The bridge to possible

Synchronizing 5G Mobile Networks

Design, Trade-offs and Deployment

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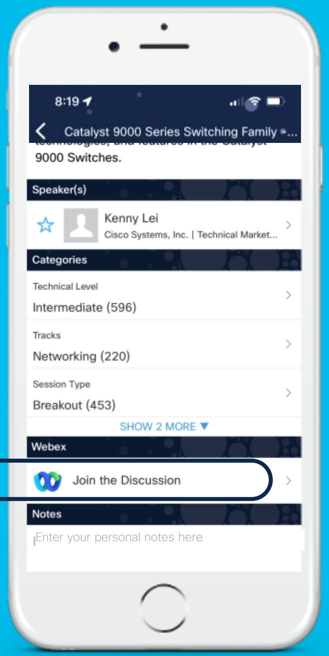

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Abstract

This session will cover Cisco's approach to address stringent 5G Timing and Synchronization requirements. Timing and Synchronization are critical components of an efficient mobile network architecture. If it is not properly designed, implemented, and managed, it can have a dramatic (negative) effect on the efficiency, reliability and capacity of the network. Subscribers will likely suffer dropped calls, interrupted data sessions, and a generally poor user experience.

Timing and Synchronization standards are evolving to address some of the synchronization requirements in fronthaul deployment options. In this session, we will cover Timing and Synchronization performance requirements, new standards and definitions, synchronization requirements to achieve 5G Services efficiency, overall deployment best practices and product positioning.

The goal of this session is to clearly articulate Cisco's solution approach to address 5G Timing & Synchronization requirements covering:

1. Timing and Synchronization requirements
2. New standards and technology options
3. Best practices & design options to address 5G fronthaul/backhaul requirements for timing & synch.

Agenda

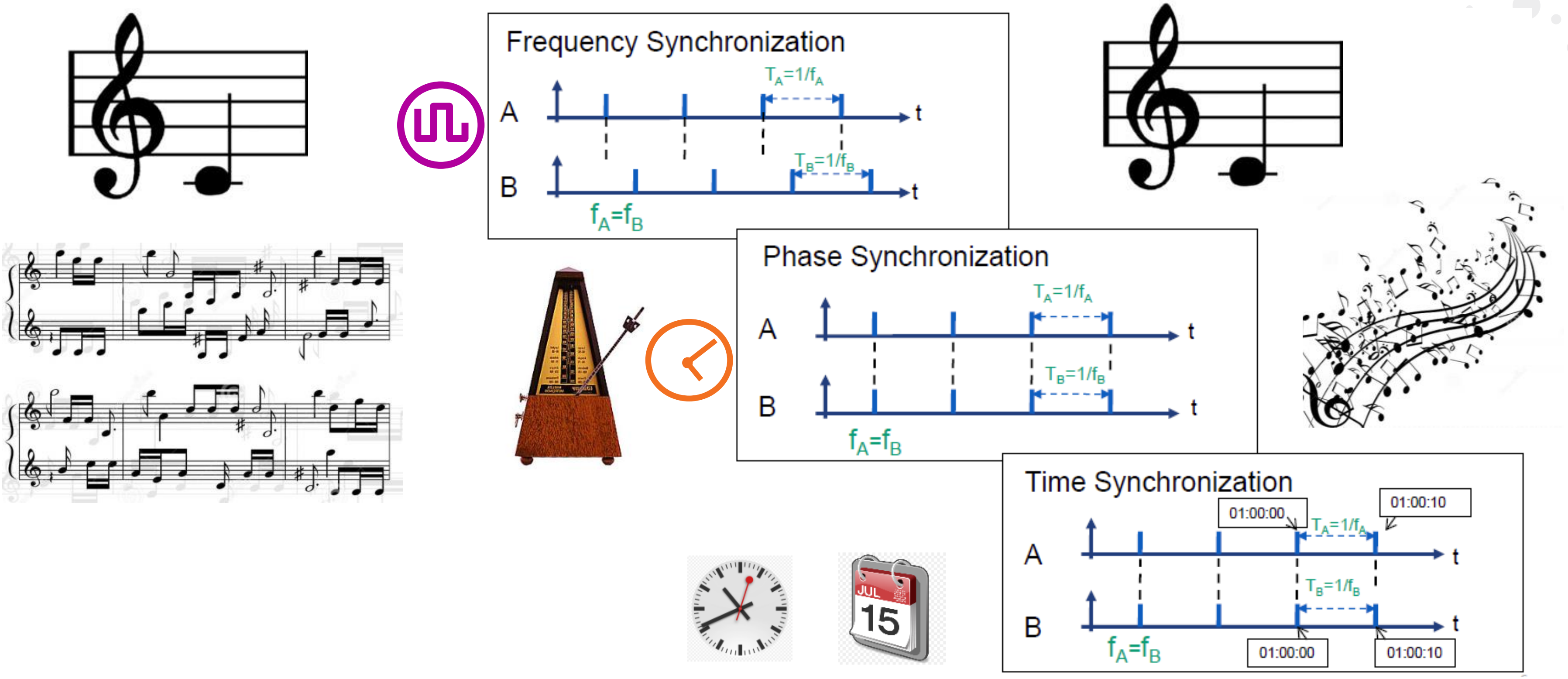
- Introduction and (very) quick refresher
- 5G synchronization requirements & standards
- 5G RAN timing solutions
- Deployment and design best practices
- Latest developments and conclusion

Introduction

Introduction

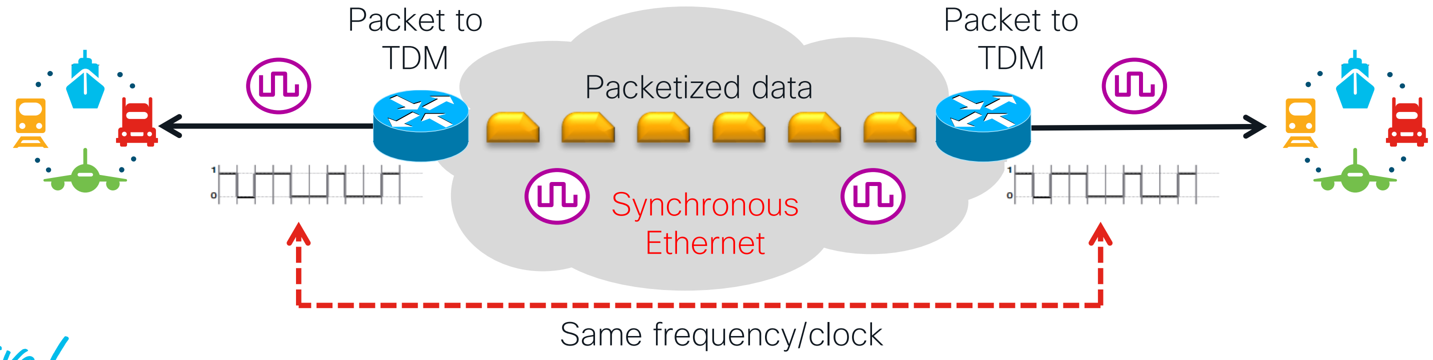
- 5G mobile radio requires "Phase Synchronization" (aka phase/time)
  - Different to, and more complex than previous "Frequency Synchronization"
  - 5G networks have strict phase/time requirements to work correctly
- Frequency Sync nowadays typically uses SyncE/Enhanced SyncE not TDM
- Driven by need to optimize the use of the radio spectrum (which is $$)
- Solutions have been standardized by the ITU-T and continue to evolve
- Solution combines atomic sources, GNSS/radio systems and network timing
- So, what is different about phase synchronization?

Different forms of Synchronization



Frequency Synchronization

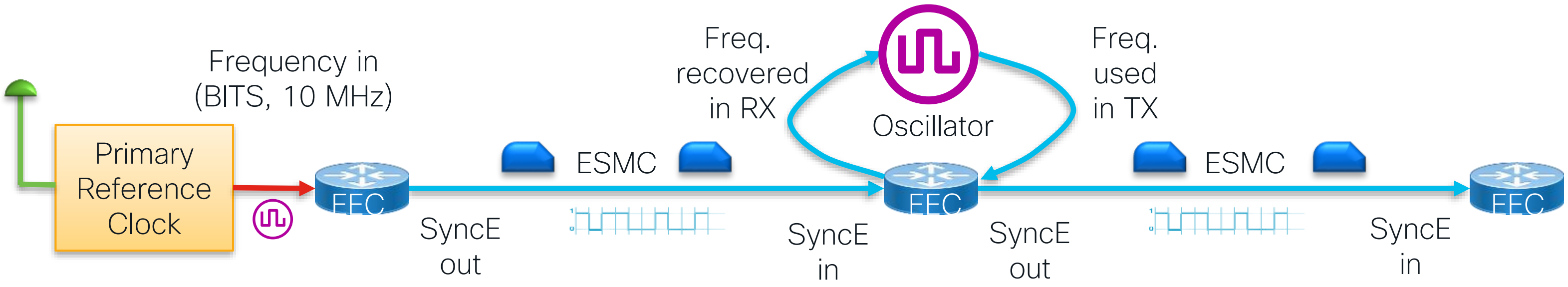
- Avoid slips on TDM interfaces (E1/T1, …) – enables Synchronous networks (SONET/SDH)
- Service providers, power grids, broadcast, railways ➔ to support Circuit Emulation (CEM)
- 2G, 3G, and later FDD Cellular Networks – ensure radios tuned to exact frequency
- Carried with (enhanced) Synchronous Ethernet (preferred) or packet transport (PTP)



How SyncE Works

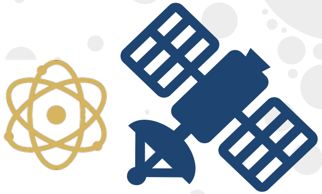
RX = reception
TX = transmission

- Accurate reference frequency (PRC) is used as source for SyncE/eSyncE timing chain
- Frequency of the TX Ethernet signal is aligned to that frequency reference
- SyncE Clock (EEC) recovers frequency from RX Ethernet; uses it to discipline its own oscillator
- In turn that oscillator is used as reference for transmission of TX SyncE/eSyncE
- ESMC is used to carry information on traceability and quality



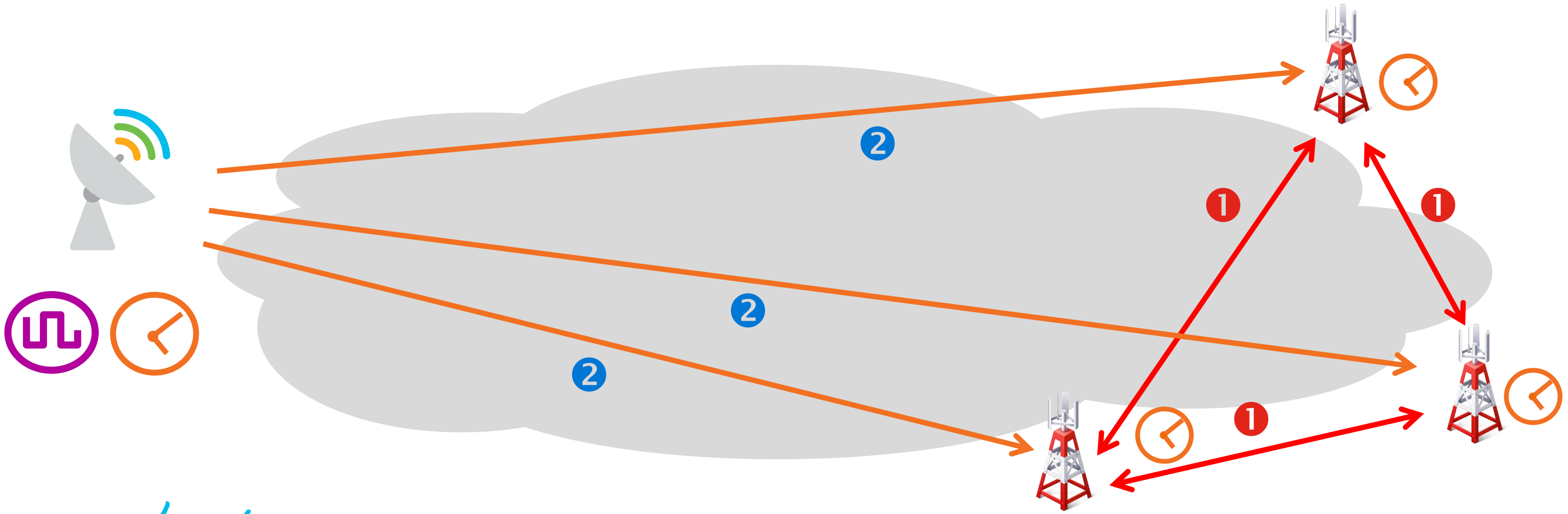
Ethernet Synchronization Message Channel (ESMC) packets signal quality level (QL) traceability
Ethernet/Synchronous Equipment Clock (EEC/SEC) = SyncE aware clock (eSEC = enhanced SyncE clock)

Phase Synchronization for 5G



❶ Requirement (TDD, LTE-A radio co-ordination): 3 µs between base stations

❷ Implementation: ±1.5 µs from a common reference time (normally UTC time)

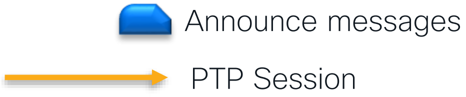


What is IEEE 1588?

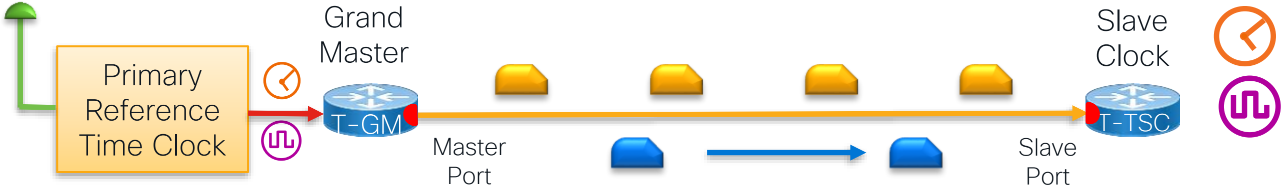
- Precision Time Protocol = PTPv2 = IEEE 1588-2008
- Packet protocol carrying timing information, via two-way* exchange of timestamps
- PTP quick history
  - Designed for sub-microsecond (nanosecond!) accuracy & precision
  - V1 for industrial automation, V2 for WAN (such as IP) deployment & extensibility
  - V2 allowed the creation of PTP “Profiles” – specific implementations for industry use cases
  - New version of PTP (V2.1) was approved in IEEE 1588-2019
- PTP Profiles
  - Profiles developed based on use cases and organization
  - For service providers (and other industries) commonly use ITU-T PTP Telecom Profiles

* = there is also a 1-way version for frequency-only use

How PTP Works



- Accurate time/phase/frequency (PRTC) is used as source for PTP time signals
- Grandmaster encodes timestamps (aligned with PRTC) into PTP packets at a “Master” port
- “Slave” recovers timestamps from PTP and calculates *offset from master* and *mean path delay*
- Oscillator is disciplined to the reference frequency (using either packet or SyncE)
- Accurate time/phase calculated and time clock is aligned to recovered time/phase
- Announce message is used to carry information on traceability and clock quality
  - The Best Master Clock Algorithm uses this information to select the best source of time information



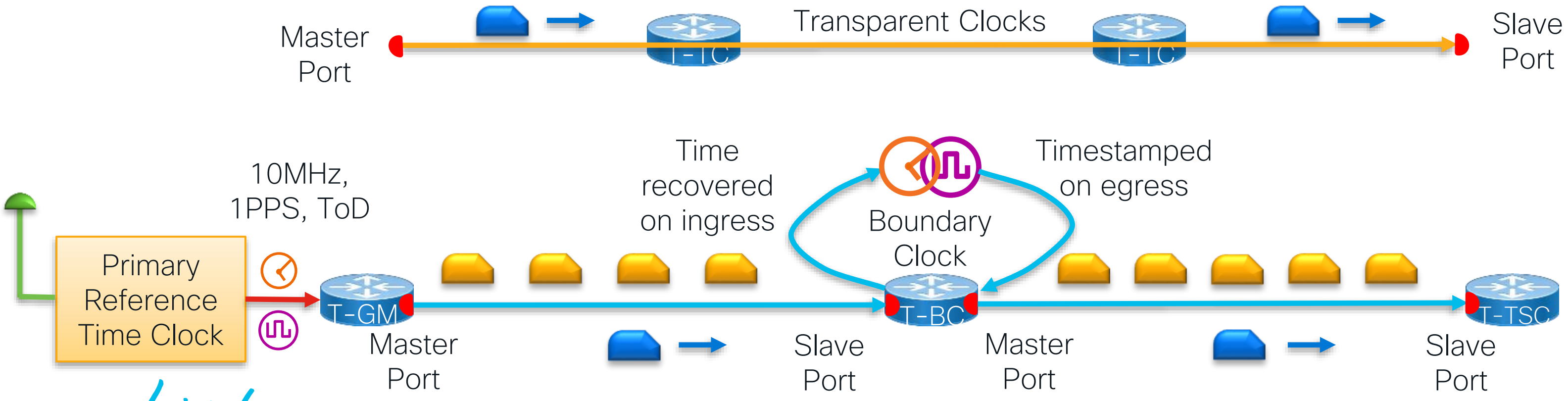
PTP Clock Types

10MHz frequency,

1 pulse per second (1PPS) phase
Time of day (ToD) time

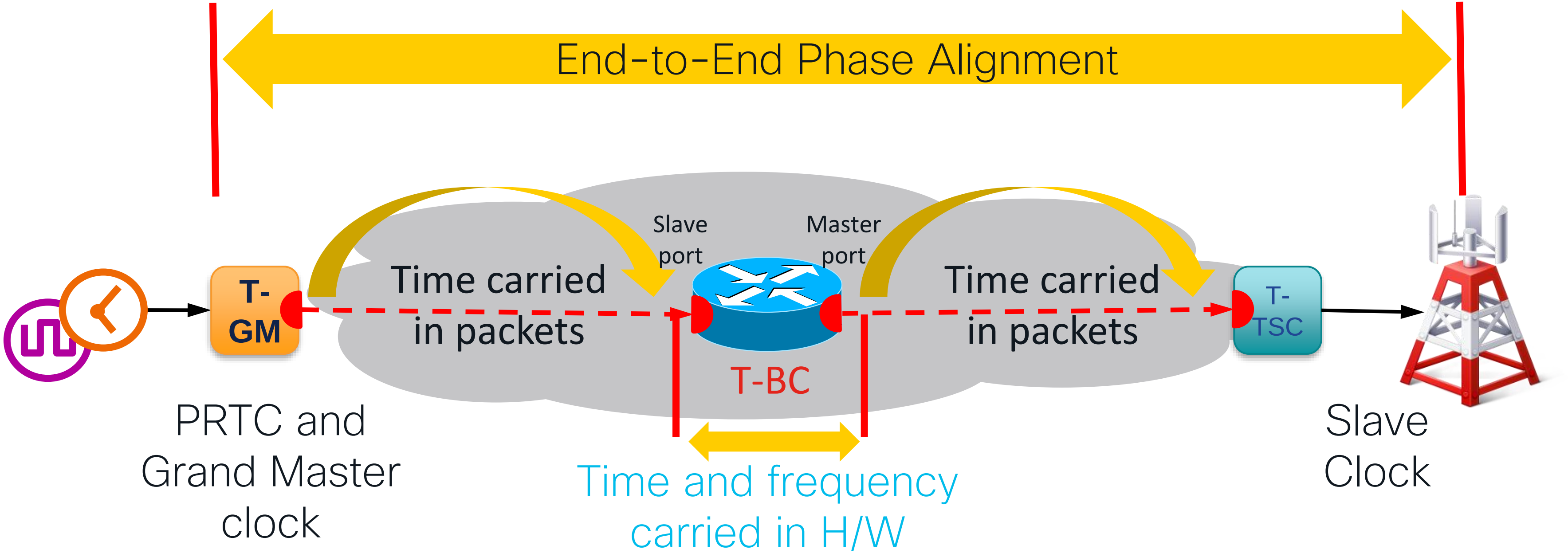
Announce messages

- Grandmasters initiate the chain of timing information
- Boundary clocks recover the clock and regenerate it with a new PTP session
- Transparent clocks allow PTP to pass and update the residence time value: correctionField
- Slave clocks terminate the timing chain (frequently embedded in the end application)



T-BC Boundary Clocks – why?

Frequency carried in packets or SyncE



Note: a PTP port maps to a traffic interface such as Ethernet

Major PTP Profiles

T-GM = Telecom Grand Master
T-TSC = Telecom Time Slave Clock
T-TC = Telecom Transparent Clock

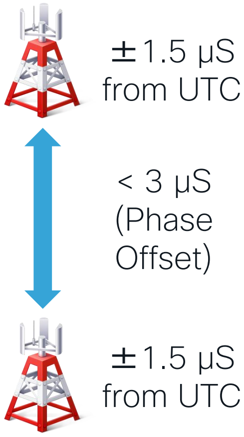
-P = Partial
-A= Assisted

	IEEE 1588 Default Profiles	IEEE 802.1AS	IEEE C37.238	ITU-T G.8265.1	ITU-T G.8275.1	ITU-T G.8275.2
Segments	Industrial	Audio/Visual	SmartGrid	Mobile	Mobile	Cable
Transport	IP, L2, etc.	L2 Ethernet	L2 Ethernet	IPv6 (IPv4)	L2	IPv6 (IPv4)
Transmission	Multi-/Unicast	Multicast	Multicast	Unicast Neg.	Multicast	Unicast Neg.
Delay Mech.	Both (J.3/J.4)	Peer-delay	Peer-delay	Delay-Resp	Delay-Resp	Delay-Resp
Clock Modes	One/Two-step	Two-step	Two-step	Any	Any	Any
BMCA	Default	Alternate	Default	Alternate	Alternate	Alternate
TLV Extns.	Optional	Yes	Yes	No	No	Yes
Clocks	OC, BC, TC	Time aware bridge & end station	OC, TC, BC	OC only	T-GM, T-BC, T-TSC, T-TC	T-GM, T-TSC-P, T-BC-P, T-TC-P, T-TSC-A
Network	Any	Full support	Full support	No on-path	Full + SyncE	Partial

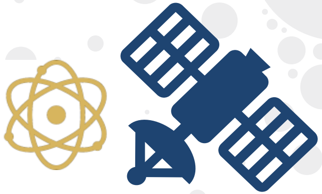
Requirements and Standards

5G Changed Sync (started with LTE-A)

- Previous mobile networks operated with the same synchronisation used since GSM days! (exception: CDMA)
  - Which was: frequency only (initially with TDM and then SyncE/Ethernet)
- Now PHASE also required for new TDD radio services/features
- Phase/Time Sync uses Precision Time Protocol (PTP)/IEEE 1588
  - Achievable accuracy is 10's – 100's of nanoseconds (10^{-9}) TE over 5–10 hops
  - Requires specialized hardware and careful network design
  - PTP/SyncE capability increasingly included in many network transport systems
  - SyncE & PTP Telecom profiles supported across Cisco Service Provider products
  - Solutions have been standardized by the ITU-T and continue to evolve



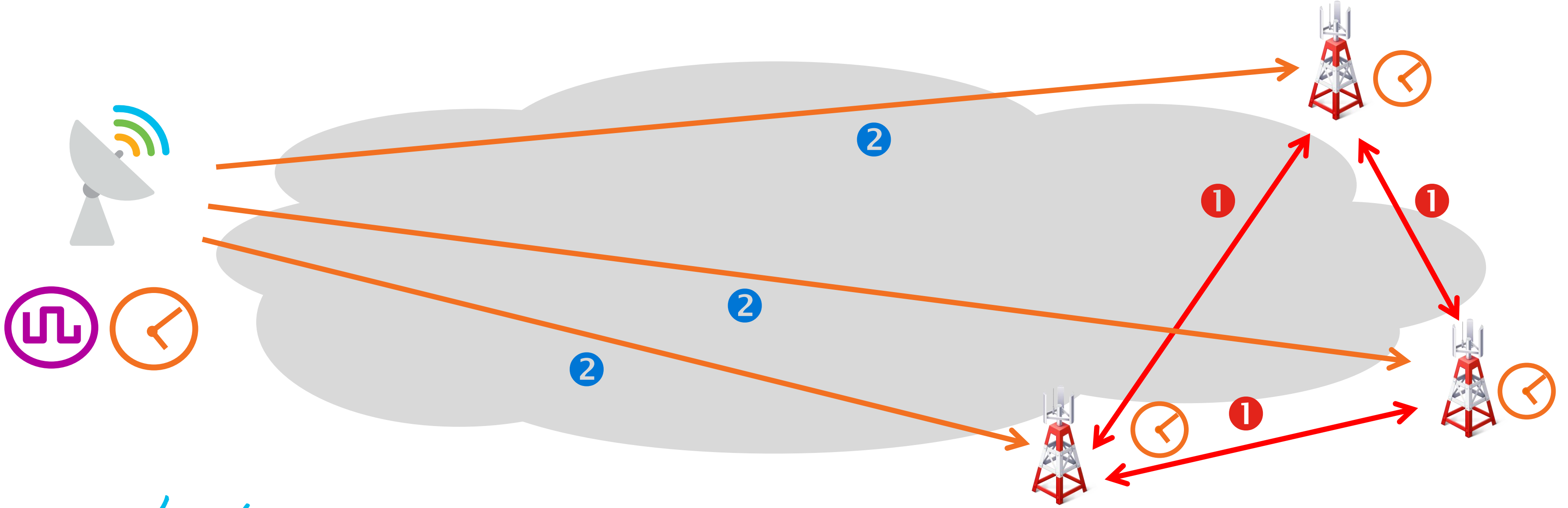
Phase Synchronization for 5G



Common Reference Time

❶ Requirement (TDD, LTE-A radio co-ordination): 3 µs between base stations

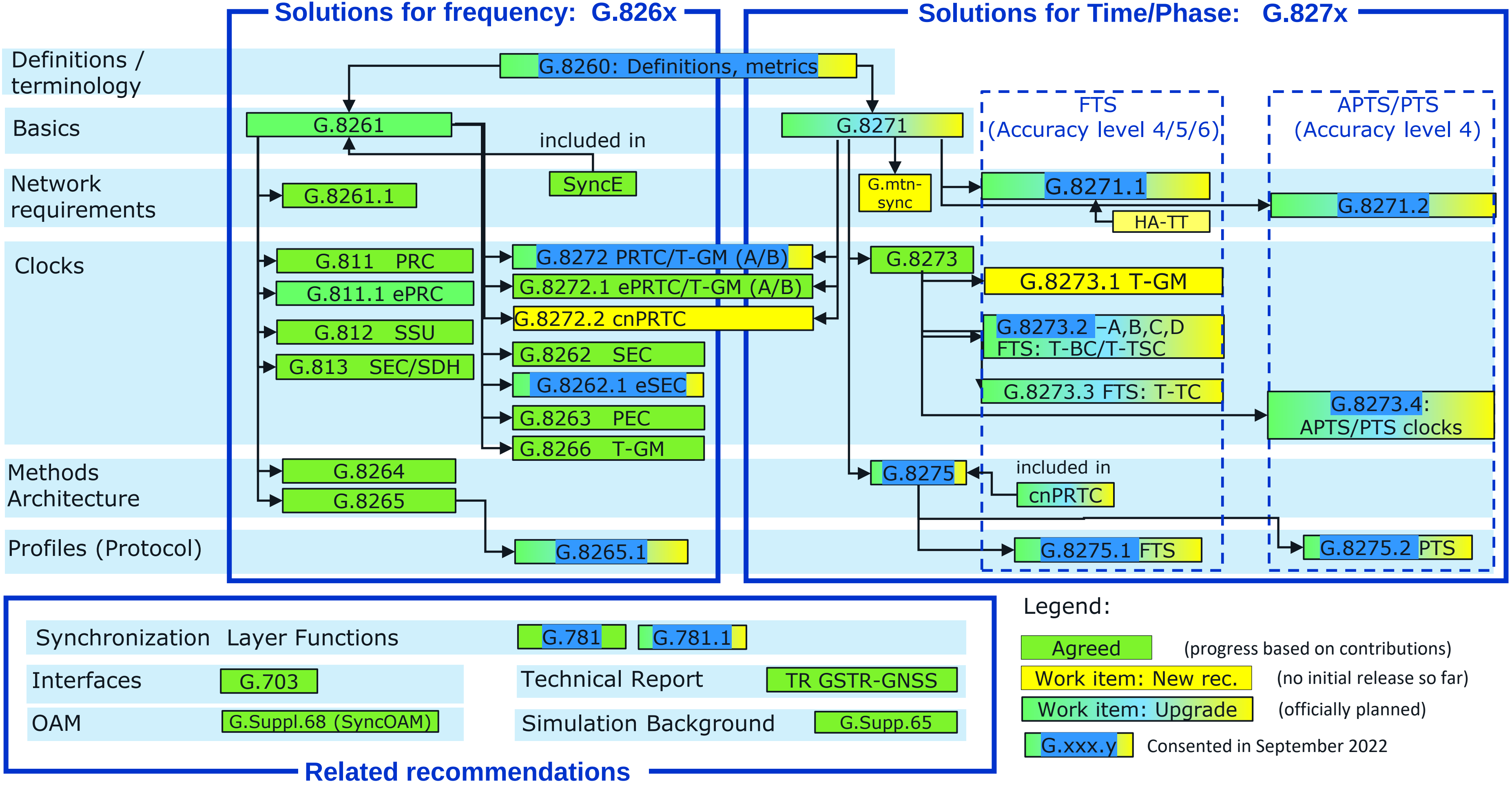
❷ Implementation: ±1.5 µs from a common reference time (normally UTC time)



ITU-T Standards Process is Solution Driven

1. Recognize the application and/or use case (define the timing budget)
2. Define end-to-end Network or Service Limits
   - Define limits for time and frequency performance at specific points in the network
3. Define Equipment Limits for each node
   - Performance of each individual network element as a unit (treat as black box)
4. Then define interfaces and transport methods (protocol/format/profile)
   - What types of interfaces between network elements carry the timing signals
   - Specify dedicated synchronization interfaces or ports for measurement
   - Define PTP profiles and other messaging systems (e.g. time of day) to implement it

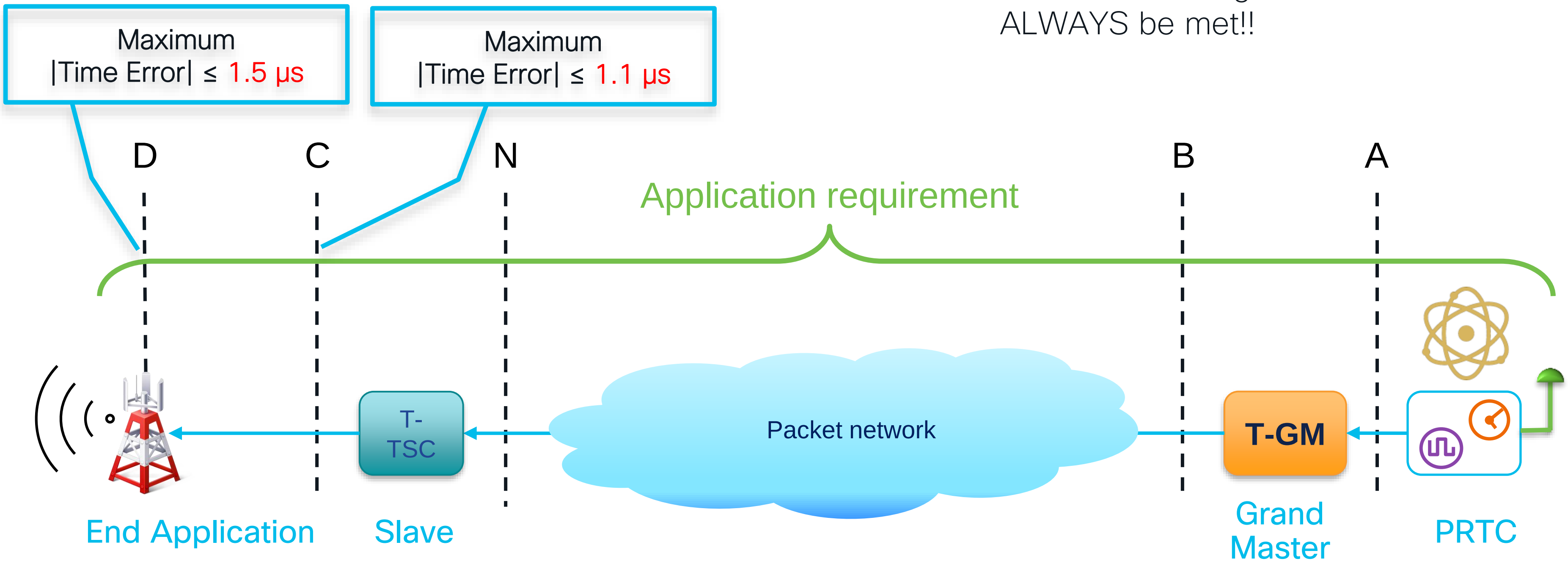
ITU-T SG15Q13: WD Q13-Recommendations



Define the Network Limits

End-to-end Timing Budget

No matter what other timing requirements there are (such as in the Fronthaul), for 5G, this end-to-end budget must ALWAYS be met!!



Source: G.8271.1

Define the Node/Clock Performance

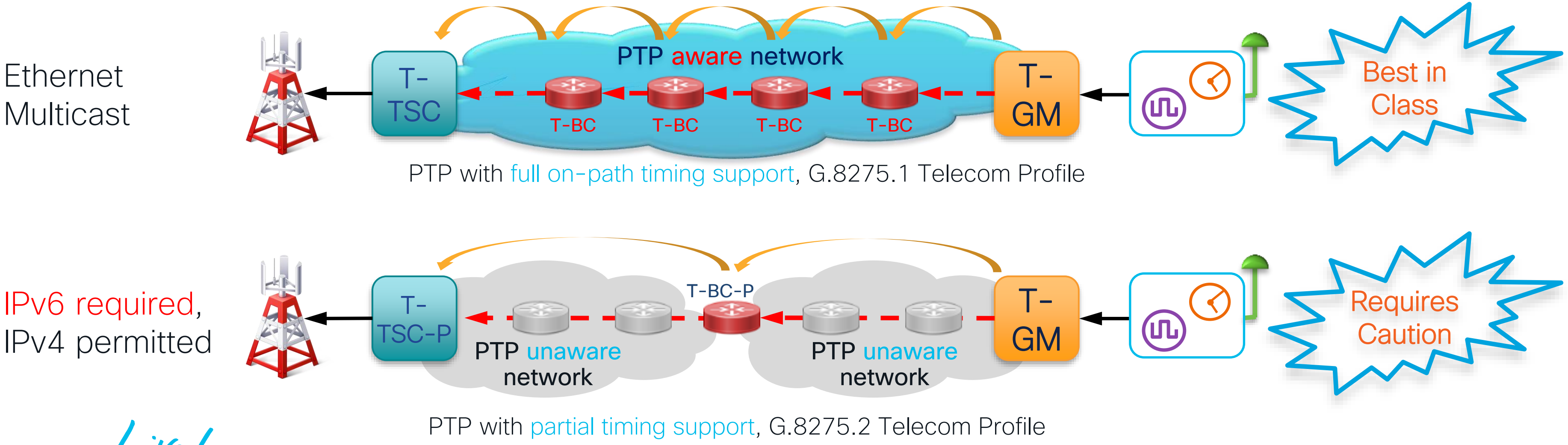
- PTP aware nodes carry time in hardware
  - Properly implemented, they have predictable performance
  - It is easy to test/confirm this performance (standardized testing)
- T-BC Performance is standardized by the ITU-T (G.8273.2)
  - Class A = original implementations, max|TE| of 100 ns, cTE of ±50 ns
  - Class B = 2nd generation devices, max|TE| of 70 ns, cTE of ±20 ns
  - Class C = now readily available, max|TE| of 30 ns, cTE of ±10 ns
  - Class D = met by some class C equipment, max$|TE_L|$ of 5 ns
  - Equivalent standard for T-TC transparent clocks for classes A, B, C (G.8273.3)
- With better clocks, can cross more hops or a meet a lower budget
  - 5G Fronthaul can have much stricter requirements than the 1.5 μs end-to end

PTP Telecom Profiles – Phase

T-BC = Telecom Boundary Clock
T-GM = Telecom Grand Master
T-TSC = Telecom Time Slave Clock
T-BC-P = Telecom Partial BC

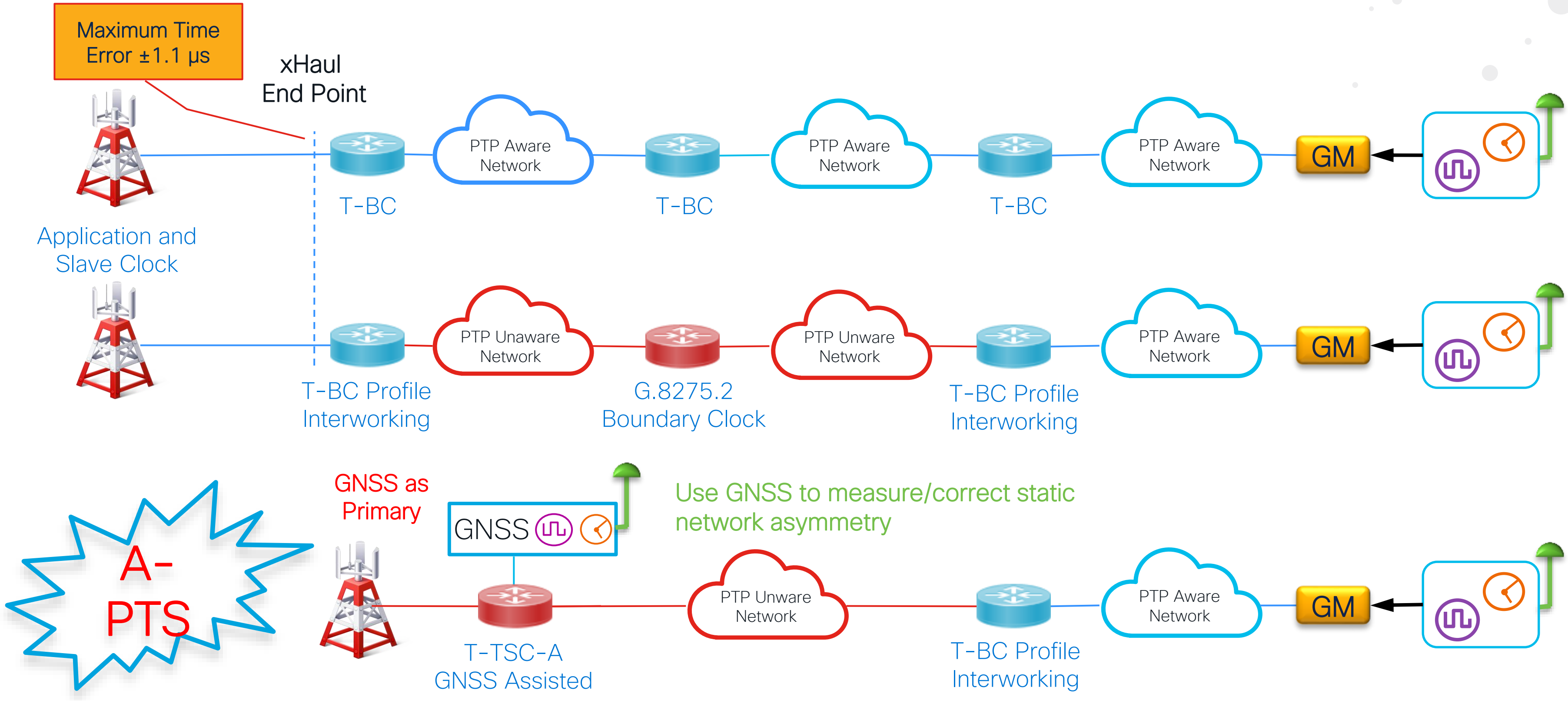
Different timing solutions for different networks models:

- Full (on-path) Timing Support (G.8271.1) – every node is a clock
- Partial Timing Support, or Assisted Partial Timing Support (G.8271.2) – gaps in timing support



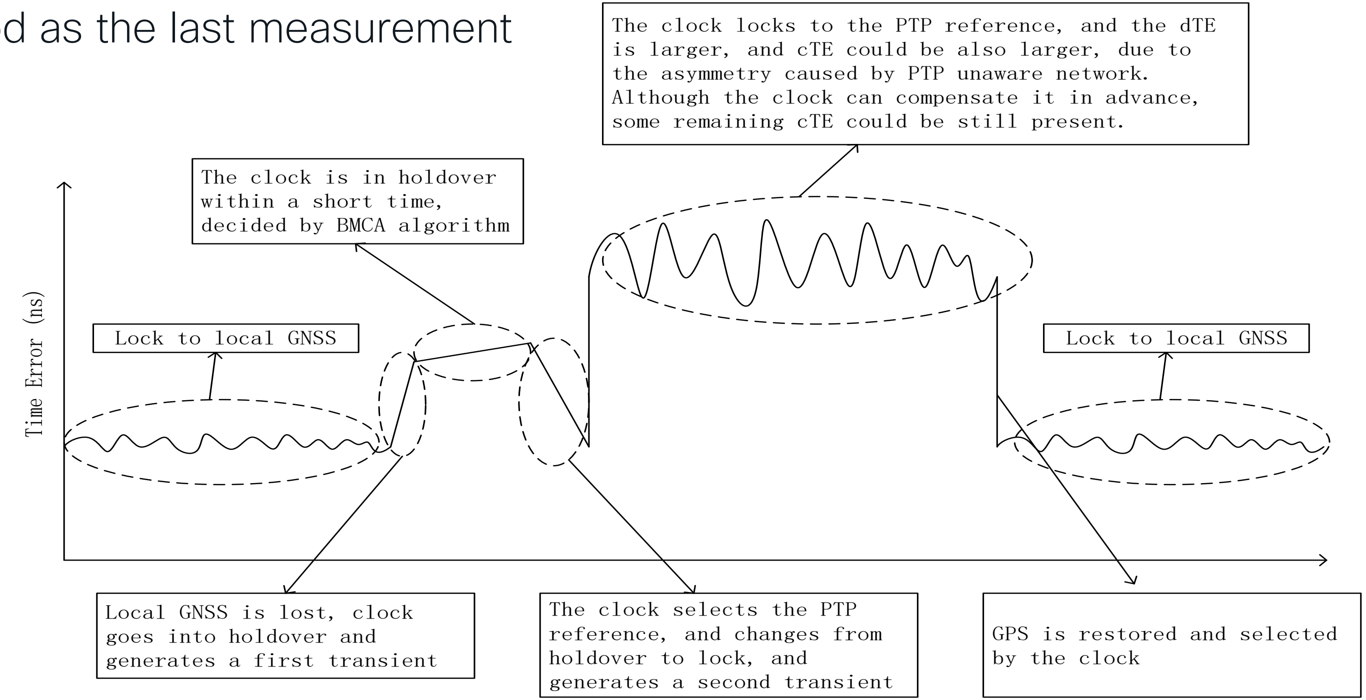
Solution Options

A-PTS = Assisted Partial Timing Support

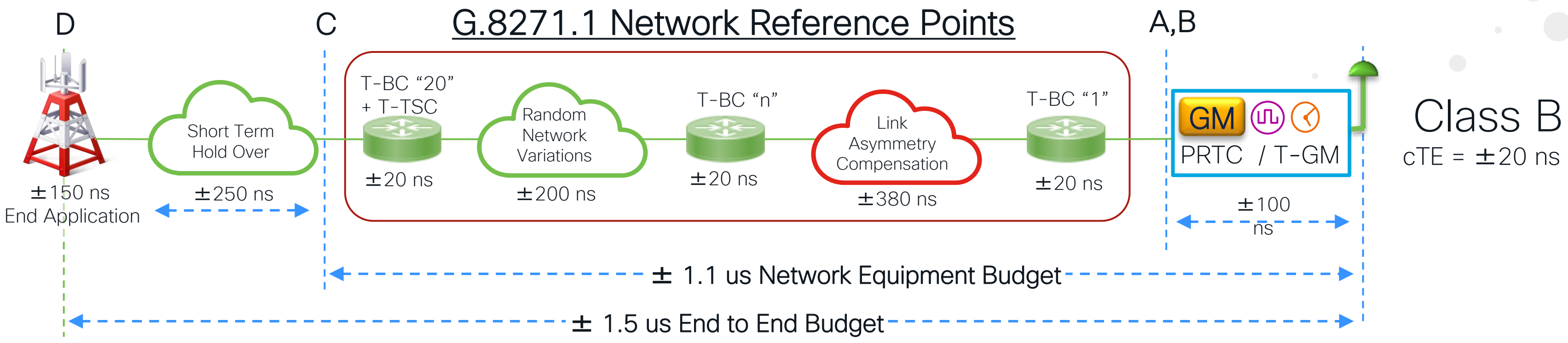


A-PTS Error Compensation

- A-PTS can correct for STATIC time error, dynamic error is still uncontrolled
- Only as good as the last measurement



Allocating Timing Budget v Node Performance



Performance Class	Max Total Time Error max|TE|	Constant Time Error cTE	Dynamic Time Error dTE_L low pass
Class A	100 ns	±50 ns	±40 ns
Class B	70 ns	±20 ns	±40 ns
Class C	30 ns	±10 ns	±10 ns
Class D	5 ns (low pass)	For further study	For further study

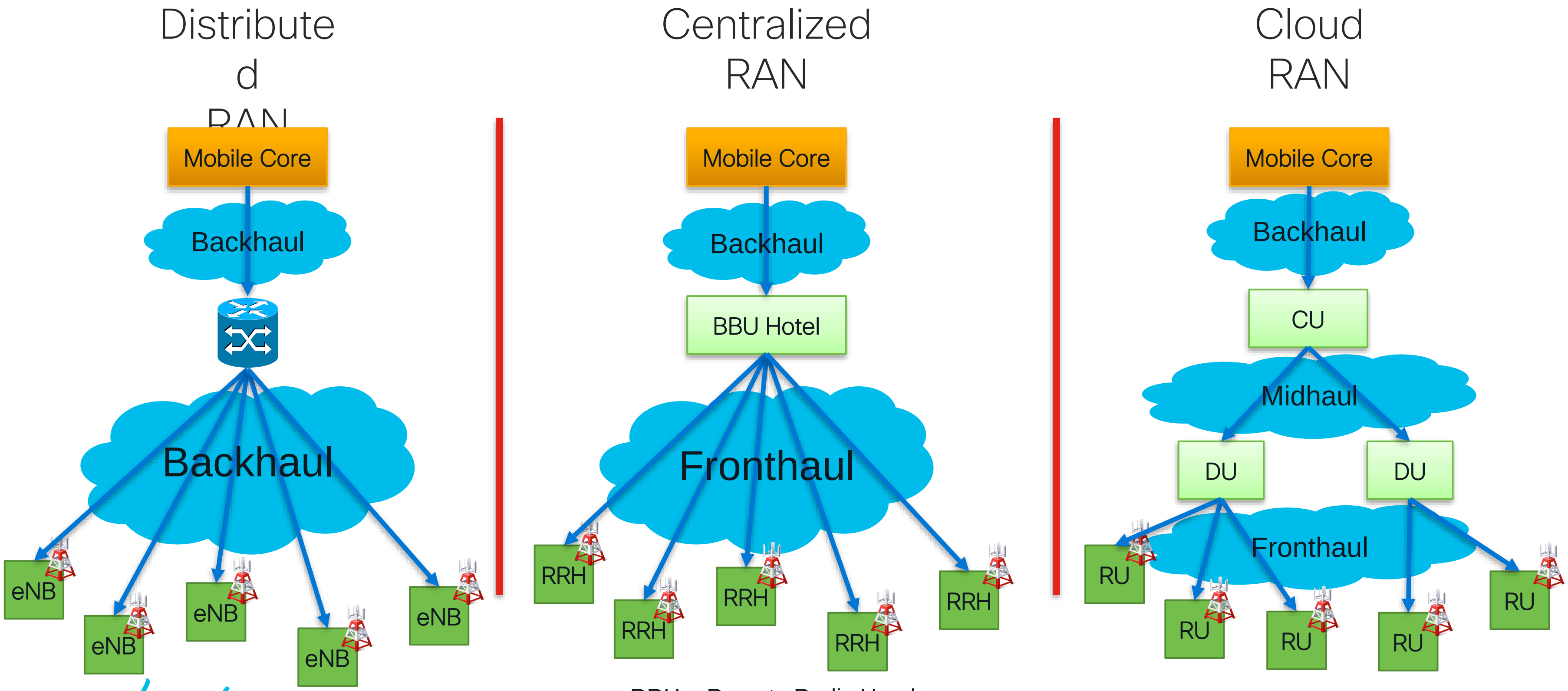
Budgeting Time Error – Sources

- Network models divide up the end-to-end budget
  - For LTE-A and 5G backhaul, this is ±1.1 μs/±1.5 μs
  - Assigns the budget to the different possible sources of time error
- G.8271.1: full timing support to the protocol level from the network (FTS)
  - Appendix IV “Constant and dynamic time error and error accumulation”
  - Appendix V “Example of design options” – budgeting max|TE|, dTE and cTE
- G.8271.2: partial timing support from the network (PTS)
- There are two Telecom Profiles defined, one for each use case
  - G.8275.1 for Full Timing Support (PTPoE multicast) “hop-by-hop”
  - G.8275.2 for Partial Timing Support (PTPoIP unicast)

5G RAN Timing Solutions

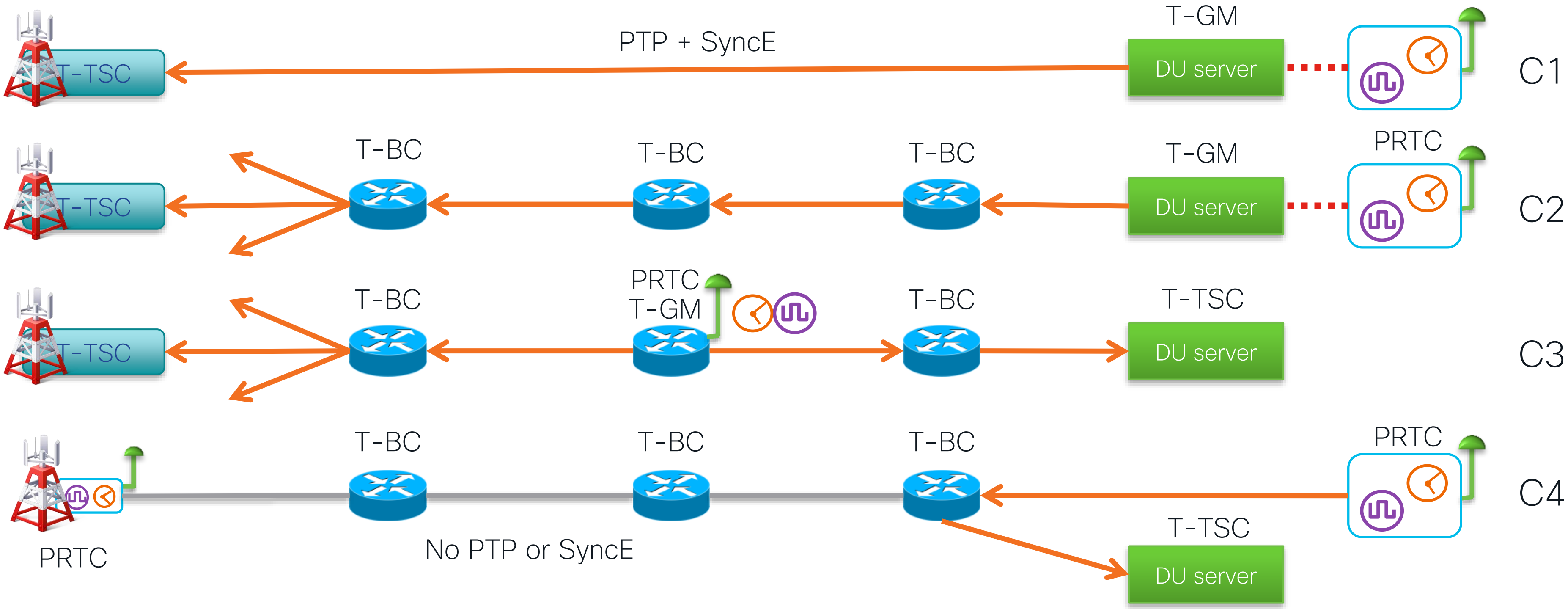
RAN Topologies

CU = Centralized Unit
DU = Distributed Unit
RU = Radio Unit



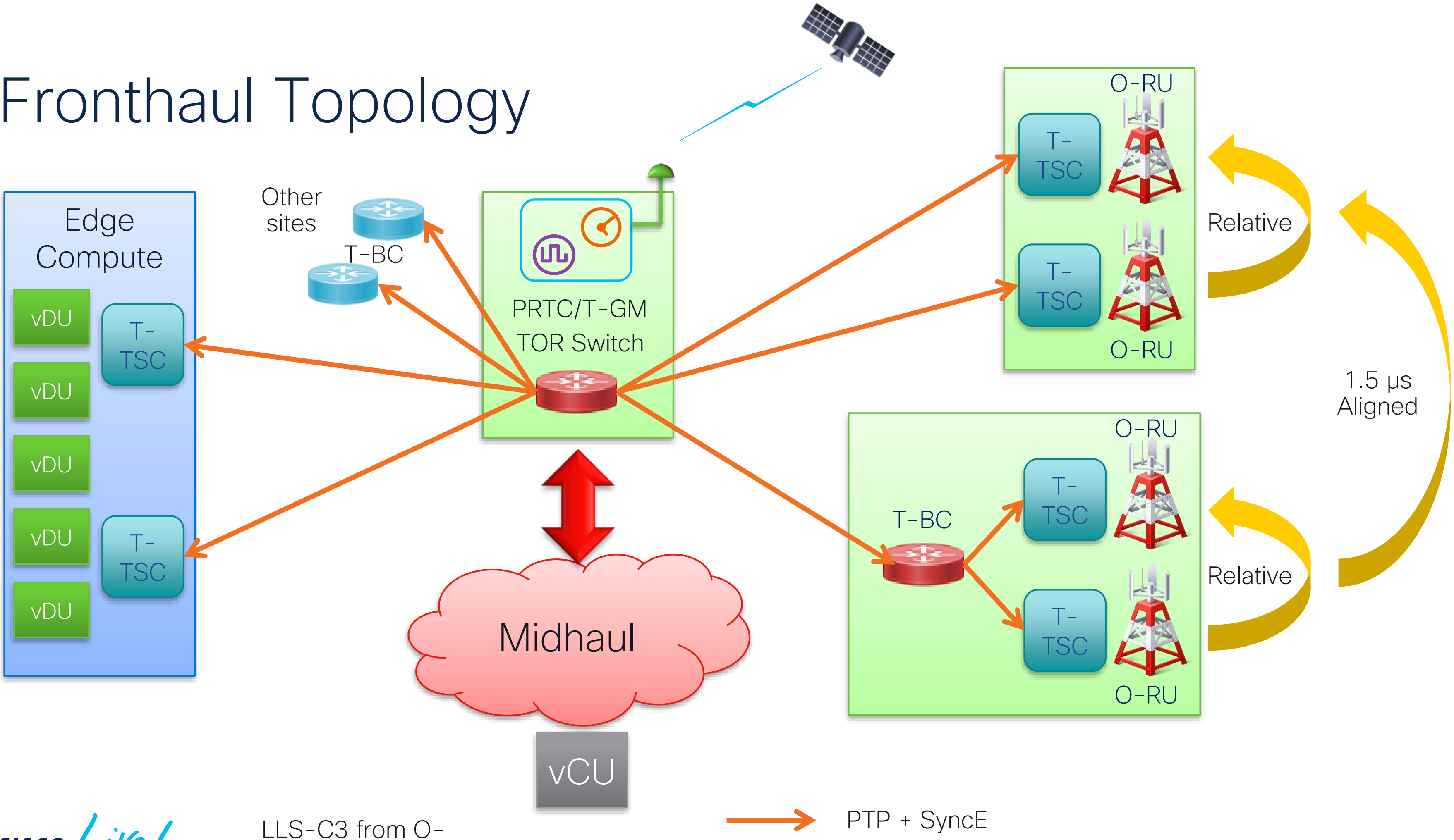
RRH = Remote Radio Head

O-RAN Fronthaul Deployment Options



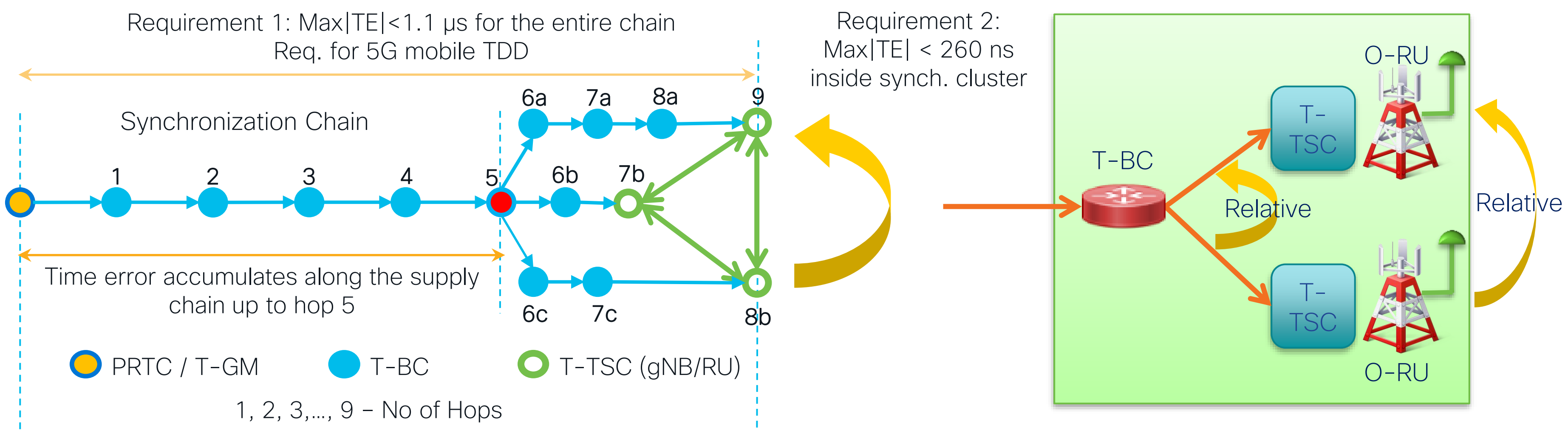
Source: O-RAN-WG4.CUS.0-v08.01

Fronthaul Topology



LLS-C3 from O-RAN

Relative Timing Requirements



- All nodes sync'd within the max|TE| of 1,100 ns
- Cluster below "5" also synced within max|TE| of < 260 ns RELATIVE to each other
- Relative time error between ports now important for advanced radio techniques

Deployment and Design Best Practices

Network Design

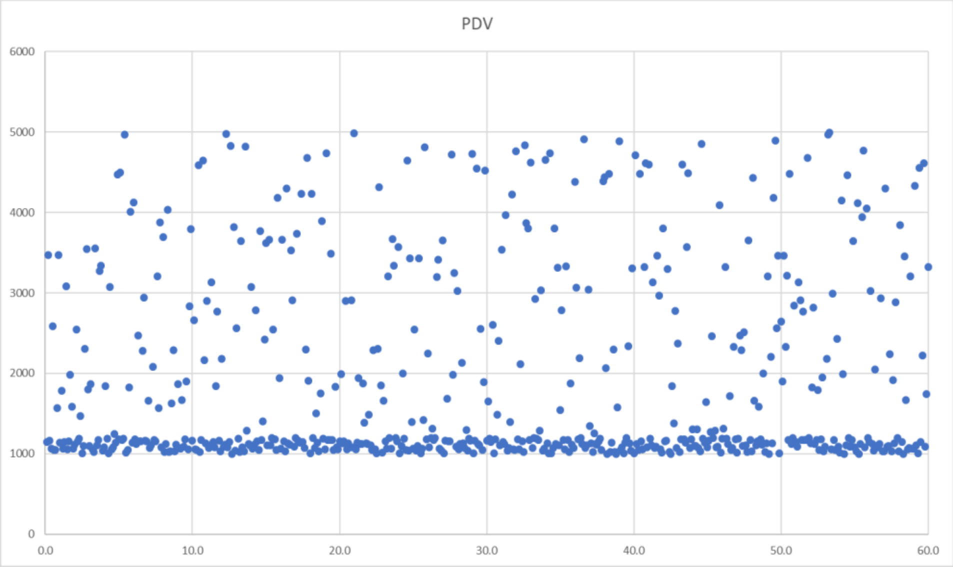
- Phase Synchronization
  - Deploy G.8275.1 with physical frequency (SyncE/eSyncE)
  - Reduce PDV (boundary clocks reset PDV back to zero)
  - Reduce asymmetry (routing, link, node, transport)—boundary clocks limit asymmetry
  - Likely requires remediation of transport layer
- Frequency Synchronization
  - If possible, use physical distribution (SyncE/eSyncE) not packet for frequency
  - G.8265.1 interoperates with SONET/SDH & SyncE (some gaps with eESMC mapping)
  - Packet distribution goal: reduce PDV (minimize hops as it disallows aware nodes)
  - Asymmetry isn't an issue for frequency over packet

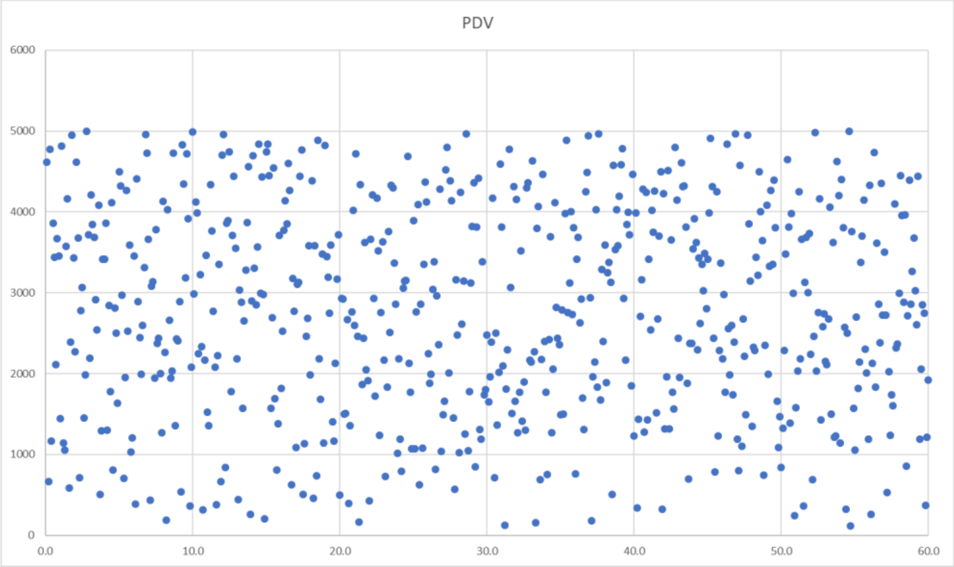
Plus/Minus of Each Profile

Feature	G.8275.1 PTPoE	G.8275.2 PTPoIP
Network Model	Full on-path support	Partial on-path support
IP Routing	Not applicable	Problematic (rings, asymmetry)
Transit traffic	Not allowed	Problematic (jitter, asymmetry)
Performance	Best	Variable
Configuration Model	Physical Port	L3 device
PTP over Bundles	No issue	Being worked on (for BC's)
Asymmetry	Reduced (T-BC on every node)	T-BC good, not T-BC = bad
PDV/jitter	Timestamping on wire (small)	T-BC good, not T-BC = bad

Reduce PDV

- Packet Delay Variation is bad for unaware nodes:
  - Must have a “floor” of lucky packets arriving in minimum time
  - Accumulates with every unaware node – fixed with T-BC’s





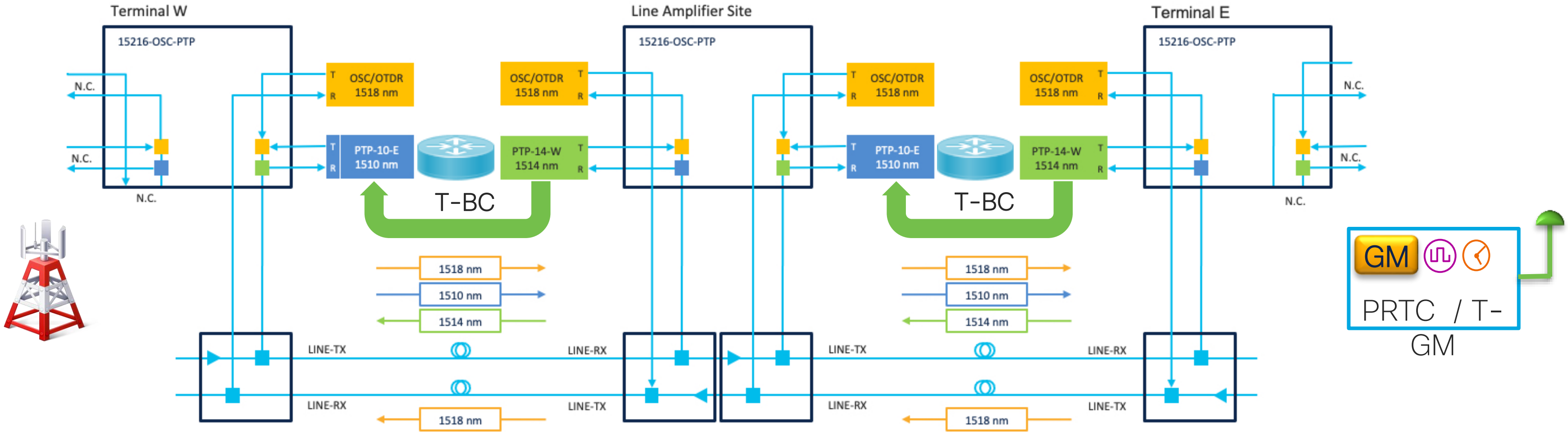
Reduce Asymmetry

- Asymmetry can come from:
  - Routing (especially in complex topologies, rings, ECMP)
  - PTP unaware transit nodes (esp. with varying traffic patterns)
  - Transport (PON, Cable, DWDM, complex optics)
  - Every 2 microseconds of asymmetry = 1 microsecond of time error
- Doing this on an unaware network is very problematic
  - QoS cannot really solve the problem – but it helps
- Boundary clocks handle the asymmetry problem in the nodes
  - Assuming they are properly engineered and built
  - Pluggable optics in T-BC need special attention

Remediating Optical Transport

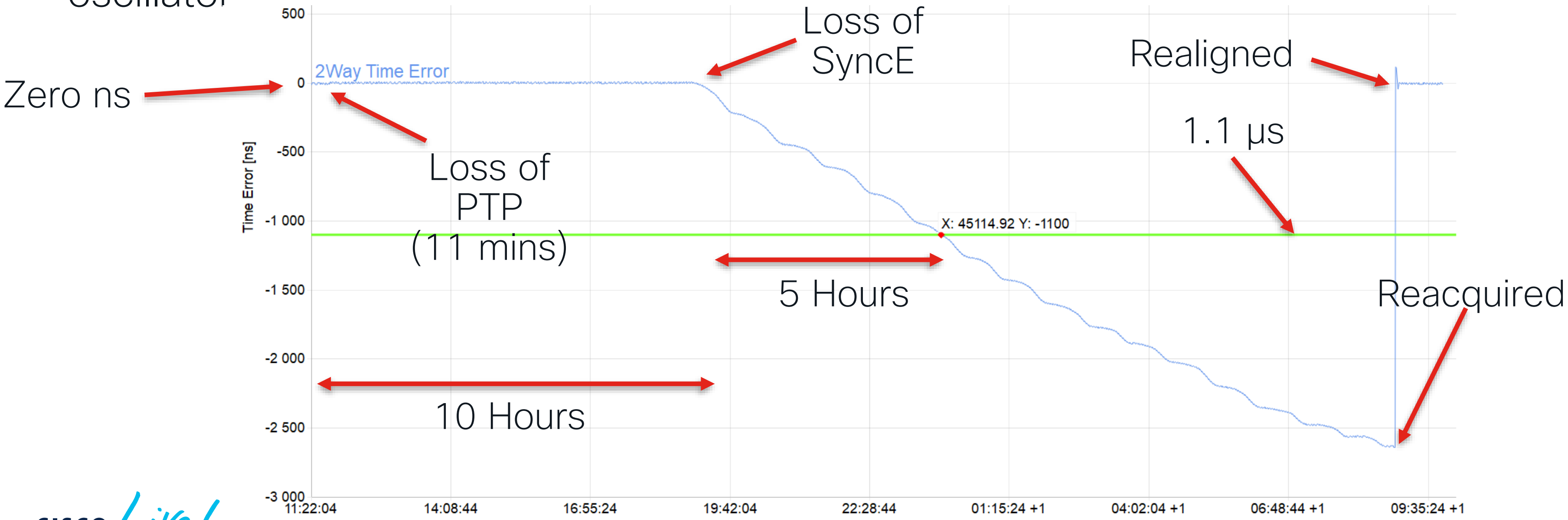
- “Smart” optical devices introduce buffering and/or complex processing
- Optical systems: separate channel for PTP (like Optical Service Channel)
- Cisco solution based on the NCS2K

Bi-directional fibre reduces asymmetry



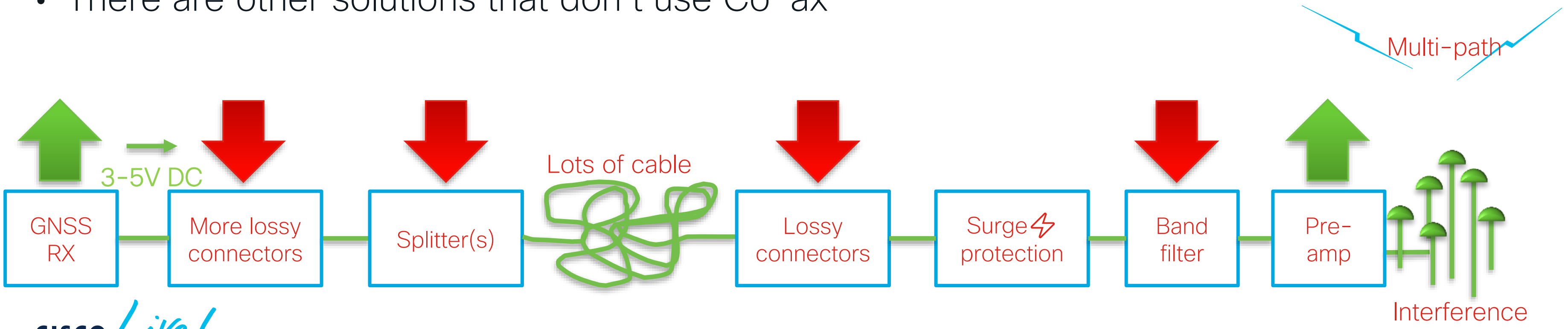
Holdover: SyncE and non-SyncE

- Holdover is either oscillator only, or assisted with external frequency (SyncE)
- Staying within 1.1 µs is only possible for several hours when relying on local oscillator



Deploying Satellite Systems

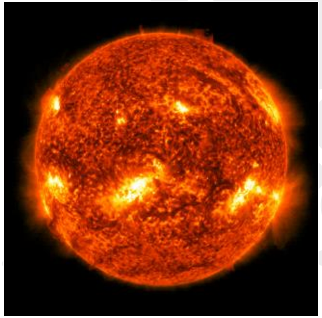
- Antenna selection: a professional installation is recommended
  - Match the gain from antenna and pre-amplifier to the loss/attenuation in the cable
    - Meet in-building regulations (fire), roof access, surge protection
  - Siting the antenna to avoid interference/multi-path distortions
  - Signal arrives at the receiver in the "sweet spot" above **35 dB-Hz (C/N_0)**
  - Initial lock must complete the "self-survey" operation with 4 satellites
- There are other solutions that don't use Co-ax



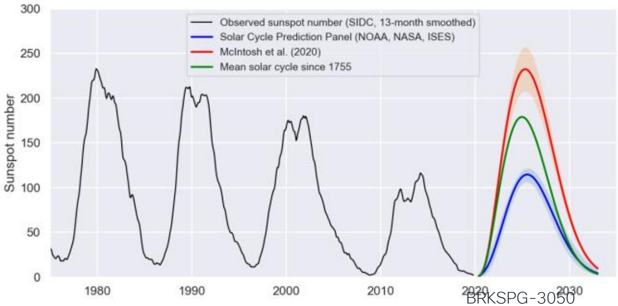
Deploying Satellite Systems

- Jamming and GNSS issues
  - Short term interruptions are ok (expected?) – but devices must support holdover
  - Jamming is not a matter of IF, but a matter of WHEN and HOW LONG?
  - Regulators are taking a hard look at organizations' resilience to GNSS jamming
- There are some solutions that help mitigate jamming/spoofing:
  - GNSS "Firewalls" from several vendors
  - "Anti-jam" antennas reject/attenuate false or overwhelming signals
  - Military-derived "active" CPRA antennas (Controlled Radiation Pattern Antennas)
  - Geographical redundancy: separating receivers (also helpful for weather events)
  - Robust holdover (especially with SyncE assistance)
  - Multi-band and multi-constellation may not help!!!

Deploying Satellite Systems

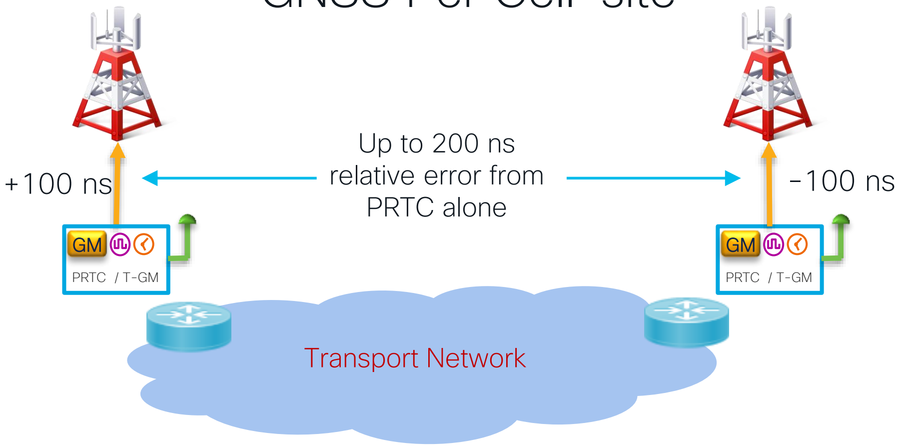


- New classes of PRTC: PRTC-A (100 ns) and PRTC-B (40 ns)
  - PRTC-B needs dual band such as GPS L1/L2 (generally), likely needs new antenna
  - Space-based Augmentation Systems (WAAS, EGNOS, etc.) not yet impacted timing
- Solar Cycle 25 progression and space weather
- Galileo (monthly UTC now ~5 ns @ 95 percentile)
  - High Accuracy Service now operational (Europe)
  - Open Service Navigation Message Authentication (OSNMA)
- Alternatives to GNSS
  - eLORAN
  - LEO satellite systems



GNSS per Cell Site vs Network Timing

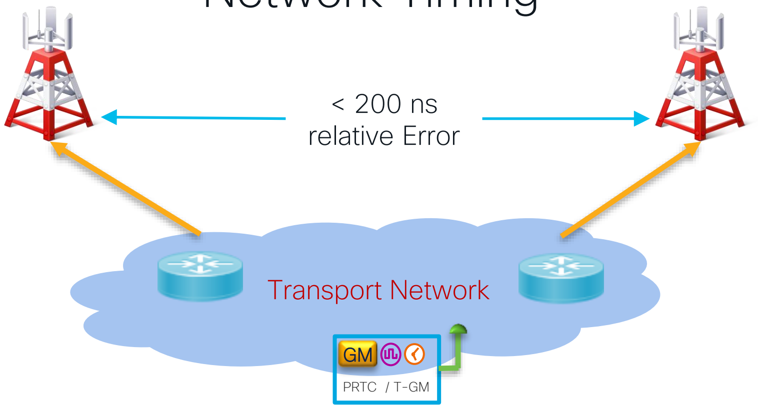
GNSS Per Cell-site



In theory: PRTC-A receiver (100 ns) per cell site may not meet budget for 5G RAN

PRTC-B (40 ns) can help

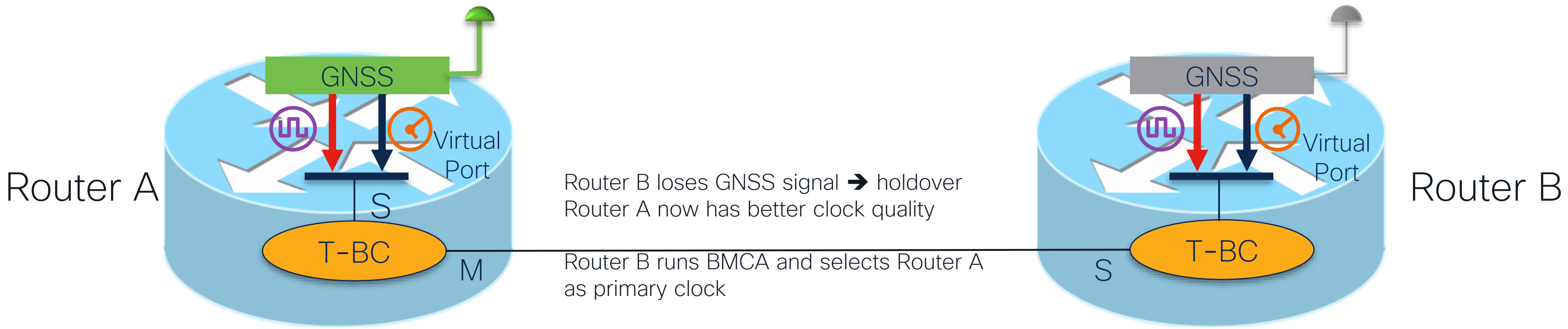
Network Timing



Centralized PRTC, can manage relative time error better via network TE budgeting

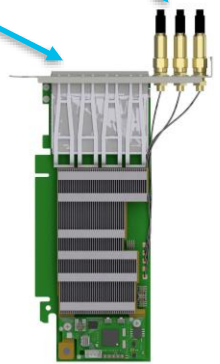
Virtual PTP Port

- Problem: T-GM can only PUSH time out, can never receive it; T-BC can
- Virtual port (G.8275 Annex B) allows frequency & phase/time inputs to T-BC
- Can configure a Boundary Clock with integrated GNSS as a virtual PTP port and run BMCA to select best time source: local GNSS or remote grandmaster
- Great redundancy option across a pair of cell sites



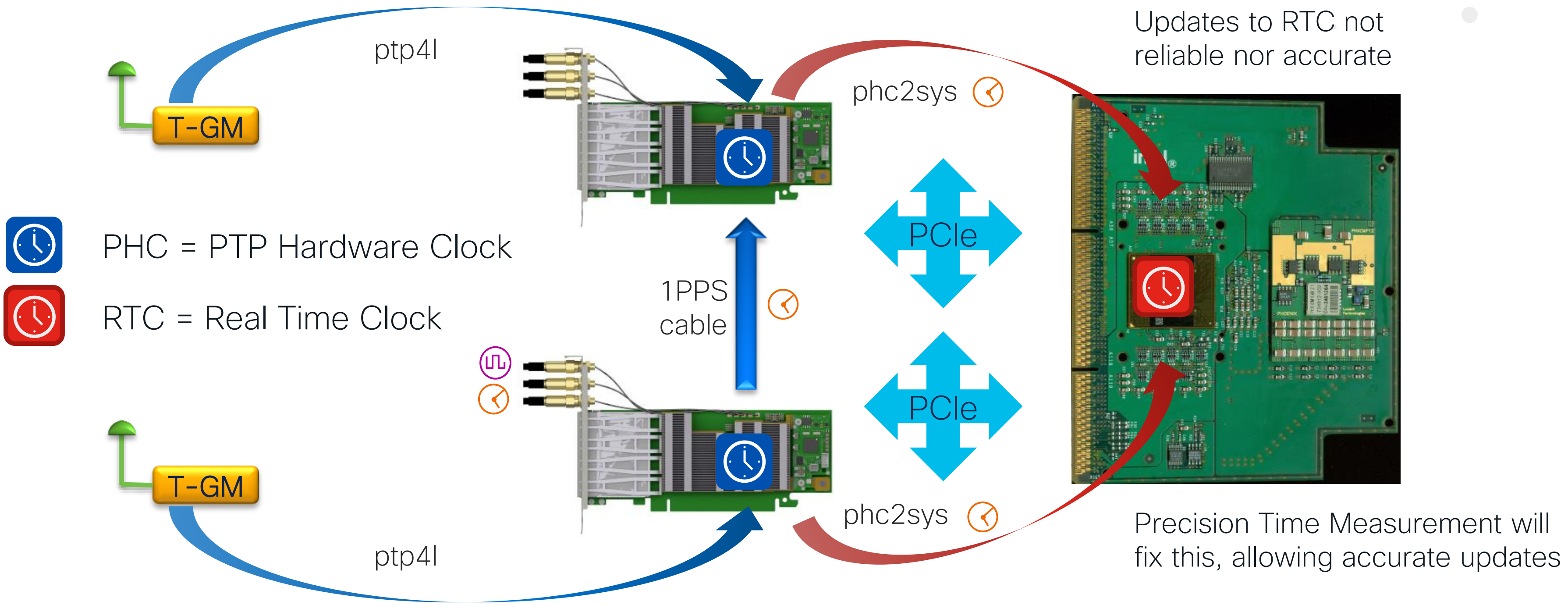
DU Compute Timing Features

- (Timing) NIC cards come with/without GNSS receiver (or HQ oscillator)
- NIC receives network timing from Fronthaul switch (O-RAN C3)
- NIC does the PTP hardware timestamping for the server:
    - Linux uses ptpl4 and phc2sys software to drive the clock
    - PTP hardware clock (PHC) is situated on each NIC card
    - No accurate centralized clock on server
    - SyncE not widely implemented either (and so poor holdover)
- Distributing clock across the server is EXTERNAL (between NIC cards)
    - Use 1PPS cables to “daisy chain” NIC cards into the same time/phase domain
- New feature (Precision Time Measurement) allows accurate clock across PCIe bus



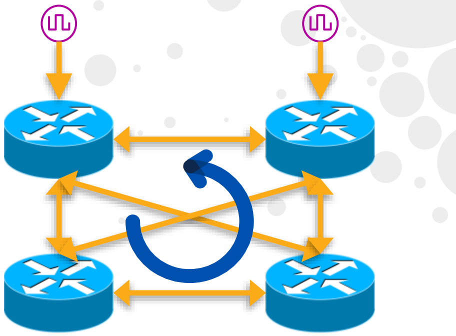
In Multi-NIC environment, failure of primary NIC will bring down the DU

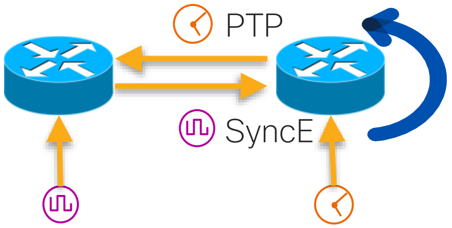
Hardware Architecture

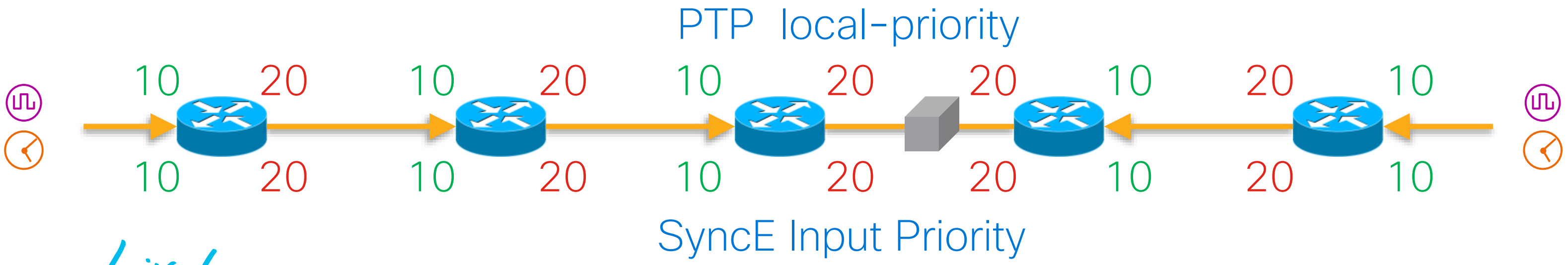


Avoiding Timing Loops (esp. SyncE)

- Configuring too many redundant paths risks timing loops
- Shows up as flapping: PHASE-ALIGNED ⇔ FREQUENCY-LOCKED
- Rings are especially a problem, need to “break the ring”
- Giving SyncE to a node that provides PTP back is a loop!!
- Best practices:
  - Make PTP and SyncE traceable back to the same clock source
  - Use PTP “local-priority” to mirror SyncE input priority







eSEC/eEEC = G.8262.1
ESMC/eESMC= G.8264

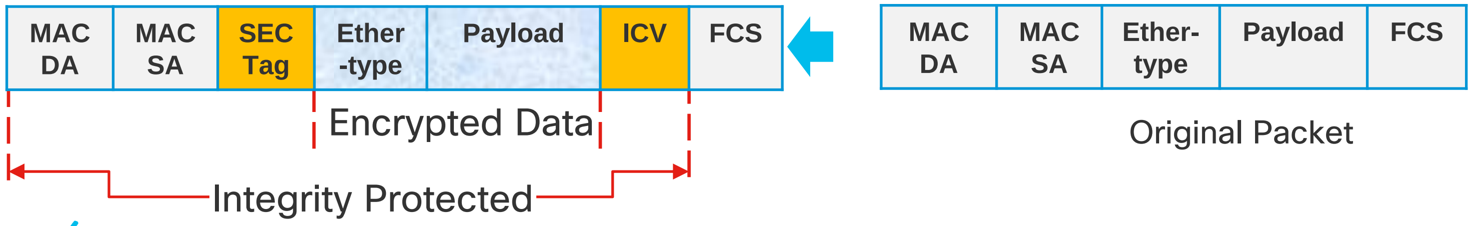
Enhanced SyncE (eSyncE and eESMC)

- eSyncE was introduced in new recommendation G.8262.1 (Jan 2019)
  - Improved performance: especially frequency wander on output
  - Increasingly rolled into components, network devices (esp. class C level T-BCs)
- Enhanced ESMC (Apr 2016 amendment) to support new clock types & functionality
  - Allowed higher accuracy clock sources, time sources, and enhanced SyncE clocks
  - Added a new TLV for “extended quality levels” such as PRTC, ePRTC, ePRC, eSEC/eEEC
  - Includes new clockIdentity of the originator of the SyncE signal
  - Separate count of the SEC/EEC and eEEC/eSEC hops from the originating source
- Significant interoperability issues can arise:
  - Nodes that do not support enhanced TLV will drop it!!!

ESMC = Ethernet Synchronization Message Channel

MACsec and Security for Timing

- MACsec is a L2 port-based security mechanism
  - Either encryption + integrity checking OR only integrity checking (IEEE 802.1AE)
  - Maybe mechanisms to choose whether to send secured/unsecured on a port
- Either asymmetry or dynamic time error can arise through:
  - Difference in time to encrypt/decrypt messages
  - Selection of receive/transmission timestamping point
  - Differences in time to encrypt/decrypt subsequent messages

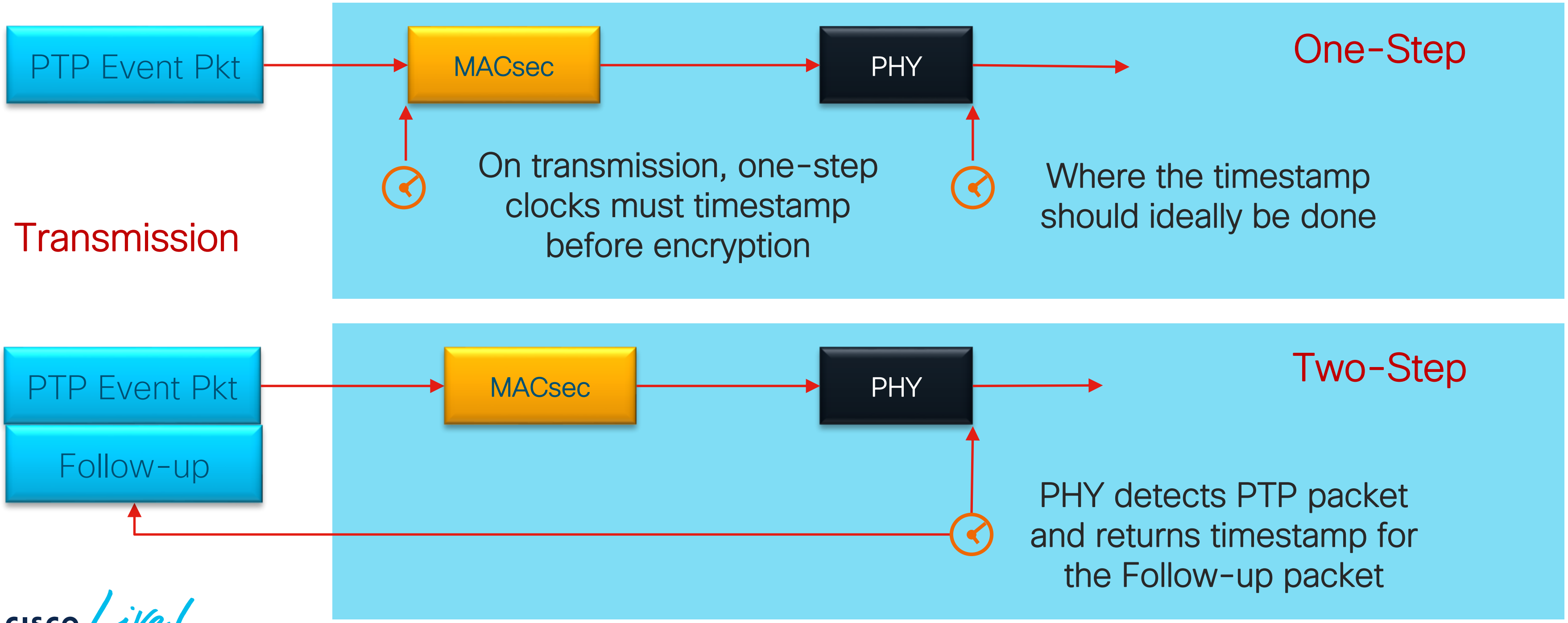


MACsec and Security for Timing

- Problems with PTP and MACsec:
  - Timestamp must be inserted into a packet BEFORE it goes through the MACsec block, after which the packet cannot be modified (or even recognized when encrypted)
  - Encryption must always take the same number of cycles (even after key rollover)
  - Therefore, PHY-based timestamping doesn't work for one-step clocks (T1 timestamp in Sync)
- Two-step clocks can mitigate this problem and still use PHY timestamping:
  - If the packet is encrypted, the PHY will not be able to recognize the outgoing sync packet as a PTP packet, so other means of identification are required
  - Decryption must happen before timestamping at the receiving end. This must take the same number of cycles as encryption, or asymmetry is introduced
- Can also try to calibrate the time for encryption and update the correctionField

Transport Security: MACsec

Implementation of PTP in combination with MACsec: 1-step v 2-step



Deploying Timing Summary

- Engineer a “timing solution” and not just solve a connectivity problem
  - Timing design is an end-to-end budgeting exercise
  - Remove as much asymmetry and PDV as possible
  - Be very cautious with PTPoIP
  - Not try to get too fancy with the packet design
- PTP aware networks limit the accumulation of PDV and time error
- Combination of SyncE with PTP, with SyncE assisted holdover
- Upgrade transport systems to be PTP and SyncE aware
- Work <u>with</u> the standard solutions rather than trying to “roll your own”

Conclusion

What’s Happening in the Standards?

- ITU-T standards developments
  - Developments around security: Security TLV for the Announce message?
  - Adopting optional features from 1588-2019 (such as Accuracy TLV)
  - Monitoring (OAM) and YANG models for Telecom Profiles (G.7721.1)
- O-RAN standards development
  - Combination of MACsec and PTP
- IEEE standards developments
  - Left-overs from 1588-2019 (one being Key Exchange for Security mechanism)
  - IEEE P1952, Resilient Positioning, Navigation, and Timing User Equipment
- BIPM (Bureau International des Poids et Mesures) decision on the leap second

Conclusion

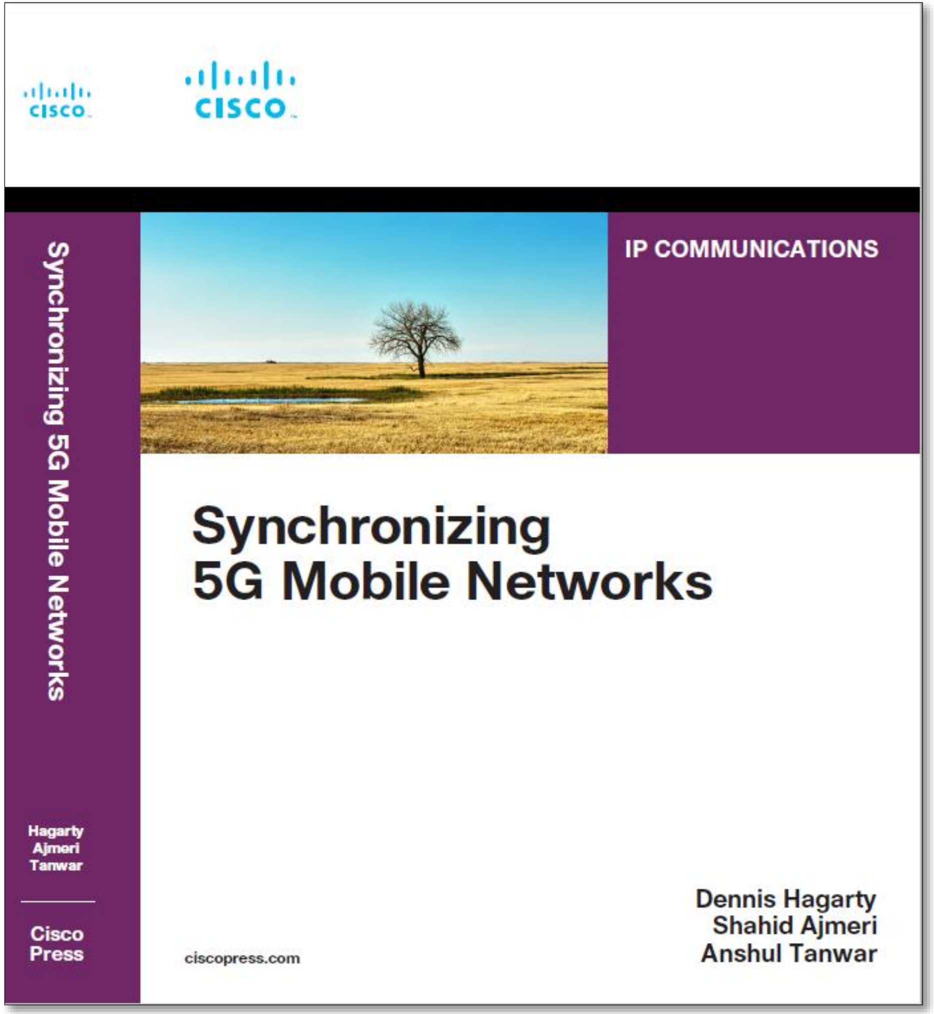
- Timing being introduced, more deeply, into more industries
- Timing requires its own specific design for both PTP and SyncE
- 5G Fronthaul introduces additional complexity with relative time
- Lots of effort now going into transport system mitigation
- MACsec with very accurate timing is still problematic
- GNSS independence/resilience should be a high priority
- Moving to an enhanced SyncE network
- Testing: seeing people still struggling with testing

Further Information

"Synchronizing 5G Mobile Networks"

- Publisher: Pearsons/Cisco Press
- eBook & Print
- Published: June 2021

https://www.ciscopress.com/store/synchronizing-5g-mobile-networks-9780136836254



Further Information: Conferences and Standards

- WSTS Workshop on Sync & Timing, March 13-16, 2023, Vancouver
  https://wsts.atis.org/
- ITSF International Timing & Sync Forum, 30 Oct to 02 Nov 2023, Antwerp, Belgium
  https://itsf2023.executiveindustryevents.com/Event/index.php
- ITU-T Study Group 15 Question 13:
  https://www.itu.int/en/ITU-T/studygroups/2022-2024/15/Pages/default.aspx
- Next ITU-T Sync Interim Meeting (6-10 February 2023 E-meeting):
  https://www.itu.int/en/ITU-T/studygroups/2022-2024/15/Pages/default.aspx
- Next ITU-T Sync Plenary Meeting (17-28 Apr 2023, Geneva, CH):
  https://www.itu.int/dms_pub/itu-t/md/22/sg15/col/T22-SG15-COL-0002!!MSW-E.docx

Further Information: GNSS Vulnerabilities

- Galileo service information: https://www.gsc-europa.eu/
- ATIS White Paper: “GPS Vulnerability”
  https://access.atis.org/apps/group_public/download.php/36304/ATIS-0900005.pdf
- “National Research and Development Plan for PNT Resilience.”
  https://rntfnd.org/wp-content/uploads/NSTC_Position_Navigation_Timing_RD_Plan_Jan2021.pdf
- Resilient Navigation and Timing Foundation
  https://rntfnd.org/

RESILIENT NAVIGATION and TIMING FOUNDATION

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- Attend any of the related sessions at the DevNet, Capture the Flag, and Walk-in Labs zones.
- Visit the On-Demand Library for more sessions at ciscolive.com/on-demand.

The bridge to possible

Thank you

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ALL IN

O-RAN Fronthaul Synch Requirements

Synchronization Metric	Requirement
Frequency Jitter and Wander	From SyncE (G.8262) or eSyncE (G.8262.1)
Air interface frequency error	TS 36.104 (LTE) and TS 38.104 (5G) specify ±50 ppb
Maximum |TE| (for features covered by 3GPP)	TS 36.104 (for LTE) and TS38.104 (for 5G)

eCPRI Fronthaul Synch Requirements

Category	Time Error Requirements at UNI |TE|			3GPP TAE requirements at antenna ports
	Case 1		Case 2	
	Case 1.1	Case 1.2		
A+	N.A.	N.A.	20 ns Relative	65 ns
A	N.A.	60 ns Relative	70 ns Relative	130 ns
B	100 ns Relative	190 ns Relative	200 ns Relative	260 ns
C	1100 ns Absolute		1100 ns Absolute	3 µs

Case 1 = T-TSC is integrated in eRE

Case 2 = T-TSC is not integrated in eREs

Case 1.1 = integrated T-TSC requirements to T-TSC Class B

Case 1.2 = enhanced integrated T-TSC requirement is total max |TE| is 15 ns

Comparisons of GNSS systems

System Name	Country	Satellites
GPS/Navstar	USA	27 MEO (global)
Galileo	European Union	24 MEO (global)
GLONASS	Russian Federation	22/24 MEO (global)
IRNSS, NavIC	India	4 IGSO, 3 MEO (regional)
QZSS	Japan	1GEO, 3 QZO (regional)
BeiDou2/Compass	China	4 GEO, 6 IGSO, 3 MEO (regional)
Beidou3	China	5 GEO, 3 ISGO, 27 MEO (global)

QZO = Quasi-Zenith Orbit, IGSO = Inclined Geosynchronous Satellite Orbit, GEO = Geosynchronous Earth Orbit