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Precision Time Protocol (PTP)

The objective of this document is to provide basic information on PTP including some details on what this protocol is, listing the hard aspects, reviewing what makes a good PTP Grandmaster, listing some best practices and describing what is next for PTP.

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Contents

INTRODUCTION

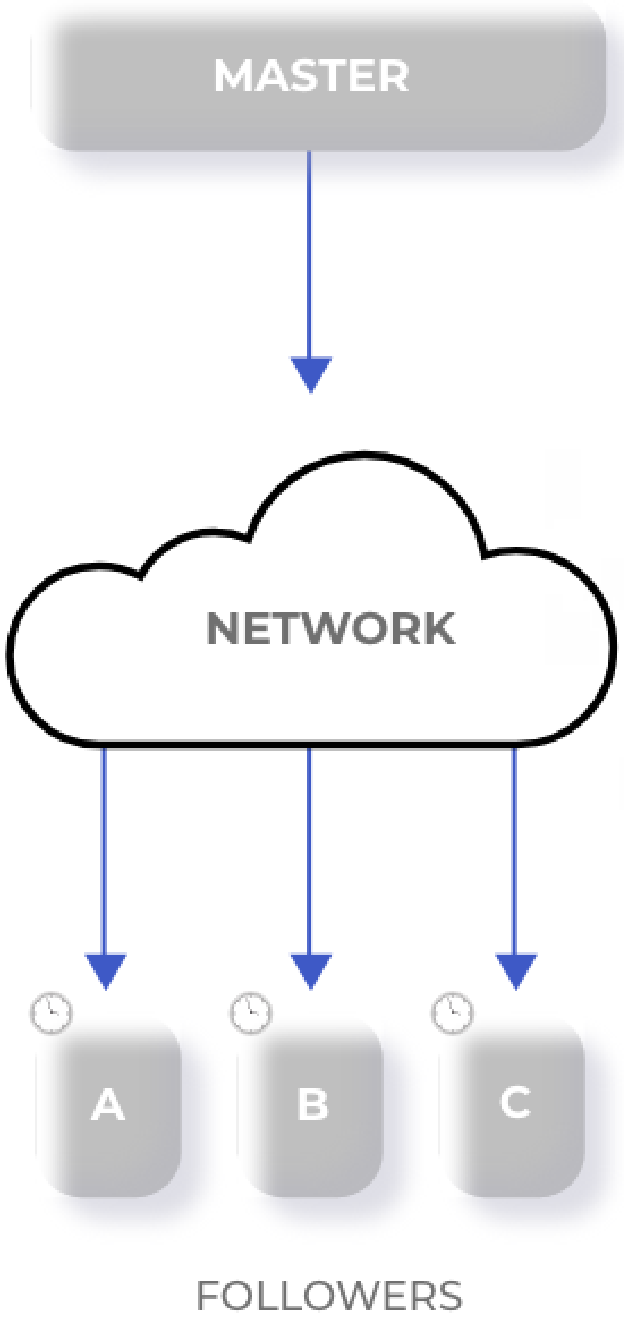
If you have been associated with the Broadcast industry in the last 4 years, you probably heard about ***SMPTE ST 2110*** and if you were directly engaged on any project or activity that involved video or audio over IP, you certainly know that the Precision Time Protocol (PTP or IEEE 1588) is literally the pulse that keeps the entire network synchronized. You definitely understand that some of the funky issues on the network are consequences of unstable PTP setup.

Nowadays, it is very easy to find in-depth tutorial videos and papers on PTP on the Internet that would give you deep details. In the interests of not boring you if you are already knowledgeable about PTP, you may skip this section if you want. However, if you feel the need for a refresher, keep on reading.

The origins of PTP go back to the 1980s with Hewlett Packard and Agilent Technologies. Some people would be surprised to find out that the original reason to write the PTP protocol was to synchronize devices in industrial automation and measurement networks. The first developers would give you that hint.

The IEEE1588-2002 committee did not have any member from the telecom industry. It was mainly formed by industrial automation and test and measurement companies. Their applications required critical device synchronization.

In 2003 Nortel Networks® proposed the application of PTP on Metro Ethernet Enterprise Solutions. Since then many other telecom applications used the PTP protocol for device synchronization and in 2008, the PTPv2 – IEEE 1588-2008 was published. It was not backward compatible to PTPv1 – IEEE 1588-2002 though. The latest PTP version is the IEEE 1588-2019 (PTPv2.1).



WHAT IS PTP?

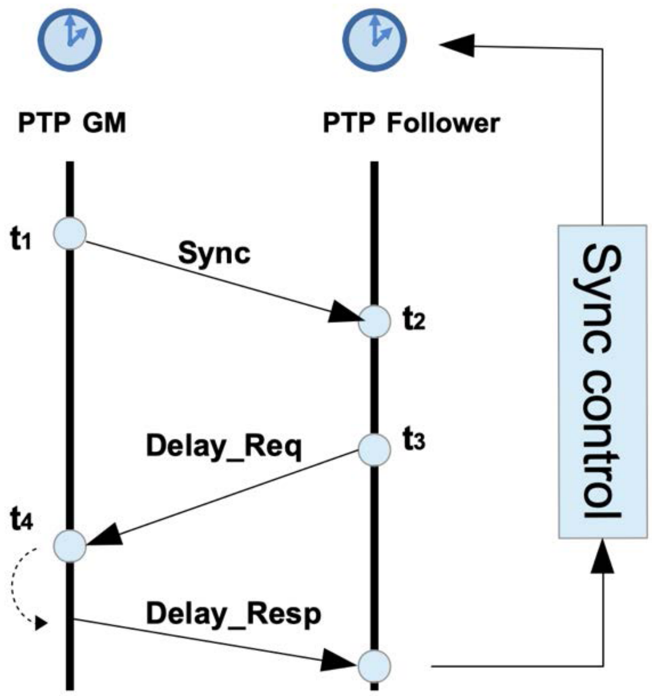
But after all, what's PTP? In a nutshell, PTP is a protocol designed to allow follower devices to be precisely synchronized to a reference device called master or PTP Grandmaster. It allows followers to match or lock frequency and phase to the master.

How precise are we talking? In broadcast applications, we target to keep all devices locked within +/- 400ns or so. Network Time Protocol (NTP), by contrast, is accurate to within 1-2ms in a Local Area Network (LAN) and often tens of milliseconds on the public Internet, so clearly we need something better.

To achieve frequency and phase alignment, there are two distinct but related activities:

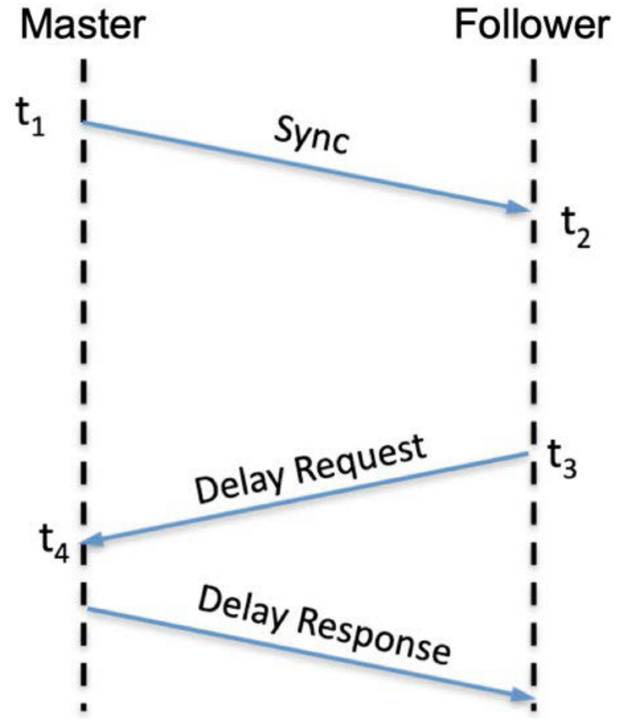
- The master periodically sends out SYNC messages which indicate the current time aligning frequency, but this mechanism does not guarantee phase alignment because there is no information about the network delay and, as we all know, the network is dynamic and the delays will change over time.
- The followers periodically perform a delay measurement to find out the flight time across the network. Each follower sends a DELAY REQUEST message to the master which will respond to each specific follower via DELAY RESPONSE messages. This process allows followers to offset the time received from the SYNC messages to phase align to the master.

The progressive exchange of PTP event messages enables a follower to track the master's timebase very precisely, even if the network delays change over time.



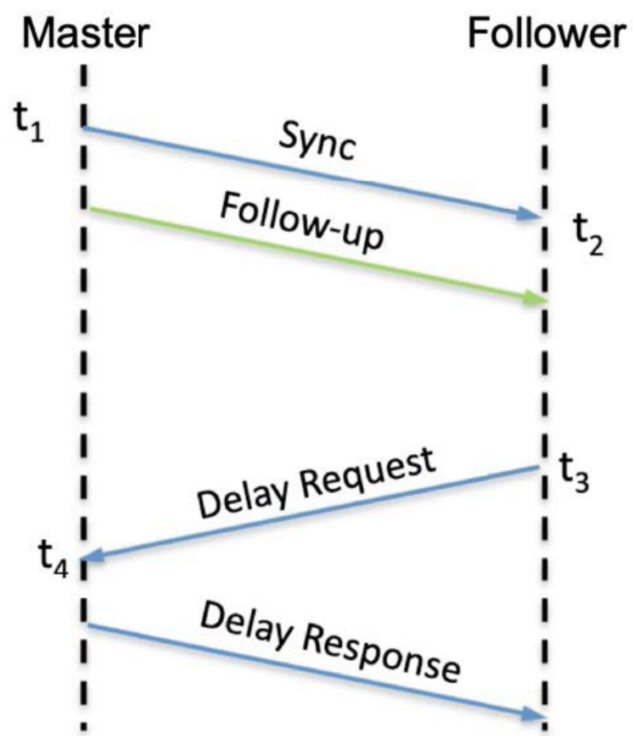
MODES

The master and the followers can exchange PTP messages in One-Step or Two-Step modes. This section summarizes how both modes work. The difference is that in Two-Step, for every SYNC message, there is a FOLLOW-UP message which complements the information and makes it easier for the followers to process the messages. All followers must support both One-Step and Two-Step modes.



Regardless of mode, it is critical that the PTP Grandmaster and Followers agree upon the intervals of SYNC and ANNOUNCE messages. These are often specified in a **PTP profile** (which we'll discuss a little later), but can often be set manually by the user. If the interval of these messages (for example 4/second), is not matched, the follower may not be able to lock to the master.

The other important thing you should know about PTP is that there could be multiple PTP masters in the network. In this case, the masters could be set in different domains and the followers would select which domain to lock to. If there is more than one master on a specific domain, the followers elect the best clock by using the Best Master Clock Algorithm (BMCA).



BEST MASTER CLOCK ALGORITHM (BMCA)

BMCA allows multiple clocks on the same domain to co-exist and only the best clock on a domain is used by the followers. If the best clock fails, the followers would automatically sync to the next best master.

The algorithm is relatively simple and is based on criteria that includes:

- **Priority 1** – User-defined priority, which overrides all other criteria
- **Accuracy** – How well does the master keep time?
- **Quality** – How good is the master's time reference?
- **Priority 2** – User-defined. If all other criteria are equal, Priority 2 will break the tie.

PTP PROFILES

Depending on the industry and application, the mode and intervals that the master and followers exchange the PTP messages require a specific configuration. To address that, there are PTP Profiles.

Examples of PTP Profiles are:

- Default profile (IEEE 1588-2008)
- AVB profile (IEEE 802.1AS, a.k.a. generalized PTP)
- SMPTE / Broadcast profile (SMPTE ST 2059-2)
- AES Profile (AES67-R16:2016)
- Telecommunication profile (ITU G.8265.1)
- Power profile (IEEE PC37.238)

The main differences between profiles are:

- Frequency and time synchronization versus just frequency alone
- Default and recommended message intervals for SYNC and ANNOUNCE messages
- Type of protocol encapsulation (Layer2 versus Layer3, Multicast versus Unicast)
- Boundary Clocks versus Transparent Clocks (explained later in this paper) topologies (End- to-End or Peer-to-Peer)
- Stratum level for clocking and time domains
- How to handle legacy nodes versus time-aware bridges
- Redundancy support
- Performance requirements such as frequency/time accuracy and lock time

WHY DO WE NEED PTP?

One could argue that there are other ways to synchronize the devices on the network, so why do we need PTP? For instance, NTP is accurate enough for many applications, however it is software based so the network latency will critically impact the accuracy. On the other hand, PTP uses dedicated hardware to generate its timestamps achieving accuracy in nanoseconds or even picoseconds depending on how time critical the application is. If your system needs an accuracy in the order of hundreds of microseconds or milliseconds you can use NTP, however if your required accuracy is around hundreds of nanoseconds or lower, you should use PTP.

Hopefully at this point you understand a little bit more about PTP, therefore you could conclude that some applications naturally require this protocol specially when the main requirement is if you need sub-microsecond accuracy. Definitely Broadcast IP deployments require a universal system timing over IP Network with nanosecond level synchronization, as provided by PTP.

Moreover, PTP replaces all other timing references in a studio such as Black Burst, Tri-Level Sync, Word Clock, Timecode, etc.

PTP-AWARE TOPOLOGIES

So far, we discussed only master and followers. At this point we should discuss about another very important component of the network which is the switch. The switches which do not support PTP have a nondeterministic forwarding delay that negatively impacts the accuracy.

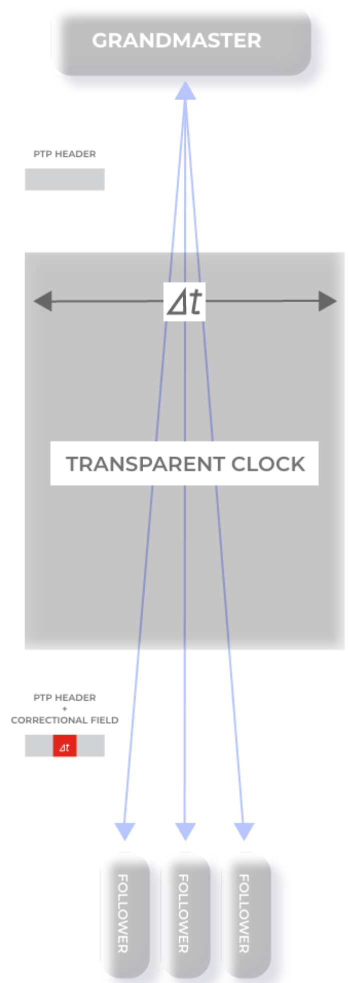
There are two modes that PTP aware switches support: Transparent Clock and Boundary Clock.

TRANSPARENT CLOCK (TC)

The switches which support TC have hardware that can measure the residence time of the PTP messages, then insert this delta time into a correction field in the header of the messages.

This process is more beneficial for End-to-End (E2E) PTP synchronization. However, it is not scalable because a huge number of followers could overwhelm the PTP Grandmaster.

For automation, control systems and power applications, the use of PTP is fundamental to guarantee that the sensors, actuators and other critical devices are synchronized in a few nanoseconds. The timestamping of logged data and messages require precise accuracy in order to provide proper system control and monitoring. Imagine a system operating a thermoelectric power plant with inaccurate synchronization. Would you consider to live close to this place?



BOUNDARY CLOCK (BC)

In this type of switch, the port which is connected to the PTP Grandmaster is set as follower. Then a clock tree is created where each downstream port of the switch acts as a PTP Master to the follower devices. In this case, the followers do not interact with the Grandmaster directly.

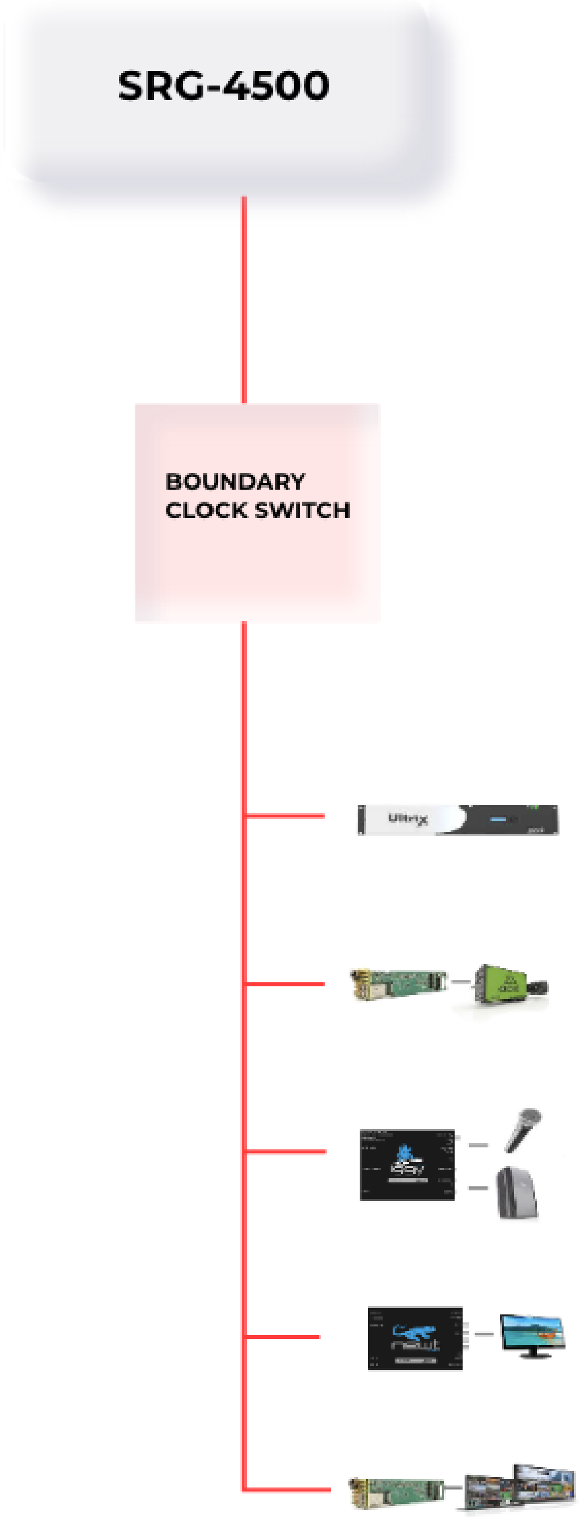
Boundary Clocks use Peer-to-Peer (P2P) PTP synchronization and significantly reduce the load on the PTP Grandmaster and eliminate the uncertainty of packet residence time in the switch.

COMMON PTP TOPOLOGIES

There are many different network topologies that can be used for PTP. This section illustrates a few of the most common use cases.

NON-REDUNDANCY

The simplest network topology for a PTP synchronization system is shown below. In this case, the PTP Grandmaster and all follower devices are connected to a Boundary Clock switch and the PTP Grandmaster is GPS-locked.



SMPTE ST 2022-7

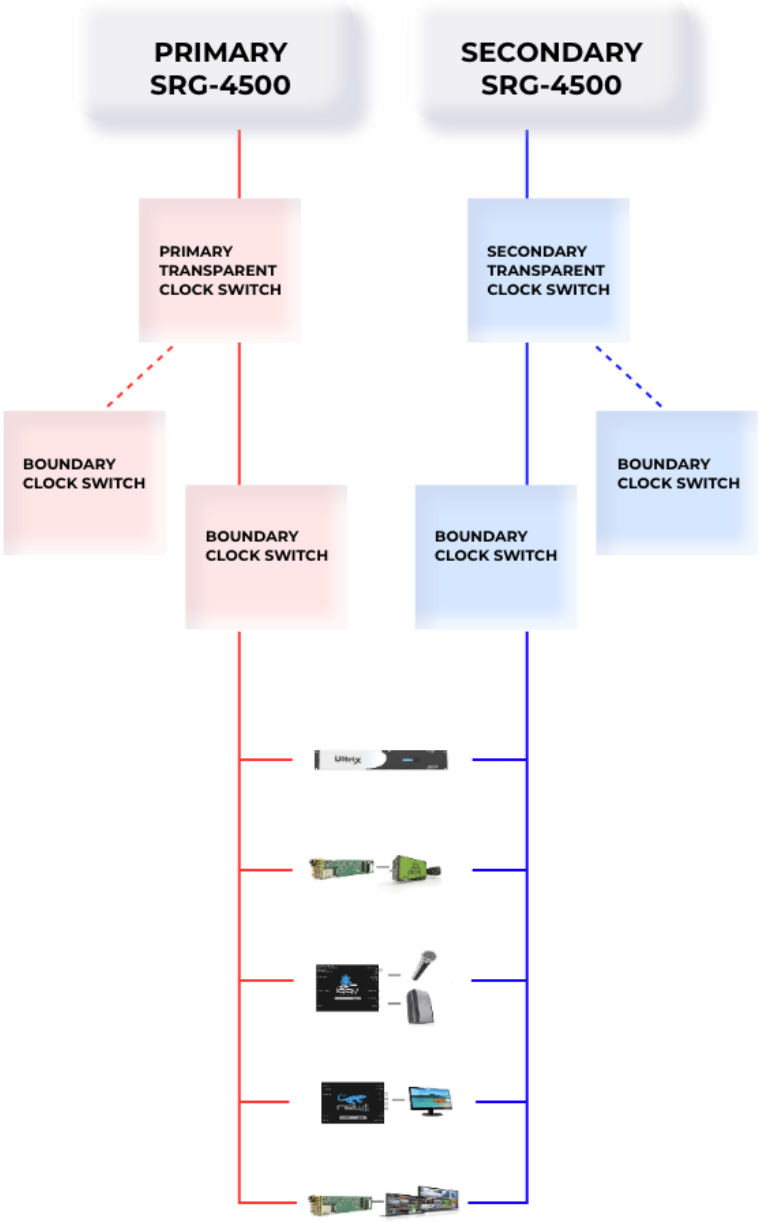
A more sophisticated topology is necessary when the system requires SMPTE ST 2022-7 which is a glitchless redundancy standard. The Red (primary) and the Blue (secondary) networks are symmetrical.

Primary and secondary PTP Grandmaster devices are connected to the respective Red and Blue Boundary Clock switches.

The follower devices must have two ports and support the SMPTE ST 2022-7 standard.

If the primary PTP Grandmaster or the Boundary Clock on the Red network fails, there are no glitches or media stream interruption because all followers will be automatically locked to the secondary PTP Grandmaster and will transmit and receive the media streams via the Blue Boundary Clock switch.

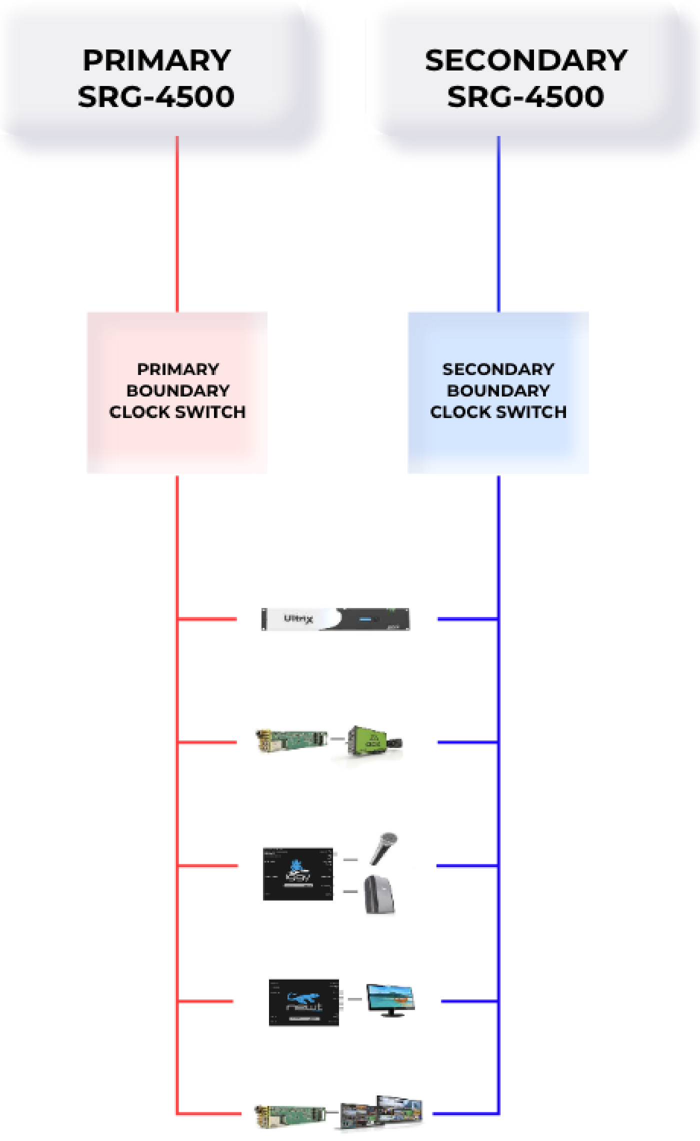
This topology offers great resilience to failures.



SPINE-LEAF

The Spine-leaf is the most robust and the most expensive network topology. The “spine” is formed by the Transparent Clock switches and the primary and secondary PTP Grandmaster which can be used on both Red and Blue networks. Only PTP messages are allowed to flow between the two networks. In this case, the secondary PTP Grandmaster should have a higher Priority2 value than the primary PTP Grandmaster.

The advantage of this setup is that BOTH PTP Grandmasters are visible to both red and blue networks but only one is being followed by the followers at a time. If either PTP Grandmaster fails, the other will still provide PTP synchronization to both networks. The followers will perform the BMCA algorithm to lock to the primary or secondary PTP Grandmaster when necessary.



WHY IS PTP CHALLENGING?

The PTP synchronization process requires a high precision environment. However, there are many aspects of the network that are unpredictable and beyond control such as: hardware dependent variations, path asymmetries and delay variations.

HARDWARE DEPENDENT VARIATIONS

There are intrinsic variations in the network devices caused by their internal oscillators that run at different rates and stabilities. In addition, the hardware contains components that will change characteristics due to ageing and temperature effects which will cause clock inaccuracy and ultimately sampling errors of packet events.

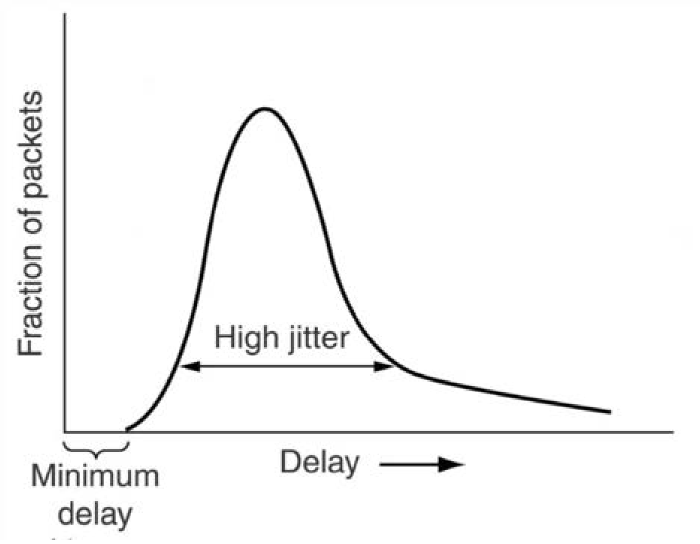
PATH ASYMMETRY

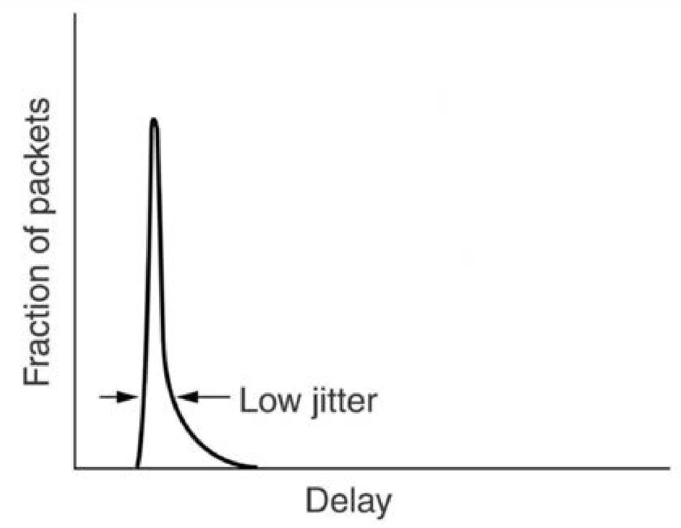
Early in this paper, there is a quick description on how the followers lock frequency and phase to the PTP Grandmaster exchanging SYNC and DELAY REQUEST messages. One negative effect that happens in the network is that the SYNC messages from master to followers have a different delay than the DELAY REQUEST messages from followers to master. This path asymmetry provokes a constant error in synchronization because the calculated roundtrip delay is always bigger than the real delay value.

PACKET DELAY VARIATION (PDV)

Non-PTP aware switches do not process the PTP messages in any special way not giving priority over any other packet. Therefore, because of traffic-related congestion, these PTP messages are queued suffering unpredictable delays increasing packet jitter and worsening the accuracy of the PTP synchronization process.

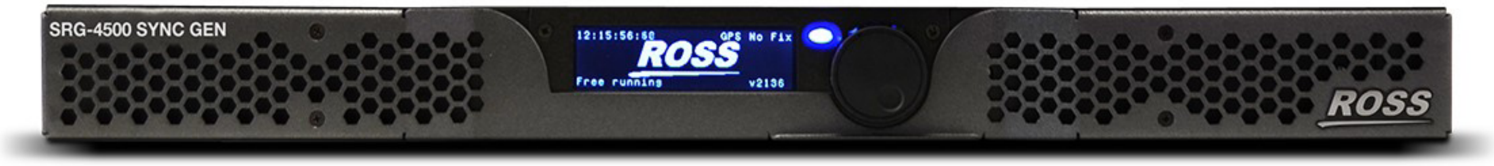
For example, a typical RTP media packet is about 1500 bytes in length and has a transmission time of about 12ms. If the Ethernet switch is just starting to transmit a media packet when a PTP arrives, it will delay the PTP packet by up to 12ms while it transmits the media packet. This 12ms is significant when we are trying for <100nS precision.





WHAT MAKES A GOOD PTP GRANDMASTER?

- In summary, a good PTP Grandmaster would have at least the following characteristics:
- Dedicated hardware – designed as PTP Grandmaster
- Offers multiple options for reference clocks
- Provides reference clocks for both IP and Baseband ecosystems
- Could function as follower to provide accurate local clock references
- Provides diagnostic capabilities



DEDICATED HARDWARE

As you may know, some IP bridge devices can act as PTP Grandmaster and depending on the application, this solution could provide a reasonable and stable synchronization, so you may be tempted to dismiss the use of a dedicated PTP Grandmaster device. However, those IP bridge devices are not designed for that purpose. It sounds obvious, but to guarantee that you will have great accuracy and long-term synchronization stability, you should consider acquiring a device that was specifically designed as PTP Grandmaster.

Since the PTP Grandmaster is one of the most important elements of the system, it is expected that the vendors who provide this kind of device, design and assemble the hardware with high quality components with tight tolerance. For sure those vendors spend many hours of product validation performing specific PTP test cases including long-term soaking and temperature cycle tests to guarantee that their products have clock stability and function as well as a PTP Grandmaster. That would explain why those devices may be a bit expensive.

Ross Video is enabling full PTP support on the very popular SRG-4500. This product is designed for high stability Master Sync and time reference operation with high degree of reliability including redundant power supply.

MULTIPLE OPTIONS FOR REFERENCE CLOCKS

For a very accurate synchronization application, you would need to use GPS as reference for your PTP Grandmaster, but at another moment or different application, you may need to synchronise your PTP Grandmaster to a video clock or other reference. Therefore, your PTP Grandmaster should be versatile and offer multiple options for reference clocks.

To meet this demand, when set as the PTP Grandmaster, the SRG-4500 can use a reference clock from the following options:

- GPS Frequency and Phase lock
- Internal oscillator (Free run)
- Genlock to Video
- Genlock to Video + VITC
- 10 MHz lock

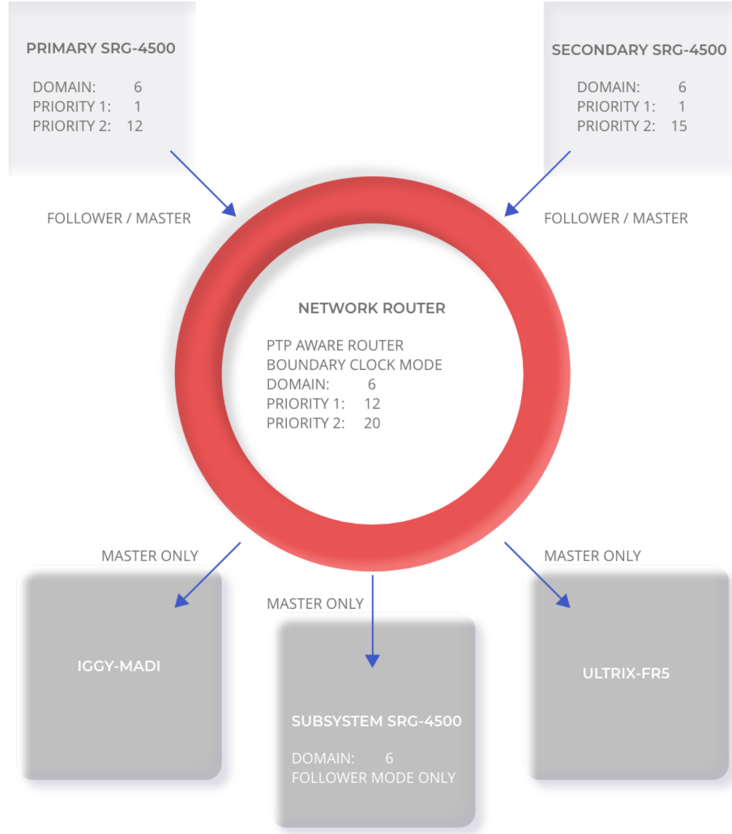
PTP AND BASEBAND TIMING GENERATION

In many installations, you will be faced with a hybrid design of IP and traditional or legacy baseband devices, such SDI. For these systems, it is crucial that you keep the IP and baseband worlds locked in time. Otherwise you will be faced with asynchronous interfaces as signals pass between SDI and IP.

The SRG-4500 provides both PTP Grandmaster plus a full selection of analog, SDI and audio test signals, and ensures these are all derived from a common core clock. This ensures that IP and baseband worlds stay locked together.

OPERATES AS FOLLOWER

You may have some devices on your system that must use studio reference clocks that are frequency and phase locked to the PTP Grandmaster. To address this issue, you can acquire a device that provides only reference clocks or you can use a PTP Grandmaster device that can be set as follower only and provides all your studio reference clocks.



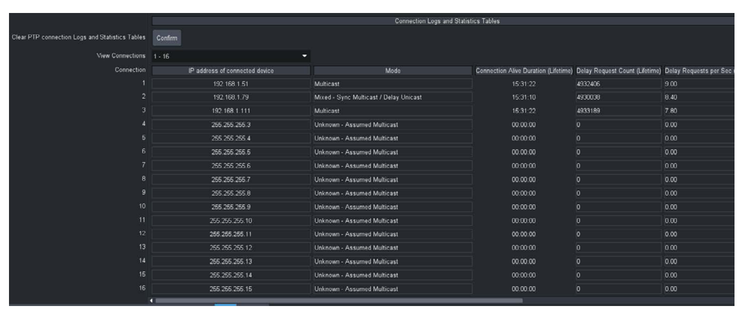
The SRG4500 provides all the required reference timing signals to precisely time complex broadcast facilities, including: Black Burst, Tri-Level Sync, Word Clock, and DARS. Additionally, the SRG-4500 provides flexible timecode generation delivered through dedicated LTC outputs or embedded VITC through analog composite and SDI video outputs.

DIAGNOSTIC CAPABILITIES

Diagnostic tools are crucial in deploying and troubleshooting PTP on your network. You should be able to check the status of the reference clock used for the PTP process, see the list of followers locked to the PTP Grandmaster as well as any relevant alarms.

The SRG-4500 provides detailed information about the PTP process via the following status files and alarms:

- **UTC Time** — Displays the current UTC Time
- **PTP MAC Address** — Displays the PTP port MAC address
- **PTP Clock ID** — Displays the PTP Clock ID
- **PTP Grandmaster Status** — Displays the current profile status
- **PTP Alert** — Displays any PTP alert message
- **PTP Status Alarm** — Displays alarm status from Unlocked, Locking and Locked


Connection Logs and Statistics Tables

Clear PTP connection Logs and Statistics Tables: Confirm

View Connections: 1 - 16

Connection	IP address of connected device	Mode	Connection Alive Duration (Lifetime)	Delay Request Count (Lifetime)	Delay Requests per Sec
1	192.168.1.51	Multicast	15:31:22	4932406	9.00
2	192.168.1.79	Mixed - Sync Multicast / Delay Unicast	15:31:10	4930038	8.40
3	192.168.1.111	Multicast	15:31:22	4933189	7.80
4	255.255.255.3	Unknown - Assumed Multicast	00:00:00	0	0.00
5	255.255.255.4	Unknown - Assumed Multicast	00:00:00	0	0.00
6	255.255.255.5	Unknown - Assumed Multicast	00:00:00	0	0.00
7	255.255.255.6	Unknown - Assumed Multicast	00:00:00	0	0.00
8	255.255.255.7	Unknown - Assumed Multicast	00:00:00	0	0.00
9	255.255.255.8	Unknown - Assumed Multicast	00:00:00	0	0.00
10	255.255.255.9	Unknown - Assumed Multicast	00:00:00	0	0.00
11	255.255.255.10	Unknown - Assumed Multicast	00:00:00	0	0.00
12	255.255.255.11	Unknown - Assumed Multicast	00:00:00	0	0.00
13	255.255.255.12	Unknown - Assumed Multicast	00:00:00	0	0.00
14	255.255.255.13	Unknown - Assumed Multicast	00:00:00	0	0.00
15	255.255.255.14	Unknown - Assumed Multicast	00:00:00	0	0.00
16	255.255.255.15	Unknown - Assumed Multicast	00:00:00	0	0.00

Supporting up to 256 followers, the SRG-4500 provides a simple and complete status of the follower connections. The DashBoard interface presents a tab with the list of followers and each respective information.

BEST PRACTICES AND MOST COMMON ISSUES

In this section we discuss some of the most common problems when setting a PTP network in a broadcast deployment and ideas on how to overcome them. Be aware that this is not the ultimate list of all the problems you may face, however you will find some valuable tips to avoid headaches and frustrations.

INFRASTRUCTURE IN GENERAL

Keep the following in mind when deploying a PTP Grandmaster:

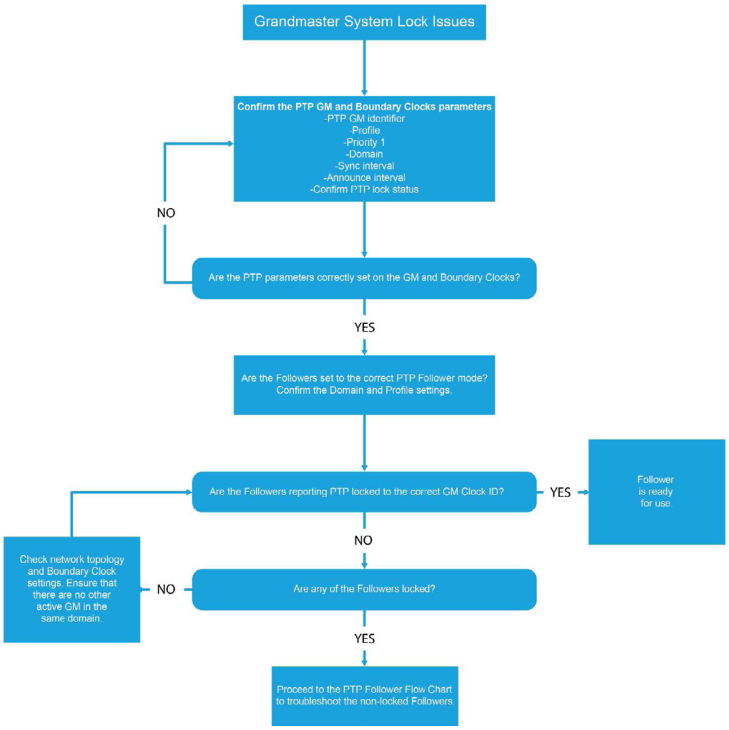
- Some IP devices can become the PTP master of the network and people decide to use them for that role in order to keep the cost down. However they are not Broadcast-grade and in a long term the synchronization may become unstable. For that reason, we strongly recommend you acquire a dedicated PTP Grandmaster device.
- In a spine-leaf topology, use Transparent Clock switches for the top stratum and Boundary Clock switches to connect your endpoint devices. This may look expensive initially, but the stability of your PTP synchronization and the easy debugging capabilities will quickly pay off.
- Use an engineering network setup to configure devices before plugging them to the production network. The ideal is that the engineering network would have the same parameters as the production network facilitating a safe and smooth deployment.
- Start your deployment by configuring your PTP Grandmaster, then the switches. Do not move to the next step until you guarantee that all Boundary Clock switches are locked to the PTP Grandmaster. Then, add the endpoint devices and confirm one at the time that all devices are locked and stable. You should always apply this motto: “If PTP is not stable, don’t even think about making connections”.
- Invest in a good monitoring and measurement system or at least get a free PTP monitoring software from the Internet. This will speed up a lot your debugging.
- Acquire endpoint devices that have embedded diagnostic tools to help you find network problems. For example, the Ross Video SDI-IP Bridge devices NEWT and RAPTOR provide statistics and details of the network and connections as well as a tool to capture PTP packets at the media ports.

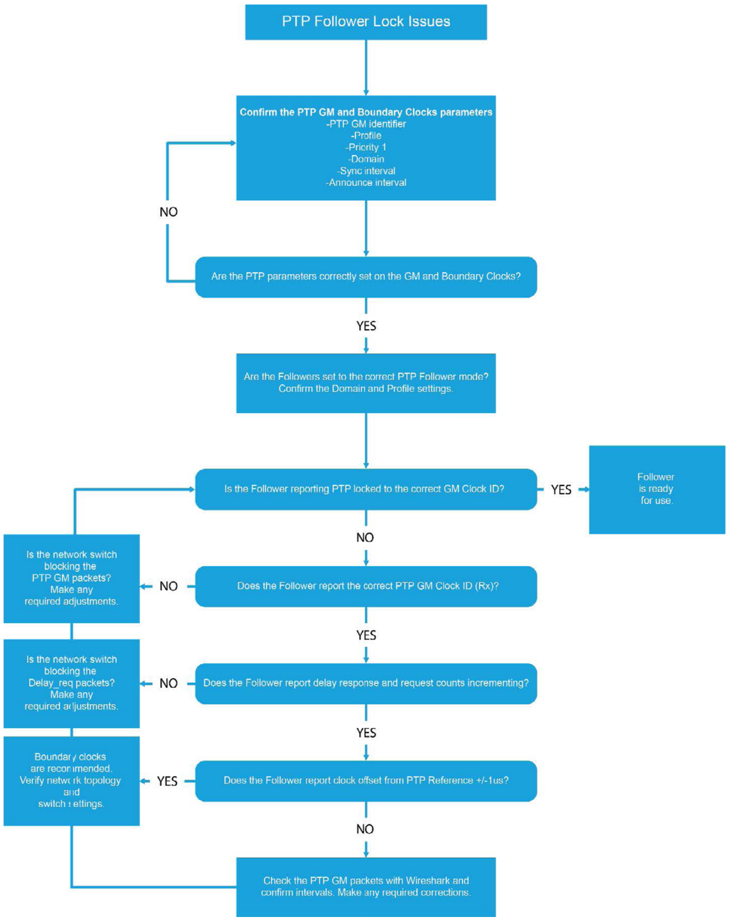
PTP GRANDMASTER/FOLLOWER SYNCHRONIZATION ISSUES

Keep the following in mind when troubleshooting synchronization issues:

- Do not use the default PTP Domain (0 or 127). This avoids situations where a new device with default domain is added, and unexpectedly takes over as the Grandmaster. If you always use a non-default domain, it forces the installer to verify the PTP settings on that device.
- Unless you know exactly what you are trying to achieve, do not change the Profile default values for SYNC and ANNOUNCE intervals. These profile defaults have been determined through extensive performance testing by industry experts and are well suited to most networks for optimal results. If you deviate, some follower devices may lock to PTP Grandmaster, even though there is a mismatch, but in the long term you may experience instabilities causing video or audio glitches.
- If you have a dedicated PTP Grandmaster, make sure all other devices are set to Follower Only mode. This will avoid that, for any reason, a device may try to become the master disturbing the network.
- Set your PTP Grandmaster to Mixed or Hybrid mode because some followers may use Unicast to send the DELAY REQUEST messages.
- To confirm that a follower is properly locked to the PTP Grandmaster, don't trust only the "locked" status. Always check if the Grandmaster Clock ID (GMID) matches the GMID on the follower (it should match the Grandmaster's Clock ID) and that if the offset from master is within +/- 1Us. The lower the value the better. A high offset from the master is usually caused by a misconfigured port of the switch.

The following flowcharts give you a few simple steps to help debug a PTP network installation.





WHAT'S NEXT FOR PTP?

In June 2020, the IEEE published the IEEE 1588-2019 (PTPv2.1) standard. Unlike the PTPv2 that could not interoperate with PTPv1, the PTPv2.1 was designed to be completely backward compatible to PTPv2.

PTPV2.1

The effort to keep this capability was well received by the users of PTPv2 because they can keep their current infrastructure and make a smooth transition to the updated standard. This is possible because all the new PTPv2.1 features are optional and built on top of the existing PTPv2 standard. Therefore, if you use the PTPv2.1 without enabling any new features, you are basically running PTPv2 and later you can enable them as needed.

In our opinion the following are the most relevant new PTPv2.1 features. However, others may be more useful for your application. Visit the IEEE website to learn more about the PTPv2.1 standard.

AUTHENTICATION TLV

The new PTPv2.1 features will increase robustness, flexibility and accuracy. Among these features, the most important one is related to security with the addition of Authentication TLV (type, length, value). The PTP messages will have cryptographic integrity checks preventing any malicious manipulation of the messages.

INTER-DOMAIN INTERACTING OPTION

The inter-domain-interacting option will allow for multiple PTP Grandmasters to be deployed in the network with different domains. This will increase robustness of the network providing the possibility that the followers could use a multi-domain clock mechanism via a single link to select the best PTP Grandmaster from other domains. If the chosen PTP Grandmaster has any issue the follower will automatically lock to the next best PTP Grandmaster in the network.

PROFILE ISOLATION FEATURE

The profile isolation feature will provide great flexibility by allowing incompatible PTP profiles to run on the same network. It uses the reserved fields of the PTP message header to assign a SdoID which is a global unique number. The followers will look for the PTP messages that match their configured SdoID and ignore the others.

MIXED MULTICAST/UNICAST OPERATION

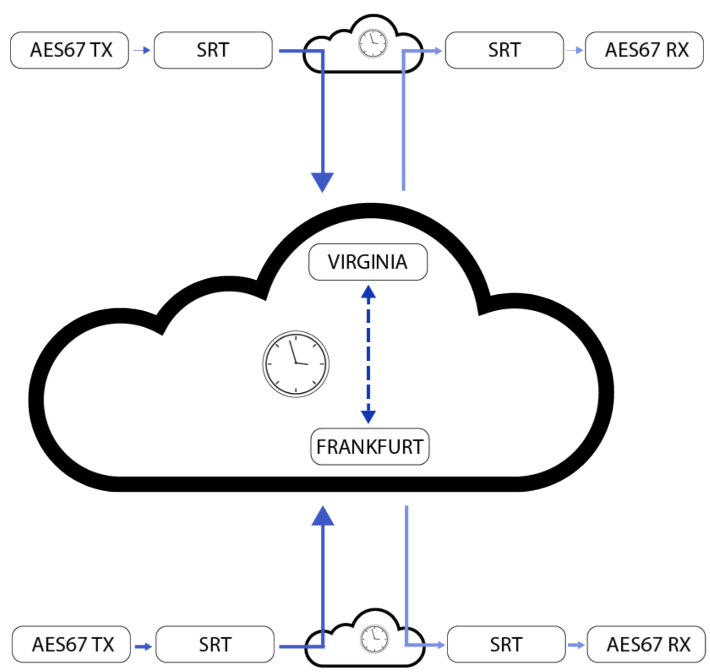
Currently some devices already support Mixed Multicast/Unicast operation, but this feature will become more regular use. Basically, the ANNOUNCE, SYNC and FOLLOW-UP messages will be multicast and the DELAY REQUEST and DELAY RESPONSE will be unicast. Overall, with this option the network will have less PTP messages when operating end to end (E2E) synchronization.

CLOUD APPLICATIONS

There is a growing demand for remote production which means video and audio being streamed between distant sites including intercontinental locations and, furthermore, part of those transmissions could be done over public WAN. One of the most critical questions that come to mind is how the remote sites will be synchronized to each other. Can we stablish PTP synchronization over public WAN? Is it necessary?

A few experimental demonstrations have been performed and new implementations are being developed to address this need. Late last year, the RAVENNA partners Ross Video, Merging and DirectOut demonstrated that AES67 streams could be streamed on both directions through the Cloud between North America and Europe. Despite the network delays being in the order of 500ms, the experiment was a success indicating that this kind of configuration is very promising.

The following diagram shows the demo summary. The synchronization was achieved by locking each site to a local PTP GM with GPS. By doing this, all sites were technically locked to the same reference ensuring synchronization across all remote locations.



The main conclusion of this demonstration was that we may not need to send PTP messages over the public WAN to achieve synchronization, we just have to guarantee that all remote sites have a common reference such as GPS. Of course, there are a few challenges to be overcome, however this solution looks promising.

There are initiatives to actually establish remote synchronization sending PTP messages over public WAN. The idea is to use only SYNC and DELAY REQUEST packets that have the lowest network delay. All the other packets with higher delay should be ignored. This filtering would reduce the Packet Delay Variation (PDV) and by consequence decrease the offset from master.

QUESTIONS OR COMMENTS?

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