QoS - Application of TSN to EtherNet/IP Networks

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February 22, 2017
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What is TSN?

An Industrial Use Case

TSN in Control Applications

Effect of TSN features on Control Applications

Network Convergence and Centralized Configuration

Conclusions
For over a decade, Industrial Automation has used:

- Cut through switching
- Time synchronization
- Traffic shaping techniques
- Scheduling algorithms
- Dynamic frame packing
- Frame fragmentation

The results are excellent!

But, no single standard exists
Opportunity

• **In general, these protocols are proprietary at layer 2**
  – Specific to 10/100 Mbit (Fast Ethernet)
  – EtherNet/IP is an exception

• **The IIoT represents a huge inflection point in the market**
  – Demands for network convergence and more data will force these standards bodies to adopt Gigabit Ethernet
  – These proprietary solutions do not scale easily to Gigabit
  – The emerging Time-Sensitive Networking (TSN) standards provide a migration path

• **ODVA is in an excellent position to leverage this transition into a competitive advantage**
What is TSN?

► A set of 802.1 sub-standards, addressing different needs
► Not all sub-standard have to be implemented
► The important sub-standards for Industrial Automation are:
  - 802.1AS (REV) Time Synchronization
  - 802.1Qbv Time Aware Traffic Shaper
  - 802.1Qbu/802.3br Preemption
  - 802.1CB Seamless Redundancy
  - 802.1Qci Ingress Policing
  - 802.1Qcc Network Management
802.1AS (REV) Time Synchronization

- In the context of TSN:
  - Time sync refers to IEEE 802.1AS and .1AS-REV:
  - uses a master-slave protocol for time synchronization
  - does not use “transparent clocks” to compensate for bridge latency
  - Peer-to-Peer mechanism requires every node be time-aware
  - Not practical for brownfield

- Good news! Other TSN features are independent of time-sync profile
  - Need to manage various time profiles.
IEEE 802.1Qbv introduces time-aware “transmission gates”.

These gates are used to enable separate transmission queues.

The Qbv shaper provides a time-based circular schedule which opens and closes the transmission gate at specific times.
Preemption (also called Interspersing Express Traffic):

- Allows the switch to stop a transmission in mid-stream to allow a higher priority packet to transmit.
- Note that only one level of traffic is defined as preemptive.
802.1CB Seamless Redundancy

- **Purpose:** Provide lightweight redundancy for reliable delivery of traffic streams
- **How?** Frame replication and elimination
- **Send** two copies of a message along maximally disjoint path to ensure delivery
- **Use** of redundant paths minimize packet loss due to
  - Link or device failures
  - Congestion
- **Discard** duplicate frames upon reception
802.1Qci  Ingress Policing

- **Purpose:** Prevent traffic overload conditions (DDoS, erroneous delivery) from affecting the receiving node
- **How?** Filtering traffic on a per stream basis by providing an input gate for each stream
- **Input gate** serves to enforce a "contract" between the talker and the listener
- **Contract functions** could be:
  - Pass/no-pass
  - "Leaky bucket" policing
  - Time/bandwidth-based
  - Threshold counter
  - Burst sizes
  - Packet sizes
  - Misuse of labels, etc.
802.1Qcc - Centralized Configuration

- Adds a User Network Interface (UNI) which allows for a centralized network configuration (CNC) entity.
  - CNC performs network calculus, scheduling and other configuration tasks
    • uses a remote management protocol such as NETCONF or RESTCONF.
  - A Centralized User Configuration (CUC) communicates to the CNC via a standard API.
    • The CUC may be used to discover end stations, retrieve end station capabilities and user requirements, and configure TSN features in end stations.
Industrial Use Case

- A single machine consisting of four different sections of machinery
  - Section delivered via different OEMs
  - Each section is a subnet with a unique VLAN
- 15 machines per site
  - Common IP addressing scheme
- 7 manufacturing sites worldwide.
- All sections synchronized and coordinated to produce final product
  - Relevant events timestamped
  - Data on the manufacturing floor can be correlated against data in the MES system and data from the supply chain.
• The entire manufacturing facility uses the same understanding of absolute time and the common notion of “wall clock time.”

• But, different 1588 profiles may be present:
  • Component A may communicate with A’
  • Component B may communicate with B’
  • Component C produces data consumed by C’ components in sections B, C, and D

• Time gateway/translation is required for components A and A’, and B and B’.
• Time bridging, or time gateway, must be provided in the layer 2 switches
• Provides the mechanism for migrating legacy technologies into a TSN system.
• This functionality has **NOT** been identified as a required work item for any standards communities. Individual suppliers could develop these bridge functions as solutions for the market.
Challenges

• **This use case illustrates the need for solutions at layer 2 (switching), layer 3 (routing) and for time bridging functions**
  • Typical for a very wide range of industrial applications

• **How does centralized management deal with such a use case?**
  • Machine segments are configured and certified by manufacturer
  • Multiple CNC/CUCs involved
  • How are the configuration and traffic specification of these segments integrated at the manufacturing site?

• **A plant-wide understanding of time becomes problematic**
  • Integration of different time profiles will be necessary (brownfield)
  • IEEE802.1AS could become the defacto standard for infrastructure devices
• Input data must arrive at Controller before the end of the input interval

• Planned data outputs should be transmitted before the end of the planner interval

• Output data must arrive at the drive before the end of the output interval

• Of course, this all assumes the drives and controller have a common understanding of time.
You will never strike oil by drilling through the map! **BUT:** this does not, in any way, diminish the value of a map! (Solomon Golomb: Mathematical models – Uses and limitations. Aeronautical Journal 1968)

Source: Dr Edward Lee (UC Berkley) TSNA’15 – The Internet of Important Things

What’s shown is a simple model intended to illustrate the effects of TSN on an Ethernet-based control solution

There are many potential points of optimization in a complex, real-world system. Assumptions made herein are for the purpose of discussion, not to suggest design approaches or solutions.
• We’ll focus on a part of the problem associated with network performance

• Ideally, we’d like all of the drives to transmit their output data simultaneously

• In this way the link between the controller and bridge is optimally utilized
A Simple Motion Control Model

• A simple model for control on a “best-effort” network
  • Assumes all network elements are time-aware
  • Assumes standard QoS/priority throughout.
  • Assume cut-through switch (cut-through latency ~2usec @ 100 Mbs; ~1usec @ 1 Gbs)
    – Important for upcoming line topology discussion
  • Assumes some control of traffic volume and the size of interfering traffic on the network
A Simple Motion Control Model

\[ \text{Max Axis} = 1 + \left\{ \frac{1}{3} \times \text{Connection Update Period} - (\text{Drive Transmission Delay} + (m + 1) \times \text{Ethernet Transmission Time} + m \times \text{Switch Latency} + \text{NIC Packet Processing Delay} + \text{Bus Interface Delay}) \right\} \div \text{NIC Packet Processing Delay} \]

- \( \text{(Where } m = \# \text{ of hops) } \)
- \( \text{Drive Transmission Delay: } \) We’ll assume all drives have outputs queued prior to transmission, so this is contribution is small with respect to other operands, effectively 0 usec
- \( \text{Assume update packets are fairly small(124 bytes), so Ethernet Transmission Time is} \) (124+20)*80ns/byte = 11.52 usec (at 100 Mbs)
- \( \text{Switch Latency} = (\text{interfering packet size}+20)\times80\text{ns/byte} \)
- \( \text{NIC Packet Processing Delay} – \) There are techniques to ensure the network is the bottleneck (e.g. 2 cycle processing): 11.5 usec for 100 Mbs, 1.15 for Gigabit.
- \( \text{Bus Interface Delay: has a lot to do with the overall system architecture. could go effectively to 0 (given good bus structure, DMA/ etc.). We’ll assume 0 for this analysis.} \)
• Performance strongly influenced by interfering traffic and thus, the number of hops

• In practice, control systems will engineer the network to limit the size of interfering packets (this example assumes 500 bytes)
• Preemption offers a standard, unified means to limit the effects of interfering traffic

• With a maximum fragment size of 64, the maximum interfering frame size is:
  • \((2 \times 64 \text{ bytes}) - 1 = 127 \text{ bytes}\)

• Simplifies the problem of isolating the control network from interfering traffic

• Still need to ensure that other traffic of the same priority is not present on the wire or that bandwidth is sufficient to deal with all such traffic

100 Mbs w/ Preemption

[Bar chart showing traffic categories with Preemption, Limit Interfering Traffic, and Standard Traffic]
• Utilization of a line topology and scheduled traffic can further minimize effect of interfering traffic
• Schedule of drives can be individually adjusted to compensate for drive transmission delay, transmission time and switch latency.
• Effects due to switch latency are minimized

• The effects of interfering traffic are of less consideration than the ability of the controller to process incoming packets

• This still assumes a somewhat isolated network (i.e. there is not other traffic of the same class which might interfere with control packets)
• Gigabit transmission speeds further reduce the effects of interfering traffic

• Note that the benefit from scheduled traffic across hops is much less significant
• Properly engineered, line topology limits the effects of interfering traffic to a single hop (i.e. control traffic is transmitted in a burst)

• With preemption, the effects of interfering traffic are minimal with respect to a 1 mS update cycle
• However, as the update frequency is increased, network effects again become significant.

• Note: this example assumes the network, rather than controller packet processing, is the bottleneck in the system.
**Conclusions:**

- Wire speed contributes to the majority of throughput and performance on the wire.
  - Number or axes
  - Jitter
- TSN functions allow for better “packing” of data at any given wire speed
- There is little difference in performance benefit between preemption and scheduling
  - However, both can be used together.

**Common Configuration**
- i7 Processor
- 2-cycle timing
- 1 millisecond motion planner
- 1500 byte non-motion packet
- 1 Switch
- Up to 50 nodes per linear segment

**Legend:**
- No TSN functions enabled
- Preemption enabled
- Scheduling enabled
• Given these results, do we need scheduled traffic?

• As deployment of Ethernet in Industrial Automation grows more data is desired. Solutions must scale.

• As the Enterprise and Automation networks become more integrated, data flows from various applications must converge.

• IEEE802.1Qcc provides a practical approach for achieving this vision
Summary

• TSN technologies offer a scalable, predictable approach to deterministic networking.

• Because Ethernet/IP products have always relied upon standardized technologies, ODVA is in an excellent position to leverage these emerging standards.

• However, significant challenges remain.

• The integration of various PTP profile and the convergence of EtherNet/IP traffic with a scheduled TSN network are chief among these challenges.
THANK YOU