drive control and other industrial real-time applications. PROFINET is a leading example of solving these challenges so that Ethernet can be adapted for real-time industrial applications.

Technology

PROFINET’s system model closely resembles the PROFIBUS fieldbus system. It is based on the controller–device communication paradigm with one or more IO-Controllers communicating with one or more devices IO-Devices. Two types of traffic are communicated over PROFINET network:

1. Real-time process data (IO data) which is exchanged cyclically between the IO-Controllers and IO-Devices in the network,
2. Non-real-time traffic which is exchanged as acyclic records between the IO-Controllers and IO-Devices or directly among different IO-Devices.

Device model PROFINET in OSI/ISO Model

PROFINET is a layer 7 technology which provides application services for device configuration and parametrization, diagnostics and alarm handling, engineering and commissioning, as well as an interface for user-defined applications to generate and consume the actual information throughout the network. Nevertheless, for real-time communication (I/O data) and in order to ensure an efficient, deterministic, and low-latency performance, PROFINET bypasses the standard TCP/IP layers and communicates directly on layer 2 with Ethertype 0x8892 and possibly a VLAN tag with a high priority.

Conformance Classes

PROFINET standard defines four conformance classes that build upon one another and are oriented to serve different applications and use-cases:

- **Conformance Class A (CC-A):** can be implemented with standard Ethernet hardware and supports basic PROFINET functions such as cyclic Real-Time (RT) communication with update times between 1 to 512ms, acyclic records exchange, parametrization, diagnostics, alarms, neighborhood detection (LLDP) and the ability to allow parallel TCP/IP communication to take place on the network.
- **Conformance Class B (CC-B):** extends CC-A with network diagnostics via SNMP, system redundancy with two IO-Controllers (only defined for Process Automation (PA) profile), in addition to some optional features like: automatic addressing of device after replacement, Configuration in Run (CiR), Fast Start-Up (FSU) and network redundancy via Media Redundancy Protocol (MRP). It is also worth mentioning that CC-B introduced the network switches with IO-Device functionality in order to provide more comprehensive network diagnostics.
- **Conformance Class C (CC-C):** extends CC-B with the support of cyclic Isochronous Real-Time (IRT) communication with update times less than 250us (can be reduced to 31.25us depending on the hardware used). This performance can be realized by using additional hardware support to achieve network-wide time synchronization and bandwidth reservation. In addition, CC-C defines some optional features like: Dynamic Frame Packing (DFP) and seamless redundancy via Media Redundancy for Planned Duplication (MRPD) protocol.
- **Conformance Class D (CC-D):** this is the most advanced PROFINET class. It utilizes Time-Sensitive Networking (TSN) capabilities such as Time-Aware Shaper (TAS) and frame preemption to achieve very high determinism and low latency. CC-D also introduces the Remote Service Interface (RSI) which bypasses TCP/IP layers for the acyclic non-real-time communication as well as for the cyclic real-time one.

Communication

Communication paths that must be established between the IO-Controller and an IO-Device are set up by the IO-Controller during system startup based on the configuration data in the engineering system. This explicitly specifies the data exchange.

Every data exchange is embedded into an Application Relation (AR). Within the AR, Communication Relations (CR) explicitly specify the data. All data for device modeling, including the general communication parameters, are downloaded to the IO-Device. An IO-Device can have multiple ARs established from different IO-Controllers. The communication channels for cyclic data exchange (IOCR), acyclic data exchange (record data CR), and alarms (alarm CR) are set up simultaneously.

Multiple IO-Controllers can be used, and it is necessary for multiple IO-Controllers to access the same data in the IO-Devices, this data sharing must be specified when configuring the IO-Devices.

An IO-Controller can establish one AR, each with multiple IO-Devices. Within an AR, several IOCRs and APIs can be used for data exchange. This can be useful, for example, if more than one user profile (PROFI-drive, Encoder, etc.) is involved in the communication and different subslots are required. The specified APIs serve to differentiate the data communication within an IOCR.

Addressing

In PROFINET, a unique name assigned to every field device is used when assigning the IP address. The Dynamic Configuration Protocol (DCP) for this purpose is integrated in every IO-Device.

The IP address is assigned with the DCP protocol based on the device name. Because Dynamic Host Configuration Protocol (DHCP) is widely used internationally, PROFINET has provided for optional address settings via DHCP or manufacturer-specific mechanisms. The addressing options supported by a field device are defined in the GSD file for the respective field device.

Optionally, the name can also be automatically assigned to the IO-Device by means of a specified topology based on neighborhood detection. A PROFINET IO-Device is addressed for direct data exchange by its MAC address.

Conformance classes

PROFINET IO is divided into three conformance classes that build upon one another and are oriented to typical applications.

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- **Conformance Class C (CC-C):** extends CC-B with the support of cyclic Isochronous Real-Time (IRT) communication with update times less than 250µs (can be reduced to 31.25µs depending on the hardware used). This performance can be realized by using additional hardware support to achieve network-wide time synchronization and bandwidth reservation. In addition, CC-C defines some optional features like: Dynamic Frame Packing (DFP) and seamless redundancy via Media Redundancy for Planned Duplication (MRPD) protocol.
- **Conformance Class D (CC-D):** this is the most advanced PROFINET class. It utilizes Time-Sensitive Networking (TSN) capabilities such as Time-Aware Shaper (TAS) and frame preemption to achieve very high determinism and low latency. CC-D also introduces the Remote Service Interface (RSI) which bypasses TCP/IP layers for the acyclic non-real-time communication as well as for the cyclic real-time one.

Standard devices

PROFINET standard defines three types of devices: IO-Controller, IO-Device and IO-Supervisor. An example of a simplified network architecture inside a factory plant is provided in Figure 1.

IO-Controller

This is typically a field device such as a sensor, actuator, drive, or distributed I/O that interacts with the physical process. It is comparable to a device in PROFIBUS. It responds to connection requests from one or more IO-Controllers, provides device-specific parameters and configuration options, and generates diagnostic information and alarms. The process data generated by the IO-Device is called "input data".

IO-Supervisor

This can be a programming device, personal computer (PC), or a human machine interface (HMI) device used for

commissioning, diagnostics, and maintenance pu
It corresponds to a Class 2 controller in PROFIBU
IO-supervisor can establish connections with PR(
devices to read/write configuration data, request
diagnostic information, and perform engineering t
without disrupting the cyclic communication betw
IO-Controllers and IO-devices. Unlike the IO-Con
the IO-supervisor is usually temporarily connecte
network for commissioning or troubleshooting pu
it also does not participate in cyclic real-time data
exchange.

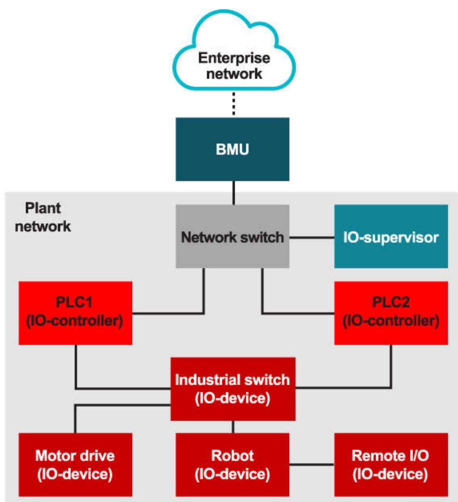

Figure 1. *PROFINET in a factory network*

IO-Device Overview

Each application process running on the IO-device is identified via an application process identifier (API). Within the application process, an IO-device is hierarchically composed of modules, submodules and channels. These elements can reflect hardware components or virtual functional units. A module can be installed into a slot or more. Each module shall have one or more submodules, each of which is installed into a subslot. A submodule contains one or more channels with each channel representing a single connection to the process (e.g. a sensor). Figure 2 shows the hierarchical structure of an IO-device which usually starts with a device access point (DAP) module.

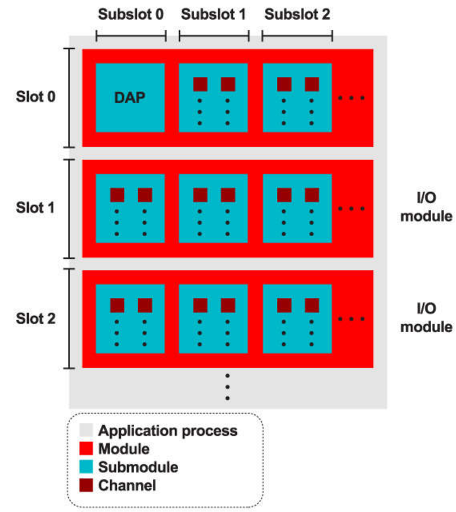

Figure 2. *IO-Device Hierarchical Structure*

A DAP module is the interface for the whole device. It is usually plugged in slot number 0 and it contains up to 16 special interface submodules plugged into subslots with numbers 0x8i00 (0x8000 up to 0x8F00). Each of these interface submodules is assigned up to 255 port submodules plugged into subslots with numbers 0x8ijj (e.g. 0x8001 up to 0x80FF for the interface submodule at 0x8000).

PROFINET differentiates between compact field devices, in which the degree of expansion is already specified by the manufacturer and cannot be changed by the user, and modular field devices, in which the degree of expansion can be customized for a specific application when the system is configured.

Device Description

Every IO-Device is accompanied by a General Station Description (GSD) file. This XML-based GSD file (also called GSDML) contains all the device-specific information needed for configuration and system engineering. It describes the device's capabilities, parameters, modules, and communication properties. It is provided by the device's manufacturer and has a standardized format following the GSDML specifications.

Communication

Before system startup, an IO-Device has to have a MAC address, an IP address and a station name. The MAC address is usually assigned by the device's manufacturer, while the station name is configured by PROFINET engineering tools via the Discovery and basic Configuration Protocol (DCP). Using these two elements while utilizing other IP services like Address Resolution Protocol (ARP) and, optionally, Dynamic Host Configuration Protocol (DHCP), the IO-Controller can assign a unique IP address to the IO-Device in order to prepare it for the system startup phase.

Once the device's address is configured correctly, the connection establishment sequence is initiated by the IO-controller. This procedure mainly includes the establishment of the Application Relation (AR) and corresponding communication relationships (CRs the parametrization of the configured submodules the IO-device. Figure 3 shows the PROFINET sta sequence.

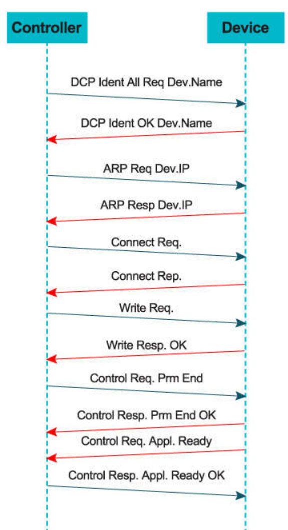

Figure 3. *PROFINET Startup Sequence*

PROFINET solution from TI

TI has already integrated PROFINET functionality into Sitara processors. The combination of Arm cores and a wide variety of peripherals and interfaces that complement PROFINET make the Sitara processors attractive devices for industrial automation equipment

Supported Conformance Classes and Features

TI’s flexible PROFINET stack supports all the conformance classes of PROFINET, as shown in Figure 4. This total integration of PROFINET has been certified for conformance class C, with features like Legacy, FSU, MRP, System Redundancy (S2) and shared device for AM243x, AM64x and AM261x.

In addition to conformance classes referred to in Figure 4, TI's PRU-firmware, explained later in paragraph 6.8, already supports conformance class D. Full support including Profinet Stack is work in progress.

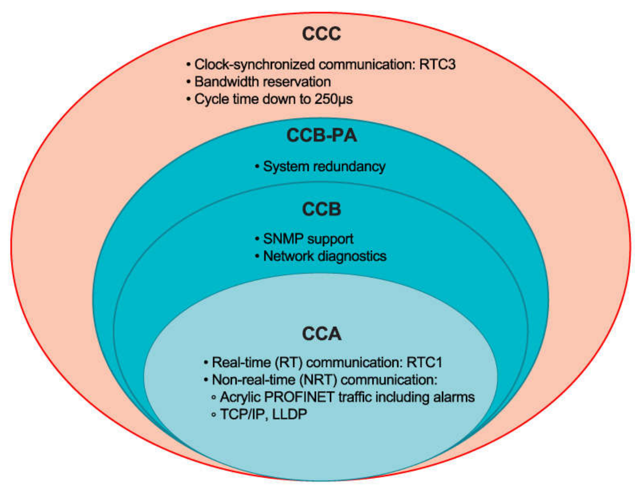

Figure 4. *TI’s PROFINET solution supported conformance classes*

High Availability

Profinet Stack integrated to TI's Sitara processors ensures device high availability via MRP, System Redundancy (S2) and Dynamic Reconfiguration support.

Shared Devices and Shared Inputs

TI’s integrated PROFINET solution on Sitara processors supports simultaneous multiple ARs with multiple controllers. It can establish up to eight ARs and eight

IOCRs at a time. It allows other controllers to establish or close a connection while it is already exchanging I/O data with a separate controller. It supports shared inputs, thus allowing access by the multiple controllers to the same slot in a device.

Performance

Sitara processors feature an integrated, fully-featured ERTEC-based PROFINET solution, which is capable of supporting a minimum Send Clock Time or Phase Duration of 250µs, thereby ensuring high degree of timing precision and synchronization which makes it suitable for demanding industrial automation applications. It supports all the valid values of Reduction Ratio from 1 to 512. Cut-through latency of the integrated switch is in range of 1 to 2µs irrespective of the frame size. CPU load measured for 1ms cycle time with one controller AR is at 5%. The device exhibits a power-on to first valid output data of around 470ms, ensuring rapid initialization and data exchange capabilities.

Robustness

The totally integrated Sitara PROFINET solution is robust as it separates the PROFINET traffic from t standard TCP/IP traffic. It has four priority queues host and port interfaces. The two highest priority are reserved for PROFINET frames and the last tw the TCP/IP frames. If a queue is full, then the fram destined to that queue are dropped. If there is too TCP/IP traffic, then it doesn't impact the PROFINI traffic as they use different queues. This separatic traffic into separate queues as per PROFINET Qo the device withstand any traffic in a large network.

Dedicated Low-Latency Interface for Cyclic Data

PROFINET integrated onto the Sitara processor implements a low-latency real-time interface for cyclic I/O data exchange between the application and PRU. Cyclic data frames are not received and transmitted through the host and port queues respectively. PROFINET cyclic data frames are terminated in the PRU-ICSS and data is directly provided to the application through triple buffer. Triple buffer management is used for exchanging the cyclic data so that the host and PRU-ICSS always find a buffer to store the data.

PROFINET Software Architecture

The PROFINET device implementation integrated on Sitara processors has three major software components. The first is microcode that implements Layer 2 functionality in the device's PRU-ICSS; the second is the PROFINET device stack that runs on the Arm core; and, the third is the industrial application. TI provides additional components such as the protocol adaptation layer and device drivers in the software development kits that support its Sitara processors. The architecture is shown in Figure 5. Any adaptions can be made by referring to TI's PROFINET API guide.

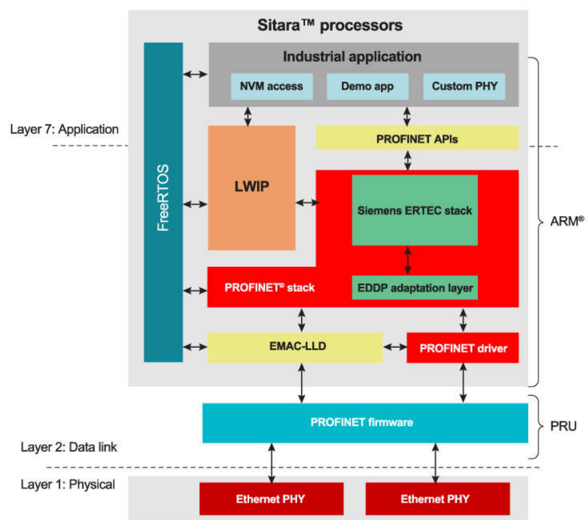

Figure 5. *Software architecture for PROFINET device on Sitara processors*

Application Processor Offloaded

As shown in Figure 5 and Figure 6, the Sitara processors feature TI's programmable real-time unit industrial communication subsystem (PRUICSS), which will support very low-level interaction with the MII interfaces. The PRU-ICSS can easily implement specialized communication protocols such as PROFINET. As in the integrated PROFINET solution on the Sitara **AM261x**, **AM243x**and **AM64x**, an entire PROFINET switch can be encapsulated in the PRU-ICSS through firmware, leaving the Arm core free for stack and application processing. Parsing of Consumer Pro Machine (CPM) frames and generation of Provide Protocol Machine (PPM) frames can be handled completely by a PRU. Any frames which are not r for the PROFINET node are cut-through to the ne by the switch included in the PROFINET PRU firm on Sitara processors where the PROFINET protoc been integrated by TI. This implementation allows use of a lower speed variant of Arm cores for sim cost-constrained applications, such as distributed

Interrupts are used for communication required w Arm core running the PROFINET stack (Layer 7) a industrial application. The PRU-ICSS can also perform frame forwarding in the reverse direction. Ethernet PHY devices, such as **DP83826**, **DP83867** or **DP83869** from TI, are used to complete TI Sitara PROFINET solution. The DP83826 offers low and deterministic latency, low power and supports 10BASE-Te, 100BASE-TX Ethernet protocols to meet stringent requirements in real-time industrial Ethernet systems. The DP83867 and DP83869 provide flexibility to connect to a MAC through MII, RMII or RGMII interfaces and also offering low latency. DP83826, DP83867 and DP83869 also provide cable diagnostics features that can quickly locate cable faults. The solution also provides the customer the flexibility to use other PHY devices.

Firmware

The firmware architecture shown in **Figure 6** shows the PROFINET device capability integrated on the PRU-ICSS. In PROFINET Layer 2, the PRUs perform the tasks of CPM/PPM processing, Data Hold Timer (DHT), DCP Identify Filter, ARP filter, cut-through switching, error detection and host interface handling. The PRU-ICSS provides an easy-to-use PROFINET register space in the internal shared memory. Thanks to the PRU's deterministic real-time processing capability, PROFINET frames are handled with consistent and predictable processing latency.

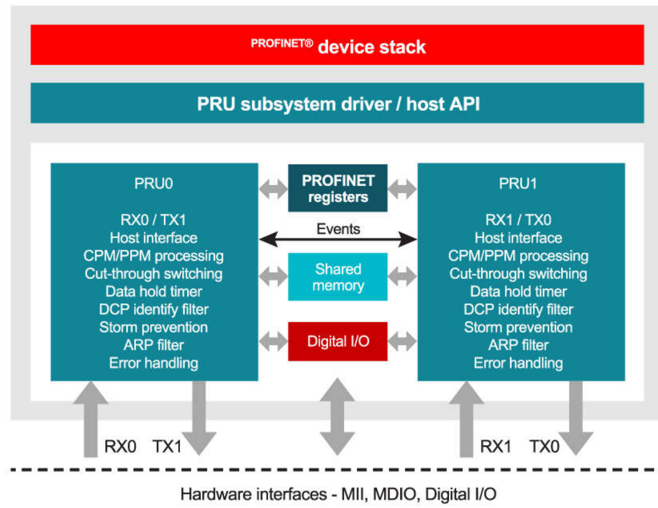

Figure 6. *PROFINET device stack*

CPM/PPM Processing

CPM frames are parsed by the firmware to check whether the host processor should be notified. If the frame ID of the received CPM frame matches with the configured frame ID for an active IOCR, then only the host is interrupted. Firmware stores the CPM frame in pre-defined buffer so that data is completely ready for host consumption before it is interrupted. PPM frames for all the active IOCRs are generated/ produced by the firmware running on the PRU- ICSS. The host only needs to initially configure all the information required for PPM frame generation for all the IOCRs using the TI's PROFINET APIs. At the start of every phase, firmware determines which all PPM frames need to be transmitted in that particular phase and transmits them out without any interference from host.

Data Hold Timer (DHT)

Data Hold Timer is implemented in the PRU-ICSS firmware, and whenever DHT expires, an interrupt is raised to the Arm core running the PROFINET stack. One DHT is maintained by firmware for each IOCR or CPM connection. Whenever a CPM frame is received, firmware updates the data hold time for the associated IOCR. If DHT expires for a particular CPM, then firmware closes down all the PPM associated with that IOCR. The host processor is only interrupted when a DHT has expired. Given that multiple IOCRs can exist simultaneously, implementing DHT in firmware significantly reduces the Arm core processing burden.

DCP Identify Filter

To reduce the number of DCP identify request frames reaching to the Arm core, DCP Identify Filter is implemented in the PRU-ICSS firmware to filter out all the DCP identify frames which are not meant for the host. An API is provided in the driver for the stack to configure the station name and length, which are then used by firmware for filtering.

Storm Prevention and ARP Filter

The stack provides stability during netload conditions by employing a storm prevention technique in the PRU-ICSS firmware. The storm prevention is done based on a credit system. By default, for every 100ms only 100 broadcast or multicast frames would be allowed and all additional frames would be dropped. This frame rate can be configured by the user from the application.

Since ARP frames are broadcast frames, the storm prevention feature makes sure that when a barrage of ARP frames are received they are dropped under high netload conditions. The ARP filter employed in the PRU-ICSS firmware makes sure that under such high traffic condition, the storm prevention is disabled for ARP frames that are directed to the DUT. This filter allows for compliance of the stack during certain netload tests.

Integrated Cut-Through Switch

handles the non-real-time traffic and can be interfaced with PROFINET and TCP/IP stacks running on the host. It implements PROFINET Filter Data Base (FDB) for multicast addresses and PROFINET quality of service (QoS) using four priority queues on host and port interfaces. Learning part of the switch is implemented on the host side.

Easy PROFINET Integration

TI streamlined the process of integrating PROFINET with Sitara processors. All the tools and software code required to integrate a PROFINET devices are available as part of the **Industrial Communications Software Development Kit (IND-COMMS-SDK)**, meaning the PROFINET Firmware, drivers, IP Stack, PROFINET Stack PROFINET APIs and a certified out-of-box example enabling customers to have a reduced time to market. The supporting documentation enables one to modify and build new features into the application.

Integrated PROFINET on End Products

In order to integrate PROFINET device into industrial equipment, customers can use TI's integrated PROFINET stack implementation on Sitara processors which is possible to download from TI.com. TI also offers different customer support packages and can support customers with their custom project also with custom PCB designs. The customer should use the latest PROFINET Test Bundle available on PI website to pass all conformance tests which should be easily possible as TI offers a pre-certified PROFINET devkit. They may also perform broader interoperability tests at PROFINET plug fests and get their product certified by a PI Test Laboratory.

Development Tools for PROFINET

To assist customers with their implementation, TI offers several industrial hardware development platforms complete with comprehensive documentation. Design data for these hardware platforms, such as schematics and layout can significantly accelerate customer designs.

Summary

TI offers a fully integrated PROFINET device capability on the Sitara processors. The integration of PROFINET with a powerful, low-power Arm core results in lower-cost end products without compromise on the functional or operational requirements. TI also offers transceivers with built-in isolation for industrial communication interfaces such as EtherCAT®, EtherNet/IP™, PROFIBUS® and more. With comprehensive software and hardware development tools, worldwide PROFINET support and an active **TI E2E™ developer community**, customers can look forward to greatly simplified PROFINET integration with the added benefit of significant cost savings.