Expansion I/O for LabVIEW RIO Systems: An In-Depth Comparison

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Overview

NI reconfigurable I/O (RIO) products are used in system-level applications that require high-speed, closed-loop control with high-precision measurement on a flexible development platform. Sometimes, these applications require more channels or a more distributed architecture than what the core system can provide. Expansion I/O systems make a 1-to-N system topology possible with one controller and "N" field-programmable gate arrays (FPGAs) and I/O nodes for flexible, high-channel-count systems that can perform both distributed control and localized processing.

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It All Starts With the Bus

The needs for high-channel-count systems are diverse, and the expansion I/O platform from National Instruments offers a complete range of products to meet the varied needs of these systems. The main difference between the expansion I/O options is in the bus that separates the I/O from the processor, as seen in Figure 1. Each bus offers unique benefits and advantages that make it ideal for a subset of expansion I/O applications.
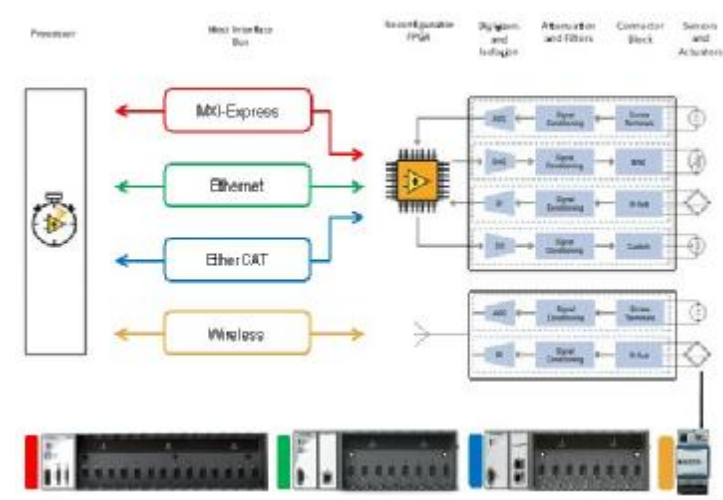

Figure 1. *Expansion I/O decouples the processor from the I/O. Each expansion option implements a different communication bus between the two and suits different application areas.*

Expansion Comparison

Each expansion I/O option is based on a unique communication bus (MXI-Express, Ethernet, EtherCAT, or wireless) that dictates certain features of the system. Table 1 summarizes some key differences between each expansion I/O option.

	MXI-Express RIO	Ethernet RIO	EtherCAT RIO	WSN
	Use the high-performance expansion chassis for high-channel-count applications.	Add FPGA-enabled I/O to anywhere on your Ethernet network.	Use deterministic I/O over EtherCAT for distributed applications.	Easily monitor your assets with reliable, battery-powered measurement nodes.
I/O Count	8 or 14 C Series slots	4 or 8 C Series slots	8 C Series slots	36 Nodes/Gateway
FPGA	Virtex-5 (LX50/LX85/LX110)	Artix-7/Spartan 2M/Spartan 6 (LX45)	Spartan 2M	N/A
Network Topology	Daisy Chain/Star	Same as Ethernet	Daisy Chain/Star	Star/Tree/Mesh
Distance	7 m between chassis	100 m before hub	100 m before repeater	Up to 300 m single hop range
Multidevice Synchronization	FPGA-based DIO	FPGA-based DIO	Implicit in bus	Shared network time base
Communication Jitter	<10 µs	No Spec	<1 µs	No Spec
Bus Throughput	250 MB/s	25 MB/s	12.5 MB/s	250 kb/s
API Support	FPGA Host Interface	FPGA Host Interface/RSI	RSI	RSI
Host	Windows/Real-Time	Windows/Real-Time	Real-Time Only	Windows/Real-Time

Table 1. *A Comparison of Key Expansion I/O Features*

MXI-Express RIO

The MXI-Express RIO expansion chassis offer a high-performance solution for applications that require high throughput, high channel counts, mixed signal conditioned I/O, and custom signal processing and control algorithms. Each MXI-Express RIO chassis supports either 8 or 14 C Series I/O modules and delivers a best-in-class Virtex-5 LX50, LX85, or LX110 FPGA. The chassis are daisy chainable up to six chassis deep, and communicate to a host controller over a cabled PCI Express x1 link for 20X greater throughput than Ethernet or EtherCAT RIO expansion chassis. This MXI-Express link makes it possible to connect to a variety of host systems, including multicore NI CompactRIO and dual- and quad-core PC, PXI, and industrial controllers running NI LabVIEW Real-Time or Windows. MXI-Express RIO systems are ideal for hardware-in-the-loop (HIL) testing, industrial machine condition monitoring, sound and vibration, and complex research applications, such as those found in big physics.

Ethernet RIO

You can use the rugged 4- or 8-slot Ethernet RIO chassis to add distributed, FPGA-enabled I/O to any Ethernet network. With the flexibility of standard CAT-5 cabling, you can connect Ethernet RIO systems to almost any host that supports Ethernet, including NI CompactRIO, real-time PXI controllers, and the NI industrial controller. You can also connect Ethernet RIO expansion systems to Windows-based PCs to create a highly distributed, flexible network of FPGA-enabled, mixed signal conditioned I/O. With the onboard FPGA, you can implement custom signal analysis, control, and safety interlocks that are local to each chassis, creating a truly modular system. Ethernet RIO-based systems are ideal for applications in which ease of use, cost, and flexibility are key concerns. These applications include distributed monitoring for single-point measurements such as temperature and flow.

EtherCAT RIO

EtherCAT (Ethernet Control Automation Technology) RIO is an 8-slot slave chassis that implements communication over Ethernet with the deterministic EtherCAT protocol. EtherCAT RIO allows you to add FPGA-enabled I/O to your high-channel-count or distributed I/O system with a defined amount of determinism and synchronization. Using EtherCAT RIO, you can daisy chain multiple slave devices from a single master and synchronize the I/O to a single master clock. EtherCAT RIO is best suited for distributed, single-point control and motion applications that require hard determinism over multiple synchronized chassis. Customers use EtherCAT RIO for structural monitoring of wind turbines, synchronized test rigs, and long-distance control applications.

Wireless Sensor Networks (WSNs)

The WSN platform allows you to add wireless I/O to any existing monitoring or control system. With the NI WSN platform, you easily can monitor your assets or environment with reliable, battery-powered measurement nodes that offer industrial ratings and local analysis and control capabilities. Each wireless network can scale from tens to hundreds of nodes and seamlessly integrate with other systems, including CompactRIO, NI PXI, and Windows PCs. WSNs are ideal for applications in which you need to overcome power or distance limitations. By eliminating the cabling to your I/O, you can monitor hard-to-reach places, moving parts, mobile assets, or outdoor locations.

I/O Count

MXI-Express RIO, Ethernet RIO, and EtherCAT RIO

MXI-Express RIO, Ethernet RIO, and EtherCAT RIO systems can connect to any sensor on any bus through C Series I/O modules. The I/O is directly available to the FPGA, where you can implement inline signal processing, custom timing, specialized triggering, and closed-loop control. Each C Series I/O module contains built-in signal conditioning and screw terminal, BNC, or D-SUB connectors. Currently, there are more than 100 NI and third-party C Series modules for different measurements including thermocouple, voltage, resistance temperature detector (RTD), current, resistance, strain, digital (TTL and other), accelerometers, and microphones. Channel counts on the individual modules range from three to 32 channels to accommodate a wide range of system requirements.

WSN

WSN measurement nodes feature direct sensor connectivity, built-in signal conditioning, and industrial ratings. Currently, WSN nodes are available that feature interfaces for +/-10 V analog input, thermocouple, RTD, resistance, RS232, RS485, digital I/O, and full/quarter/half-bridge strain gages.

FPGA

MXI-Express RIO, Ethernet RIO, and EtherCAT RIO

FPGA chip adoption across all industries is driven by the fact that FPGAs combine the best parts of application-specific integrated circuits (ASICs) and processor-based systems. FPGAs provide hardware-timed speed and reliability, but they do not require high volumes to justify the large upfront expense of custom ASIC design.

Reprogrammable silicon also has the same flexibility of software running on a processor-based system, but it is not limited by the number of processing cores available. Unlike processors, FPGAs are truly parallel in nature, so different processing operations do not have to compete for the same resources. Each independent processing task is assigned to a dedicated section of the chip, and can function autonomously without any influence from other logic blocks. As a result, the performance of one part of the application is not affected when you add more processing.

Chassis	FPGA	Gates	Flip-Flops	LUTs	Multiplier	Block RAM (kbit)
Ethernet RIO						
NI 9149	Artix-7	--	106,400	53,200	220	4,480
NI 9148	Spartan-3 2000	2 million	40,960	40,960	40	720
NI 9147	Artix-7	--	106,400	53,200	220	4,480
NI 9146	Spartan-6 LX45	--	54,576	54,576	58	2,088
EtherCAT RIO						
NI 9144	Spartan-3 2000	2 million	40,960	40,960	40	720
MXI-Express RIO						
NI 9159	Virtex-5 LX110	--	69,120	69,120	64	4,608
NI 9157, NI 9155	Virtex-5 LX85	--	51,840	51,840	48	3,456
NI 9154	Virtex-5 LX50	--	28,800	28,800	48	1,728

Table 2. *See FPGAs used in Expansion RIO products.*

Network Topology

MXI-Express RIO

On MXI-Express RIO, you can use star or daisy-chain configurations. The number of chassis possible is system-dependent, but, in general, you can achieve up to six chassis per daisy chain. Total chassis in a star configuration is dependent on available PCI bus segments in the host controller, with more than 40 chassis possible on a single controller.

EtherCAT RIO

The theoretical device limit for an EtherCAT network is 65,535 slaves, and Fast Ethernet (100 Mbit/s) limits are similarly high. The real limiting factor in the maximum number of devices in this system is the number of I/O channels you are deploying, the speed of the controller, and the application you are running.

Note that all chassis in a daisy chain share the same "pipe" or bandwidth back to the host controller when configuring a system and calculating total throughput requirements. Also, loop rate is affected by device count and data on the bus, as each chassis and cable adds latency to the system.

WSN

Each WSN system consists of nodes and gateways. The distributed measurement nodes interface with sensors or instruments to collect data and communicate wirelessly to a central gateway, which acts as the network coordinator in charge of node authentication, message buffering, and bridging from the wireless network to the host system. Routers are a special type of measurement node that you can use to extend WSN distance and reliability. WSN systems can be connected in star, tree, or mesh configurations, as seen in Figure 2.
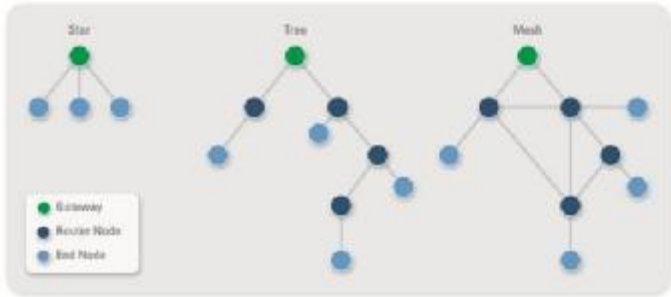

Figure 2. *Network Topologies for NI WSN Systems*

Distance

MXI-Express RIO, Ethernet RIO, and EtherCAT RIO

MXI-Express RIO is limited to 7 m distances between chassis on the bus. Both Ethernet RIO and the EtherCAT slave chassis support up to 100 m before needing a hub, switch, or repeater between devices.

Note: To extend the range of an EtherCAT network, you must use an EtherCAT compatible device; a normal Ethernet switch is not compatible with an EtherCAT network.

WSN

In WSN systems, you can achieve communication distances up to 900 m from the gateway. Actual distances and wireless signal strengths vary depending on several factors, including RF environment, line of sight, and the WSN radio version certified in your region—the Americas version features transmit power of 17 dBm, while the Europe/Asia version features transmit power of 10 dBm. These versions correspond to single hop communication ranges of 300 m and 200 m, respectively. Using routers, you can extend overall network range and position nodes up to three hops from your gateway, resulting in 900 m overall network range. To see what version of the node is certified for your region, reference Wireless Product Certifications by Country.

Multidevice Synchronization

Timing and synchronization allows for the correlation or coordination of events in time, which is an integral part of many control and measurement applications, especially as they scale to high channel counts.

MXI-Express RIO and Ethernet RIO

MXI-Express RIO and Ethernet RIO chassis do not support native synchronization over the communication bus (MXI-Express and Fast Ethernet, respectively). Clock sharing is not built into the bus architecture and the delay induced by missed packets or collision due to network topology is not accounted for (communication between nodes on the system is asynchronous). However, all modules in a single chassis can be synchronized because they share the chassis backplane, and multiple MXI-Express RIO or Ethernet RIO chassis can be synchronized using a C Series digital I/O module to distribute a reference clock signal among chassis. A reference architecture that demonstrates this synchronization method is available in DSA Module Synchronization Reference Design for Multiple CompactRIO Chassis.

EtherCAT RIO

EtherCAT RIO is synchronized to other parts of the system automatically because the EtherCAT bus communication standard defines a master system clock that all devices on the network reference. This makes the EtherCAT bus an ideal choice for systems that require tight synchronization (less than one microsecond) and hard determinism.

WSN

NI WSN systems do not offer built-in synchronization between individual nodes, but the entire network does share a common time base. Every data sample is time stamped at the time of acquisition and sent to the gateway with the timing information attached to the data. This means that all data across an entire network can be plotted on the same time axis as the host. The NI WSN network manages the shared time base, and corrects for drift at regular intervals. At any given time, each individual node clock is within one second of the gateway/host clock.

Communication Jitter

This specification refers to the jitter introduced by the communication bus only. The main source of jitter in a system is usually associated with the controller rather than the communication bus (especially if it's a Windows controller). Also, jitter in a system is dependent on the system architecture and the number of chassis the data must negotiate in a daisy chain to reach the host.

Deterministic communication is important in applications where communication of data between distributed real-time computing nodes is an integral part of the control loop. This means that any jitter induced by the network results in jitter for the control loop. Acceptable control loop jitter depends on the system in question, but a standard range is ±10 percent of the control-loop time. Considering a 1 kHz control loop, this means each iteration could execute in anywhere from 900 to 1,100 μs and the system would still respond appropriately.

The communication jitter for MXI-Express RIO and EtherCAT RIO is less than 10 microseconds and less than one microsecond, respectively. Ethernet RIO and NI WSN devices do not have a specification for jitter. This is because Fast Ethernet and wireless transmission are not deterministic methods of transferring data.

Bus Throughput

MXI-Express RIO provides the biggest pipe back to the controller with 250 MB/s maximum theoretical bandwidth compared to 25 MB/s for Ethernet RIO, 12.5 MB/s for EtherCAT, and 250 kbit/s for WSN. Keep in mind that bus performance depends on more than just the theoretical maximum bandwidth of the bus; consider factors such as latency, implementation, power requirements, and your application in addition to bandwidth. For high-throughput applications, MXI-Express RIO is the best option. The throughput capabilities of Ethernet RIO and EtherCAT RIO is sufficient for most control and monitoring applications. NI WSN throughput is ideal for slow sample rates (around 1 S/s).

API

An API, or application program interface, is a set of routines used as the building blocks for software applications. There are two methods of programming expansion I/O targets: CompactRIO Scan Mode or the LabVIEW FPGA Host Interface API.

You can use CompactRIO Scan Mode (also called the RIO Scan Interface or RSI) on the EtherCAT and Ethernet chassis as well as WSN. CompactRIO Scan Mode automatically detects your I/O modules and adds them to a LabVIEW project. You can then drag and drop the I/O variables onto your LabVIEW Real-Time and host VI block diagrams and instantly read and write scaled, calibrated I/O data without any FPGA programming or compiling.
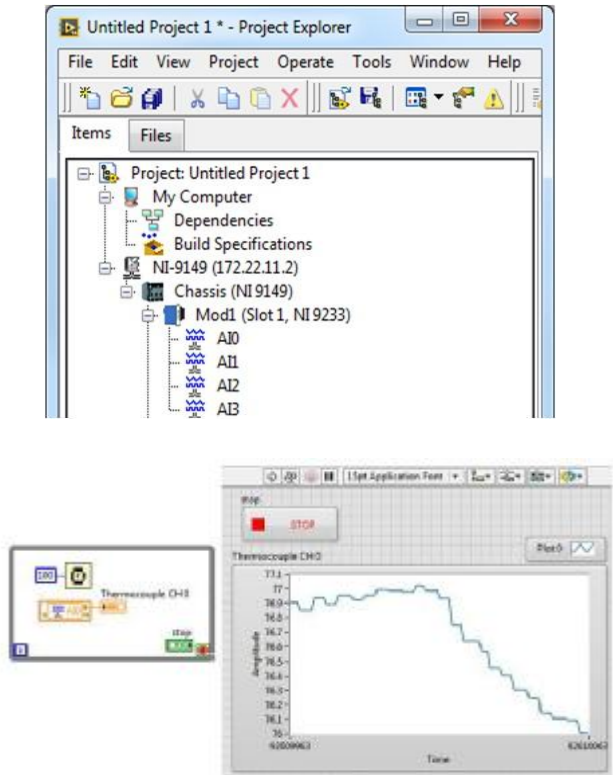

Figure 3. *Using CompactRIO Scan Mode*

If you want to program the FPGA directly, use the LabVIEW FPGA Module. Once you have written your FPGA VI, it is compiled to a bitstream and deployed to the FPGA. To communicate with the FPGA from your host application, use the LabVIEW FPGA Host Interface API. This allows you to perform functions such as reading and writing to registers, and DMA transfers.

Note that with the EtherCAT chassis, you can use only user-defined I/O variables to talk between the controller's real-time VI and the expansion chassis' FPGA VI. (User-defined I/O variables are used to synchronize FPGA data with the NI Scan Engine.) This means that for the expansion chassis' FPGA VI, you have no FPGA Host Interface, DMA transfer functions, or front panel debugging.

You can only use the LabVIEW FPGA Host Interface API to interface with the MXI-Express RIO.

There are also some limitations on the types of C Series modules that are compatible with each chassis based on the modules' ability to support NI Scan Mode. Because MXI-Express RIO supports only LabVIEW FPGA, modules that rely on NI Scan Mode, such as the NI 986x CAN modules, are not compatible with MXI-Express RIO. For a complete list of C Series compatibility, see the NI C Series Compatibility Chart.

Host Controllers

All four expansion options use different buses, so they require different connections on the controller side.

MXI-Express RIO

MXI-Express RIO requires a MXI-Express interface to the host system: options include multicore CompactRIO, PXI, or industrial controllers, as well as PCs running a Windows or real-time OS that have a MXI-Express PCI card interface. You can use a MXI-Express ExpressCard adapter to connect the MXI-Express RIO chassis to controllers that don't already have a MXI-Express interface, but do have a built-in ExpressCard slot such as the NI PXIe-8115. You can also use the NI PXIe-8364 MXI-Express interface to connect a MXI-Express RIO to your PXI system. You can use a MXI-Express to PCI or PCI Express adapter to connect MXI-Express RIO to a PC. Before using the MXI-Express RIO chassis with third-party controllers, reference the PCI Express Clock Specifications and Effect on NI MXI-Express RIO Interoperability document for more information.

Ethernet RIO

Ethernet RIO can plug into any system that has an Ethernet port, and can be used with most standard network topologies. To connect the Ethernet RIO directly to the secondary Ethernet port of a real-time controller, see Connecting an Ethernet RIO Expansion Chassis to the Secondary Ethernet Port on a Real-Time Controller. The 9149 and 9147 Ethernet RIO chassis also include a USB port for easy device configuration. This port is not, however, meant to be used in place of the Ethernet port.

EtherCAT RIO

The EtherCAT RIO chassis is compatible with all real-time controllers with two Ethernet ports, including the CompactRIO, PXI, and industrial controller platforms. Note that for EtherCAT, if a real-time PXI controller does not have two Ethernet ports, you must include an NI PXI-8231/8232 Ethernet interface (the NI 8234 Ethernet interface is not compatible), which is supported only on real-time controllers. You also need the NI-Industrial Communications for EtherCAT driver software, and the second Ethernet port must be in "EtherCAT" mode.

WSN

In an NI WSN system, the gateway acts as the network coordinator in charge of node authentication, message buffering, and bridging from the wireless network to the host system. There are three different options for WSN gateways: the NI WSN-9791 Ethernet gateway, the NI 9792 programmable gateway, and the NI 9795 C Series gateway. The Ethernet gateway can connect to any Ethernet-supported host controller, such as CompactRIO, NI PXI, or Windows PCs. The NI 9792 programmable gateway is a LabVIEW Real-Time target and can operate autonomously without host connection. The NI 9795 C Series gateway delivers tight integration between the NI WSN and CompactRIO platforms. The C Series gateway plugs into any available slot in your CompactRIO system so you can complement existing systems with wireless expansion I/O.

Summary: Application Characteristics

Many different applications require the ability to expand your I/O beyond the confines of your controller. Whether your application requires hundreds of channels of waveform streaming, distributed control, or remote monitoring there is an expansion option for you as seen in Figure 4.
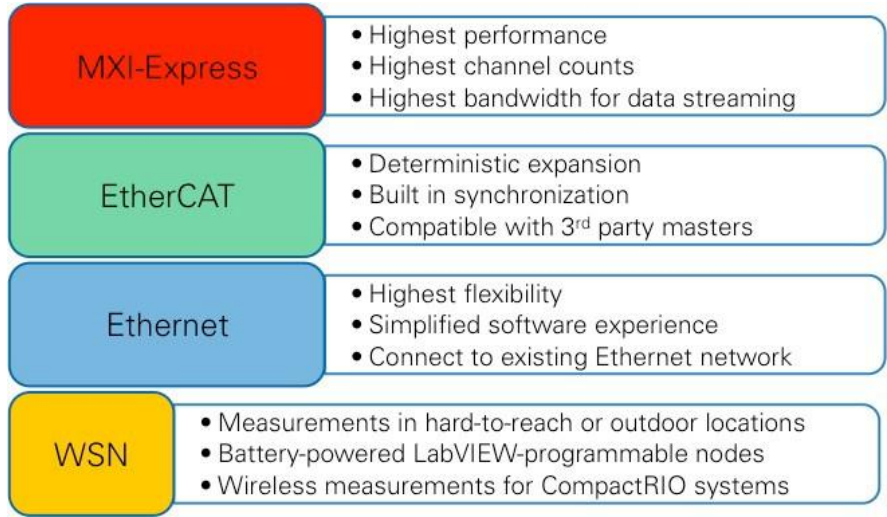

Figure 4. *See expansion options for your LabVIEW RIO system and the characteristics of applications they are best suited for.*

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