ANALOG DEVICES

AN-1482
APPLICATION NOTE

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A TSN Network By Example

by Volker E. Goller

INTRODUCTION

The time sensitive networking (TSN) evaluation kit allows customers to connect almost any existing Ethernet device to a TSN network. In the simplest case, such a network is a pure line topology, consisting of several of these TSN evaluation kits.

However, the kit can operate with TSN solutions from other vendors as long as they support the same feature set. Presently, the kit supports 802.1Qbv (scheduled traffic) and 802.1AS (clock synchronization).

The kit provides three Ethernet ports, see Figure 1. Nearly any standard Ethernet device is supported, including devices that run EtherNet/IP, PROFINET RT, ModbusTCP, BACnet IP, or any other IP-based protocol except PROFINET IRT, EtherCAT, SERCOS, or POWERLINK.

This application note is designed to lead a user of the Analog Devices, Inc., TSN evaluation kit (referred to as the TSN kit throughout) through the processes necessary to configure and run a TSN network.

This application note does not replace or remove the need to read the TSN kit documentation and must be used in conjunction with the *TSN Evaluation Kit Quick Start Guide* and the fido5100/fido5200 *Real-Time Ethernet Multiprotocol (REM) Switch* data sheet.

EVALUATION BOARD DIAGRAM

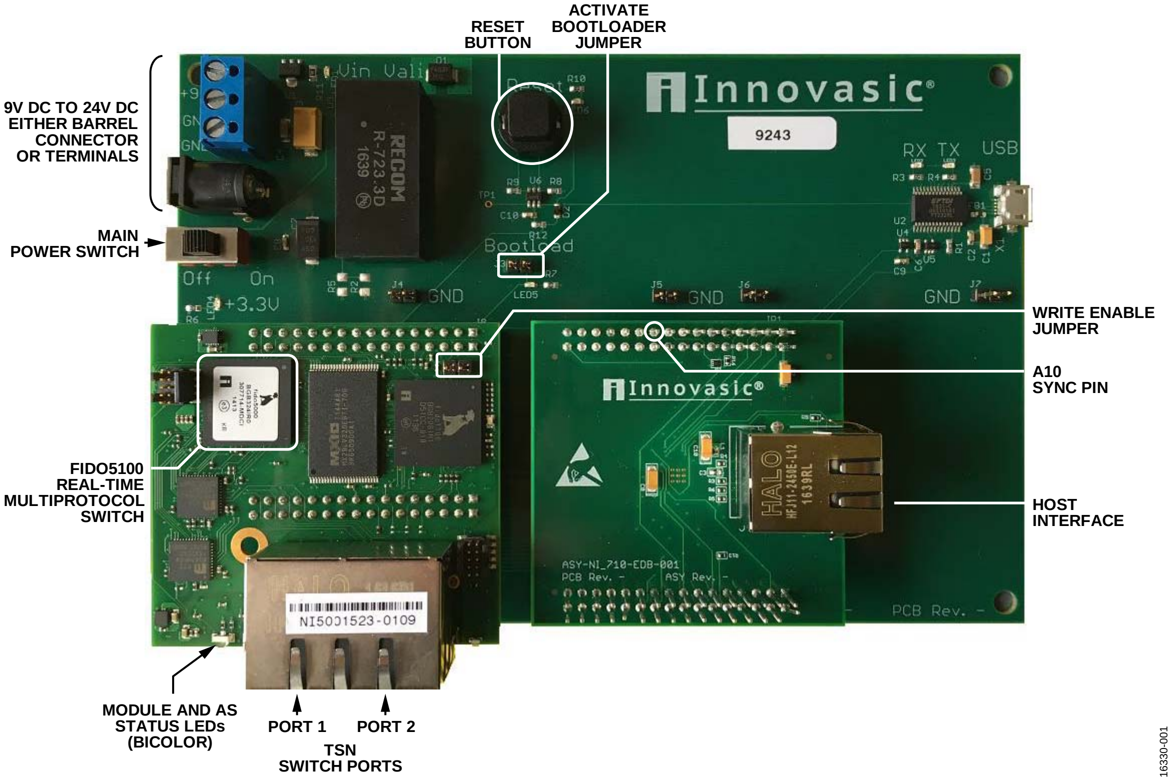

RESET BUTTON
ACTIVATE BOOTLOADER JUMPER
9V DC TO 24V DC EITHER BARREL CONNECTOR OR TERMINALS
MAIN POWER SWITCH
WRITE ENABLE JUMPER
A10 SYNC PIN
FIDO5100 REAL-TIME MULTIPROTOCOL SWITCH
HOST INTERFACE
MODULE AND AS STATUS LEDs (BICOLOR)
PORT 1
PORT 2
TSN SWITCH PORTS
16330-001

Figure 1. The Evaluation Kit

TABLE OF CONTENTS

REVISION HISTORY

10/2017—Revision 0: Initial Version

GETTING STARTED

Follow the documentation in the *TSN Evaluation Kit Quick Start Guide* to setup the PC and connect it to the TSN evaluation kit.

EVALUATION BOARD PORTS

It is important to connect the PC to one of the TSN Ethernet ports for configuration. There are three ports: the host port (located on the narrow side of the printed circuit board (PCB)), where an existing Ethernet device must be connected. The standard Ethernet traffic of the device is forwarded to the switched TSN ports (located on the wide side of the PCB). It is essential that such forwarding is working prior to configuring any TSN feature.

It is not possible to access the configuration website via the host port. The IP address of a TSN kit out of the box is 192.168.1.1.

POWER SUPPLIES

Power the device using the power supply that is shipped with the kit. Alternatively, the screw terminals can also be used to provide power. The board is designed for 9 V to 24 V dc range.

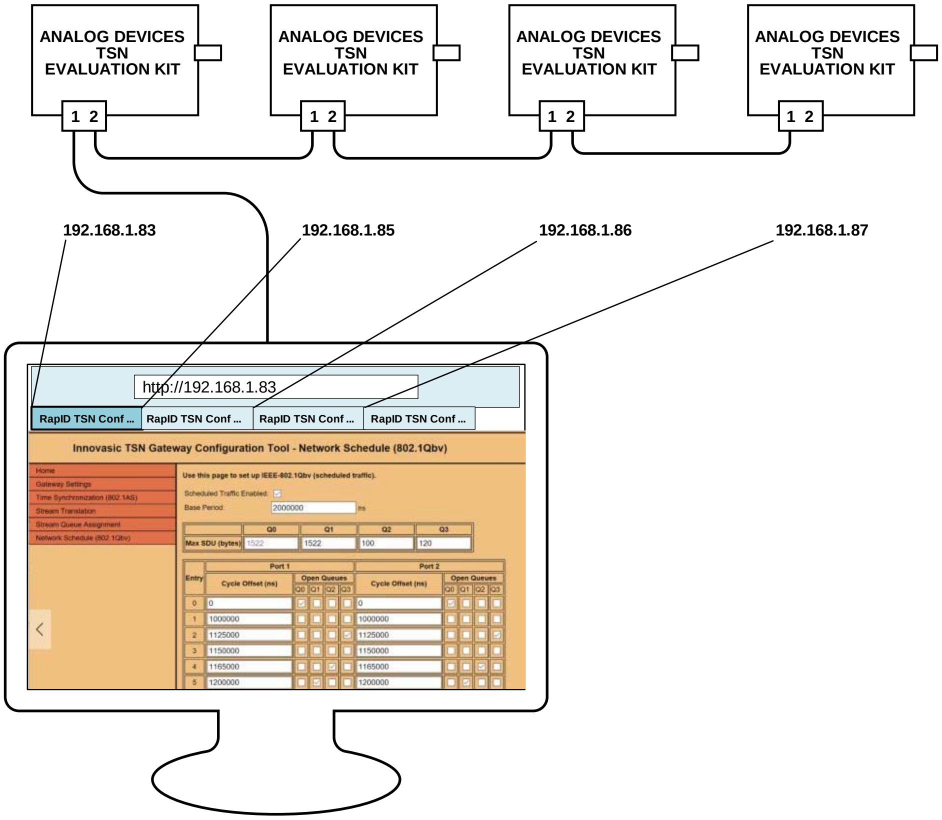
If the screw terminals are used, be careful to connect per the markings on the PCB. Note that the PCB is delivered turned off.

CONFIGURING THE TSN KITS

In the following example, four TSN kits are configured in a line topology; therefore, all TSN kits are configured with unique media access control (MAC) addresses, as well as unique IP addresses. These addresses are set via the menu selection, **Gateway Settings**, on the TSN evaluation kit webpage. Take care to enable writing of MAC addresses by closing the write enable jumper first. It is necessary to set up one TSN kit at a time.

Note that it is best practice when setting MAC and IP, to use the lowest three digits of the device serial number for the lowest three digits of the respective addresses. Because the serial number is always printed on the dual RJ45 connector of the TSN ports (see Figure 1 for the location of RJ45), the lowest three digits are 109). In the rare case of an address conflict, use more of these digits from the device serial number. Doing so helps to keep track of the multiple boards/IP addresses.

If used in a line topology, it is best to lay down the boards in the order of ascending or descending IP numbers, whatever makes more sense to the user. This helps to keep track of the changes made to the boards. On the PC used to configure the kits, open a separate tab in the browser for each board and connect those tabs to the kits in the same physical order of appearance (see Figure 2).



Innovasic TSN Gateway Configuration Tool - Network Schedule (802.1Qbv)

Use this page to set up IEEE-802.1Qbv (scheduled traffic).

Scheduled Traffic Enabled: ☑

Base Period: 2000000 ns

	Q0	Q1	Q2	Q3
Max SDU (bytes)	1522	1522	100	120

Entry	Port 1					Port 2				
	Cycle Offset (ns)	Open Queues				Cycle Offset (ns)	Open Queues			
		Q0	Q1	Q2	Q3		Q0	Q1	Q2	Q3
0	0	☑	□	□	□	0	☑	□	□	□
1	1000000	□	□	□	□	1000000	□	□	□	□
2	1125000	□	□	□	☑	1125000	□	□	□	☑
3	1150000	□	□	□	□	1150000	□	□	□	□
4	1165000	□	□	☑	□	1165000	□	□	☑	□
5	1200000	□	☑	□	□	1200000	□	☑	□	□

16330-002

Figure 2. Organizing Addresses and TSN Kits, Ports Aligned with the Layout of the Schedule Configuration Page)

THE EXAMPLE SETUP

The full setup is shown in Figure 3. The four TSN kits are connected in a line topology and form the TSN segment. At this stage, TSN is not configured and everything runs standard Ethernet. On the boundary ports (the open ports at the ends of a TSN segment), standard non-TSN devices are connected. In this demo, a webcam is to the right and a display or PC to show the video from the webcam is on the left of the TSN segment.

To display the webcam livestream, the same PC used to configure the demonstration can also be used to display the livestream. That way, the webcam video can be shown while still being able to tweak the TSN kit setups via the web servers.

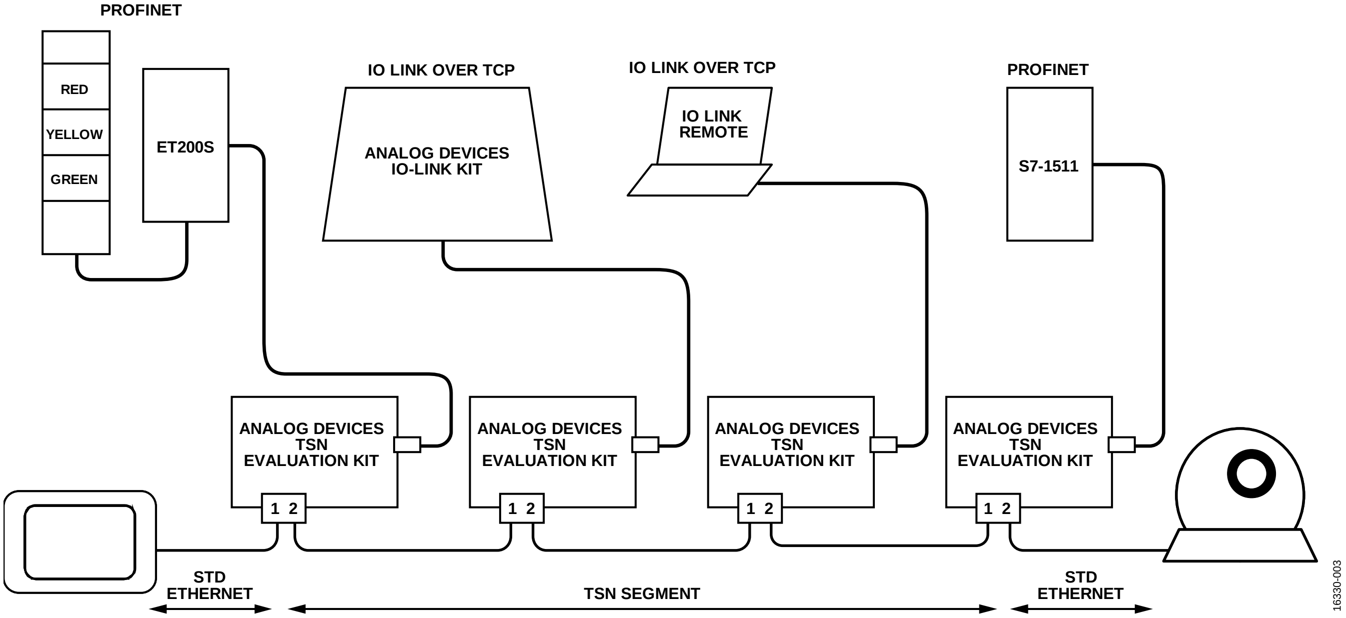

PROFINET
RED
YELLOW
GREEN
ET200S
IO LINK OVER TCP
ANALOG DEVICES IO-LINK KIT
IO LINK OVER TCP
IO LINK REMOTE
PROFINET
S7-1511
ANALOG DEVICES TSN EVALUATION KIT
1 2
ANALOG DEVICES TSN EVALUATION KIT
1 2
ANALOG DEVICES TSN EVALUATION KIT
1 2
ANALOG DEVICES TSN EVALUATION KIT
1 2
STD ETHERNET
TSN SEGMENT
STD ETHERNET
16330-003

Figure 3. Example Setup

THE HOST PORT

One important step in setting up a TSN network using the TSN kit is to make the MAC address of the device that is connected to the host port known to the gateway. By assigning this address to the host port, the 2-port TSN switch can identify packets that are directed to this port, or more precisely, directed to the device that is connected on that port. Technically, this MAC address is added to the switches static forwarding database.

To accomplish the task of setting the host MAC, the MAC addresses of the device that is connected to the host port must be known. On automation equipment, such as PROFINET devices, the MAC is printed on the device housing, see Figure 4.

Once identified, the host MAC address needs to be entered in the **client MAC** field in the gateway settings page of the web server.

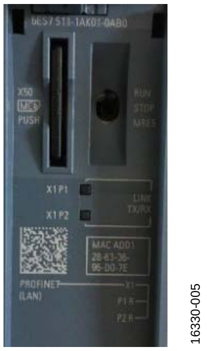
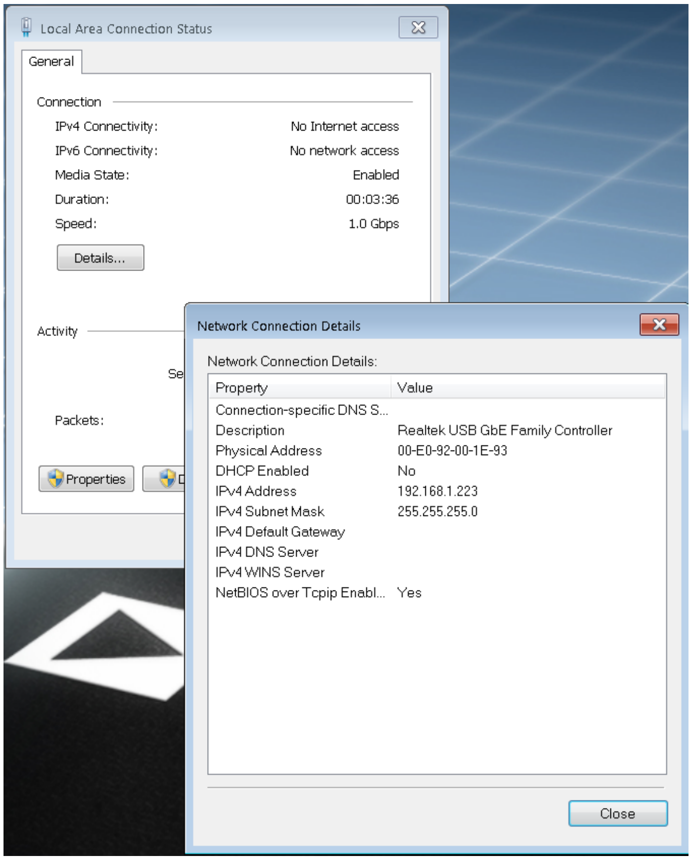


Figure 4. Siemens S7-1511 Controller MAC Address

On Windows® systems, the physical address can be retrieved via the network adaptor status. Click the **Details** button in the **General** tab located in the **Local Area Connection Status** dialog box. See Figure 5 for more information.



Connection

IPv4 Connectivity: No Internet access
IPv6 Connectivity: No network access
Media State: Enabled
Duration: 00:03:36
Speed: 1.0 Gbps

Network Connection Details:

Property	Value
Connection-specific DNS S...	
Description	Realtek USB GbE Family Controller
Physical Address	00-E0-92-00-1E-93
DHCP Enabled	No
IPv4 Address	192.168.1.223
IPv4 Subnet Mask	255.255.255.0
IPv4 Default Gateway	
IPv4 DNS Server	
IPv4 WINS Server	
NetBIOS over Tcpip Enabl...	Yes

Figure 5. Locating the Windows Adaptor MAC Address

USING WIRESHARK AND A TAP

If the MAC is not available, the easiest method may be to use a tool like Wireshark to observe the packets that enter and exit the device. Packets ingressing the device have the MAC address in the destination MAC address field of an Ethernet frame (as long as no multicast or broadcast message is used), and packets that egress the device have the device MAC address in the source MAC address field of the Ethernet frame.

Using Wireshark is essential to debug a setup. Installing and becoming familiar with Wireshark is highly recommended prior to setting up the TSN evaluation kit.

However, with Wireshark, not all traffic is visible because packets are not flooded within an Ethernet network; instead, they use the forwarding database in each switch to determine through which port they should egress for the shortest routing path to their destination. Therefore, acquiring an Ethernet wire test access point (TAP) is recommended.

A TAP is a passive Ethernet component that does not send traffic on its own nor does it introduce delays; rather, it allows one to listen to all packets that flow by in either direction. TAPs are available from many vendors, a quick internet search for "Ethernet TAP" or "Ethernet test access point" returns many options, including build-at-home options. For this example, the KUNBUS TAP2100 is used because it can TAP two connections simultaneously and has a built-in high resolution clock base (8 ns). Being able to TAP two channels simultaneously facilitates debugging, allowing a TAP before and after a switch to determine if the switch filtered a message out or if it translated a message into a TSN stream correctly.

BASIC SETUP COMPLETED AND OPERATIONAL

When all boards and devices for the demonstration are wired according to the example setup shown in Figure 3, all TSN kits can be accessed using the web browser, according to the configuration shown Figure 2, all host MAC addresses are added to the gateways settings, and the basic setup is completed. TSN aside, this setup should work just as any other Ethernet Layer 2 segment.

An advantage of TSN is that it is an extension to standard Ethernet and the switches talk on Layer 2 rather than on Layer 3, permitting the use of different IP subnet addresses to avoid address conflicts.

Without dealing with TSN, it is still possible to set up all the communication relationships that are needed:

- Create a project to connect the S7-1511 with the ET200S. IP subnet is 192.168.0.xxx.
- Connect the IO Link demo using IP subnet 192.168.10.xxx.
- Set up and connect the webcam using IP subnet 192.168.21.xxx

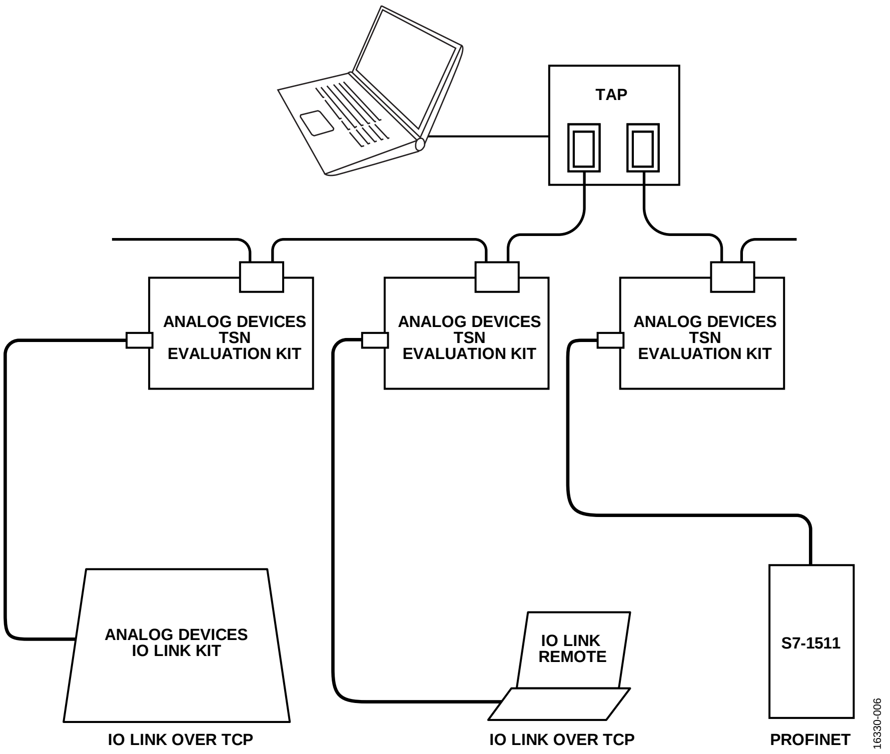

TAP
ANALOG DEVICES TSN EVALUATION KIT
ANALOG DEVICES TSN EVALUATION KIT
ANALOG DEVICES TSN EVALUATION KIT
ANALOG DEVICES IO LINK KIT
IO LINK REMOTE
S7-1511
IO LINK OVER TCP
IO LINK OVER TCP
PROFINET
16330-006

Figure 6. An Ethernet Wire TAP in the Setup

CHECKING 802.1AS

After setup, the 802.1AS time synchronization is operational. One of the boards assumes the role of the grandmaster clock, identified by the 802.1AS status LED turning red (see Figure 1). On a sync slave device, the 802.1 status LED turns green when clock sync has been established.

Checking the status of AS on the TSN evaluation kit webpage, it is important to understand that AS is a peer-to-peer clock. The grandmaster is in the master role to both TSN ports, but the other kits report a slave role towards the grandmaster and a master role towards nodes that are further away from the grandmaster. The **Port Role** box reports if the port is in slave or master mode. If the gateway is not a grandmaster, one port reports that it is in slave mode and the other port reports that it is in master mode. If the gateway is the grandmaster on the TSN network, then both ports report that they are in master mode, see the *TSN Evaluation Kit Quick Start Guide* for more information. The peer-to-peer scheme is shown in Figure 7.

Note that after a schedule is created and enabled, the 802.1AS service requires Queue 3 to be open at some point during the TAS cycle.

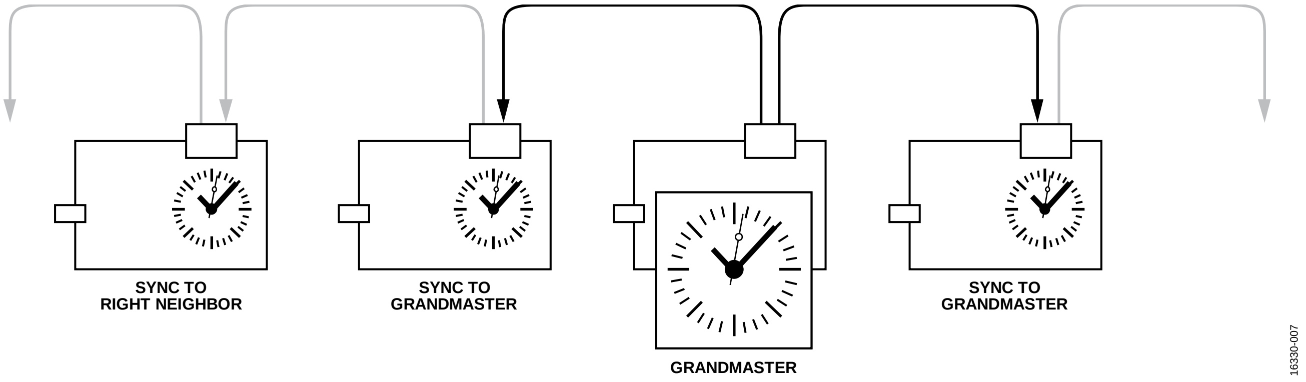
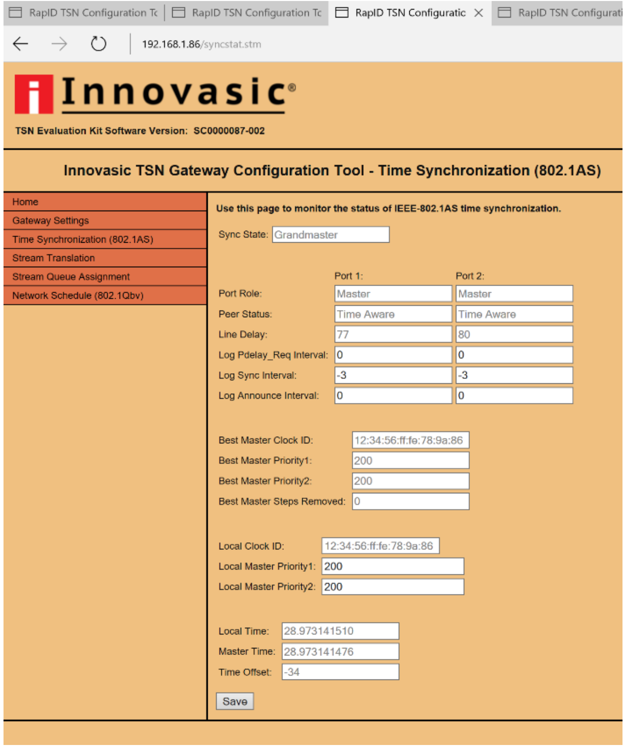


Figure 7. 802.1AS Peer to Peer Sync

Assign the Grandmaster Function

On startup, the devices select a clock grandmaster using a best master clock algorithm (BMCA). In most cases, this is adequate and does not require further attention. However, there may be scenarios where a fixed grandmaster is preferred.

Using the **Local Master Priority1:** and **Local Mater Priority2:** entries on the **Time Synchronization** page, the best master algorithm can be steered to select a specific board for the grandmaster clock. Figure 8 shows an adjusted TSN kit. Priority 1 is set to 200 (higher priority than the default 248; therefore, this board is assigned the grandmaster clock role).


RapID TSN Configuration Tc
RapID TSN Configuration Tc
RapID TSN Configuratic
RapID TSN Configurati
192.168.1.86/syncstat.stm
Innovasic
Home
Gateway Settings
Time Synchronization (802.1AS)
Stream Translation
Stream Queue Assignment
Network Schedule (802.1Qbv)
Save
16330-008

TSN Evaluation Kit Software Version: SC0000087-002

Innovasic TSN Gateway Configuration Tool - Time Synchronization (802.1AS)

Use this page to monitor the status of IEEE-802.1AS time synchronization.

Sync State: Grandmaster

	Port 1:	Port 2:
Port Role:	Master	Master
Peer Status:	Time Aware	Time Aware
Line Delay:	77	80
Log Pdelay_Req Interval:	0	0
Log Sync Interval:	-3	-3
Log Announce Interval:	0	0

Best Master Clock ID: 12:34:56:ff:fe:78:9a:86
Best Master Priority1: 200
Best Master Priority2: 200
Best Master Steps Removed: 0

Local Clock ID: 12:34:56:ff:fe:78:9a:86
Local Master Priority1: 200
Local Master Priority2: 200

Local Time: 28.973141510
Master Time: 28.973141476
Time Offset: -34

Figure 8. Assigning Grandmaster to a TSN Kit

SETTING UP THE TSN STREAMS

A TSN stream identifications (IDs) is constructed of a locally administered multicast address and an 802.1Q VLAN tag. In this example setup, the following streams are used, as listed in Table 1.

Table 1. MAC, PCP, and VLAN Settings for Demo

Stream	TSN Multicast MAC	Priority Code Point (PCP)	VLAN ID (VID)
PROFINET			
S7-1511 to ET200S	F1:D0:F1:D0:01:05	4	0x0000
ET200S to S7-1511	F1:D0:F1:D0:01:01	4	0x0000
IO Link			
Master to Demo	F1:D0:F1:D0:00:05	2	0x0000
Demo to Master	F1:D0:F1:D0:00:01	2	0x0000

There are many degrees of freedom to setup the MAC, PCP, and VLAN values, as long as all TSN nodes are controlled. For this setup, the PROFINET cyclic communication receives the highest priority. IO Link and PROFINET TSN streams are set apart by the second lowest byte of the MAC address; however, the VLAN ID can be used for the very same purpose. In such a case, the following list in Table 2 represents a valid setup. The streams are shown in Figure 9.

Table 2. Alternative MAC, PCP, and VLAN Settings

Stream	TSN Multicast MAC	Priority Code Point (PCP)	VLAN ID (VID)
PROFINET			
S7-1511 to ET200S	F1:D0:F1:D0:00:05	4	0x0001
ET200S to S7-1511	F1:D0:F1:D0:00:01	4	0x0001
IO Link			
Master to Demo	F1:D0:F1:D0:00:05	2	0x0002
Demo to Master	F1:D0:F1:D0:00:01	2	0x0002

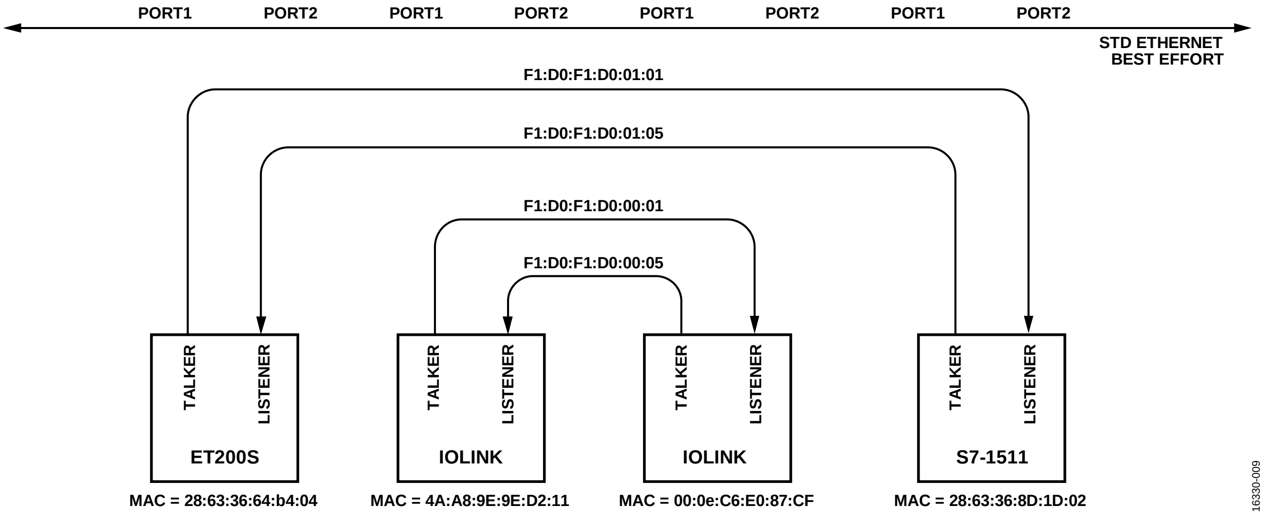
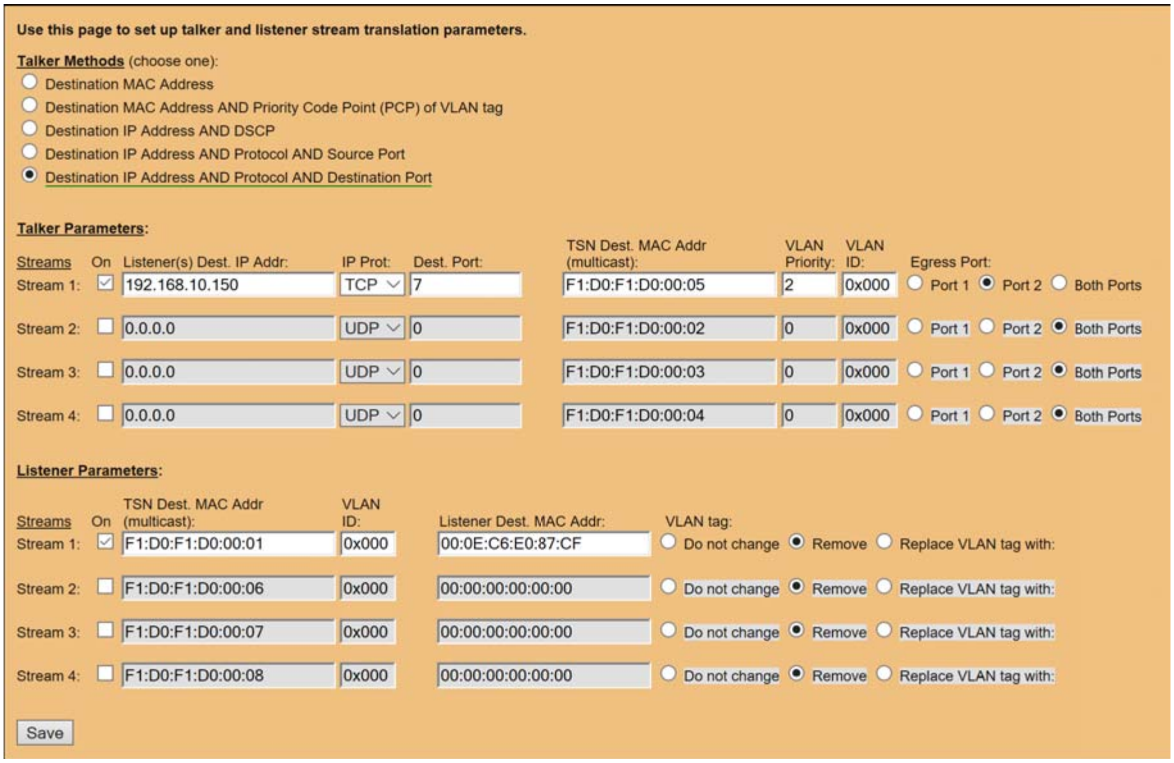


Figure 9. Streams



Use this page to set up talker and listener stream translation parameters.

Talker Methods (choose one):

○ Destination MAC Address
○ Destination MAC Address AND Priority Code Point (PCP) of VLAN tag
○ Destination IP Address AND DSCP
○ Destination IP Address AND Protocol AND Source Port
● Destination IP Address AND Protocol AND Destination Port

Talker Parameters:

Streams	On	Listener(s) Dest. IP Addr:	IP Prot:	Dest. Port:	TSN Dest. MAC Addr (multicast):	VLAN Priority:	VLAN ID:	Egress Port:
Stream 1:	☑	192.168.10.150	TCP	7	F1:D0:F1:D0:00:05	2	0x000	○ Port 1 ● Port 2 ○ Both Ports
Stream 2:	□	0.0.0.0	UDP	0	F1:D0:F1:D0:00:02	0	0x000	○ Port 1 ○ Port 2 ● Both Ports
Stream 3:	□	0.0.0.0	UDP	0	F1:D0:F1:D0:00:03	0	0x000	○ Port 1 ○ Port 2 ● Both Ports
Stream 4:	□	0.0.0.0	UDP	0	F1:D0:F1:D0:00:04	0	0x000	○ Port 1 ○ Port 2 ● Both Ports

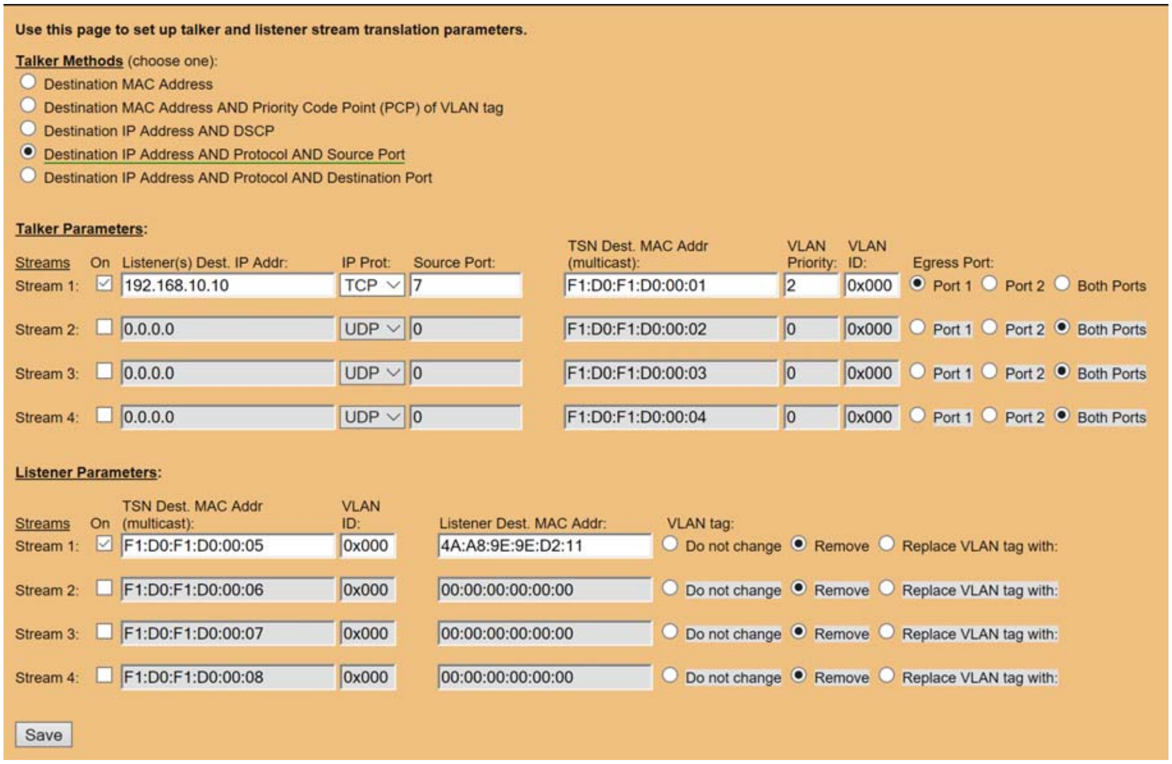
Listener Parameters:

Streams	On	TSN Dest. MAC Addr (multicast):	VLAN ID:	Listener Dest. MAC Addr:	VLAN tag:
Stream 1:	☑	F1:D0:F1:D0:00:01	0x000	00:0E:C6:E0:87:CF	○ Do not change ● Remove ○ Replace VLAN tag with:
Stream 2:	□	F1:D0:F1:D0:00:06	0x000	00:00:00:00:00:00	○ Do not change ● Remove ○ Replace VLAN tag with:
Stream 3:	□	F1:D0:F1:D0:00:07	0x000	00:00:00:00:00:00	○ Do not change ● Remove ○ Replace VLAN tag with:
Stream 4:	□	F1:D0:F1:D0:00:08	0x000	00:00:00:00:00:00	○ Do not change ● Remove ○ Replace VLAN tag with:

Figure 10. IO Link Device Stream Setup

There is one major difference between IO Link and PROFINET traffic. Whereas PROFINET traffic uses **Destination MAC Address AND Priority Code Point (PCP) of VLAN tag** as a method to identify the traffic that requires translation (talker method) to a TSN stream, the IO Link demo uses a transmission control protocol (TCP) connection. Therefore, it uses **Destination IP Address AND Protocol AND Source Port** on the talker side an**d Destination IP Address AND Protocol AND Destination Port** for the IO Link PC (listener side). As with most TCP connections, the server side port address is usually stable, although the client port number may be different. This is similar to a web server where the default port is 80 (see Figure 10).

Using **Destination MAC Address AND Priority Code Point (PCP) of VLAN tag** for PROFINET allows assignment of the high priority data traffic to a TSN stream. PROFINET tags all prioritized traffic using VLAN PCP 6 (see Figure 11).



Use this page to set up talker and listener stream translation parameters.

Talker Methods (choose one):

○ Destination MAC Address
○ Destination MAC Address AND Priority Code Point (PCP) of VLAN tag
○ Destination IP Address AND DSCP
● Destination IP Address AND Protocol AND Source Port
○ Destination IP Address AND Protocol AND Destination Port

Talker Parameters:

Streams	On	Listener(s) Dest. IP Addr:	IP Prot:	Source Port:	TSN Dest. MAC Addr (multicast):	VLAN Priority:	VLAN ID:	Egress Port:
Stream 1:	☑	192.168.10.10	TCP	7	F1:D0:F1:D0:00:01	2	0x000	● Port 1 ○ Port 2 ○ Both Ports
Stream 2:	□	0.0.0.0	UDP	0	F1:D0:F1:D0:00:02	0	0x000	○ Port 1 ○ Port 2 ● Both Ports
Stream 3:	□	0.0.0.0	UDP	0	F1:D0:F1:D0:00:03	0	0x000	○ Port 1 ○ Port 2 ● Both Ports
Stream 4:	□	0.0.0.0	UDP	0	F1:D0:F1:D0:00:04	0	0x000	○ Port 1 ○ Port 2 ● Both Ports

Listener Parameters:

Streams	On	TSN Dest. MAC Addr (multicast):	VLAN ID:	Listener Dest. MAC Addr:	VLAN tag:
Stream 1:	☑	F1:D0:F1:D0:00:05	0x000	4A:A8:9E:9E:D2:11	○ Do not change ● Remove ○ Replace VLAN tag with:
Stream 2:	□	F1:D0:F1:D0:00:06	0x000	00:00:00:00:00:00	○ Do not change ● Remove ○ Replace VLAN tag with:
Stream 3:	□	F1:D0:F1:D0:00:07	0x000	00:00:00:00:00:00	○ Do not change ● Remove ○ Replace VLAN tag with:
Stream 4:	□	F1:D0:F1:D0:00:08	0x000	00:00:00:00:00:00	○ Do not change ● Remove ○ Replace VLAN tag with:

16330-011

Figure 11. PROFINET Master Stream Setup

CREATING AND SETTING UP AN 802.1Qbv SCHEDULE

After the hardware and the communication is set up and the 802.1AS clocks are synchronized, a schedule can be created. However, it is advisable to recap some Ethernet basics first

Recap: the Ethernet Frame and TSN

From a software point of view, an Ethernet frame consists of the Layer 2 header (destination and source address, EtherType), up to 1500-byte data (assuming jumbo frames are not used) and a CRC32. The Ethernet header and the data field are the portion of the Ethernet frame that is copied into the main memory of a computer when it receives a frame.

In addition, on the wire an Ethernet framecontains a 63-bit preamble, a 1-bit start delimiter, and a minimum of a 12-byte line silence gap (see Figure 12). An Ethernet frame must have a minimum length of 64 bytes (including CRC). The relatively long preamble and silence time, and the minimum length have their origins in older Ethernet standards; however, they are still maintained and guaranteed. Whereas some PHYs allow shortening the preamble to 16 bits, this is not a common approach.

A TSN stream adds four bytes to the standard Ethernet frame, the VLAN tag. The stream always includes a VLAN tag. The VLAN tag consists of a priority (PCP) and a VLAN ID. Together with the destination MAC, the VLAN ID identifies a TSN stream. Each TSN stream can have one, and only one, transmitter (talker) and one or many receivers (listeners). These four bytes must be added in any frame length calculation (see Table 3). The minimum time a frame occupies on the wire, at 100 Mbps, is 6.72 µs, and the time for a full 1500-byte data frame is 123.36 µs.

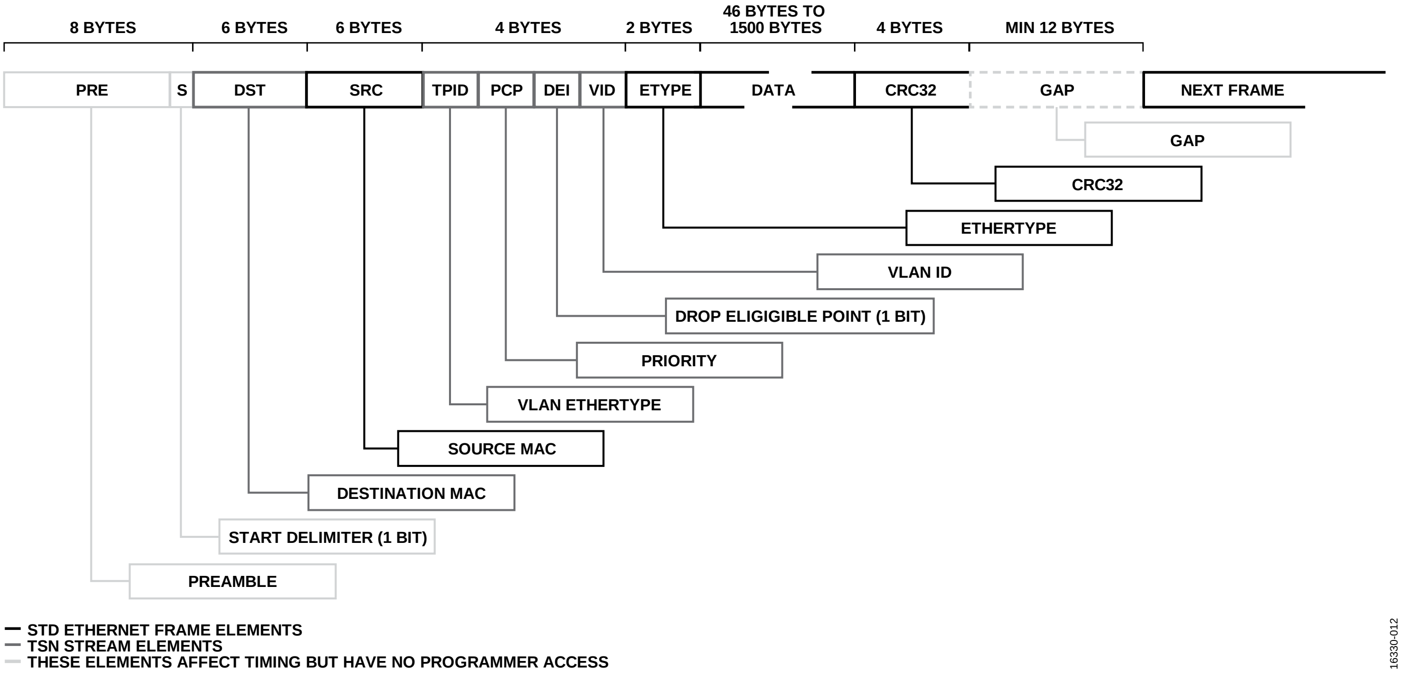


Figure 12. An Ethernet Frame

Table 3. Ethernet Frame Timing

Rate (Mbps)	Rate (MBps)	Byte Time (µs)	Layer2 (Byte)	Preamble (Byte)	Gap (Byte)	SDU, Minimum (Byte)	Slot, Minimum (Byte)	Slot Time, Minimum (µs)	Slot Time, Maximum (µs)
10	1.25	0.8	22	8	12	42	84	67.2	1233.6
100	12.5	0.08	22	8	12	42	84	6.72	123.36
1000	125	0.008	22	8	12	42	84	0.672	12.336

Timing of the Ethernet Infrastructure

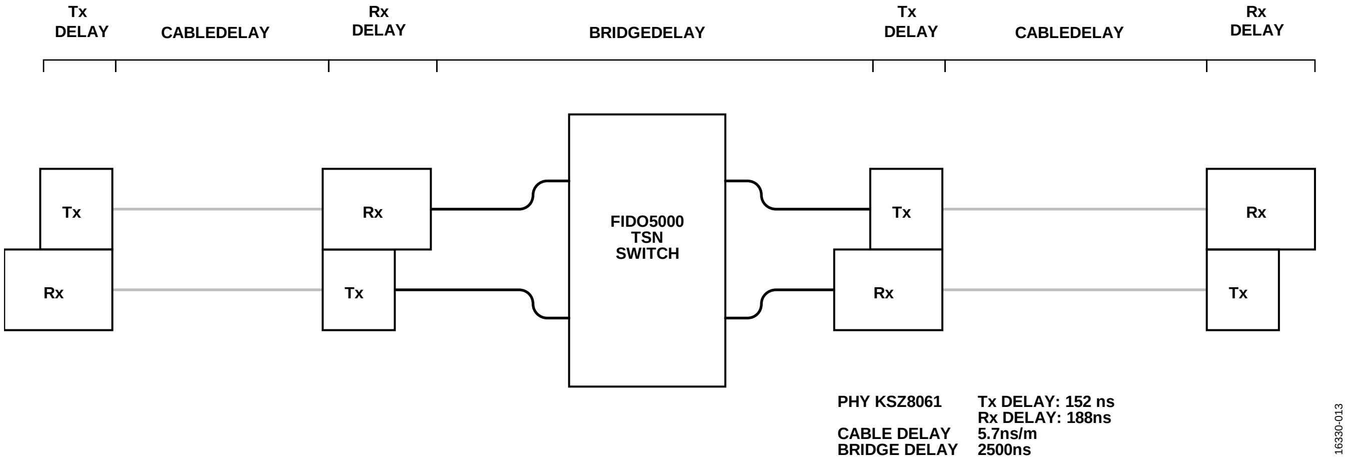


Figure 13. TSN 2-Port Switch Timing Mode

The Timing Model of an Ethernet Transmission Channel

Although Ethernet is fairly fast, there are delays in the transmission channel to consider. For a 100 Mbps, full-duplex Ethernet environment, consider the following parameters:

- PHY delays: the Ethernet PHYs introduce delays during receiving and transmitting that are caused by the internal processing of the data. The receive (RX) delay is usually greater than the transmit (TX) delay. Also, the RX timing may cause some jitter in the range of a few nanoseconds. These delays are in the range of a few hundred nanoseconds and are a parameter of the PHY components. Because a single byte occupies 80 ns each, the PHY delays are actually in the range of a 1-byte to 4-byte delay.
- Bridge delay: the Ethernet switch introduces a bridge delay (the time a message is delayed traversing through a switch). In the case of a fast cut-through, 2-port switch, the bridge delay is small. The switch must receive an 8-byte preamble plus a 12-byte source/destination MAC plus a 4-byte VLAN tag before making a forwarding decision. These requirements add up to a minimum 1.92 μs bridge delay (note that there are other factors that may result in slightly higher bridge delays, as well).
- Cable delay: a typical CAT5 cable has a cable delay of 5.7 ns per meter, or approximately half a bit transmitted. For any tabletop setup or cabinet with short cables, the cable delay is about one order of magnitude below the PHY delays. However, for a full 100 m Ethernet cable, the cable delay adds another 570 ns (equivalent to ~7 bytes).

To calculate a complex schedule for a system with serious physical span (long cables) and/or many nodes requires that all of these delays be considered. For this tabletop demonstration, add a margin of 10,000 ns to the schedules for dependable results.

802.1Qbv Scheduler Operation

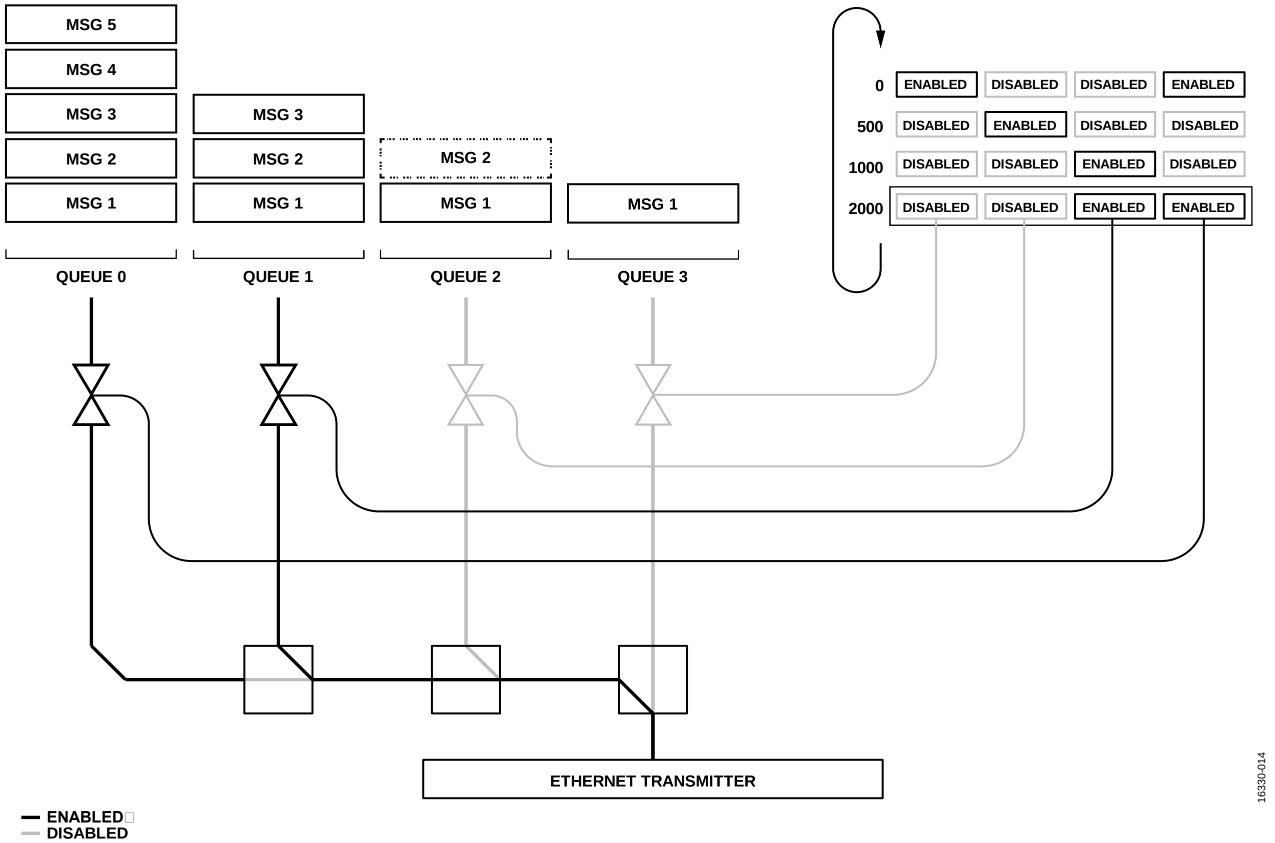
IEEE defines up to eight queues for Qbv, also referred to as time aware shaper (TAS). IEEE also defines an array of bytes, one byte for each defined offset within the cycle. The bits in those bytes enable or disable a queue accordingly. With each time slice within a cycle, a byte defines which of the queues are enabled and which not. Among the enabled queues, the ones with higher priorities are served. It is important to understand that the slices can have any start offset within the cycle; these offsets are defined in nanoseconds. The cycle time is also defined in nanoseconds.

The Ethernet transmitter, when idle, fetches an Ethernet frame from the enabled queue that has the highest priority of all enabled queues. While the transmitter is busy sending that frame, it does not fetch further frames (which means there is not another transmit queue).

The current implementation of TAS on the TSN kit is limited to 4 queues and up to 16 offsets, also called gate open events, within a cycle.

Figure 14 shows a block diagram of a TAS scheduler. In this diagram, all queues have some Ethernet frames queued up and four offsets are defined: 0 ns, 500 ns, 1000 ns, and 2000 ns. In this example, the cycle time is 2500 ns. Figure 14 shows an active 2000 ns offset, resulting in blocking Queue 2 and Queue 3 and enabling Queue 0 and Queue 1. Because Queue 1 has a higher priority than Queue 0, the transmitter fetches the next frame from Queue 1 until Queue 1 is either empty or the current slice is completed. If the current slice is completed, the next slice at Offset 0 has Queue 0 enabled, but as Queue 3 has messages queued up and has higher priority, the next frame to be sent is selected from Queue 3.

When all queues are enabled at the same time, the TAS works like a classical quality of service (QoS) priority queue, serving the highest priority queue first.



0	ENABLED	DISABLED	DISABLED	ENABLED
500	DISABLED	ENABLED	DISABLED	DISABLED
1000	DISABLED	DISABLED	ENABLED	DISABLED
2000	DISABLED	DISABLED	ENABLED	ENABLED

Figure 14. 802.1Qbv Scheduler

Guard Band

When using a schedule to guard bandwidth, it is necessary to ensure that if a higher priority gate is open, the transmitter is idle. If the transmitter is not idle, a potential long frame of lower priority can potentially block, or at least delay, higher priority traffic. To guarantee that the transmitter is idle and can start immediately sending higher priority traffic, a guard band is inserted. While active, the guard band inhibits the transmitter from fetching next frames.

To be effective, the guard band must be long enough so that the longest possible message that can be queued in a particular queue completes fully before the next gate open event occurs. The size of that longest frame that can be queued is defined in the parameter, maximum service data unit (maxSDU), in bytes.

There is no need to manually create guard bands by disabling all queues because the TSN kit automatically attends to the guard band.

Figure 15 shows a simple example. At t_0, the scheduler is enabled for the first time. Prior to that time, left of t_0, all gates are open. For the transmission gate enabled time, the transmitter can fetch frames from Queue 0 (Q0, in this example, wherein one gate at a time is opened). The guard band time (see Figure 15) is the guard band ahead of the Queue 3 open event and is wide enough so that a full 1522 SDU size frame can be sent safely, before the Q3 gate event occurs.

When Q3 is open, both periods are much shorter because Q3 is configured to transport shorter frames only. Its maxSDU may be just 200 bytes.

The maxSDU for Queue 0 is fixed at 1522 to allow web traffic for the configuration web server to pass through Queue 0 without being dropped.

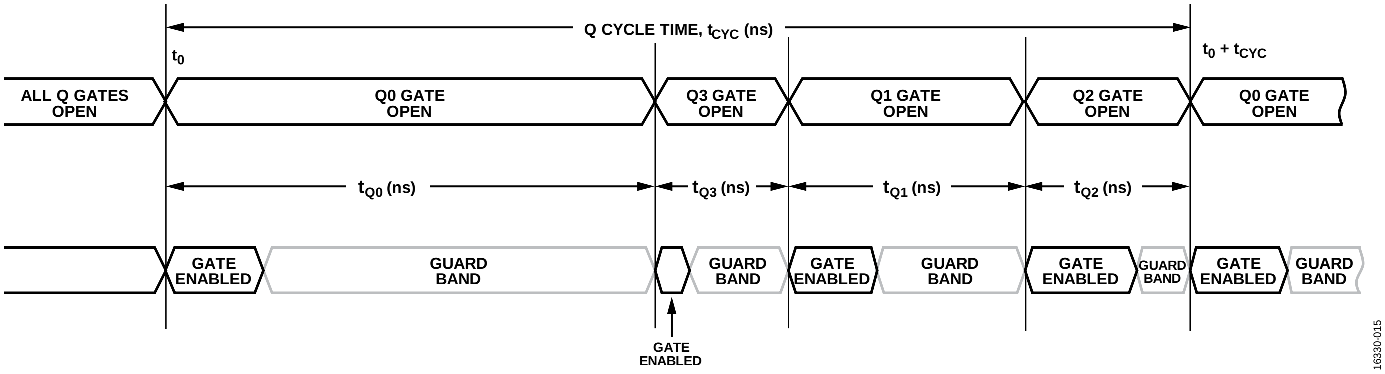


Figure 15. Schedule Timing, Startup, Guard Band

Ethernet Frame Size, Frame Rate, and Asynchrony

Because the frame size must be defined for each queue, knowledge of the protocol being placed on a designated queue is required. For a cyclic communication, length and rate of the traffic is easily calculated. However, for protocols that use a variable packet size (for example, anything over TCP) a worst-case value is required. For example, ModbusTCP can be used for cyclic communication; however, TCP uses very short handshake packets in addition to the data packets. In addition, Modbus knows several commands to access a device, some of which are longer than others. To place a ModbusTCP into a schedule requires worst-case estimates on the maxSDU bytes.

For PROFINET RT, it is possible to define a stream for the cyclic data exclusively, requiring few or no extra frames in the stream. Thus, estimating the maxSDU is more precise. Whereas the TSN kit is not synchronized with PROFINET RT (and the PROFINET RT protocol has no means to do such), the cyclic communication of PROFINET runs on its own clock. To guarantee that each frame transmits within the PROFINET cycle time, the TAS cycle time must be smaller (faster) than that of PROFINET; for best practice, a factor of 2 faster.

The reasons why creating an effective, tight schedule is not simple are as follows:

- Frame size may vary. For the schedule, the worst rather than the most frequent case must be taken into account.
- Frame rate may vary because of additional frames sent (handshake, rare commands, and so forth).
- Application cycle is not synchronized with the TAS cycle (oversampling required).
- Streams with different cycle times need to coexist on one wire. One way to solve such problems is to use a slower TSN schedule and open the gate for the faster traffic multiple times within the TSN cycle. See Figure 16 as an example.

It is possible to synchronize an application with the TAS scheduler. The TAS sync pulse (when a cycle is starting or completed) is available on Pin A10 of the CPU module on the TSN kit. An application can use this signal to synchronize to the TAS cycle; consequently, oversampling is not required.

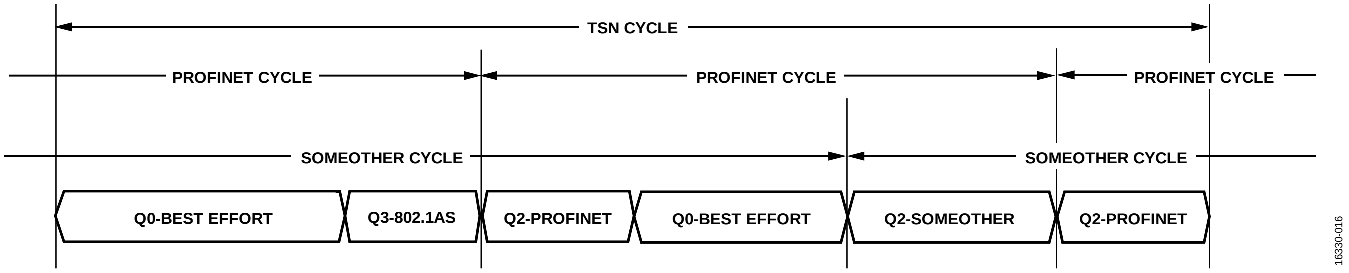


Figure 16. A Schedule Supporting Different Cycle Times; PROFINET Is Scheduled Twice As Many Times As "SomeOther" Traffic

Lastly, the block diagram of the TSN kit (see Figure 17) must be considered. There is a TAS scheduler for each Ethernet port. If a frame is received through one of the Ethernet ports, the TSN kit checks for a known TSN stream ID. In a case where a TSN stream is identified, the reverse stream translation is applied and the frame is sent out to the host port. If it is unidentified, or if it is best effort traffic without a matching IP address, the frame is placed in the "other ports" TAS queue for transmission.

In PROFINET IRT, which used scheduled traffic even before TSN became available; this simplified forwarding is referred to as relative forwarder. Only traffic that is not forwarded is identified and the transmission time for the forwarded frames is relative to the receive time (plus the bridge delay). This contrasts with an absolute forwarder in PROFINET nomenclature.

An absolute forwarder looks up the destination port first and then sends out the frame at an absolute time (within the schedule). This absolute time must account for the bridge delay and the lookup time. Therefore, an absolute forwarder is slightly slower and quite a bit more complex than a relative forwarder. One application for an absolute forwarder is a multiport switch, where the lookup for the egress port must occur anyway.

If a frame is received through the host port, it is checked according to the defined stream translation filters. If it is not translated, the traffic is queued in the best effort queue of the TAS. The appropriate port is selected by means of the dynamic forwarding database of the switch; however, if a stream translation occurs, it can be defined through which port the frame is to egress. Therefore, the stream translation configuration page offers a selection of Port 1, Port 2, or both ports simultaneously for the desired egress port.

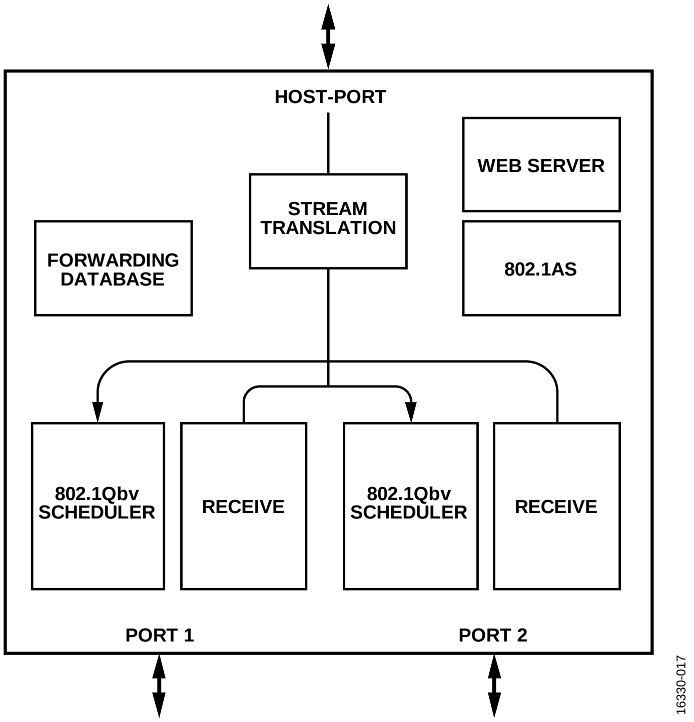


Figure 17. Block Diagram of the TSN Kit

THE SCHEDULE FOR THIS DEMO

For this demonstration, a TAS cycle time of 2 ms is selected with more than 50% of the bandwidth assigned to best effort traffic (1 ms). The traffic timing is listed in Table 5.

On the far right and far left ends of the TSN segment of this demonstration, the traffic towards the TSN segment is scheduled only. The resulting schedule is the same for each port (see Table 4).

Table 4. Port Schedule Results

PORT 1	Scheduled
0	Q0, best effort
1,000,000 ns	Q3
1,011,400 ns	Q2
1,029,400 ns	Q1
1,117,760 ns	Q0, best effort
= 1,882,240 ns	Total for Q0

Table 5. Traffic and Timing

Stream	Queue	Protocol	maxSDU	Rate	Slot Time	Margin
Best Effort	0	http, video stream	1522	N/A[1]	1,882,240 ns	N/A[1]
F1:D0: F1:D0:00:01	1	TCP, IO Link	1000	<<<TAS	81,600 ns	6670 ns
F1:D0: F1:D0:00:05	1	TCP, IO Link	1000	<<<TAS	81,600 ns	6670 ns
F1:D0: F1:D0:01:01	2	PROFINET IO	80	4 ms	8000 ns	10,000 ns
F1:D0: F1:D0:01:05	2	PROFINET IO	80	4 ms	8000 ns	10,000 ns
802.1AS	3	PTP	110[2]	2 ms	10,400 ns	1000 ns

[1] N/A means not applicable.

[2] In this example, 110 is the length of a PTP frame. However, in a bigger network a TLV within the follow_up message can grow substantially. In such cases, the actual size or a worst-case size must be applied.

SUMMARY

When 802.1Qcc, the configuration protocol for TSN, becomes commonly available, no one must calculate a schedule manually nor be concerned about how to configure a board using a web-server. However, understanding the implications and the benefits of a scheduled network is a first step into this technology. Debugging and understanding performance of a scheduled network requires this level of understanding. The knowledge gathered is valuable for when TSN is implemented fully in the field.

The Analog Devices TSN evaluation kit is a convenient and inexpensive way to gather real-world experience with TSN.

REFERENCES

TSN Evaluation Kit Quick Start Guide, Analog Devices, Inc.

IEEE TSN Standards: 802.1AS, 802.1Q, 802.1Qbv

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