



Audio Video Bridging (AVB)  
with Cisco Catalyst Switches



DR180707F

24 August 2018

Miercom

[www.miercom.com](http://www.miercom.com)

# Contents

|  |    |
|--|----|
| 1 – Executive Summary .....  | 3  |
| 2 – About Audio Video Bridging (AVB).....  | 5  |
| 3 – Product Overview.....  | 7  |
| Catalyst 9300 Stackable Switch .....   | 7  |
| Catalyst 3850 Stackable Switch .....   | 8  |
| 4 – Test Bed: How We Did It .....  | 9  |
| 5 – Grandmaster Clock Selection .....  | 11 |
| 6 – Multi-Stream Reservation Protocol (IEEE 802.1Qat) and Forwarding and<br>Queueing Enhancements for Time Sensitive Systems (IEEE 802.1Qav) ..... | 14 |
| 7 - Latency .....  | 20 |
| 8 – Maximum Number of AVB Streams .....  | 22 |
| 9 – AVB Scale Test.....  | 23 |
| 10 – About "Miercom Performance Verified" Testing .....  | 25 |
| 11 – About Miercom .....   | 25 |
| 12 – Use of This Report.....   | 25 |

# 1 – Executive Summary

Miercom was engaged by Cisco Systems to independently assess Catalyst switch support for Audio Video Bridging (AVB), as specified in the IEEE's 802.1BA standard and subordinate specifications. AVB support enables the transmission over Ethernet of time-sensitive audio and video streams that had traditionally required their own dedicated network and cabling.

Testing was conducted in a well-equipped lab using the latest AVB test system from Ixia, running software that fully exercises all the protocols and functionality of the IEEE AVB standard. Testing employed six Cisco Catalyst 9300 and 3850 switches connected in series, comprising a full seven-hop network – the IEEE-specified configuration for measuring AVB performance.

## Key Findings and Observations:

- **Clocking and synchronization.** Our testing found that the Catalysts fully comply with the IEEE timing and synchronization requirements for AVB, including the selection of a Grandmaster clock and the ongoing synchronization of all nodes in the AVB domain.
- **Multi-stream Reservation Protocol.** The Cisco switches all properly implement the rules for handling a mix of AVB and non-AVB (Best Effort) traffic. Bandwidth for AVB real-time traffic was properly allocated and enforced. AVB Class A and Class B priorities are maintained, and AVB requests where bandwidth is insufficient are properly rejected.
- **Forwarding and Queueing of Time Sensitive Streams.** Offers impressive handling of traffic scheduling and shaping for guaranteed QoS of reserved path streams through LAN. It includes protocol prioritization and the capability to remark non-AVB traffic using same VLAN and Class of Service (COS) values as AVB, to protect the higher priority AVB traffic.
- **Minimal end-to-end latency.** Tests confirmed that AVB traffic traversing our seven-hop Catalyst test-bed network incurred less than five percent of the 2-millisecond maximum end-to-end delay specified in the IEEE standards.
- **Maximum AVB streams.** We found that, with the Catalyst switches, we could create and concurrently run 130 functional Class A streams and 150 functional Class B streams.

Based on results which meet, or exceed, performance requirements specified in the IEEE 802.1BA Audio Video Bridging standard, we proudly award the **Miercom Performance Verified** certification to the Cisco Catalyst 9300 and 3850 switches running IOS XE with the latest AVB software support.

Robert Smithers

CEO

Miercom



## 2 – About Audio Video Bridging (AVB)

Audio and video equipment have traditionally sent analog ‘signals’ over dedicated, single-purpose, point-to-point and one-way cabling. Sending the equivalent information in IP packets through an Ethernet infrastructure, a long-sought goal, has not been easy. That’s because Ethernet was originally designed to deliver packets from many sources to many destinations on a best-effort basis. The unique requirements of audio and video traffic – requiring prioritization, bandwidth reservation, traffic shaping, delay and jitter control, timing synchronization – all had to be addressed.

Now it has. A series of IEEE and IETF standards developed in recent years have vested Ethernet with new and enhanced capabilities designed to enable it to handle real-time traffic. A flurry of protocol standards has addressed prioritization, bandwidth reservation, even timing synchronization between sending and receiving end nodes.

In late 2011, the IEEE finalized IEEE Std 802.1BA, a 45-page ‘umbrella’ standard for implementing “Audio Video Bridging (AVB) Systems.” This standard defines profiles for features, options, configurations, defaults and procedures for implementing the over-Ethernet equivalent of a dedicated-cabling audio and/or video network. Rather than develop all new protocols, the AVB spec incorporates and references many of these existing protocol standards. They include:

- The Stream Reservation Protocol (SRP) / Multiple Stream Reservation Protocol (MSRP), per IEEE 802.1Qat
- The Precision Time Protocol (PTP) / generalized PTP (gPTP), per IEEE 802.1AS, which provides for timing and synchronization for time-sensitive applications in bridged LANs
- Forwarding and queuing for time-sensitive streams, as specified in IEEE 802.1Qav

Readers should understand the capabilities and scope of IEEE-compliant AVB networks:

- Network-infrastructure devices – switches, routers, even Wi-Fi Access Points – are regarded as “bridges” in the AVB environment. That’s because AVB functions at Layer 2. Network-layer (IP) and higher protocols and procedures are not affected by AVB.
- Besides “bridges,” AVB end stations are either “talkers” or “listeners.” Listeners subscribe to an AVB stream, sent by a Talker end node. All participating AVB devices are constantly reporting availability, synchronization and performance information.
- All links in an AVB network – whether copper, fiber or wireless – must be 100 Mbps or higher speed and full-duplex. Interconnected AVB-capable nodes – endpoints and bridges – collectively comprise an AVB “domain.”
- There can be no **non**-AVB-capable nodes or endpoints in an AVB Domain. Non-AVB-capable equipment can still be connected in the same network, but cannot participate in the transmission, relay or receipt of AVB traffic.

- AVB transmission employs the notion of “channels” – akin to the synchronized time slices of TDM (time-division multiplexed) WAN facilities – like T1 and T3 links – that have been used for time-sensitive, mainly digital voice, traffic since the 1960s.
- In the current version of the specification, AVB connections between endpoints cannot exceed seven hops (relay points, or bridges). That’s because of the tight end-to-end latency and jitter performance requirements of AVB. Even so, varied configurations including daisy-chaining and point-to-multipoint transmission are supported.
- There are two “classes” of AVB-connection service specified – Class A and Class B.
  - Class A is the highest performance AVB connection. A maximum of just 2 milliseconds (ms) of cumulative, seven-hop, end-to-end latency is allowed for connections carrying Class A traffic. In addition, the Class A Audio stream can experience no more than 125 microseconds (µs) of worst-case jitter. Class A traffic packets are effectively limited to a maximum of 1170 bytes.
  - Class B is designed for network performance that doesn’t meet, or else AVB Video streams that don’t need, the stringent requirements of Class A connections. Class B AVB is well suited for video. AVB Class B performance requirements are still tight: A maximum of 50 ms of cumulative, seven-hop, end-to-end latency is allowed. Packet size up to 1500 bytes is supported, and 1000 µs (or 1 millisecond) of worst-case jitter is permitted.
- AVB connections are established based on stream-reservation request limitations, equal to 75 percent of total bandwidth. When exceeded, all stream connections are declined.

**Avnu for AVB.** Most of the specifications and protocols for AVB were finalized within the IEEE in the 2010-2011 time frame. Since then, a growing number of vendors have implemented AVB in products. Test equipment, such as the Ixia gear ([www.ixiacom.com](http://www.ixiacom.com)) used in this testing, helps ensure that product implementations are indeed compliant with, and properly implement, all the AVB standards and protocols.

Finalized AVB products are then typically submitted to a trade group, the Avnu Alliance (based in Beaverton, OR – [administration@avnu.org](mailto:administration@avnu.org)) that was formed to promulgate AVB in products and out into the marketplace. Products are checked for compliance and, when appropriate, an Avnu certification is issued.

At the time of this report, 26 AVB products – a mix of endpoints and bridges – had been certified as properly compliant and AVB-capable. The Cisco Catalyst 3850 is the Avnu certified derivation product family, as seen in the Avnu product certification page, in addition to the Cisco Catalyst 3650 switch. Avnu certification is pending for other Catalyst switches.

## 3 – Product Overview

Support for the IEEE's Audio Video Bridging (AVB) standard including all its subordinate protocols has been built into the latest versions of the Cisco IOS XE operating system that runs on Cisco Catalyst Switches. There is no special hardware required, and models which support AVB are listed here: <http://www.cisco.com/go/avb>. Note, though, that some legacy networks and older switch gear may not be capable of delivering the stringent performance that the AVB specification requires – in terms of end-to-end delay, jitter, and capacity. For example, all AVB links must support at least 100 Mbps of full-duplex bandwidth.

The test bed we built for this report, described more in the following section, employed six Catalyst switches: Three were Catalyst 9300 models and three were Catalyst 3850 Multigigabit versions. The six switches were necessary to confirm that our test-bed network performance was "AVB-capable," which specifies maximum end-to-end latency and jitter for a maximum seven-hop AVB domain.

### Catalyst 9300 Stackable Switch

Nine models of the Catalyst 9300 switch series support 24 or 48 RJ-45 copper ports, in various configurations. Ports can operate up to 1 Gbps, or higher on Multigigabit links. In addition, a swappable module (shown on right side of the switch in the below picture) provides uplinks or inter-switch connections over 4 x 1-Gbps, 4 x Multigigabit, 2 x 40-Gbps, 2 x 25-Gbps or 8 x 10-Gbps links. It is noteworthy that Cisco Catalyst 3850 uplink modules also work in Catalyst 9300 switches.



Source: Cisco

Additionally, the Catalyst 9300 fully supports Cisco StackWise and StackPower architectures. The 9300 also supports a host of power options over copper links. These include: dual redundant modular power supplies; power stacking among stack members for power redundancy; full IEEE 802.3at (PoE+) with 30W power on all copper ports; and Cisco Universal Power over Ethernet (Cisco UPOE, with 60W power).

The Catalyst 9300 model C9300-24U was used in this testing, running software image CAT9K\_IOSXE, Early Field Trial (EFT) version of 16.8.2.

## Catalyst 3850 Stackable Switch

Physically, this switch supports 24 and 48 RJ-45 or fiber/SFP+ ports, in various configurations. Ports can operate up to 10 Gbps. The 3850 also features an integrated wireless controller that can manage up to 100 APs (Access Points) and up to 2,000 wireless clients.

The switch accepts any of five optional uplink modules. These provide four 1-Gbps (1-Gigabit Ethernet) via SFP/fiber ports; two or four 10-Gbps SFP+ ports, or two 40-Gbps QSFP+ ports.

The Catalyst 3850, like the 9300 model, supports Cisco StackWise technology and versatile StackPower options: dual redundant modular power supplies; power stacking among stack members for power redundancy; full IEEE 802.3at (PoE+) with 30W power on all copper ports; Cisco Universal Power over Ethernet (Cisco UPOE, with 60W power); and Perpetual Power over Ethernet (PPoE).



Source: Cisco

The photo shows the tested Catalyst 3850 unit (model WS-C3850-12X48U) with 36 x 1-Gbps + 12 Multigigabit ports, for a total of 48 ports. The 3850 switches ran software image CAT3K\_CAA-UNIVERSALK9, version 16.6.4.

## 4 – Test Bed: How We Did It

Most of the testing for this report was done over six Cisco Catalyst switches (see below). The switches – three Catalyst 9300s and three Catalyst 3850s in alternating order – were connected in series in the same rack.



Source: Miercom

Six Cisco Catalyst switches were used, and all the test traffic passed through all six switches to achieve the seven-hop maximum configuration of the IEEE AVB standard. The 12-slot Ixia ([www.ixiacom.com](http://www.ixiacom.com)) XGS12 chassis test system, featured below, was mounted under the switches. The Catalyst 3850 and 9300 switches were alternated in the rack and connected in series, using the seven-hop configuration where the Ixia test system was the first hop.

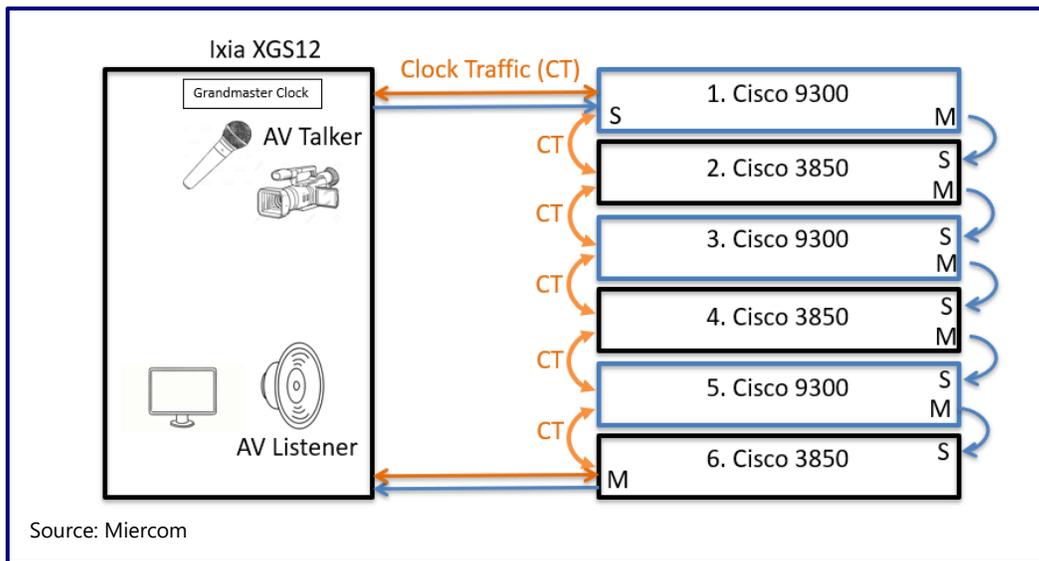
The Ixia XGS12 is a versatile multi-slot test system which accepts various port modules and offers a special software load for running IEEE-specified AVB performance tests.

The below diagram shows the link connections between the Ixia test system and the Cisco Catalyst switches. All tests were run on this seven-hop configuration, which is specified in the AVB standard as the worst-case signal-delay environment for AVB systems.



Source: Ixia

## Link Connections – Ixia Test System and Cisco 9300 & 3850 Switch Links



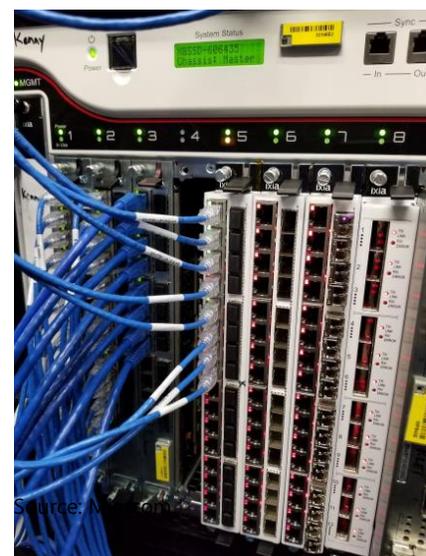
*In the diagram above, the S indicates the slave port and M denotes the master port of each switch. Each node has a master port connected to a downstream slave port. The master port of the Ixia system connects to the downstream slave of the first switch, the Cisco 9300. The slave node determines its offset from the master and resets its own system time. The switch egress port becomes the master to the next switch, the Cisco 3850, which becomes the slave. This process repeats with synchronization via PTP messages to update clocks throughout the AVB domain.*

The Ixia test system was configured with the Novus 10/1G x 16-port module (NOVUS10/1GE16DP). A special license is required for the Ixia to run the AVB-test features, which include gPTP (generalized Precision Time Protocol) and MSRP (Multiple Stream Reservation Protocol) test applications. The license package, 930-2120, is the Ixia IxNetwork AVB/TSN for NOVUS 10GE/1GE/100M Modules.

Shown at the right is the hook-up from the Ixia test system to and from the Catalyst switches. The 16-port module comes enabled with 8 ports for AVB. The 4 ports were allotted to both the first and last switch.

As the source and destination of the AVB test traffic, the Ixia system meticulously monitors and reports dropped packets, as well as the delay and jitter incurred by the Catalyst-based AVB "Domain."

The following sections describe the conduct and relevance of the tests we conducted.



## 5 – Grandmaster Clock Selection

### What was tested

We validated the selection of the Grandmaster Clock and the ability of the Catalyst-based AVB Domain to dynamically change the Grandmaster node when its clock priority changes.

As part of the gPTP protocol, all associated AVB nodes constantly exchange messages to determine which node's clock is to be the "Grandmaster" clock, given the priority and accuracy of the various clocks in the AVB domain. Once the Grandmaster clock is selected, the clocks on the other nodes sync accordingly and adopt "offsets," so that the audio or video frames will be played when the time stamp in each frame matches the system time, as sync'd with the Grandmaster.

Each AVB frame is set to play a specified number of microseconds ( $\mu\text{sec}$ ) in the future. A field in the protocol packets assures the audio and video is sync'd to within 2 milliseconds (ms) for Class A AVB streams or 50 ms for Class B. This time synchronization is continually checked over the life of each AVB connection to ensure a minimum delay, so there is no noticeable lag in the audio or video sent through the network of AVB-capable nodes.

### How we did it

We allowed the system (all nodes in the AVB domain) to settle down, and then observed which node had the Grandmaster Clock. Then we lowered that clock's priority and observed that all nodes acknowledged that the Grandmaster clock had switched. We then switched back to the original node with the Grandmaster clock (by re-establishing its high priority) and ran the remaining tests with the original Grandmaster on the Ixia first node (the AVB "Sender.").

### Findings, conclusions

Using packet trace as well as checking counters, we confirmed that all nodes' clocks in the AVB system were properly synchronized and then resynchronized in accordance with the PTP/gPTP protocol. Specifically, each AVB port was appropriately exchanging peer timing messages with its neighbor, and the measured delay did not exceed the specified maximum (neighborPropDelayThresh). The Ixia port did not receive multiple messages (Pdelay\_Resp or Pdelay\_Resp\_Follow\_Up) in response to a single request message (Pdelay\_Req). We verified, too, that the port does not receive a response from itself or another port synchronized to the same time-aware system.

Conclusion: The AVB PTP protocol works as specified; the nodes in our test bed all handled master/slave ports correctly.

## Timing is Everything – Notes on the Precision Time Protocol (PTP)

At start-up of an AVB system (domain), a first PTP polling process decides which node has the Grandmaster clock – the clock with the best credentials and the highest priority. In our testing the Ixia test system usually ended up with the Grandmaster clock. The below screen shots show that the Grandmaster has been selected and configured.

| Grouping        | Topology | Device Group      | Device# | Status    | Session Info | PTP State   | Master Clock ID           | Clock Role | Custom Clock ID | Clock Identity            | Profile      |
|-----------------|----------|-------------------|---------|-----------|--------------|-------------|---------------------------|------------|-----------------|---------------------------|--------------|
| gPTP 1: 1 ports | TS1      | gPTP Master Clock | # 1     | 1 of 1 Up |              | Grandmaster | 0x00:00:00:00:00:00:00    | Master     |                 | 0x00:00:00:00:00:00:01    | IEEE 802.1AS |
| Ethernet - 001  | TS1      | gPTP Master Clock | # 1     | Up        |              | Slave       |                           | Slave      |                 | 0x00:00:00:01:00:00:00:01 | IEEE 802.1AS |
| gPTP 2: 1 ports | TS2      | gPTP Slave Clock  | # 1     | 1 of 1 Up |              | Slave       | 0x94:D4:69:FF:FE:85:24:00 | Slave      |                 |                           | IEEE 802.1AS |
| Ethernet - 002  | TS2      | gPTP Slave Clock  | # 1     | Up        |              |             |                           |            |                 |                           |              |

| Grouping        | Topology | Device Group      | Device# | Status    | Session Info | Delay Mechanism | Communication Mode | Step Mode | Domain | Port Number | Announce Receipt Timeout | Log Announce Interval | Log Sync Inter    |
|-----------------|----------|-------------------|---------|-----------|--------------|-----------------|--------------------|-----------|--------|-------------|--------------------------|-----------------------|-------------------|
| gPTP 1: 1 ports | TS1      | gPTP Master Clock | # 1     | 1 of 1 Up |              | Peer Delay      | Multicast          | Two-Step  | 0      | 1           | 3                        | 0 (1 per second)      | -3 (8 per second) |
| Ethernet - 001  | TS1      | gPTP Master Clock | # 1     | Up        |              | Peer Delay      | Multicast          | Two-Step  | 0      | 1           | 3                        | 0 (1 per second)      | -3 (8 per second) |
| gPTP 2: 1 ports | TS2      | gPTP Slave Clock  | # 1     | 1 of 1 Up |              | Peer Delay      | Multicast          | Two-Step  | 0      | 1           | 3                        | 0 (1 per second)      | -3 (8 per second) |
| Ethernet - 002  | TS2      | gPTP Slave Clock  | # 1     | Up        |              | Peer Delay      | Multicast          | Two-Step  | 0      | 1           | 3                        |                       |                   |

| Topology | Device Group      | Port           | Protocol | Device# | Status | Configured Role | PTP State   | Offset [ns] | Max Offset [ns] | Min Offset [ns] | Avg Offset [ns] | Path Delay [ns] | Max Path Delay [ns] |
|----------|-------------------|----------------|----------|---------|--------|-----------------|-------------|-------------|-----------------|-----------------|-----------------|-----------------|---------------------|
| 1 TS1    | gPTP Master Clock | Ethernet - 001 | gPTP 1   | 1       | Up     | Master          | Grandmaster | 0           | 0               | 0               | 0               | 116             | 130                 |
| 2 TS2    | gPTP Slave Clock  | Ethernet - 002 | gPTP 2   | 1       | Up     | Slave           | Slave       | -2          | 152,929,142     | -137,837,169    | 18,136          | 20              | 32                  |

Source: Miercom

Each node has a “master” port that is connected to a downstream “slave” port. The master port of the Ixia connects to a downstream slave – the first Cisco switch. The slave node determines its offset from the master and resets its own system time. The Cisco switch’s outbound port then becomes a master to the next switch in line, which is a slave, and the process repeats on down the line. Synchronizations is maintained by ongoing PTP messages, which continue to monitor and update clocks throughout the AVB domain.

We started with the Ixia talker being selected as the Grandmaster for the AVB domain.

| Grouping        | Topology | Device Group      | Device# | Status    | Session Info | PTP State   | Master Clock ID            | Clock Role | Custom Clock ID | Clock Identity            | Profile      | One Way | Delay M |
|-----------------|----------|-------------------|---------|-----------|--------------|-------------|----------------------------|------------|-----------------|---------------------------|--------------|---------|---------|
| gPTP 1: 1 ports | TS1      | gPTP Master Clock | # 1     | 1 of 1 Up |              | Grandmaster | 0x00:00:00:00:00:00:00     | Master     |                 | 0x00:00:00:00:00:00:01    | IEEE 802.1AS | Peer D  |         |
| Ethernet - 001  | TS1      | gPTP Master Clock | # 1     | Up        |              | Slave       | 0x04:6C:19D:FF:FE:1F:33:00 | Master     |                 |                           | IEEE 802.1AS | Peer De |         |
| gPTP 2: 1 ports | TS2      | gPTP Slave Clock  | # 1     | 1 of 1 Up |              | Slave       |                            | Slave      |                 | 0x00:00:00:01:00:00:00:01 | IEEE 802.1AS | Peer De |         |
| Ethernet - 002  | TS2      | gPTP Slave Clock  | # 1     | Up        |              | Slave       | 0x94:D4:69:FF:FE:85:24:00  | Slave      |                 |                           | IEEE 802.1AS | Peer De |         |

Source: Miercom

We then increased the clock priority of the first switch (Catalyst 9300 – with clock ID \*\*\*1F:33:00), making it the Grandmaster. It is important to note the PTP state change once clock priority was manually modified. The original Grandmaster (Ixia Talker port, clock ID \*\*\*00:00:00:00:00) was converted to Slave.

| Grouping        | Topology | Device Group      | Device # | Status    | Session Info | PTP State | Master Clock ID          | Clock Role | Custom Clock ID | Clock Identity            | Profile      | One Way | Delay M |
|-----------------|----------|-------------------|----------|-----------|--------------|-----------|--------------------------|------------|-----------------|---------------------------|--------------|---------|---------|
| gPTP 1: 1 ports | TS1      | gPTP Master Clock | # 1      | 1 of 1 Up |              | Slave     | x04:6C:9D:FF:FE:1F:33:00 | Master     |                 | 0x00:00:00:00:00:00:01    | IEEE 802.1AS |         | Peer De |
| Ethernet - 001  | TS1      | gPTP Master Clock | # 1      | Up        |              | Slave     | x04:6C:9D:FF:FE:1F:33:00 | Master     |                 | 0x00:00:00:00:00:00:01    | IEEE 802.1AS |         | Peer De |
| gPTP 2: 1 ports | TS2      | gPTP Slave Clock  | # 1      | 1 of 1 Up |              | Slave     | x94:D4:69:FF:FE:85:24:00 | Slave      |                 | 0x00:00:00:01:00:00:00:01 | IEEE 802.1AS |         | Peer De |
| Ethernet - 002  | TS2      | gPTP Slave Clock  | # 1      | Up        |              | Slave     | x94:D4:69:FF:FE:85:24:00 | Slave      |                 | 0x00:00:00:01:00:00:00:01 | IEEE 802.1AS |         | Peer De |

Source: Miercom

This is then reflected in the “Master Clock ID” column value for the Ixia Talker port – now having the clock ID of the new Grandmaster of the first switch, the Catalyst 9300. PTP state for the Ixia Listener port remains a Slave, with a Master Clock ID matching the last switch (Catalyst 3850) in the series.

PTP message counters for the Ixia Talker and Listener ports are shown below.

| Topology | Device Group | Port              | Protocol       | Device# | Min Path Delay [ns] | Avg Path Delay [ns] | Time Slope | Port Identity | Master Port Identity    | Grandmaster Port Identity | Sync Messages Received  |
|----------|--------------|-------------------|----------------|---------|---------------------|---------------------|------------|---------------|-------------------------|---------------------------|-------------------------|
| 1        | TS1          | gPTP Master Clock | Ethernet - 001 | gPTP 1  | 1                   | 98                  | 115        | 0.000         | 00:13:01:ff:fe:00:00:01 | 00:00:00:00:00:00:00      | 00:00:00:00:00:00:00    |
| 2        | TS2          | gPTP Slave Clock  | Ethernet - 002 | gPTP 2  | 1                   | 0                   | 18         | 1.000         | 00:14:01:ff:fe:00:00:01 | 94:d4:69:ff:fe:85:24:00   | 00:13:01:ff:fe:00:00:01 |

| Port             | Announce Messages Sent | Announce Messages Received | Sync Messages Sent | Sync Messages Received | FollowUp Messages Sent | FollowUp Messages Received | DelayReq Messages Sent | DelayReq Messages Received |
|------------------|------------------------|----------------------------|--------------------|------------------------|------------------------|----------------------------|------------------------|----------------------------|
| 1 Ethernet - 001 | 645                    | 0                          | 5,153              | 0                      | 5,153                  | 0                          | 0                      | 0                          |
| 2 Ethernet - 002 | 0                      | 641                        | 0                  | 5,121                  | 0                      | 5,121                      | 0                      | 0                          |

| Port             | PdelayReq Messages Sent | PdelayReq Messages Received | PdelayResp Messages Sent | PdelayResp Messages Received | PdelayRespFollowUp Messages Sent | PdelayRespFollowUp Messages Received |
|------------------|-------------------------|-----------------------------|--------------------------|------------------------------|----------------------------------|--------------------------------------|
| 1 Ethernet - 001 | 545                     | 544                         | 544                      | 545                          | 544                              | 545                                  |
| 2 Ethernet - 002 | 545                     | 544                         | 544                      | 543                          | 544                              | 543                                  |

Source: Miercom

## 6 – Multi-Stream Reservation Protocol (IEEE 802.1Qat) and Forwarding and Queueing Enhancements for Time Sensitive Systems (IEEE 802.1Qav)

### **What was tested**

Bandwidth reservation and Forwarding and Queueing for Time Sensitive Systems (FQTSS) – two key components of AVB networks – were tested. From a high-level perspective, AVB works by reserving a part of the available Ethernet bandwidth for AVB traffic. AVB packets are sent regularly in the allocated timeslots. As this bandwidth is reserved, there are no collisions.

On AVB connections there are three classes of data: Class A, typically including audio; Class B, usually including video; and “background” or Best Effort (or “all other”) data. Best Effort data is the lowest priority data on these AVB-designated links.

A rigid set of rules govern AVB stream assignment and bandwidth allocation. Most of the bandwidth is earmarked for AVB packets. In the AVB domain, up to 75 percent of the link bandwidth belongs to AVB packets and 25 percent is set aside for Best Effort data,

That may seem to shortchange non-AVB data but, if there is no AVB data for a time then Best Effort data can use as much of the bandwidth as the link contains, including the unused AVB bandwidth. If there is AVB data present, it gets up to 75 percent and Best Effort data gets whatever is left over.

If there is both Class A and Class B AVB data, and they total more than 75 percent of the link bandwidth, Class A gets top priority and can take as much of the 75 percent as it needs. Class B gets access to the rest of the 75 percent that Class A doesn’t use, and then Best Effort data gets whatever is left over.

Besides bandwidth allocation there are reservation requests. Each AVB data stream must register for the amount of data bandwidth it expects to use. If the registration request exceeds the available bandwidth of a particular link, then that registration request is disallowed.

### **How we did it**

The below diagram is the Ixia test system’s view of our seven-hop test bed, with regards to AVB Talker, Listener and intervening Bridges. As noted, the Ixia contains both the AVB Talker and Listener “nodes,” implemented in software within the test system. In this dual role it can accurately measure the received packet statistics, such as percent dropped, Mbps of the received stream and the latency of the traffic. The Ixia then contrasts the received stream with the stream it sent and analyzes the differences.

In this testing we used three streams of data. All connections throughout the AVB domain were 1-Gbps links, across all seven hops. We started one stream at a time, generated by the Ixia, to see what the shaping algorithms do with the traffic bandwidth. Then we incrementally added the second stream, the third, and so on. All the streams were unidirectional.

With 1 Gbps of bandwidth on each link:

- 75 percent of the bandwidth reserved for Class A and Class B would be 750 Mbps.
- 25 percent of the bandwidth reserved for Best-Effort traffic would be 250 Mbps.

## Findings, conclusions

We created two streams – one for Class A traffic at 400 Mbps and the second for Class B traffic at 300 Mbps. Both streams were reserved successfully via MSRP, as the combined requirement was allowed within 75 percent bandwidth levels. In our tests, stream reservation occurs at the beginning, when we run the protocols on the Ixia setup and when actual traffic flow is generated.

Initially, we sent a single Best-Effort stream at 450 Mbps, shown as Traffic Item 3 below.

| Traffic Item   | Tx Frames  | Rx Expected Frames | Rx Frames  | Frames Delta | Loss % | Tx Frame Rate | Rx Frame Rate | Tx L1 Rate (bps) | Rx L1 Rate (bps) |
|----------------|------------|--------------------|------------|--------------|--------|---------------|---------------|------------------|------------------|
| Traffic Item 1 | 0          | 0                  | 0          | 0            | 0      | 0.000         | 0.000         | 0.000            | 0.000            |
| Traffic Item 2 | 0          | 0                  | 0          | 0            | 0      | 0.000         | 0.000         | 0.000            | 0.000            |
| Traffic Item 3 | 20,002,354 | 20,002,354         | 20,002,330 | 24           | 0.000  | 669,643.000   | 669,643.000   | 450,000,096.000  | 450,000,096.000  |

Source: Miercom

The table below shows the configuration of the AVB domain, in terms of bandwidth, and the results of the Best-Effort stream. As expected, the only data on the link used full bandwidth access, with no loss.

Table 1: Best-Effort Stream of 450 Mbps Reserved Bandwidth

| Traffic       | Reserved Rate (Mbps) | Actual Tx Rate (Mbps) | Actual Rx Rate (Mbps) | Loss (%) |
|---------------|----------------------|-----------------------|-----------------------|----------|
| Best-Effort   | 450                  | 450                   | 450                   | 0        |
| Class A       | 400                  |                       |                       |          |
| Class B       | 300                  |                       |                       |          |
| Total Traffic |                      | 450                   | 450                   |          |

We added a 400-Mbps Class A stream to the Best-Effort stream, shown below in Traffic Item 1.

| Traffic Item   | Tx Frames  | Rx Expected Frames | Rx Frames  | Frames Delta | Loss % | Tx Frame Rate | Rx Frame Rate | Tx L1 Rate (bps) | Rx L1 Rate (bps) | Rx Bytes     |
|----------------|------------|--------------------|------------|--------------|--------|---------------|---------------|------------------|------------------|--------------|
| Traffic Item 2 | 0          | 0                  | 0          | 0            | 0      | 0.000         | 0.000         | 0.000            | 0.000            | 0            |
| Traffic Item 1 | 11,602,049 | 11,602,049         | 11,602,034 | 15           | 0.000  | 368,000.000   | 368,000.000   | 400,384,000.000  | 400,384,000.000  | 1,345,835... |
| Traffic Item 3 | 53,484,509 | 53,484,509         | 53,484,481 | 28           | 0.000  | 669,643.000   | 669,643.500   | 450,000,096.000  | 450,000,432.000  | 3,423,006... |

Source: Miercom

The results of both streams are shown in the table below. Both the Best-Effort and Class A streams use their respective reserved bandwidth, totaling 850 Mbps. The Class A stream can use up to 750Mbps (75 percent of the link bandwidth), leaving 350 Mbps of unused bandwidth in the Class A allocation.

Table 2: Added Class A Stream to Best-Effort Stream with 850 Mbps Total Reserved Bandwidth

| Traffic       | Reserved Rate (Mbps) | Actual Tx Rate (Mbps) | Actual Rx Rate (Mbps) | Loss (%) |
|---------------|----------------------|-----------------------|-----------------------|----------|
| Best-Effort   | 450                  | 450                   | 450                   | 0        |
| Class A       | 400                  | 400                   | 400                   | 0        |
| Class B       | 300                  |                       |                       |          |
| Total Traffic |                      | 850                   | 850                   |          |

Next, we added a Class B stream at 300 Mbps. Class B was able to use leftover bandwidth from Class A traffic, for up to a maximum of 750 Mbps for Class A and B combined. The Class B stream is shown below as Traffic Item 2.

| Traffic Item   | Tx Frames   | Rx Expected Frames | Rx Frames   | Frames Delta | Loss % | Tx Frame Rate | Rx Frame Rate | Tx L1 Rate (bps) | Rx L1 Rate (bps) | Rx Bytes     |
|----------------|-------------|--------------------|-------------|--------------|--------|---------------|---------------|------------------|------------------|--------------|
| Traffic Item 2 | 14,098,841  | 14,098,841         | 14,098,838  | 3            | 0.000  | 35,013.500    | 35,013.500    | 300,275,776.000  | 300,275,776.000  | 14,831,97... |
| Traffic Item 1 | 167,634,088 | 167,634,088        | 167,634,054 | 34           | 0.000  | 368,000.000   | 367,999.500   | 400,384,000.000  | 400,383,456.000  | 19,445,55... |
| Traffic Item 3 | 337,413,179 | 337,413,179        | 244,792,570 | 92,620,609   | 27.450 | 669,643.000   | 439,625.500   | 450,000,096.000  | 295,428,336.000  | 15,666,72... |

Source: Miercom

The total of the three streams exceeded the capacity of the 1-Gbps link. As a result, a portion of the Best-Effort traffic was dropped, as shown in the table below.

Table 3: Addition of 300 Mbps Class B Stream Exceeds 1-Gbps Link

| <i>Traffic</i>       | <b>Reserved Rate (Mbps)</b> | <b>Actual Tx Rate (Mbps)</b> | <b>Actual Rx Rate (Mbps)</b> | <b>Loss (%)</b> |
|----------------------|-----------------------------|------------------------------|------------------------------|-----------------|
| <i>Best-Effort</i>   | 450                         | 450                          | 295.4                        | 34.3            |
| <i>Class A</i>       | 400                         | 400                          | 400                          | 0               |
| <i>Class B</i>       | 300                         | 300                          | 300                          | 0               |
| <i>Total Traffic</i> |                             | 1150                         | 995.4                        |                 |

We further increased the traffic rate of Class B from 300 to 400 Mbps. We observed Class B traffic dropping beyond 300 Mbps, as that is how much bandwidth has been reserved for the Class B stream.

Table 4: Increase from 300 Mbps to 400 Mbps for Class B Steam

| <i>Traffic</i>       | <b>Reserved Rate (Mbps)</b> | <b>Actual Tx Rate (Mbps)</b> | <b>Actual Rx Rate (Mbps)</b> | <b>Loss (%)</b> |
|----------------------|-----------------------------|------------------------------|------------------------------|-----------------|
| <i>Best-Effort</i>   | 450                         | 450                          | 295.4                        | 34.3            |
| <i>Class A</i>       | 400                         | 400                          | 400                          | 0               |
| <i>Class B</i>       | 300                         | 400                          | 300                          | 0               |
| <i>Class B #2</i>    | 300                         | 400                          | 300                          | 25              |
| <i>Total Traffic</i> |                             | 1150                         | 995.4                        |                 |

Conclusions:

- The total bandwidth sought by the three streams, 1.150 Gbps, exceeds the maximum bandwidth capacity of the 1-GbE link. Since Best-Effort is the lowest priority, that stream will get whatever is left over after Class A and B consume their allocated share.
- Class A and Class B traffic total 700 Mbps, which is still below their 75 percent link-bandwidth authorization, 750 Mbps. So together they use 700 Mbps, leaving 50 Mbps, plus the 25 percent authorized, for the Best-Effort traffic.
- Bandwidth sought by the Best-Effort traffic, 450 Mbps, exceeded the 300 Mbps left over for non-AVB streams, resulting in dropped frames
- Table 3 and 4 shows the percent of loss based on Mbps of bandwidth. The Ixia system reports loss based on the number of frames dropped.

The last test used a modified configuration where two streams were created – SR Class A and SR Class B, each with approximately 400 Mbps reserved rates, for a total of 800 Mbps – greater than 75 percent of the 1-GbE link. The Best-Effort traffic did not require a reservation.

| Traffic Item   | Loss %  | Tx Frame Rate | Rx Frame Rate | Tx L1 Rate (bps) | Rx L1 Rate (bps) | Rx Bytes      | Tx Rate (Bps)  | Rx Rate (Bps)  | Tx Rate (bps)   | Rx Rate (bps)   | Tx Rate (Kbps) | Rx Rate (Kbps) | Tx Rate (Mbps) | Rx Rate (Mbps) |
|----------------|---------|---------------|---------------|------------------|------------------|---------------|----------------|----------------|-----------------|-----------------|----------------|----------------|----------------|----------------|
| Traffic Item 1 | 0.000   | 45,620.500    | 45,620.500    | 400,000,544.000  | 400,000,544.000  | 4,302,901,404 | 49,087,658.000 | 49,087,658.000 | 392,701,264.000 | 392,701,264.000 | 392,701.264    | 392,701.264    | 392.701        | 392.701        |
| Traffic Item 2 | 100.000 | 45,620.500    | 0.000         | 400,000,544.000  | 0.000            | 0             | 49,087,658.000 | 0.000          | 392,701,264.000 | 0.000           | 392,701.264    | 0.000          | 392.701        | 0.000          |

Source: Miercom

MSRP bandwidth reservation for Class A is processed, reserving about 400 Mbps on port for Class A. The switch rejects bandwidth reservation for Class B since the allowable bandwidth for AVB is exceeded (by 5 percent at 800 Mbps) on the egress port.

The Class A stream was 100 percent allowed and fully accepted, well within bandwidth limitations – whereas SR Class B traffic get dropped 100 percent, as expected.

Notes and observations:

- Class A and Class B streams of 400 Mbps traffic each result in Class A stream sent fully and unimpeded
- Class B attempted 400 Mbps of traffic but, when combined with Class A, the AVB bandwidth (75 percent of 1-GbE) was exceeded. All 400 Mbps of the Class B stream was dropped since reservation for this stream was unsuccessful.

The critical FQTTSS (IEEE 802.1Qav) functionality of “QoS Ingress Remarking” was verified for its ability to protect AVB traffic. The Best-Effort, or “non-AVB”, stream in this case comes in with a COS (Layer-2 priority) value of 3. This priority matches AVB traffic. The non-AVB stream coming from a boundary port, having the same VLAN priority as AVB traffic, gets remarked by the switch implicitly to the default priority of 0 to get lesser preference.

| Name                       | Value          |
|----------------------------|----------------|
| Frame                      | length: 64     |
| Ethernet II                |                |
| VLAN                       |                |
| VLAN Header                |                |
| VLAN-Tag                   |                |
| VLAN Priority              | 3              |
| Canonical Format Indicator | 0              |
| VLAN-ID                    | 2              |
| Protocol-ID                | 0x<Auto>ffff   |
| Payload                    | Increment Byte |
| Ethernet II (Trailer)      |                |

Source: Miercom

After going through the port registration process, the VLAN priority was reset to 0, making the Best-Effort (non-AVB) stream have the lowest priority on AVB links. The packet capture below shows traffic received on the other end where the Best-Effort stream priority has been reset.

```

378450 0.56513350 00:15:01:00:00:01 00:12:01:00:00:40 0xffff 64 PRI: 0 CFI: 0 ID: 2
378451 0.56513678 00:15:01:00:00:01 00:12:01:00:00:41 0xffff 64 PRI: 0 CFI: 0 ID: 2
378452 0.56513824 00:15:01:00:00:01 00:12:01:00:00:42 0xffff 64 PRI: 0 CFI: 0 ID: 2
378453 0.56513968 00:15:01:00:00:01 00:12:01:00:00:43 0xffff 64 PRI: 0 CFI: 0 ID: 2
378454 0.56514128 00:15:01:00:00:01 00:12:01:00:00:44 0xffff 64 PRI: 0 CFI: 0 ID: 2
378455 0.56514286 00:15:01:00:00:01 00:12:01:00:00:45 0xffff 64 PRI: 0 CFI: 0 ID: 2
378456 0.56514432 00:15:01:00:00:01 00:12:01:00:00:46 0xffff 64 PRI: 0 CFI: 0 ID: 2
:
1 Frame 235101: 64 bytes on wire (512 bits), 64 bytes captured (512 bits) on interface 0
  Ethernet II, Src: 00:15:01:00:00:01 (00:15:01:00:00:01), Dst: 00:12:01:00:00:75 (00:12:01:00:00:75)
    Destination: 00:12:01:00:00:75 (00:12:01:00:00:75)
    Source: 00:15:01:00:00:01 (00:15:01:00:00:01)
      Type: 802.1Q Virtual LAN (0x8100)
    802.1Q virtual LAN
      000 ..... = Priority: 0
      ...0 ..... = CFI: 0
      ... 0000 0000 0010 = ID: 2
      Type: unknown (0xffff)
    Data (46 bytes)
  
```

Source: Miercom

## 7 - Latency

### What was tested

The end-to-end latency for AVB Class A and Class B traffic traversing a seven-hop test bed.

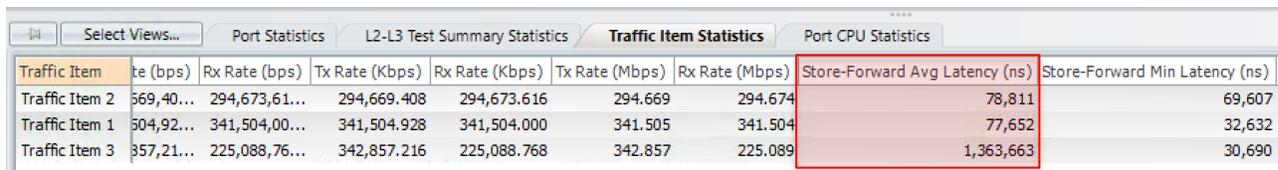
Per the AVB standards, Class A streams must be assured of experiencing no more than 2 milliseconds (ms) of end-to-end delay through a seven-hop connection. That was an awesome requirement just a few years ago, but the latest Cisco Catalyst switches, running the latest IOS XE operating software with AVB support, can manage it – with time to spare, it seems.

The delay for AVB Class B streams is considerably more luxurious, latency speaking. Class B streams, typically used for video, can incur as much as 50 milliseconds of end-to-end delay over a seven-hop network connection.

The millisecond metric represents a value in thousands of a second. The 2-ms limit is a tight allowance, just two thousandths of a second. Most test equipment today measures delay in microseconds ( $\mu$ s), and the latest, most advanced gear measures in nanoseconds (ns). A millisecond equals 1 thousand microseconds, or 1 million nanoseconds.

### How we did it

We ran a test to see what the latency was over our 7-hop configuration and noted the latency for both Class A and Class B. The Ixia display including latency – reported in nanoseconds – is shown below.



| Traffic Item   | Rate (bps) | Rx Rate (bps) | Tx Rate (Kbps) | Rx Rate (Kbps) | Tx Rate (Mbps) | Rx Rate (Mbps) | Store-Forward Avg Latency (ns) | Store-Forward Min Latency (ns) |
|----------------|------------|---------------|----------------|----------------|----------------|----------------|--------------------------------|--------------------------------|
| Traffic Item 2 | 569,40...  | 294,673,61... | 294,669.408    | 294,673.616    | 294.669        | 294.674        | 78,811                         | 69,607                         |
| Traffic Item 1 | 504,92...  | 341,504,00... | 341,504.928    | 341,504.000    | 341.505        | 341.504        | 77,652                         | 32,632                         |
| Traffic Item 3 | 857,21...  | 225,088,76... | 342,857.216    | 225,088.768    | 342.857        | 225.089        | 1,363,663                      | 30,690                         |

Source: Miercom

Traffic Item 1 in the above display is the Class A stream. Traffic Item 2 is the Class B stream, and Traffic Item 3 is Best-Effort traffic.

### Findings, conclusions

The table below shows the end-to-end, seven-hop latency measured for Class A and Class B streams through the six Catalyst switches, by frame size. As it turns out, the latencies for Class A and Class B are nearly the same. That's because the Catalysts are line-rate switches and there is no congestion, since bandwidth is reserved and cannot be exceeded.

Table 5: Seven-Hop, End-to-End Latency (in milliseconds)

| Frame size (bytes) | Class A (ms)      | Class B (ms)      |
|--------------------|-------------------|-------------------|
| 64                 | 0.033             | 0.033             |
| 128                | 0.035             | 0.035             |
| 256                | 0.041             | 0.041             |
| 512                | 0.050             | 0.050             |
| 1024               | 0.070             | 0.070             |
| 1280               | 0.081             | 0.081             |
| 1518 & larger      | Too large for AVB | Too large for AVB |

Note: Measurements in milliseconds were rounded to the nearest microsecond.

Using a mix of Catalyst switches, the accumulated, worst-case, seven-hop latency for AVB streams was less than 5 percent of the most demanding, 2-millisecond end-to-end delay budget.

We observed, too, that Best Effort traffic did incur appreciable latency (1.363 milliseconds) in our test case. This was likely because Best-Effort traffic exceeded the amount of authorized bandwidth, resulting in congestion and dropped Best-Effort frames.

## 8 – Maximum Number of AVB Streams

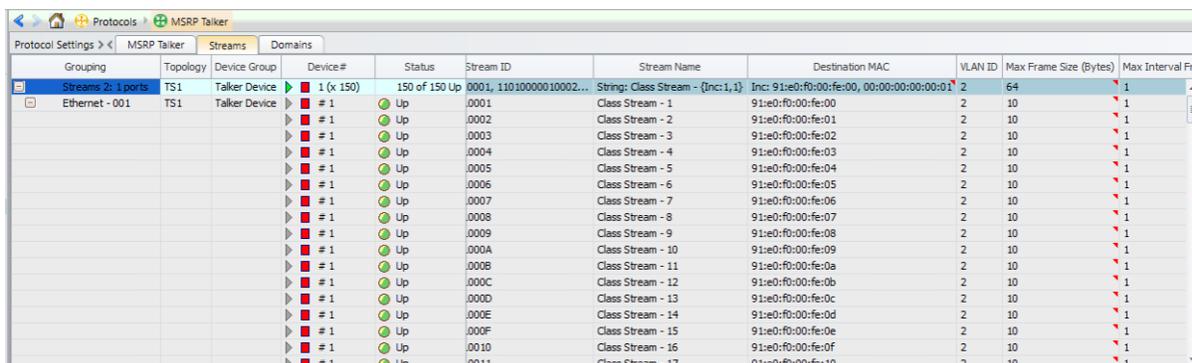
### What was tested

The maximum overall number of active AVB streams that the Catalyst switch supports. Due to memory limitations there is a maximum number of total AVB registrations that may be recorded by a Bridge. This limit varies between implementations. The registration limits will typically also vary depending on AVB Listener and Talker attributes.

### How we did it

The Catalyst switches in our test bed are specified to handle the registration of 130 streams for Class A and 150 streams for Class B traffic. We started by registering and then sending 120 registered streams, each carrying about 6 Mbps of data, and then incrementally increased the number AVB streams registering and sending data.

All AVB registration and traffic generation per AVB stream was instrumented through the Ixia test system. All stream traffic was unidirectional and passed through the full seven-hop test bed. The image below illustrated how streams were built in the Ixia system.



The screenshot shows the Ixia MSRP Talker interface with a table of 150 active streams. The table columns include Grouping, Topology, Device Group, Device#, Status, Stream ID, Stream Name, Destination MAC, VLAN ID, Max Frame Size (Bytes), and Max Interval. The streams are listed as Class Stream - 1 through Class Stream - 17, with a total of 150 streams shown as '150 of 150 Up'.

| Grouping           | Topology | Device Group  | Device#   | Status        | Stream ID               | Stream Name                       | Destination MAC                            | VLAN ID | Max Frame Size (Bytes) | Max Interval |
|--------------------|----------|---------------|-----------|---------------|-------------------------|-----------------------------------|--|---------|------------------------|--------------|
| Streams 2: 1 ports | TS1      | Talker Device | 1 (x 150) | 150 of 150 Up | 0001, 11010000010002... | String: Class Stream - {Inci 1,1} | Inci: 91:e0:f0:00:fe:00, 00:00:00:00:00:01 | 2       | 64                     | 1            |
| Ethernet - 001     | TS1      | Talker Device | # 1       | Up            | .0001                   | Class Stream - 1                  | 91:e0:f0:00:fe:00                          | 2       | 10                     | 1            |
|                    |          |               | # 1       | Up            | .0002                   | Class Stream - 2                  | 91:e0:f0:00:fe:01                          | 2       | 10                     | 1            |
|                    |          |               | # 1       | Up            | .0003                   | Class Stream - 3                  | 91:e0:f0:00:fe:02                          | 2       | 10                     | 1            |
|                    |          |               | # 1       | Up            | .0004                   | Class Stream - 4                  | 91:e0:f0:00:fe:03                          | 2       | 10                     | 1            |
|                    |          |               | # 1       | Up            | .0005                   | Class Stream - 5                  | 91:e0:f0:00:fe:04                          | 2       | 10                     | 1            |
|                    |          |               | # 1       | Up            | .0006                   | Class Stream - 6                  | 91:e0:f0:00:fe:05                          | 2       | 10                     | 1            |
|                    |          |               | # 1       | Up            | .0007                   | Class Stream - 7                  | 91:e0:f0:00:fe:06                          | 2       | 10                     | 1            |
|                    |          |               | # 1       | Up            | .0008                   | Class Stream - 8                  | 91:e0:f0:00:fe:07                          | 2       | 10                     | 1            |
|                    |          |               | # 1       | Up            | .0009                   | Class Stream - 9                  | 91:e0:f0:00:fe:08                          | 2       | 10                     | 1            |
|                    |          |               | # 1       | Up            | .000A                   | Class Stream - 10                 | 91:e0:f0:00:fe:09                          | 2       | 10                     | 1            |
|                    |          |               | # 1       | Up            | .000B                   | Class Stream - 11                 | 91:e0:f0:00:fe:0a                          | 2       | 10                     | 1            |
|                    |          |               | # 1       | Up            | .000C                   | Class Stream - 12                 | 91:e0:f0:00:fe:0b                          | 2       | 10                     | 1            |
|                    |          |               | # 1       | Up            | .000D                   | Class Stream - 13                 | 91:e0:f0:00:fe:0c                          | 2       | 10                     | 1            |
|                    |          |               | # 1       | Up            | .000E                   | Class Stream - 14                 | 91:e0:f0:00:fe:0d                          | 2       | 10                     | 1            |
|                    |          |               | # 1       | Up            | .000F                   | Class Stream - 15                 | 91:e0:f0:00:fe:0e                          | 2       | 10                     | 1            |
|                    |          |               | # 1       | Up            | .0010                   | Class Stream - 16                 | 91:e0:f0:00:fe:0f                          | 2       | 10                     | 1            |
|                    |          |               | # 1       | Up            | .0011                   | Class Stream - 17                 | 91:e0:f0:00:fe:10                          | 2       | 10                     | 1            |

Source: Miercom

### Findings, conclusions

We found we could create and concurrently run 130 active, fully functional Class A streams and 150 functional Class B streams.

Each stream was running with approximately 6 Mbps of traffic across all seven hops with 1-Gbps links between each hop.

## 9 – AVB Scale Test

We tested how the Cisco AVB system scales by sending 50 Class A AVB streams from the Ixia system through the six Cisco 9300 and 3850 switches, connected in series. Each of the switches had successfully reserved the required bandwidth for all 50 Class A streams. At the final switch, four listeners were configured to receive all 50 incoming streams individually. We verified that all 50 streams multiplexed out the four ports, back to the Ixia receiver. The multiplexing or multicast replication only occurred on the last switch in the series where the listeners were connected. This created 4 x 50, or 200, streams of Class A AVB data split across the four listeners.

| Grouping         | Topology | Device Group  | Device# | Status      | VLAN ID | Max Frame Size (Bytes) | Max Interval Frames | Per Frame Overhead (Bytes) | Class Measurement Interval (µs) | SR Class | Bandwidth (Mbps) |
|------------------|----------|---------------|---------|-------------|---------|------------------------|---------------------|----------------------------|---------------------------------|----------|------------------|
| Stream 0 - Ixora | TS1      | Talker Device | # 0     | 50 of 50 Up | 2       | 64                     | 1                   | 42                         | 125                             | Class A  | 6.78             |
| Ethernet - 001   | TS1      | Talker Device | # 1     | Up          | 2       | 64                     | 1                   | 42                         | 125                             | Class A  | 6.78             |
|                  |          |               | # 2     | Up          | 2       | 64                     | 1                   | 42                         | 125                             | Class A  | 6.78             |
|                  |          |               | # 3     | Up          | 2       | 64                     | 1                   | 42                         | 125                             | Class A  | 6.78             |
|                  |          |               | # 4     | Up          | 2       | 64                     | 1                   | 42                         | 125                             | Class A  | 6.78             |
|                  |          |               | # 5     | Up          | 2       | 64                     | 1                   | 42                         | 125                             | Class A  | 6.78             |
|                  |          |               | # 6     | Up          | 2       | 64                     | 1                   | 42                         | 125                             | Class A  | 6.78             |
|                  |          |               | # 7     | Up          | 2       | 64                     | 1                   | 42                         | 125                             | Class A  | 6.78             |
|                  |          |               | # 8     | Up          | 2       | 64                     | 1                   | 42                         | 125                             | Class A  | 6.78             |
|                  |          |               | # 9     | Up          | 2       | 64                     | 1                   | 42                         | 125                             | Class A  | 6.78             |
|                  |          |               | # 10    | Up          | 2       | 64                     | 1                   | 42                         | 125                             | Class A  | 6.78             |
|                  |          |               | # 11    | Up          | 2       | 64                     | 1                   | 42                         | 125                             | Class A  | 6.78             |
|                  |          |               | # 12    | Up          | 2       | 64                     | 1                   | 42                         | 125                             | Class A  | 6.78             |
|                  |          |               | # 13    | Up          | 2       | 64                     | 1                   | 42                         | 125                             | Class A  | 6.78             |
|                  |          |               | # 14    | Up          | 2       | 64                     | 1                   | 42                         | 125                             | Class A  | 6.78             |
|                  |          |               | # 15    | Up          | 2       | 64                     | 1                   | 42                         | 125                             | Class A  | 6.78             |
|                  |          |               | # 16    | Up          | 2       | 64                     | 1                   | 42                         | 125                             | Class A  | 6.78             |
|                  |          |               | # 17    | Up          | 2       | 64                     | 1                   | 42                         | 125                             | Class A  | 6.78             |
|                  |          |               | # 18    | Up          | 2       | 64                     | 1                   | 42                         | 125                             | Class A  | 6.78             |
|                  |          |               | # 19    | Up          | 2       | 64                     | 1                   | 42                         | 125                             | Class A  | 6.78             |
|                  |          |               | # 20    | Up          | 2       | 64                     | 1                   | 42                         | 125                             | Class A  | 6.78             |

Source: Miercom

Below is a portion of the output. All 50 streams show the same 64-byte frame coming in at the same 6.78 Mbps bandwidth, as shown in the last column in the figure above.

| Traffic Item   | Tx Frames | Rx Expected Frames | Rx Frames  | Frames Delta | Loss % | Tx Frame Rate | Rx Frame Rate | Tx L1 Rate (bps) | Rx L1 Rate (bps)  | Rx Bytes      | Tx Rate (Bps) | Rx Rate (Bps) | Tx Rate (bps) | Rx Rate (bps) |
|----------------|-----------|--------------------|------------|--------------|--------|---------------|---------------|------------------|-------------------|---------------|---------------|---------------|---------------|---------------|
| Traffic Item 1 | 6,907,514 | 27,630,056         | 27,629,996 | 60           | 0.000  | 395,047.500   | 1,580,188.000 | 335,000,280.000  | 1,339,999,424.000 | 2,376,179,656 | 33,974,085... | 135,896,16... | 271,792,68... | 1,087,16...   |

Source: Miercom

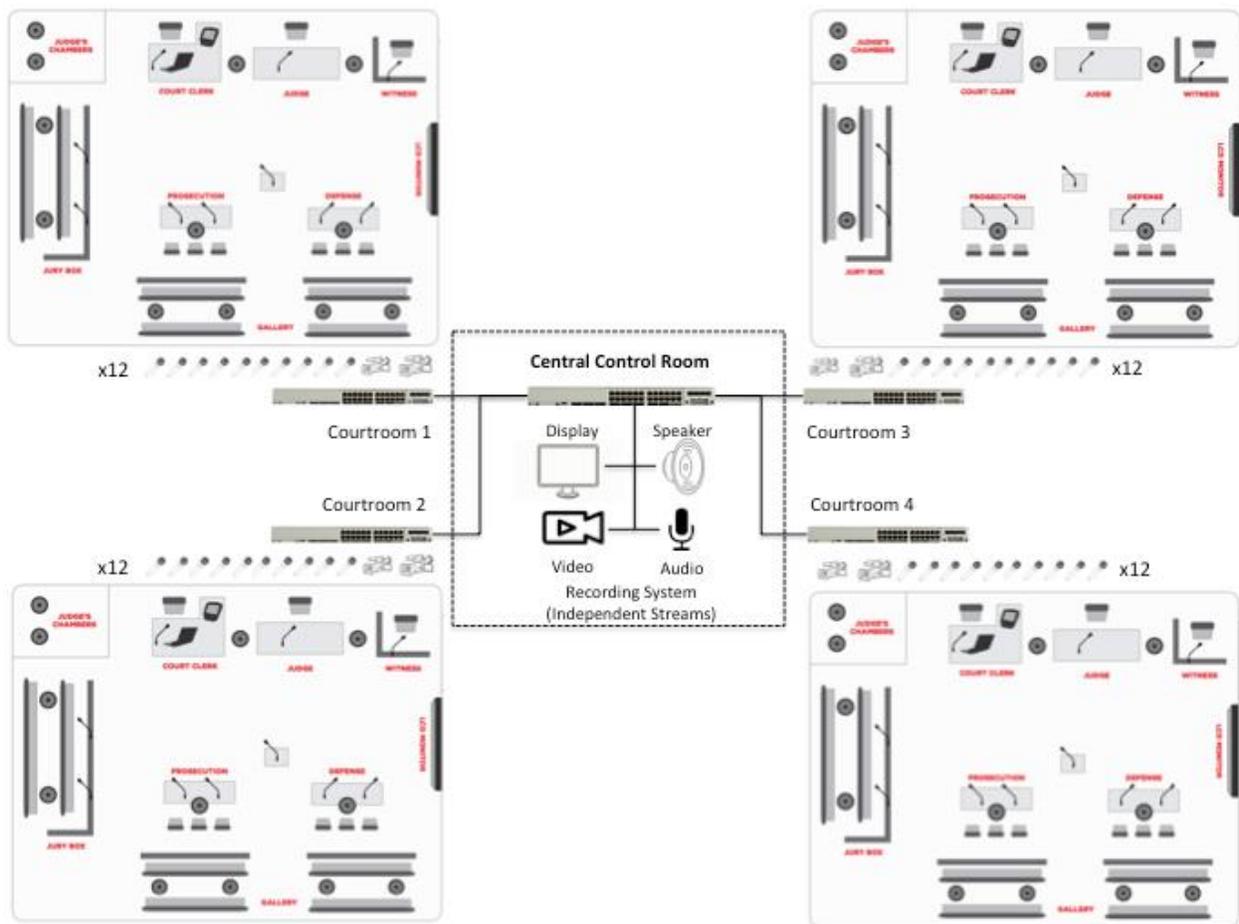
Ixia traffic statistics show the output packet rate from the Ixia Talker to be 330 Mbps and input packet rate from the Ixia Listener to be 1,320 Mbps. The Receive rate after six layers of Cisco listeners and then multiplexed with all 50 streams going out each of the four ports, back to the Ixia final listener, is 4 x 330 Mbps – or 1.32 Gbps.

| Traffic Item   | Tx Frame Rate | Rx Frame Rate | Tx L1 Rate (bps) | Rx L1 Rate (bps)  | Tx Rate (Bps)  | Rx Rate (Bps)   | Tx Rate (bps)   | Rx Rate (bps)     | Tx Rate (Kbps) |
|----------------|---------------|---------------|------------------|-------------------|----------------|-----------------|-----------------|-------------------|----------------|
| Traffic Item 1 | 384,028.500   | 1,536,114.000 | 325,656,168.000  | 1,302,624,672.000 | 33,026,451.000 | 132,105,804.000 | 264,211,608.000 | 1,056,846,432.000 | 264,211.608    |

Source: Miercom

Below is an image depicting multiple streams coming from different sources. In this case, there are twelve streams from four rooms, for a total of 48 different streams into the networks of four types of listeners in a central monitoring location. These types are: video display, audio distribution, video recording system and audio recording system. Each listener systems gets all 48 streams or so and can choose what kind of service to provide, respectively.

This use case could reflect a courthouse with four courtrooms, with a central switch functioning as the listener. The talkers send out multiple AVB data streams with audio and video synchronized to the common Grandmaster clock.



Source: Miercom

## 10 – About "Miercom Performance Verified" Testing

This report was sponsored by Cisco Systems, Inc. The data was obtained completely and independently by Miercom engineers and lab-test staff as part of our Performance Verified assessment. Testing such as this is based on a methodology that is jointly co-developed with the sponsoring vendor. The test cases are designed to focus on specific claims of the sponsoring vendor, and either validate or repudiate those claims. The results are presented in a report such as this one, independently published by Miercom.

## 11 – About Miercom

Miercom has published hundreds of network-product-comparison analyses in leading trade periodicals and other publications. Miercom's reputation as the leading, independent product test center is undisputed.

Private test services available from Miercom include competitive product analyses, as well as individual product evaluations. Miercom features comprehensive certification and test programs including: Certified Interoperable, Certified Reliable, Certified Secure and Certified Green. Products may also be evaluated under the Performance Verified program, the industry's most thorough and trusted assessment for product usability and performance.

## 12 – Use of This Report

Every effort was made to ensure the accuracy of the data contained in this report, but errors and/or oversights can occur. The information documented in this report may also rely on various test tools, the accuracy of which is beyond our control. Furthermore, the document relies on certain representations by the vendors that were reasonably verified by Miercom but beyond our control to verify to 100 percent certainty.

This document is provided "as is," by Miercom and gives no warranty, representation or undertaking, whether express or implied, and accepts no legal responsibility, whether direct or indirect, for the accuracy, completeness, usefulness or suitability of any information contained in this report.

No part of any document may be reproduced, in whole or in part, without the specific written permission of Miercom or Cisco Systems, Inc. All trademarks used in the document are owned by their respective owners. You agree not to use any trademark in or as the whole or part of your own trademarks in connection with any activities, products or services which are not ours, or in a manner which may be confusing, misleading or deceptive or in a manner that disparages us or our information, projects or developments.

© 2018 Miercom. All Rights reserved. No part of this publication may be reproduced, photocopied, stored on a retrieval system, or transmitted without the express written consent of the authors. Please email [reviews@miercom.com](mailto:reviews@miercom.com) for additional information.