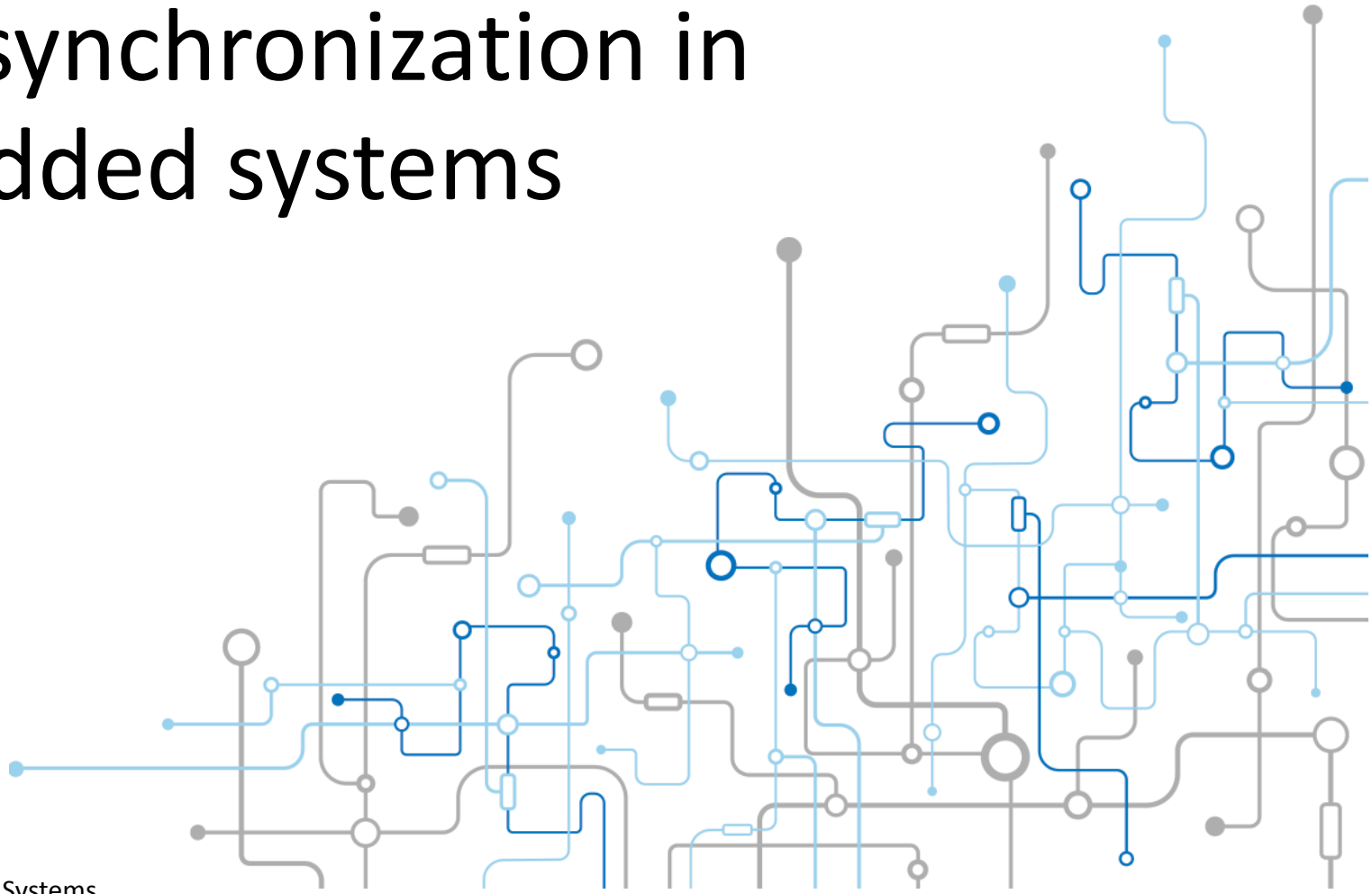
Time synchronization in embedded systems

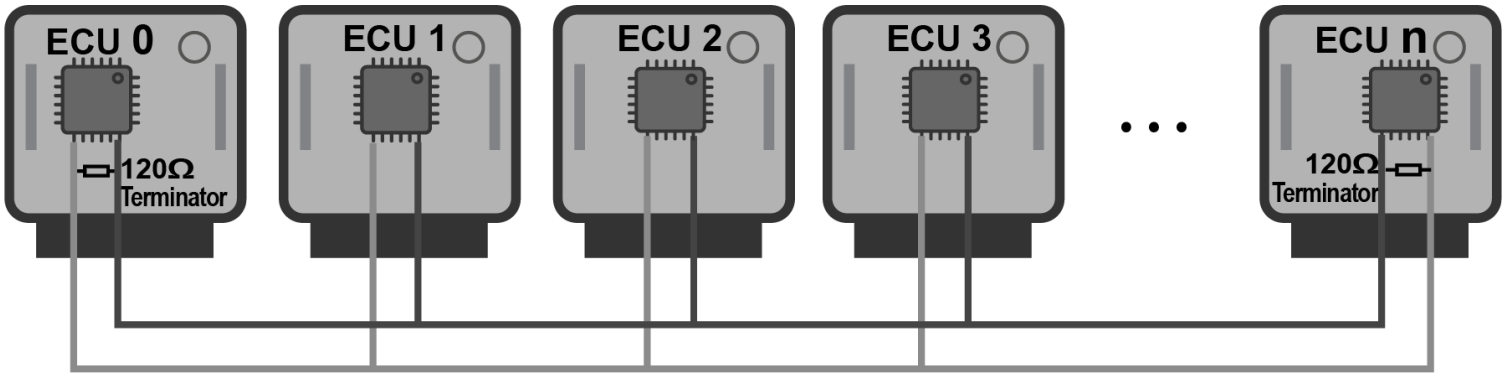


Colt Correa
COO – Intrepid Control Systems

Agenda

- Time Coordinated Embedded Controls Across a Network
  - Sources of Message Latencies
  - CAN Simple Best Effort Approach
  - Audio / Video Playback (AVB)
  - Sensor Fusion (TSN)
- When Time Synchronization is Needed or Not Needed
- Sources of Clock Errors
- gPTP Discussion (Ethernet Solution)

Common BUS Network Example

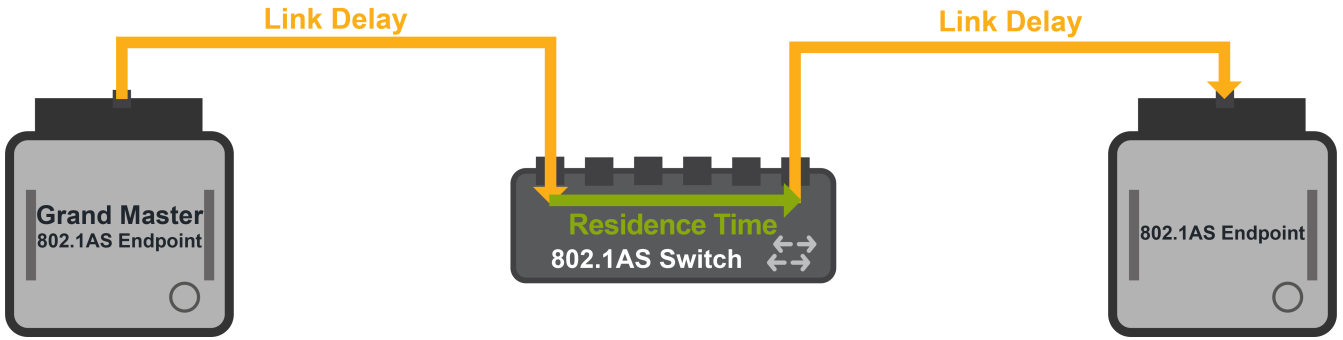


- Example CAN at 500kbps, 8byte Msg is approximately 256us in length
  1. ECU transmitter must collect sensor data
  2. Wrap data in a frame and transmit
  3. The transmit will take 256us
  4. The receiver must receive the message and process it.
  5. Steps 1-4 generally take up to 1-2ms to occur on a CAN 500kps network

This 1-2ms is best effort and often OK for many control applications

Message Latencies in a Network

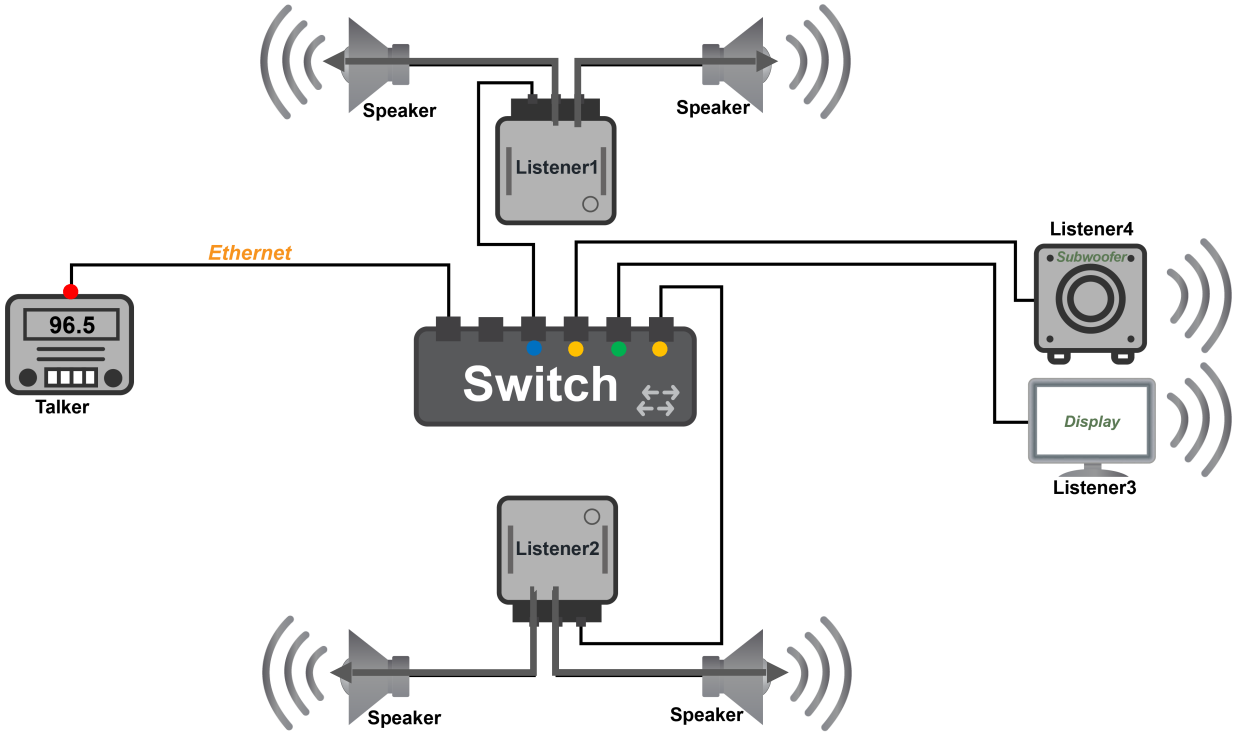
- **Link Delay** – Propagation delay through the physical medium
- **"Residence Time"** – the time required for a frame to pass in one port of a switch and out another port.



- Example Ethernet 100Mbps, 1500byte Msg is approximately 111us in length
  1. ECU transmitter must collect sensor data
  2. Wrap data in a frame and transmit
  3. The transmit will take 111us (for each link!!)
  4. The receiver must receive the message and process it
  5. Steps 1-4 generally take up to 1-2ms to occur on a 100Mbps network

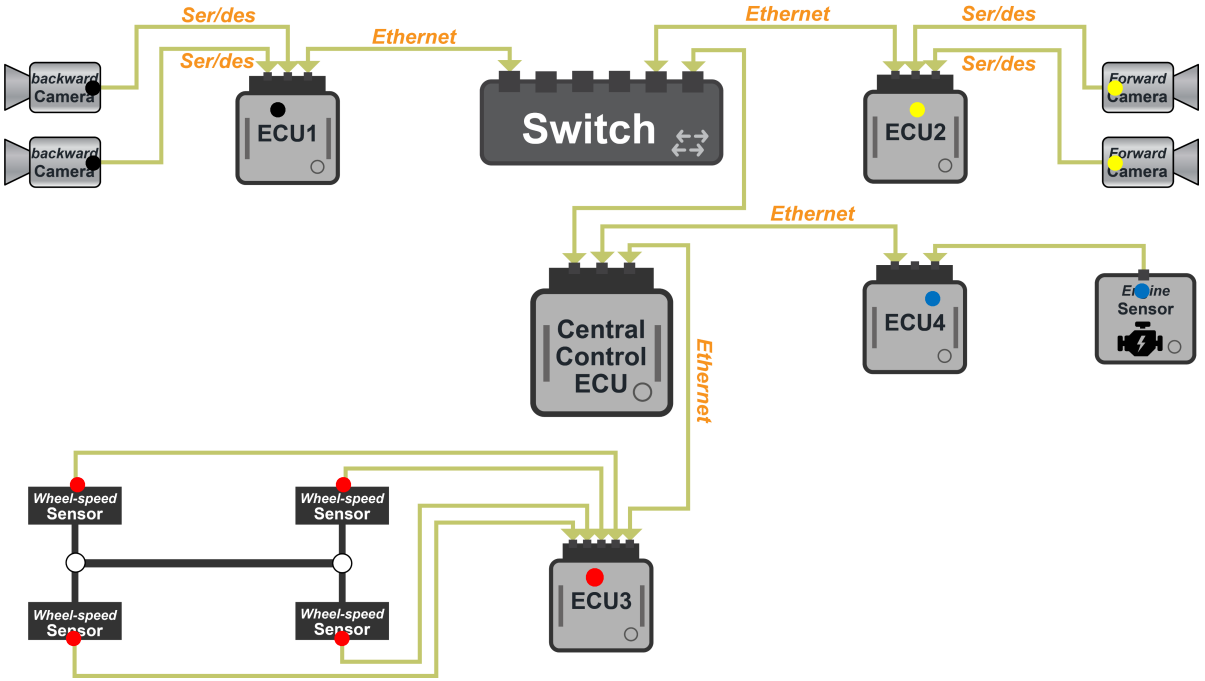
This 1-2ms is best effort and often OK for many control applications

Example when Synchronization is needed (AVB)



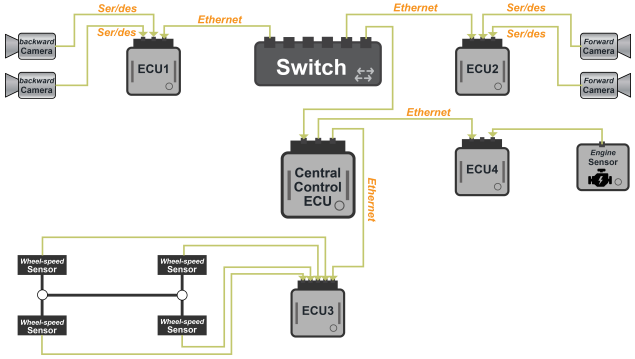
- Source or Talker transmits Audio and Video data
- Listeners must output the data in unison even if the data arrives at different times. All output must wait on the slowest data!

Example when Synchronization is needed (Sensor Fusion)

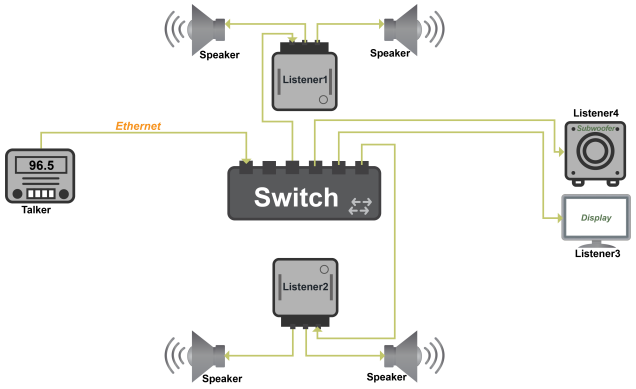


- Many sources of data transmit to a central ECU for processing
- Central Control ECU must time align all data from all sensors

Things Necessary for Data to be Time aligned



AVB

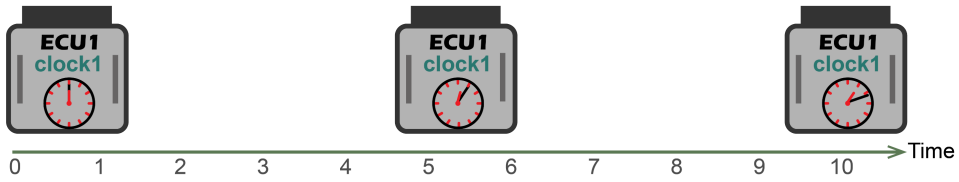


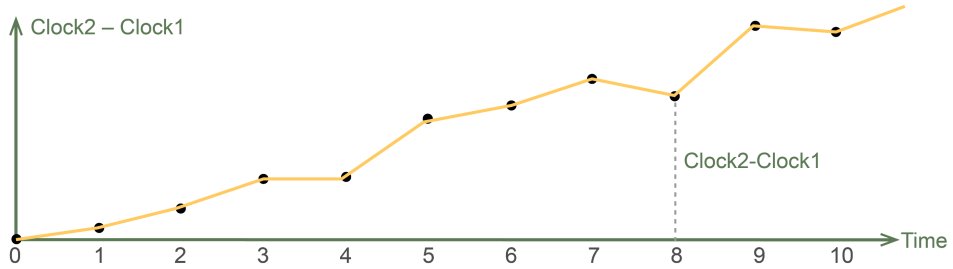
Sensor Fusion (TSN)

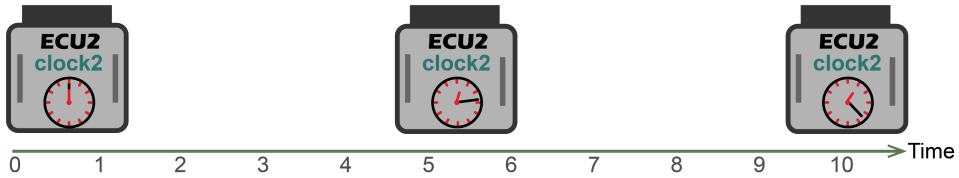
1. Each source ECU must timestamp data
2. Each ECU must have its clock synchronized with all other clocks
3. Output or Control ECU must buffer and align incoming data based on the time stamp
4. Step 3 always introduces some latency must take worst case scenario into consideration

Clock Errors in ECUs

$F_1 = F_{Ideal} + F_{Clock1Error}$







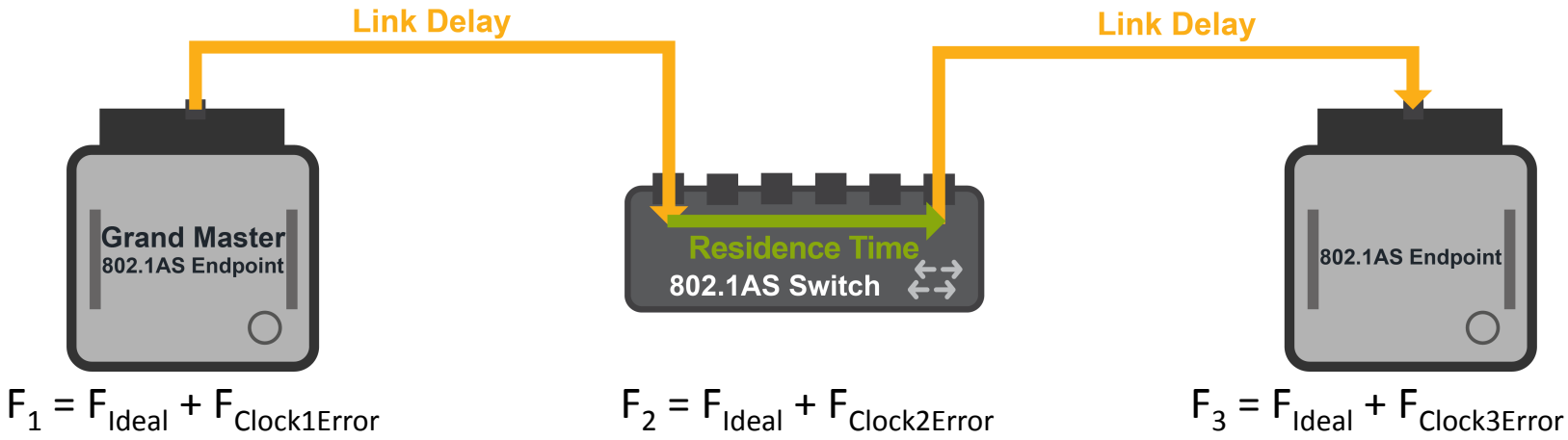
$F_2 = F_{Ideal} + F_{Clock2Error}$

- Clock1 at t = 10.000s may be 9.998
- Ideal clock at t = 10.000s is 10.000s
- Clock2 at t = 10.000s may be 10.001

- Clock1 and Clock2 start at the same time at t=0
- Over time Clock2 and Clock1 drift from another

Message Latencies In a Network

- **Link Delay** – Propagation delay through the physical medium
- **"Residence Time"** – the time required for a frame to pass in one port of a switch and out another port.



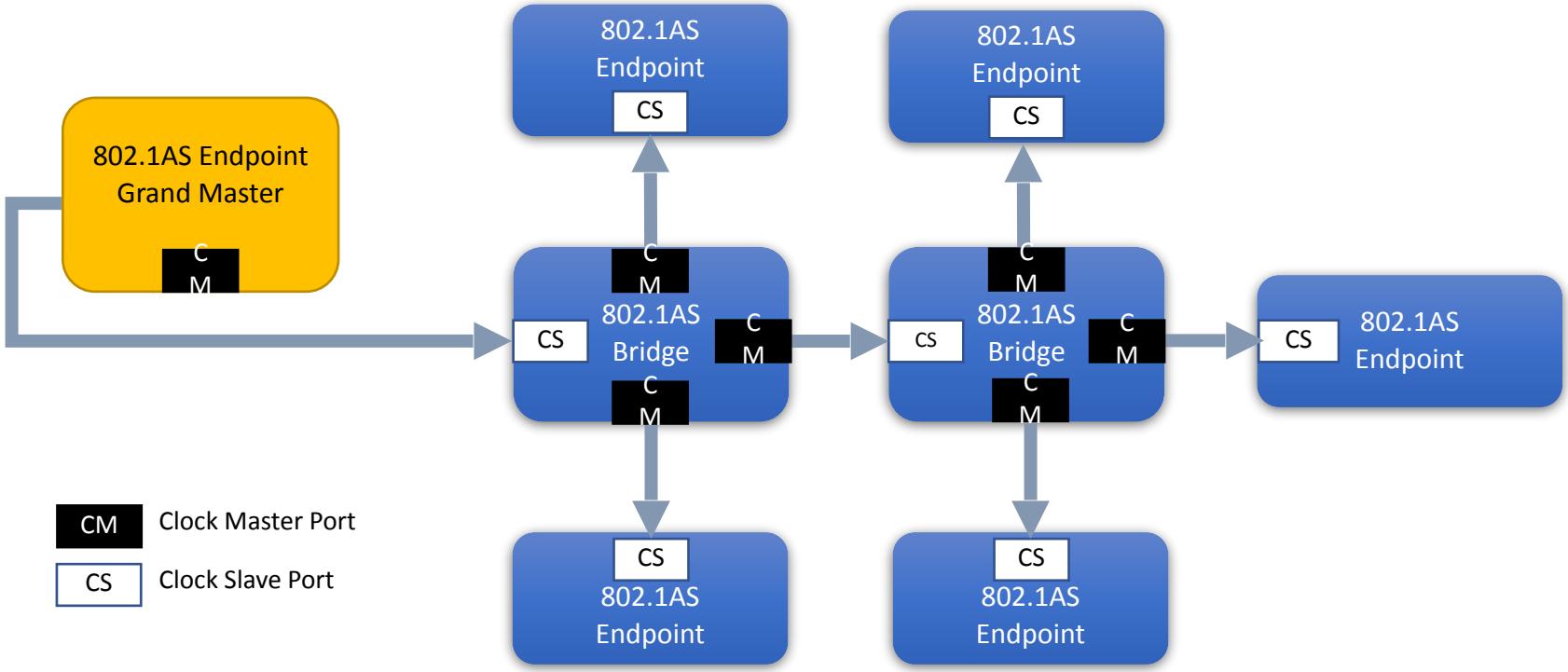
- **Clock frequency offsets** and drift between the Grand Master and the rest of the domain.

Generalized Precision Time Protocol (gPTP)

- IEEE802.1AS
  - Reduced scope of IEEE 1588 (PTP)
  - Hence “generalized”
- Used to time-synch devices to a “Grandmaster”
- Two primary responsibilities:
  - Measuring propagation delay across the network
    - “Pdelay Request”: 1 or 2-step method of measuring Link Delay
    - Switches measure their own Residence Time
    - Clock Syntonization (adjust for clock frequency offsets)
  - Transmitting clock synchronization information
    - Sync/Follow-up sequence
- Goal: 500 ns accuracy over 7 hops (100 ppm oscillators)

gPTP Architecture

All devices in the domain maintain synchronization with a clock in an Endpoint designated as the “Grand Master.”



gPTP Messages

802.3 Ethernet frame structure								
Preamble	Start of frame delimiter	MAC destination	MAC source	802.1Q tag (optional)	Ethertype (Ethernet II) or length (IEEE 802.3)	Payload	Frame check sequence (32-bit CRC)	Interframe gap
7 octets	1 octet	6 octets	6 octets	(4 octets)	2 octets	46-1500 octets	4 octets	12 octets
		← 64-1518 octets (68-1522 octets for 802.1Q tagged frames) →						
← 84-1538 octets (88-1542 octets for 802.1Q tagged frames) →								

Ethertype = 88F7 hex

Offset	Byte	1							
		1	2	3	4	5	6	7	8
0	1	messageType				transportSpecific			
1	1	versionPTP				reserved			
2	2	messageLength (...)							
4	1	domainNumber							
5	1	reserved							
6	2	flags (...)							
8	8	correctionField (...)							
16	4	reserved (...)							
20	10	sourcePortIdentity (...)							
30	2	sequenceId (...)							
32	1	control							
33	1	logMessageInterval							

Byte

Bit

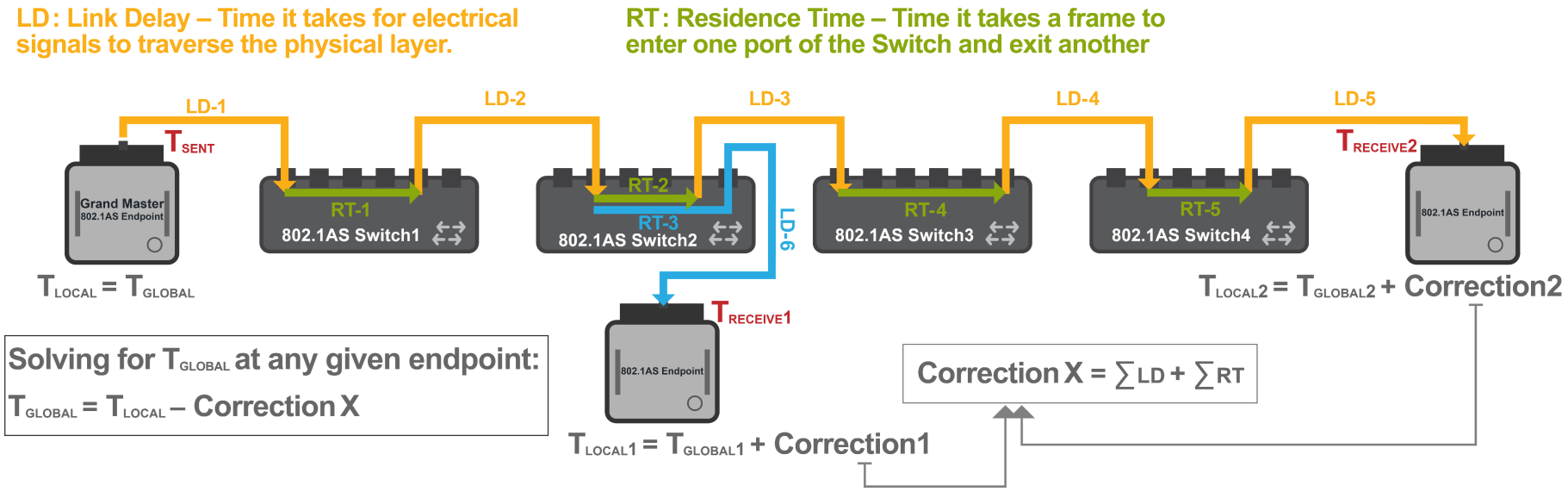
gPTP header format.

Message type	Value
Sync	0x0
Pdelay_Req	0x2
Pdelay_Resp	0x3
Follow_Up	0x8
Pdelay_Resp_Follow_Up	0xA
Announce	0xB
Signaling	0xC

Values for messageType field.

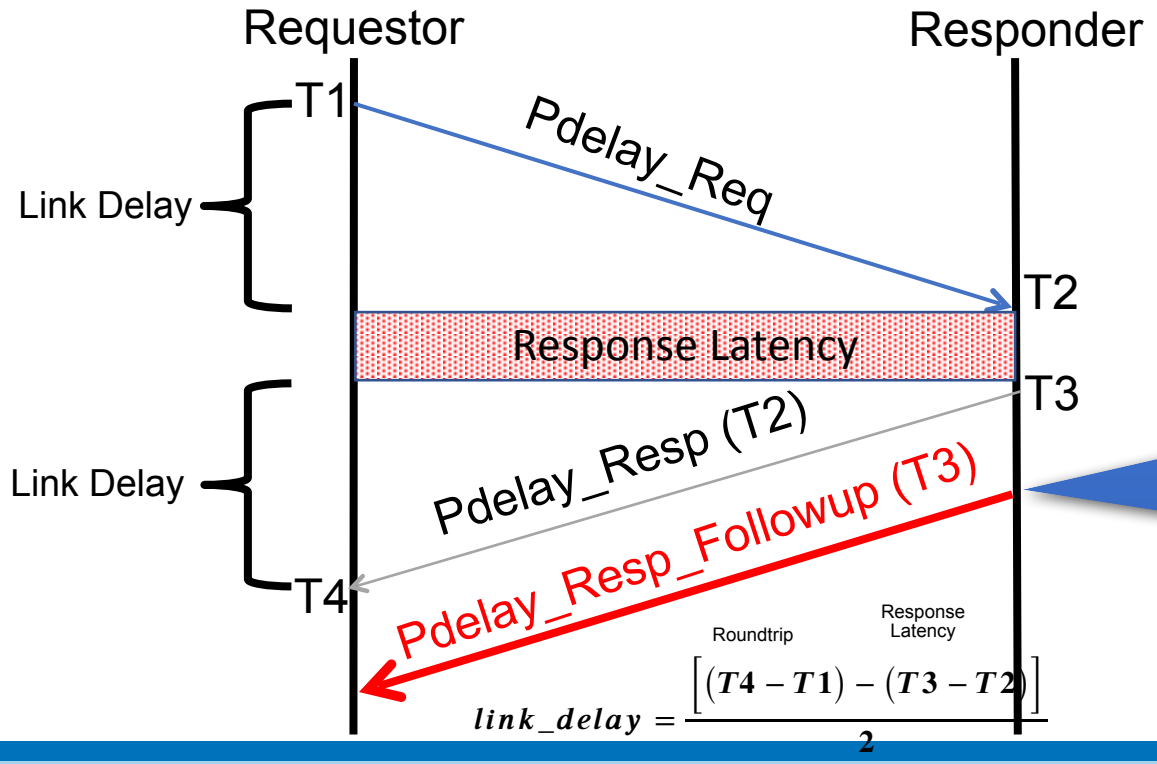
Overview of gPTP

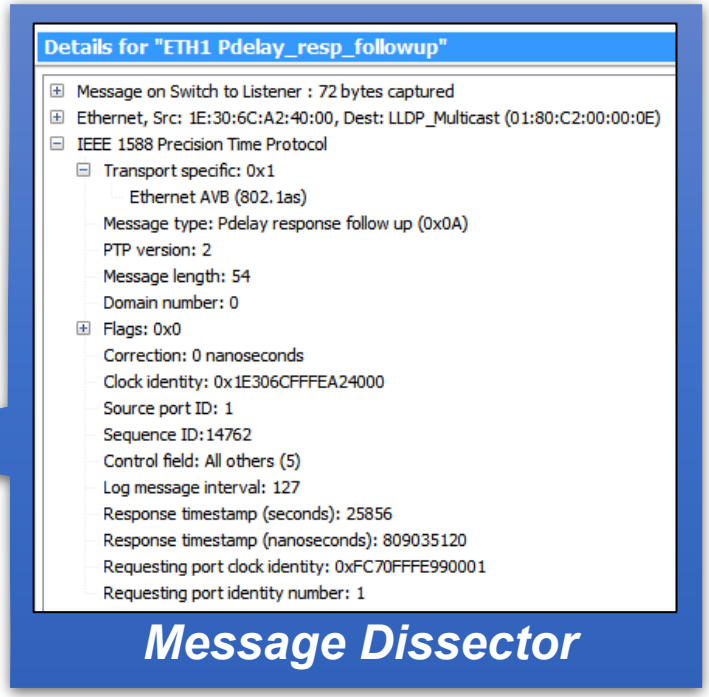
- Video Streams encode a “Presentation Time” for synchronization.
  - For this to be effective, all clocks must be synchronized
  - Lip Sync detectible with presentation time offset on the order of 10ms
- Sensor fusion – aggregating data from multiple sources



Measuring Link Delay: Two-Step Clock

	Line	Time (abs/rel)	N...	Network	Description	Source	Destination	EtherType	Len	MsgID	SeqID	PTP Timestamp	Timestamp
Filter						PTP		PTP		pdelay			
⊞	205	999.910 ms		Listener to Switch	ETH2 Pdelay_req	Intrepid_99:00:01	LLDP_Multicast	PTP	72	Pdelay_Req	14761	0	2017/08/31 20:03:28:624183
⊞	206	137 µs		Switch to Listener	ETH1 Pdelay_resp	1E:30:6C:A2:40:00	LLDP_Multicast	PTP	72	Pdelay_Resp	14761	25855.80859936	2017/08/31 20:03:28:624320
⊞	207	98 µs		Switch to Listener	ETH1 Pdelay_resp_followup	1E:30:6C:A2:40:00	LLDP_Multicast	PTP	72	Pdelay_Resp_Follow_Up	14761	25855.8087232	2017/08/31 20:03:28:624418
⊞	208	1.000085 s		Listener to Switch	ETH2 Pdelay_req	Intrepid_99:00:01	LLDP_Multicast	PTP	72	Pdelay_Req	14762	0	2017/08/31 20:03:29:624503
⊞	209	136 µs		Switch to Listener	ETH1 Pdelay_resp	1E:30:6C:A2:40:00	LLDP_Multicast	PTP	72	Pdelay_Resp	14762	25856.80891128	2017/08/31 20:03:29:624639
⊞	210	98 µs		Switch to Listener	ETH1 Pdelay_resp_followup	1E:30:6C:A2:40:00	LLDP_Multicast	PTP	72	Pdelay_Resp_Follow_Up	14762	25856.80903512	2017/08/31 20:03:29:624737



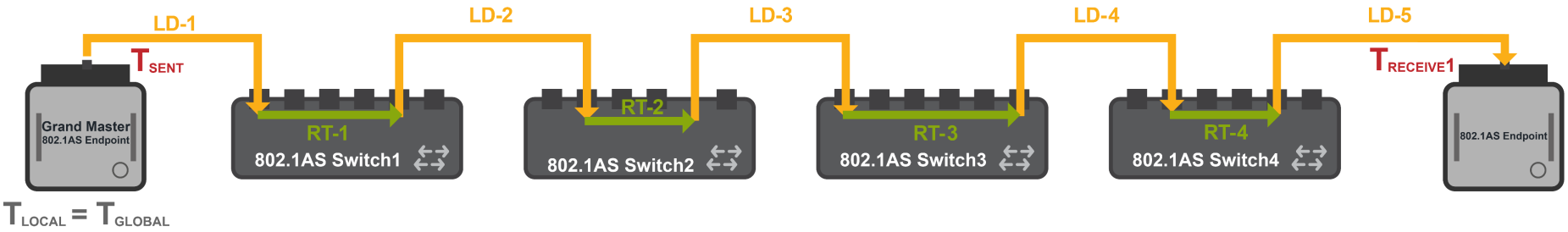


Time Synchronization: Sync/Followup

LD: Link Delay – Time it takes for electrical signals to traverse the physical layer.

RT: Residence Time – Time it takes a frame to enter one port of the Switch and exit another

Correction = ∑LD + ∑RT

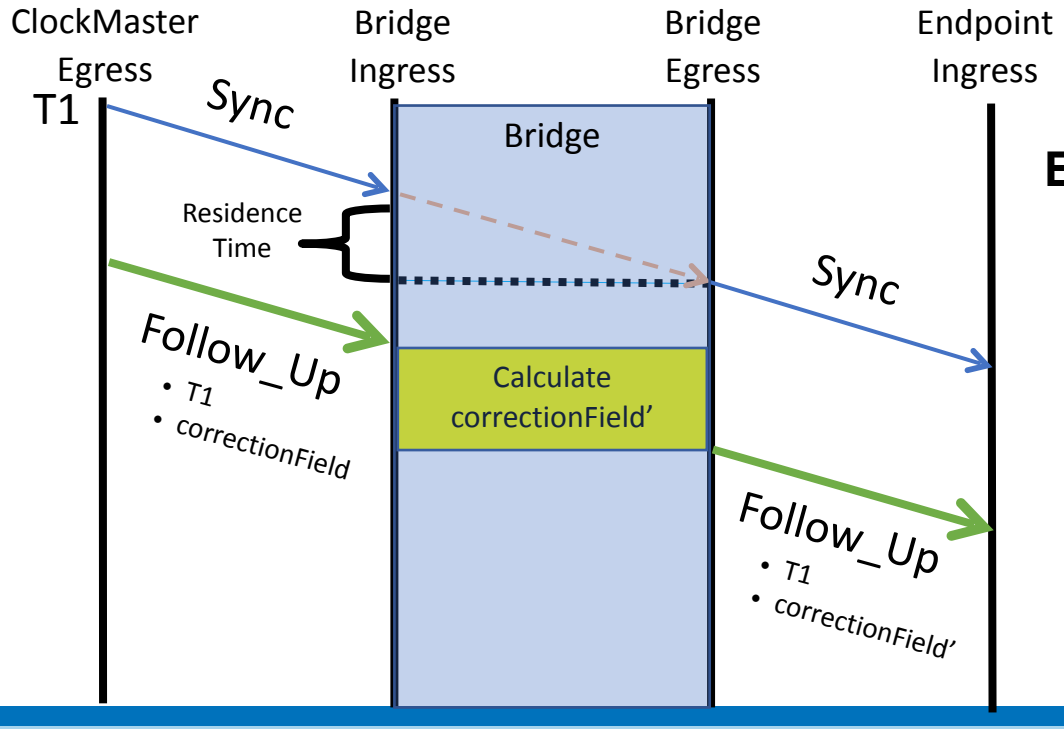


End-to-End Propagation Delay:

- Global Timestamp delivered via Sync message to all domain participants.
- Follow-up message propagates across the network with each node adding its incremental link delay and residence time.

Time Synchronization: Sync/Followup

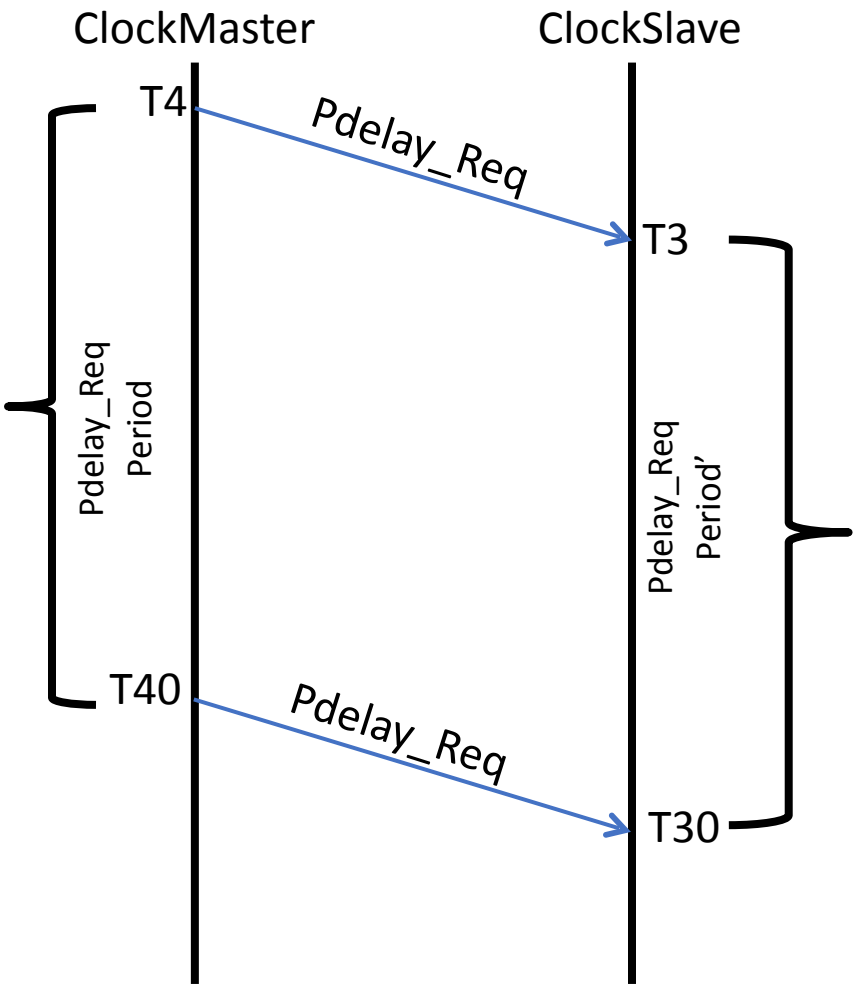
	Line	Time (abs/rel)	N...	Network	Description	Source	Destination	EtherT...	Len	MsgID	SeqID	PTP Timestamp	Timestamp
Filter								PTP					
	2836	123.613 ms		Talker to Switch	ETH11 Sync	00:FC:00:99:00:02	LLDP_Multicast	PTP	64	Sync	36044	0	2017/08/31 23:04:11:772501
	2837	105 µs		Switch to Listener	ETH1 Sync	00:FC:00:99:00:02	LLDP_Multicast	PTP	64	Sync	36044	0	2017/08/31 23:04:11:772606
	2838	148 µs		Talker to Switch	ETH11 Followup	00:FC:00:99:00:02	LLDP_Multicast	PTP	94	Follow_Up	36044	1503686718.228285	2017/08/31 23:04:11:772754
	2839	1.261 ms		Switch to Listener	ETH1 Followup	00:FC:00:99:00:02	LLDP_Multicast	PTP	94	Follow_Up	36044	1503686718.228285	2017/08/31 23:04:11:774015
	2840	123.745 ms		Talker to Switch	ETH11 Sync	00:FC:00:99:00:02	LLDP_Multicast	PTP	64	Sync	36045	0	2017/08/31 23:04:11:897760
	2841	104 µs		Switch to Listener	ETH1 Sync	00:FC:00:99:00:02	LLDP_Multicast	PTP	64	Sync	36045	0	2017/08/31 23:04:11:897864
	2842	278 µs		Talker to Switch	ETH11 Followup	00:FC:00:99:00:02	LLDP_Multicast	PTP	94	Follow_Up	36045	1503686718.353535	2017/08/31 23:04:11:898143
	2843	1.133 ms		Switch to Listener	ETH1 Followup	00:FC:00:99:00:02	LLDP_Multicast	PTP	94	Follow_Up	36045	1503686718.353535	2017/08/31 23:04:11:899276



End-to-End Propagation Delay:

- Each bridge calculates its delay from the GrandMaster
- Pdelay + Residence Time
- Corrected with RateRatio
- Accumulated in Follow_Up message

Syntonization: neighborRateRatio



If clocks were perfectly Syntonized…

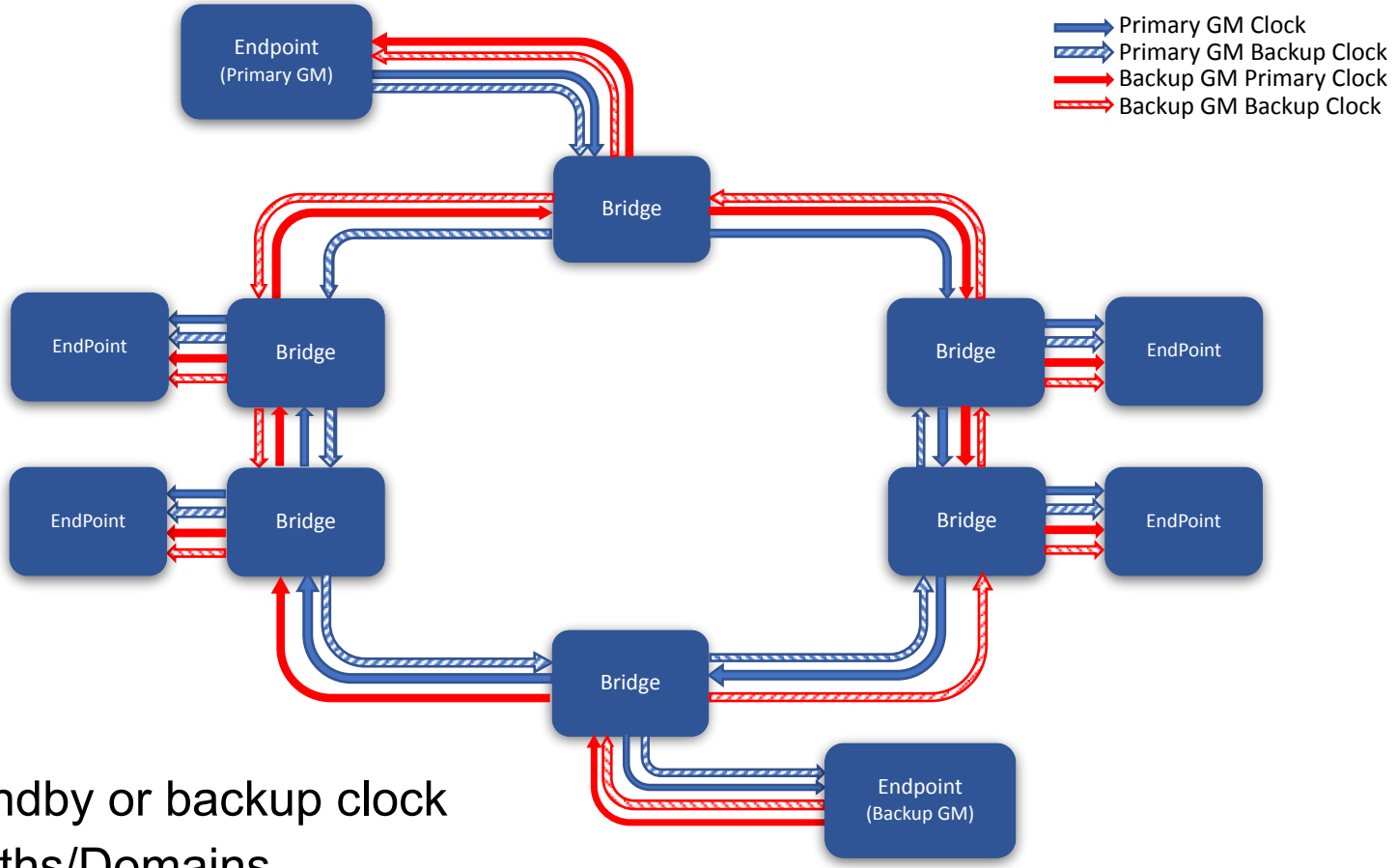
$$(T40 - T4) = (T30 - T3)$$

But in the physical world….

$$\text{neighborRateRatio} = \frac{(T30 - T3)}{(T40 - T4)}$$

IEEE802.1AS-Rev(Asbt)

Timing and Synchronization for Time-Sensitive Applications



- Adds a standby or backup clock
- Multiple Paths/Domains

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Questions?

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