Using Real-Time Ethernet as a Backbone to Optimize Machine Performance

Background

Traditional mechatronic systems rely on a centralized CPU connected to a high speed back plane (VME, PCI, etc) in order to sequence and control a complex embedded system. The backplane typically hosts a central CPU and a collection of I/O boards and provides a shared memory interface to access I/O data and communicate with other devices such as drives, encoders, motors, sensors, etc. While these types of hardware architectures work well for smaller noise-free environments, they tend to be problematic for larger systems where high-speed I/O signals have to travel a long distance. Sending high speed I/O data (analogue of digital) makes a system susceptible to electro-magnetic noise which consequently manifests itself as wrong data, or unscheduled and unexpected interrupts resulting in erroneous system behavior. Such behavior is often sporadic and extremely hard to debug.

Remote I/O

Field busses such as CAN, RS485 were introduced to solve this problem and introduced the concept of Remote I/O. In such systems the field bus replaces the central backplane bus. I/O signals are digitized, packetized, and sent back to the controller over the field bus. Similarly commands from the controller are packetized and sent to the drives, motors and actuators over the same bus. For many years this remote I/O architecture proved to be very effective and inexpensive. Over time as machines became more complex, the amount of I/O nodes increased, the I/O frequency requirement increased, and larger amounts of data were needed, rendering the old field bus technology inadequate. This led the automation industry to consider higher bandwidth remote I/O over Industrial Ethernet.

Which Flavor of Ethernet?

Although the pre-eminent network of the workplace, Ethernet TCP/IP does not provide the determinism needed for manufacturing processes. Data packets are allowed to crash and be resent with delays that won't be noticed when waiting for a page to print. This is unacceptable in applications where many nodes must be tightly synchronized to achieve high precision and speed with absolute reliability. Increasingly, this is the world of the mobile equipment design.

Modern silicon strategies have rendered economies of scale irrelevant in terms of chip cost versus performance tradeoffs. Field programmable gate arrays (FPGAs) have made purpose-built solutions cost competitive, so it's no longer necessary to compromise functionality to leverage the cost of high volume application-specific integrated circuits (ASICs). In capital equipment, these performance advantages quickly outweigh the few dollars potentially saved; a fact that machine tool designers came to realize as early as the 1980's.

One industrial Ethernet standard has emerged that warrants the attention of mobile equipment designers because it has proven extremely robust yet truly open source; meaning license- and patent-free. It features an open source safety protocol, conforms to IEE 802.3 and IEC 61784-2 and is endorsed by the products of thousands of industrial device and machinery makers worldwide.

POWERLINK is a patent-free, open source protocol that is very efficient and effective at handling large real-time data requirements of modern off-road vehicles and equipment. This report will show how this real-time Ethernet standard addresses both data and control needs on a single wire, while reducing design costs and minimizing system jitter to achieve maximum system performance; all while using standard Cat 5 or 7 Ethernet cables and connectors (which any other flavor of Ethernet likely will not).

Why POWERLINK?

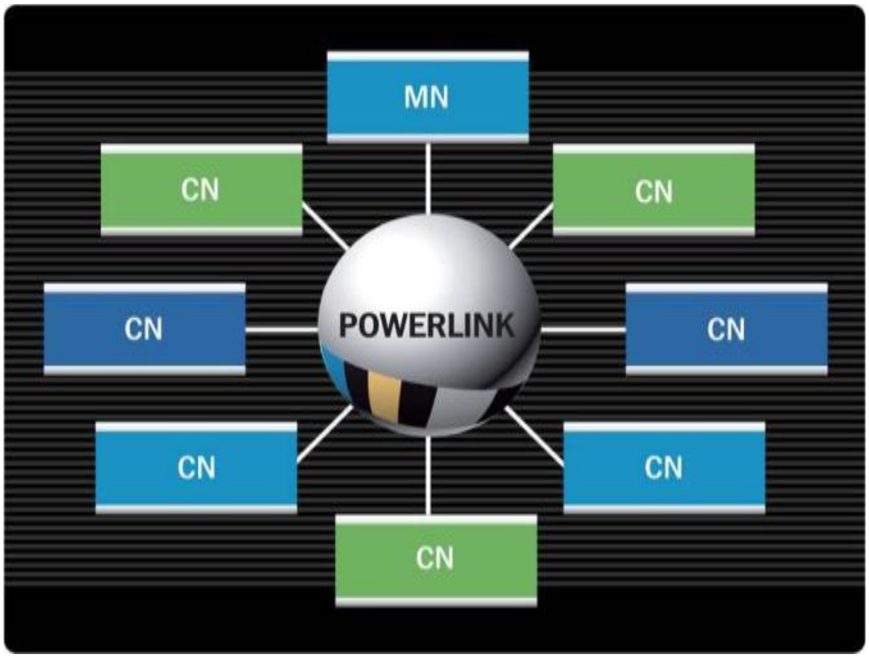

Figure 1

POWERLINK was designed and developed to address the needs for reliable and deterministic real-time communications for automation. POWERLINK is an open source protocol which solves the determinism problem using a simple collision avoidance scheme. The POWERLINK protocol uses standard Ethernet frames. It introduces the concept of a bus master (figure 1) called the Managing Node (MN). All other components on the network are Control Nodes (CN). POWERLINK is a cyclical protocol. The bus cycle time is determined at the time of configuration. The cycle is split into two phases (figure 2). During the first phase of the cycle (isochronous phase) the-time critical information is transmitted by the MN and CNs in a scheduled manner, avoiding frame collisions. During the second part of the cycle (asynchronous phase) all nodes may communicate as needed using standard Ethernet protocols such as TCP/IP, SNMP, etc., to communicate non time-critical data.

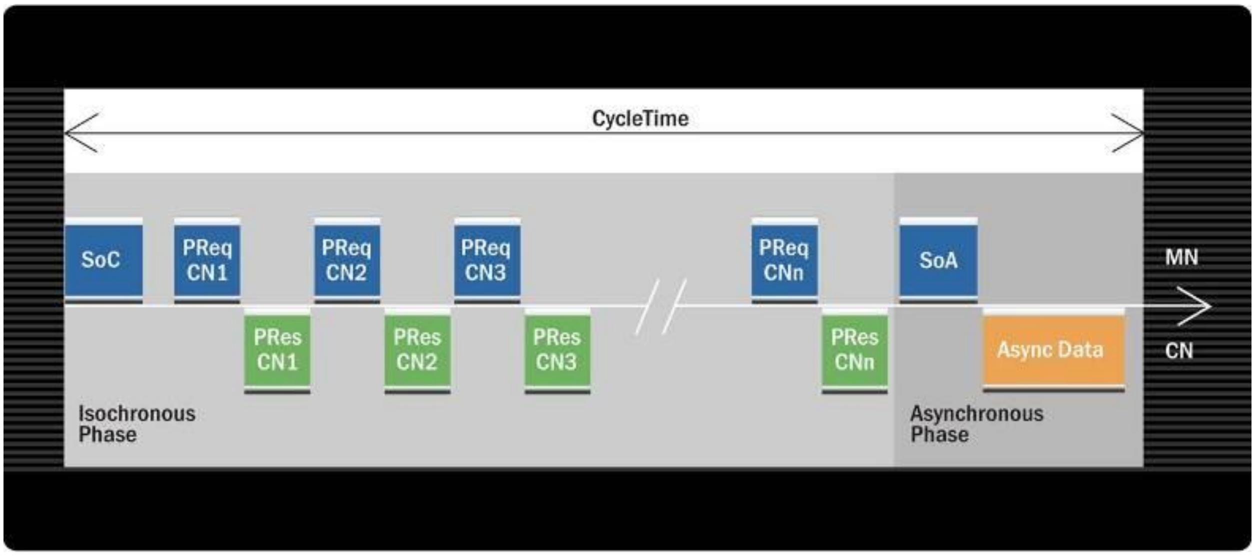

Figure 2

The cycle is initiated by the MN placing a start-of-cycle (SoC) frame on the bus. This indicates that each node must get ready to transmit its frame. To start the data communication for each cycle, the MN sends a Poll Request Frame (PReq) to each individual CN on the network. Each CN then responds by immediately placing its data in an Ethernet multicast frame (PRes), making the data available to all nodes on the network. This mechanism allows for real-time deterministic cross-communication and synchronization between all nodes on the network

An automation network typically contains a variety of components such as drives and encoders (requiring high frequency data updates) and sensors (requiring lower frequency updates). To make the network efficient, the network protocol must allow for high frequency data to be placed on the bus at every cycle, while low frequency data is only placed on the bus every nth cycle. The bus multiplexing feature in POWERLINK addresses this requirement as shown in figure 3.

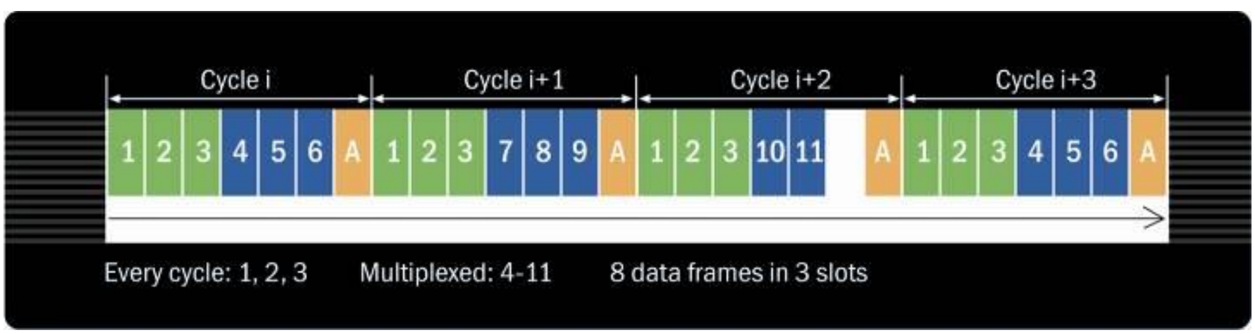

Figure 3

Figure 3 shows how nodes 1, 2, and 3 publish their data every cycle while nodes 4, 5, 6, nodes 7, 8, 9 and nodes 10, 11 are multiplexed. This multiplexing scheme is configured at startup. Bus multiplexing allows all components to operate optimally on the network without degradation in performance for the component or the network itself.

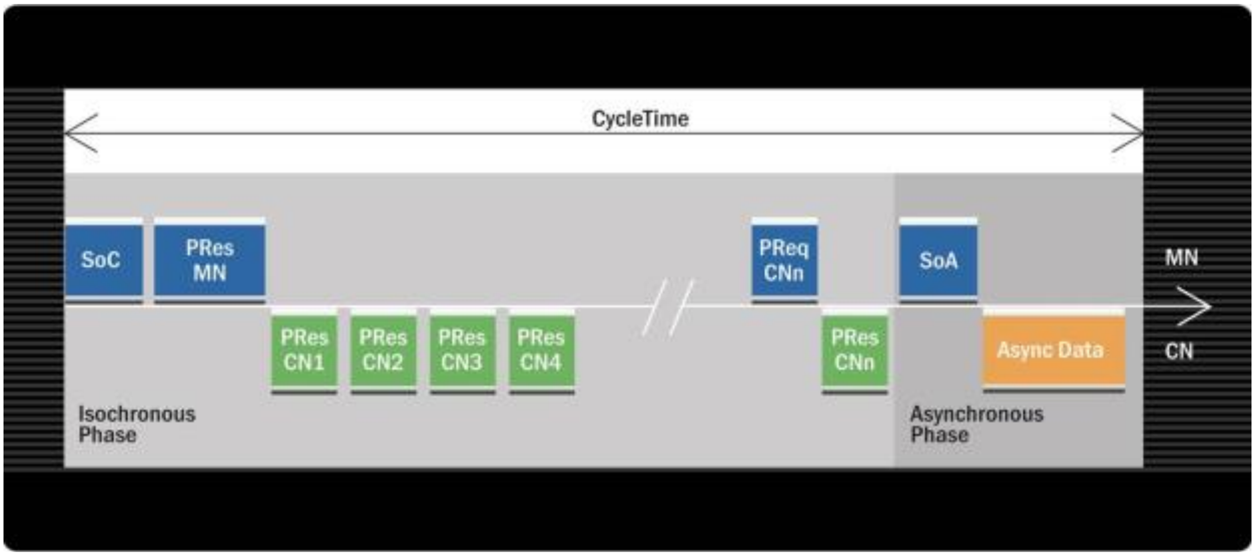

Figure 4

Another form of network efficiency is illustrated in figure 4. This mode is known as Poll Request Chaining. In this mode the MN issues one poll request to all nodes which prompts each node to place its data on the network after a unique set delay which is configured for each node during startup. This is ideal for network scenarios containing many nodes running at high frequencies.

POWERLINK and CAN

POWERLINK = CANopen over Ethernet

POWERLINK uses the same device description files as CANopen, the same Object Dictionaries, and the same communication mechanisms, such as Process Data Objects (PDO), Service Data Objects (SDO), and Network Management (NMT). As with CANopen, direct cross-traffic is also one of POWERLINK's essential features. All CANopen applications and device profiles can immediately be used in POWERLINK environments as well. Applications will not see a difference between the protocols. POWERLINK can therefore also be referred to as CANopen.

Application complexity is generally increasing, which leads to a greater number of nodes, rising data load and higher performance requirements. A simple migration to POWERLINK is an ideal alternative for users who wish to continue to enjoy CANopen's benefits in spite of more demanding requirements. Moreover, POWERLINK gives them one consistent medium throughout the entire application.

CAN networks tend to operate at a maximum baud rate of 1Mbit/sec, and CAN frames have a typical payload of a few bytes. POWERLINK tends to operate at 100Mbit/sec with an Ethernet frame of 1.5K byte thus allowing for a much higher bandwidth of data. While CAN Networks tend to operate at minimum of 2 to 3 millisecond cycle-times, POWERLINK typically runs at 250 to 400 micro second cycle times for medium-size systems. For small systems even considerably lower cycle times are possible.

Alternative Real-Time Ethernet Solutions

Alternative real-time Ethernet protocols provide a fast and low latency communications solution, based on a token-ring concept. They use the concept of a sum frame whereby an individual frame is passed from one node to the next on a ring. Each node adds its own data to the frame and passes the frame onto the next node on the ring. While this approach works well on systems with a small number of nodes it has the following limitations:

Limited Network Topology:
If the Network topology is anything other than a ring, e.g. a star or tree topology, the communication becomes more inefficient. The frame starts at the central node and then gets passed to each leaf node, and back to the central node. This process is repeated for each leaf node slowing the network down significantly with the addition of each new node to the network. With POWERLINK, adding more nodes to the network introduces minimal delays.

No Cross Communications:
Using the sum-frame concept, node-to-node communications and synchronization slows down as the number of nodes on the network increases. With POWERLINK all nodes use multi-cast frames so data published by a node is available to all nodes on the network at once. As the number of nodes increases the communication between nodes does not slow down.

EMI (Electromagnetic Interference):
Passing a single frame, from one node to the next increases the probability of frame corruption due to EMI, as the number of nodes on the network increases. Using POWERLINK, resistance to EMI is much larger and the probability of failure is substantially lower in noisy environments such as slip rings.

Non real-time data
The POWERLINK cycle is split into two phases. The first phase (isochronous phase) is where all the real-time communications takes place. The second phase (asynchronous phase) is used for standard TCP/IP, UDP, SNMP, or any other status and non-real-time communications. This allows networked components to transmit status data, or any other low priority data such as video frames without impeding the performance of the network.

High Availability Networks

It is typically very costly when an automation network goes down, requiring the protocol to support high availability capabilities. POWERLINK is designed to handle three forms of high availability. The simplest form is ring redundancy shown in figure 5. Each POWERLINK CN has two Ethernet ports connected internally by a hub. To form a ring, the CNs are daisy-chained and the last CN is connected back to the MN. In this configuration the network will continue to operate if any single cable is broken or accidentally disconnected.

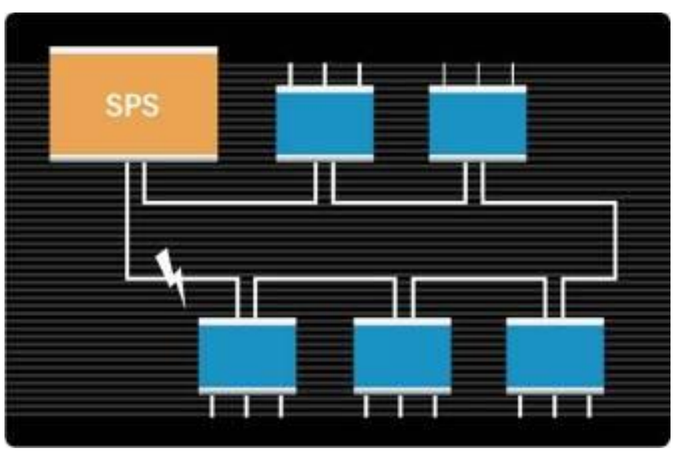

Figure 5

Full medium redundancy is another form or high availability (figure 6). In this scheme there are 2 physical cables and networks connected to each node via a link selector. The link selector will detect when the network on one cable is down and will automatically switch over to the network on other cable.

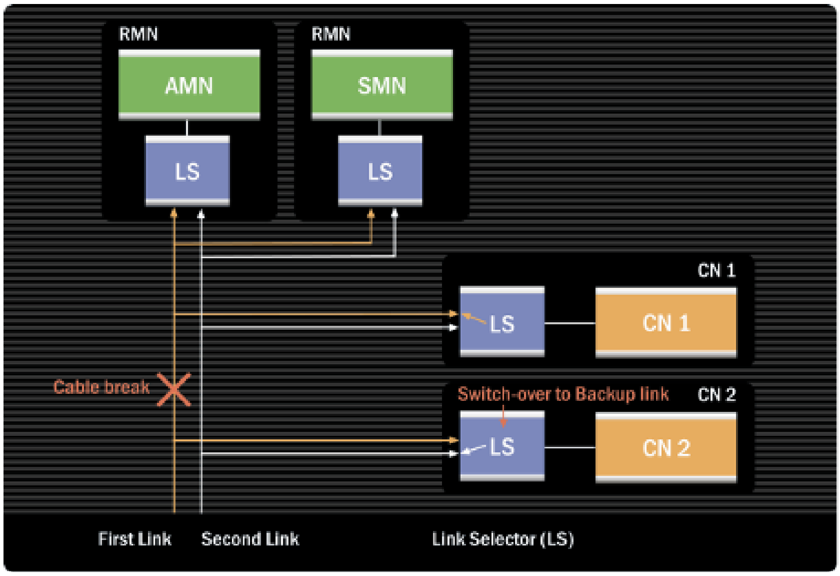

Figure 6

Figure 6 also shows a third form of high availability implemented through Master Node redundancy. The MN is responsible for the network timing and synchronization. If the MN goes down the entire network will halt. To avoid this from happening POWERLINK allows up to 9 additional redundant masters, where control will automatically get passed to an available MN should the main MN go does. This switchover takes place within one bus cycle and causes minimal interruption to the network.

Performance and Diagnostics

Due to its guaranteed collision-free behavior it's easy to intuitively understand why the POWERLINK protocol can deliver high performance in automation even at high percentages of network utilization. As an example, it is possible to run a system with 800 digital I/O points, 180 analog I/Os, and 24 axes of motion at a 250 micro-second cycle time.

Due to the recommended use of hub technology, the network transparency afforded by hubs make it very easy to debug a POWERLINK network using standard tools such as Wireshark, Omnipeak, etc. Figure 7 illustrates a typical network configuration being debugged.

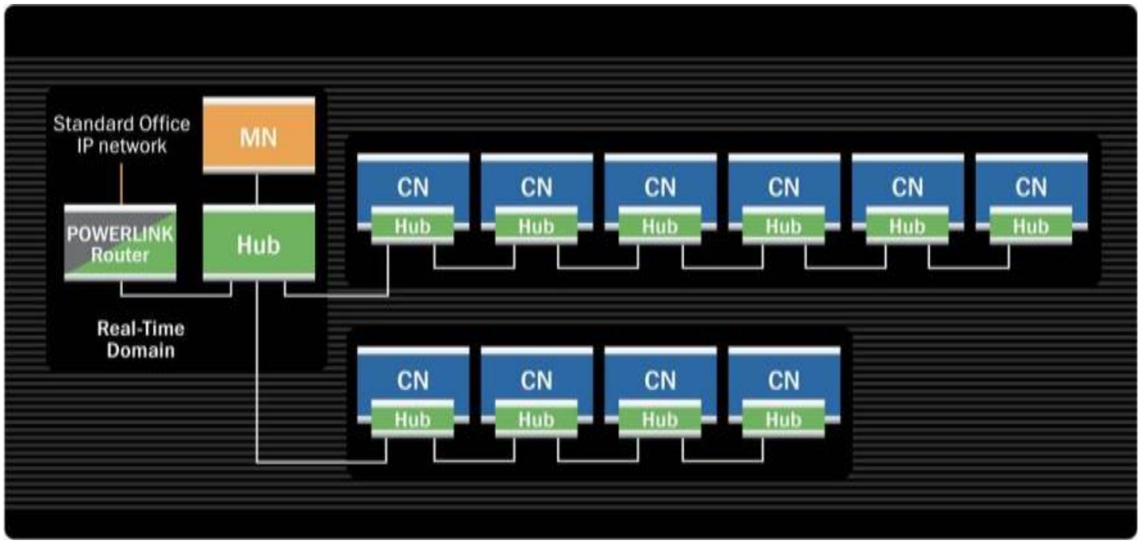

Figure 7

Adhering to Open Standards

The Ethernet standard has been available since 1972. Ethernet POWELINK has been designed to use standard Ethernet frames with Ethertype 0x88AB. This is significant because it allows for standard hardware to be used. It also allows for standard software tools to be used to analyze the network. It is simple to connect standard Ethernet devices to a POWERLINK network. However, they need to be connected to the network through a gateway. The gateway essentially passes frames to and from the standard devices during the asynchronous phase of the cycle ensuring that each device does not speak out of turn during the time-critical isochronous phase. This feature makes it easy for service technicians to plug their laptop into the network for system maintenance and diagnosis.

POWERLINK is compliant with IEE 802.3 and IEC 61784-2. Adhering to standards allows POWERLINK devices to be hot-pluggable. So any device may be replaced without shutting down the network. This reduces the cost of service and maintenance.

POWERLINK is open source, patent-free and license free. The source code may be downloaded from Sourceforge.net. The network interface may be implemented as a software-only solution running on a microprocessor. However, microprocessors running a standard RTOS may suffer from jitter thus reducing efficiency. For a jitter-free high performance environment a POWERLINK network interface may be implemented using an FPGA (FPGA code is also available in open source) or using many off-the-shelf ASICS developed by leading ASIC manufacturers such as Hilscher, HMS, Intel, ST and TI.
Standard Ethernet has a high degree of immunity to Electromagnetic Inductance, making POWERLINK ideal for implementing remote I/O in environments with a high degree of electrostatic noise.

Conclusion

POWERLINK allows system designers to build a completely integrated architecture with all remote I/O connected to one network. Having an open standard define how devices communicate in a uniform and efficient manner allows device manufacturers (sensors, motors, actuators, vision systems) to focus on developing best-in-class devices without being concerned with efficiency or communications overhead. It also allows OEMs, machine builders and system integrators to develop high performance systems with a large choice of components without being limited to a single component provider.

POWERLINK users enjoy six main benefits:

i) Open source technology: The technology is freely available, license free and patent free.
ii) Flexible Communications Scheme: A cycle allows for a real-time communications phase and asynchronous phase guaranteeing that important real-time data is not lost, while low bandwidth non-real-time data is also passed through.
iii) High availability and redundancy: With 3 forms of redundancy POWERLINK system developers can deliver highly reliable systems.
iv) Hot pluggable: Devices may be swapped out without shutting down the network. This means the cost of maintenance is significantly reduced.
v) Network Topology: A system may be commissioned and deigned with any network topology without degrading performance.
vi) Low sensitivity to Electromagnetic Inductance: This means that the system will be highly immune to electrical noise.

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