IEC/IEEE 60802 Time Synchronization Developments and Results

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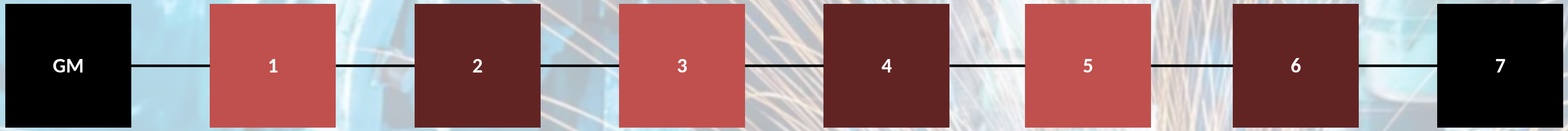
IEEE 802.1BA

1 µs

IEC IEEE 60802



IEC/IEEE 60802

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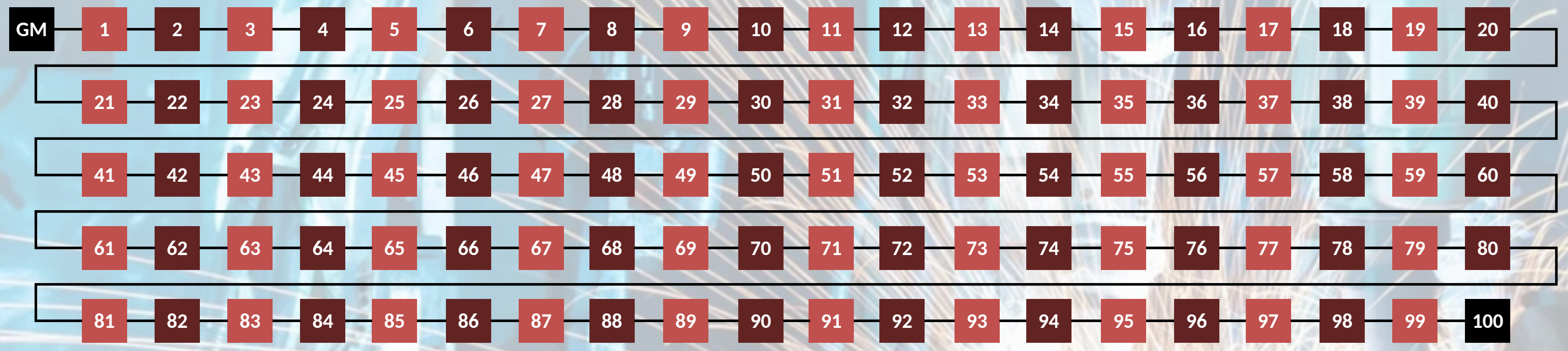

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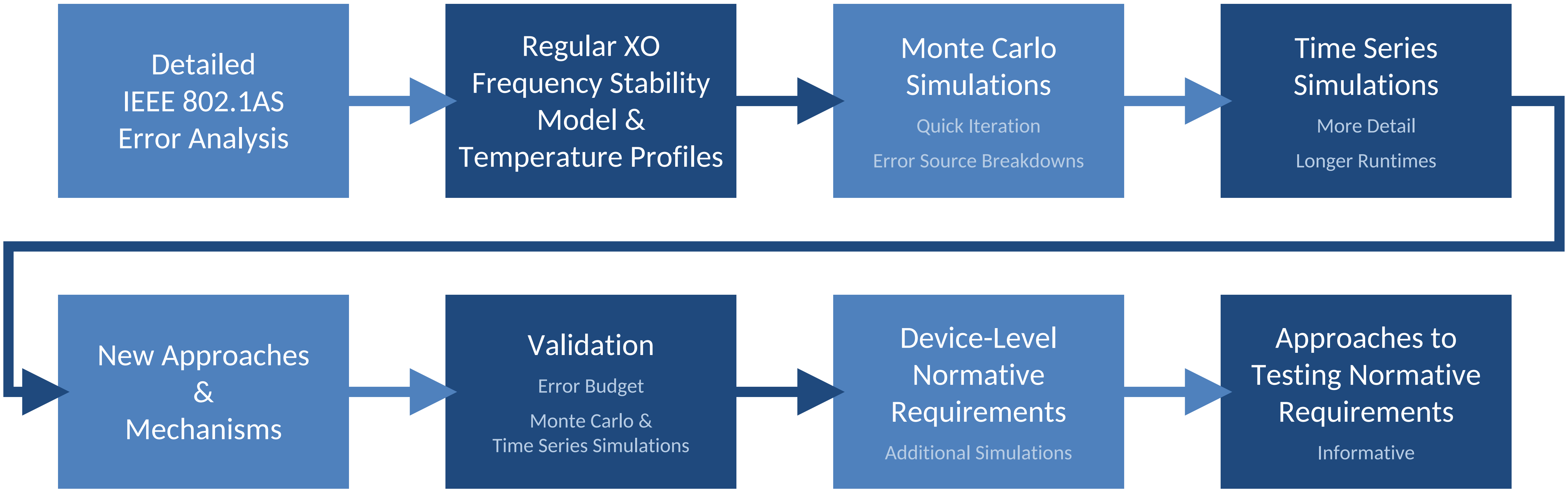
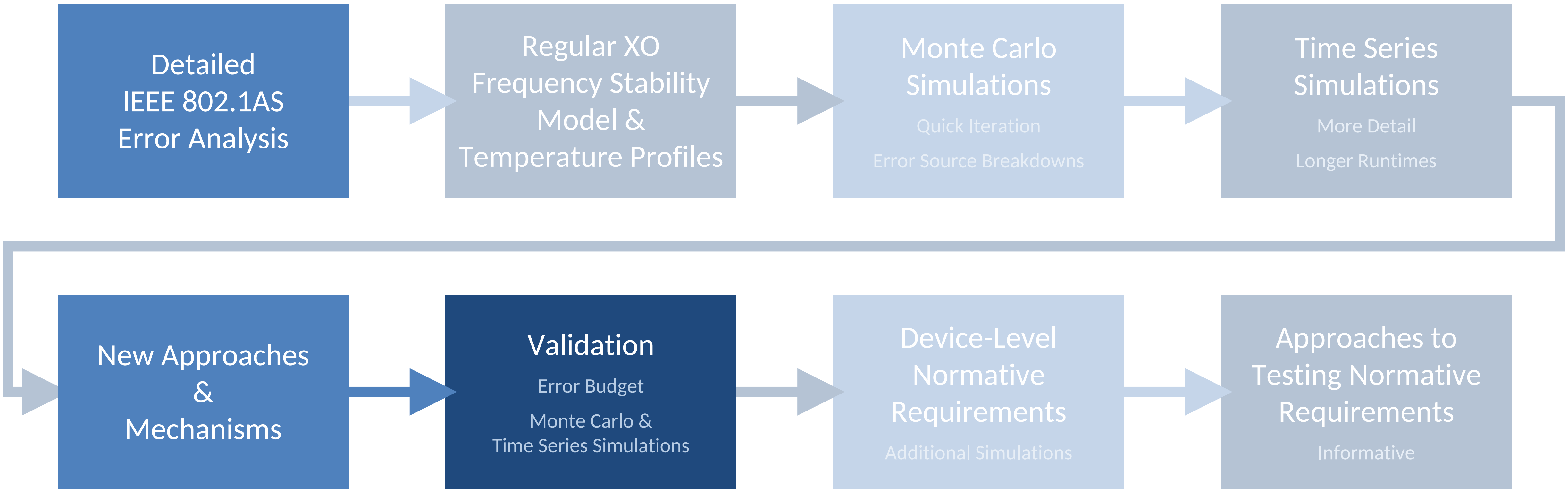
IEEE 60802

Low Cost XOs

Existing Silicon

1 µs


Detailed IEEE 802.1AS Error Analysis
Regular XO Frequency Stability Model & Temperature Profiles
Monte Carlo Simulations
Quick Iteration
Error Source Breakdowns
Time Series Simulations
More Detail
Longer Runtimes
New Approaches & Mechanisms
Validation
Error Budget
Monte Carlo & Time Series Simulations
Device-Level Normative Requirements
Additional Simulations
Approaches to Testing Normative Requirements
Informative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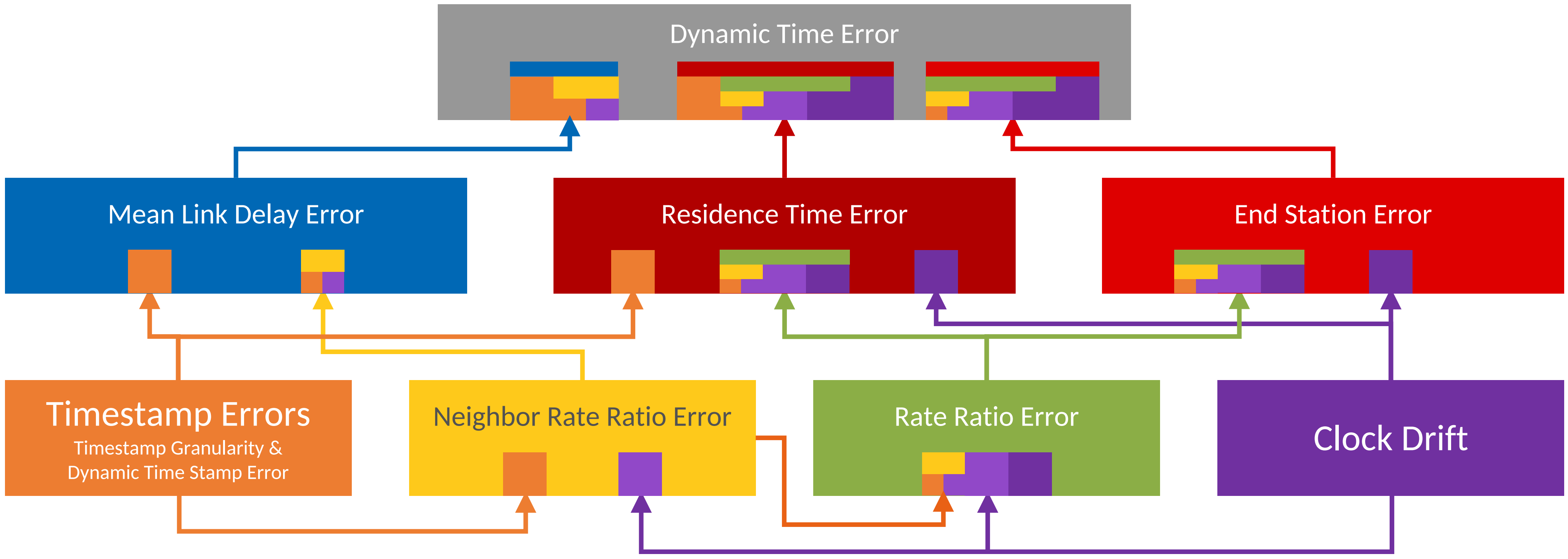
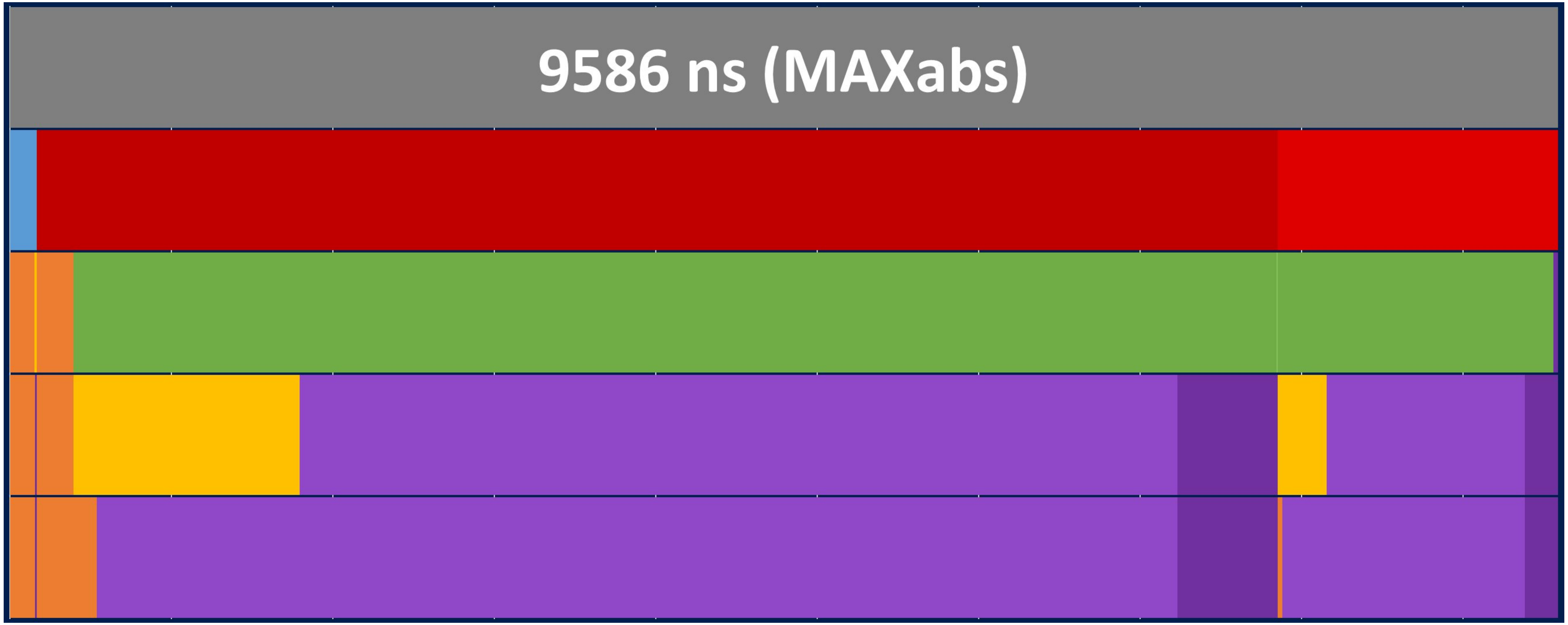
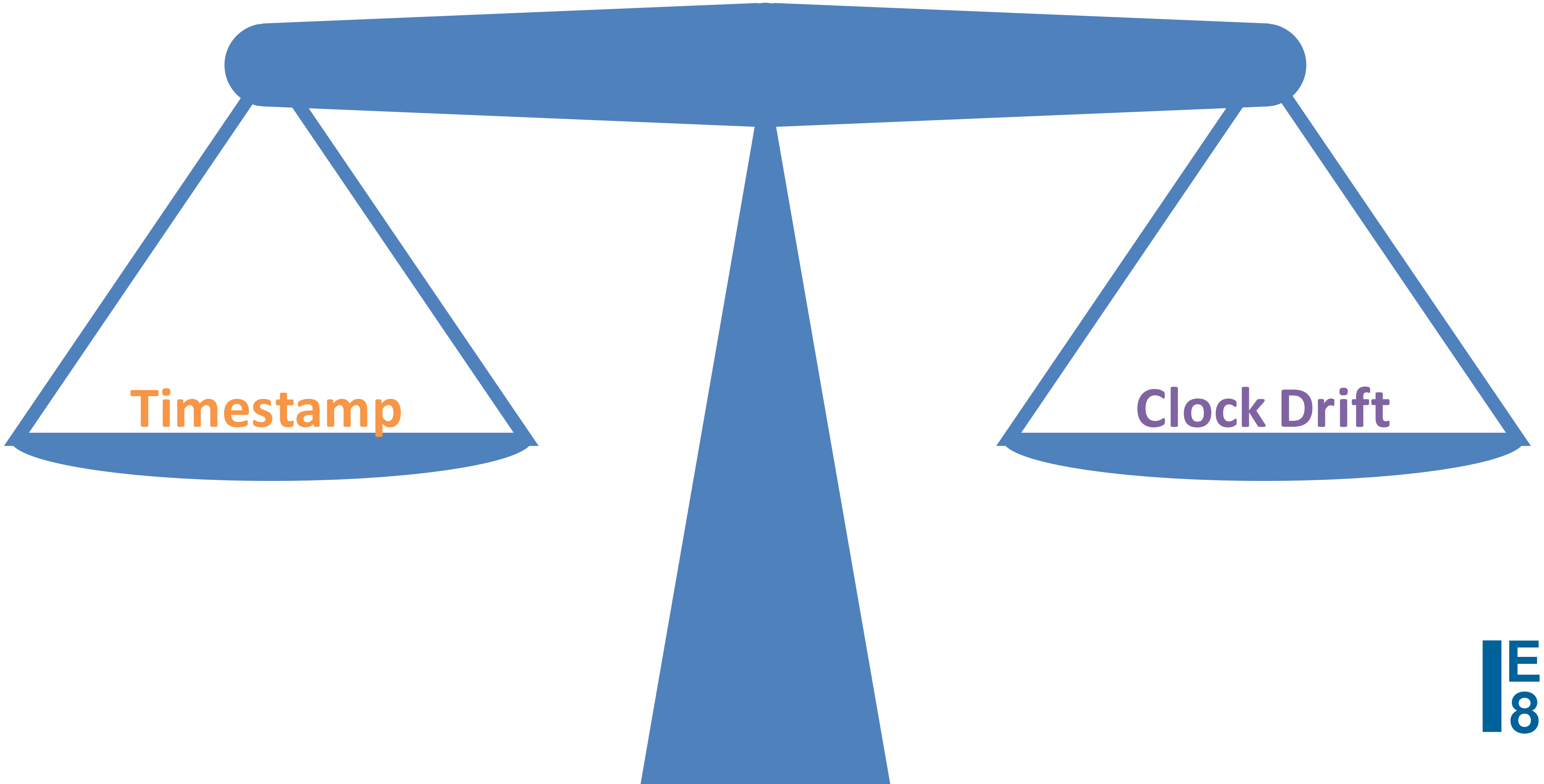
Error Analysis - dTE



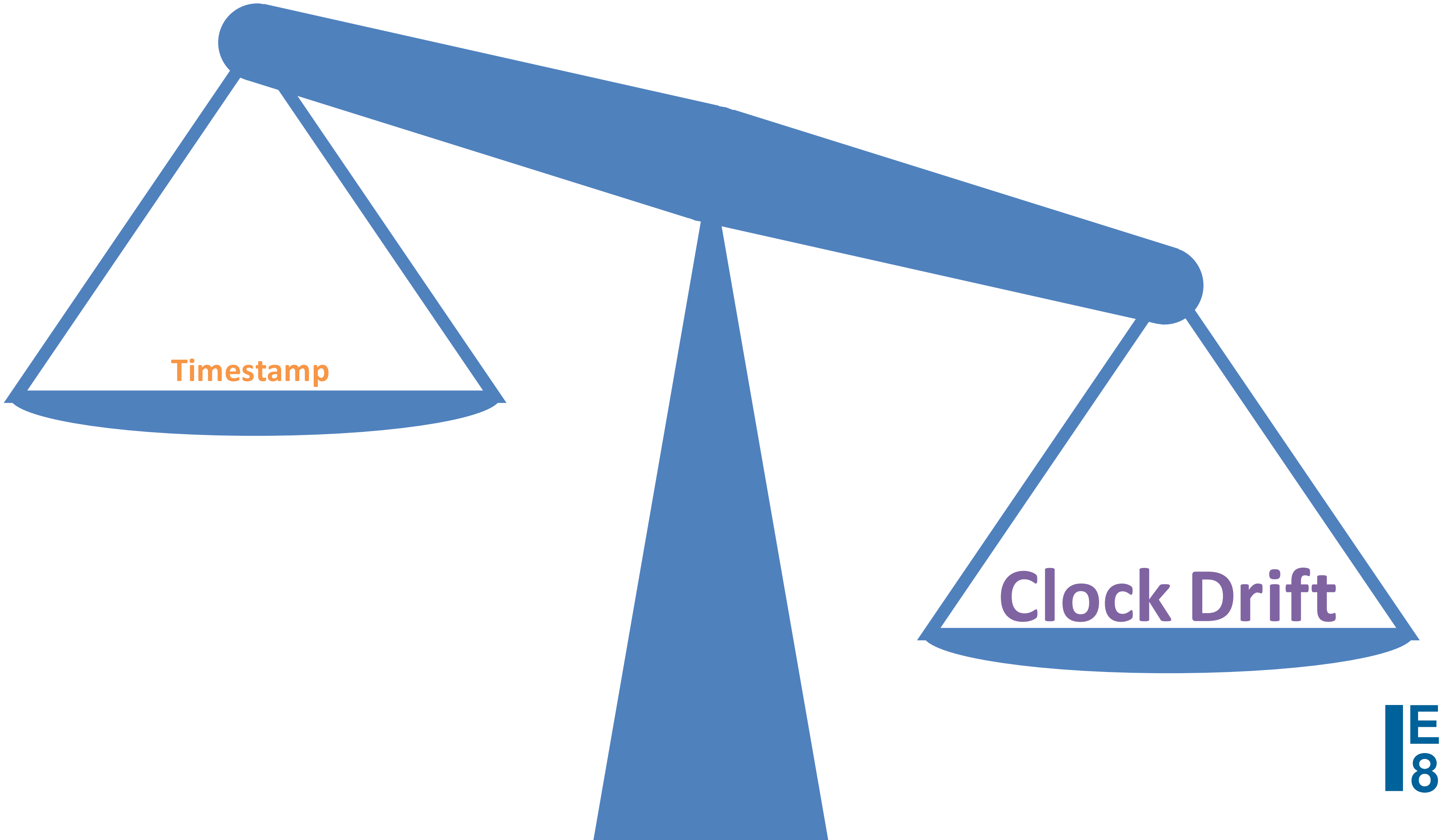
Visualising Error Component Contribution

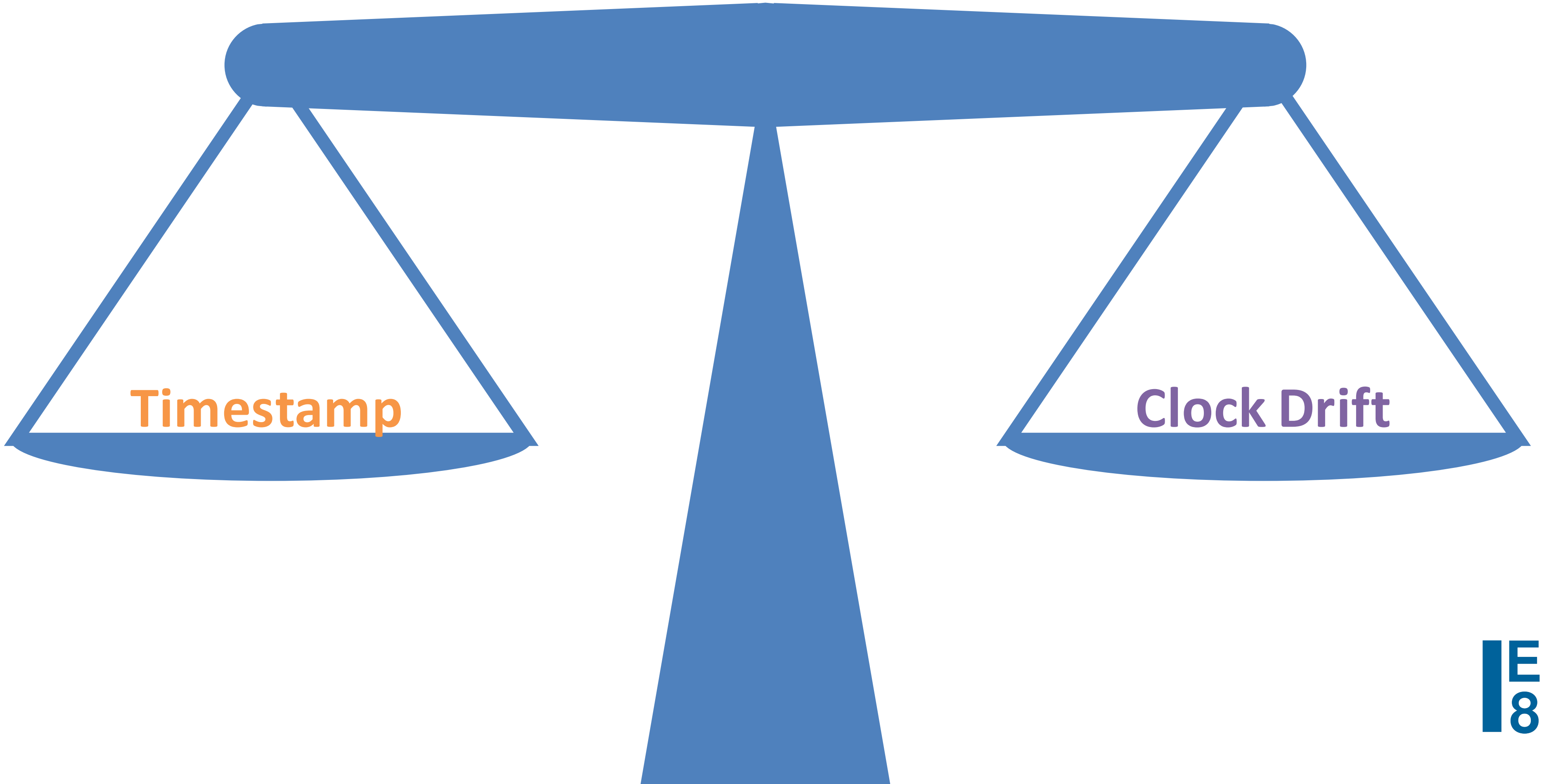
Processed output of Monte Carlo Simulations – Example uses IEEE 802.1AS defaults over 100 hops



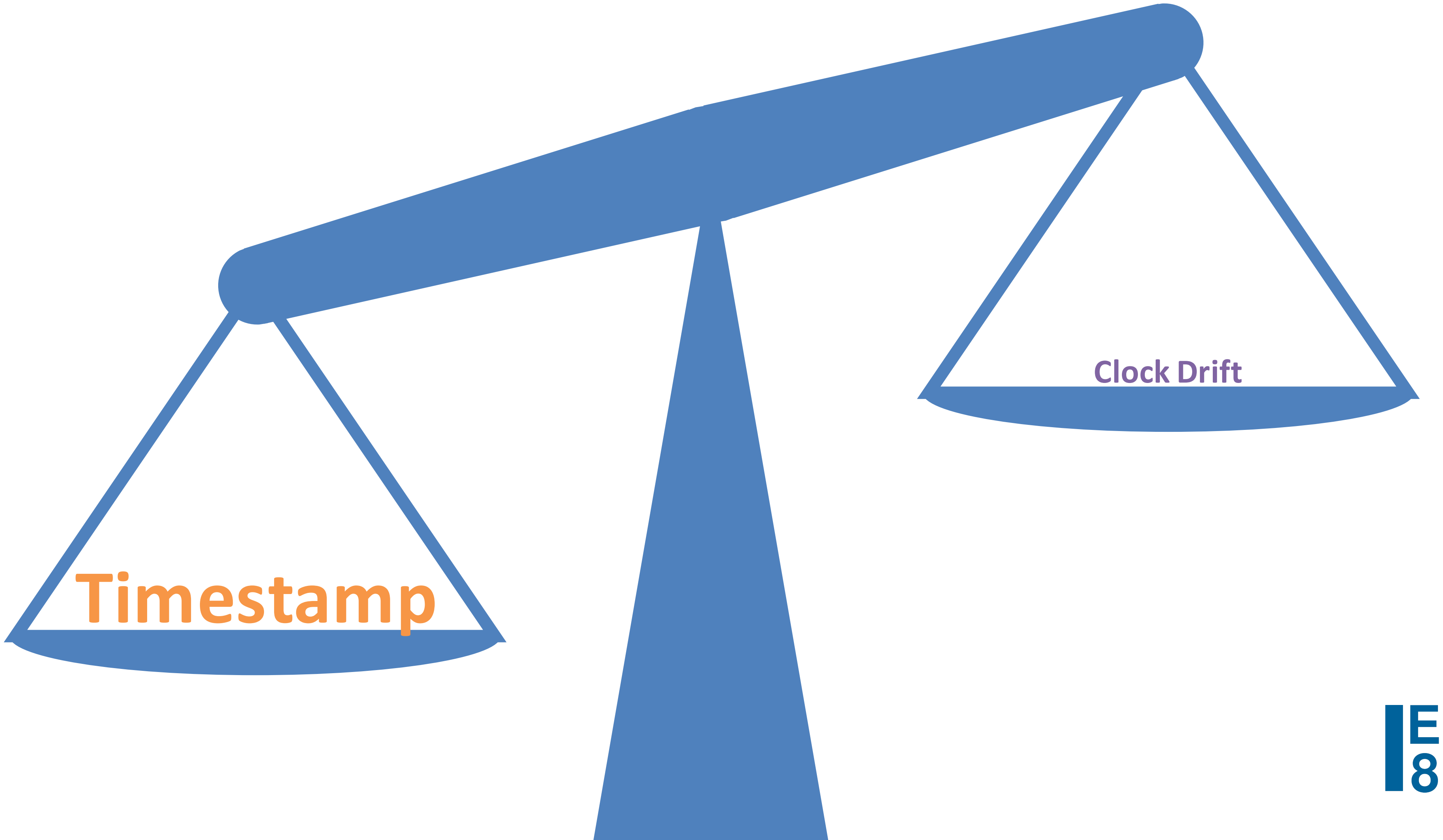

Timestamp
Clock Drift

Long Measurement Interval




Timestamp
Clock Drift

Short Measurement Interval



New Approaches & Mechanisms

New Approaches & Mechanisms

- Statistics
- Configuration (including a new TLV)
- Clock Drift Measurement & Error Compensation

1. Nominal Sync Interval: 125 ms

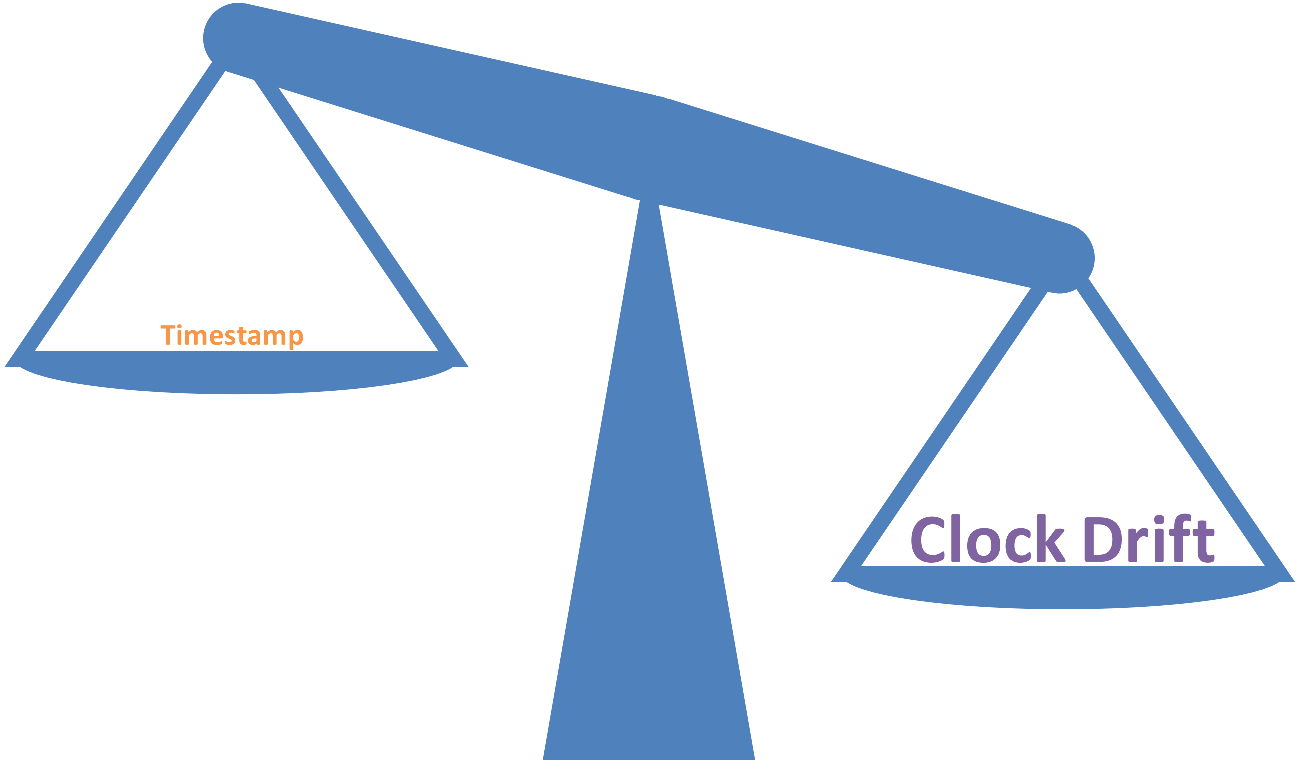
- Reduces error accumulation at End Instance between Sync messages

1. Nominal Sync Interval: 125 ms

+

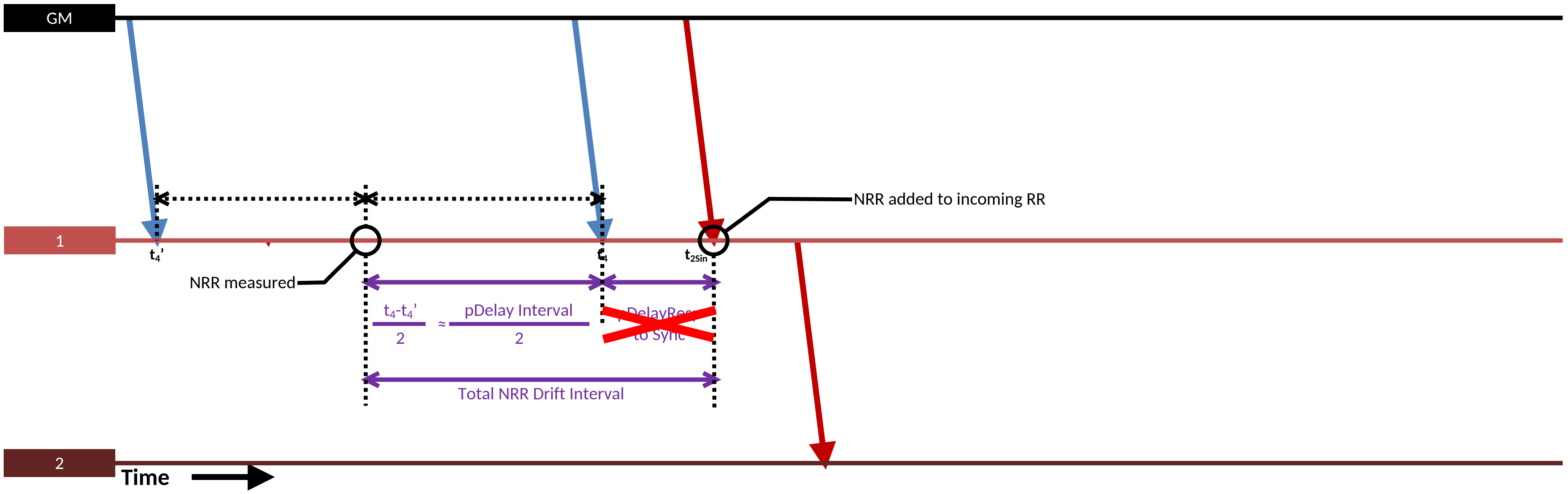
2. NRR Smoothing

(Not quite a simple average)



3. New “Drift Tracking” TLV

- 3a – syncEgressTimestamp in Sync or Follow_Up message



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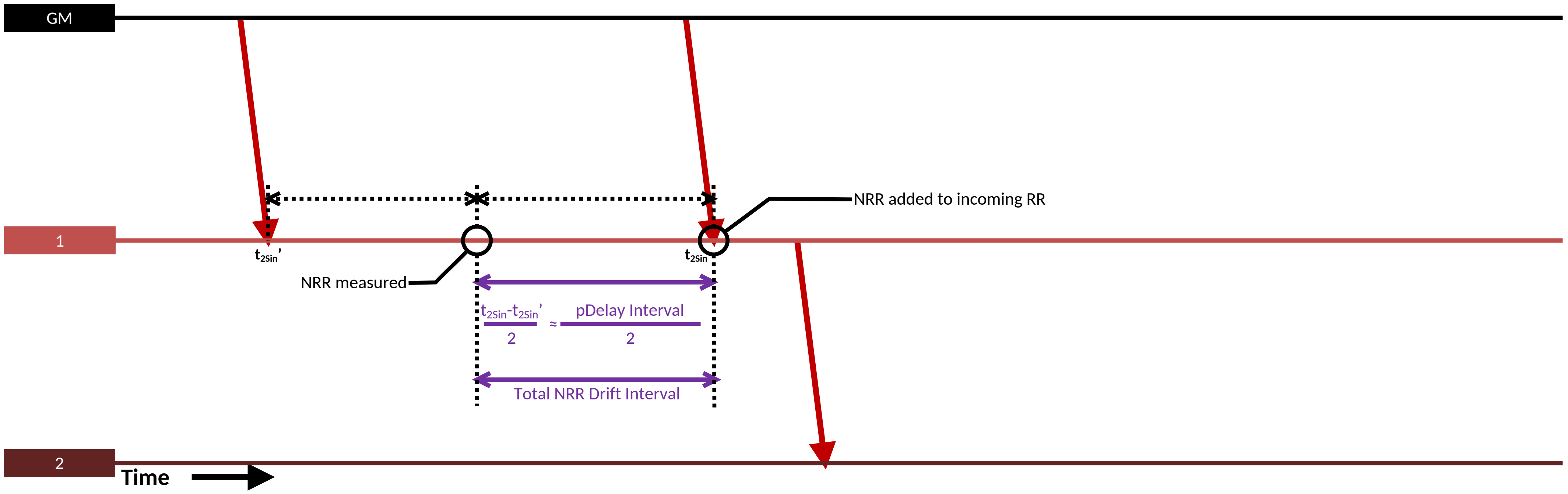
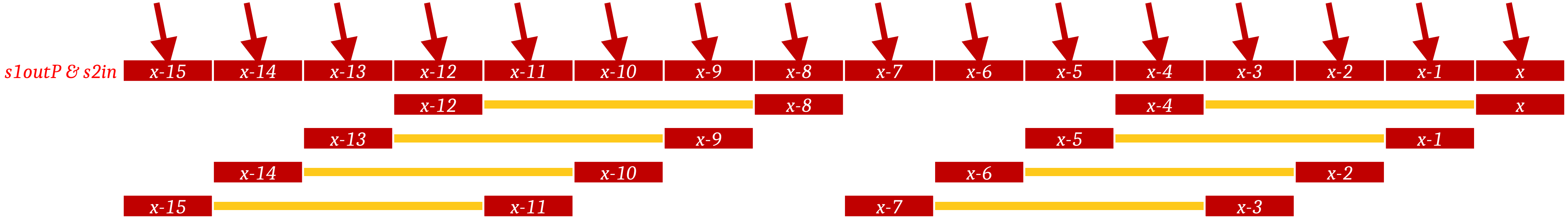


4. NRR Drift Tracking & Error Compensation

- 4a – NRR Drift Tracking



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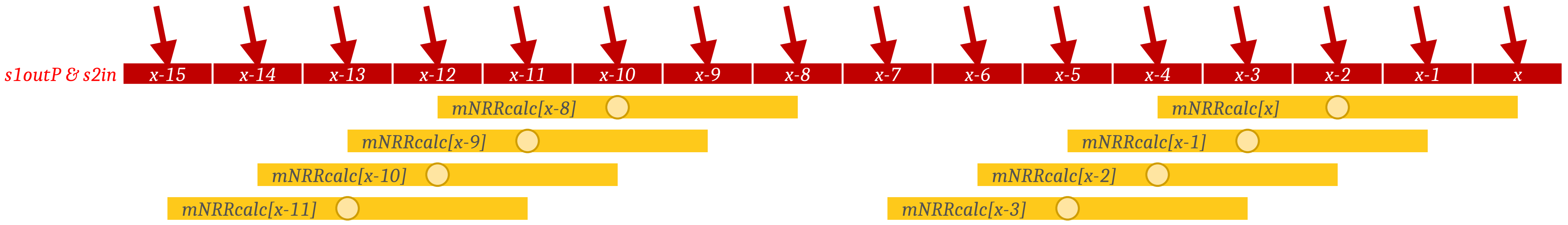

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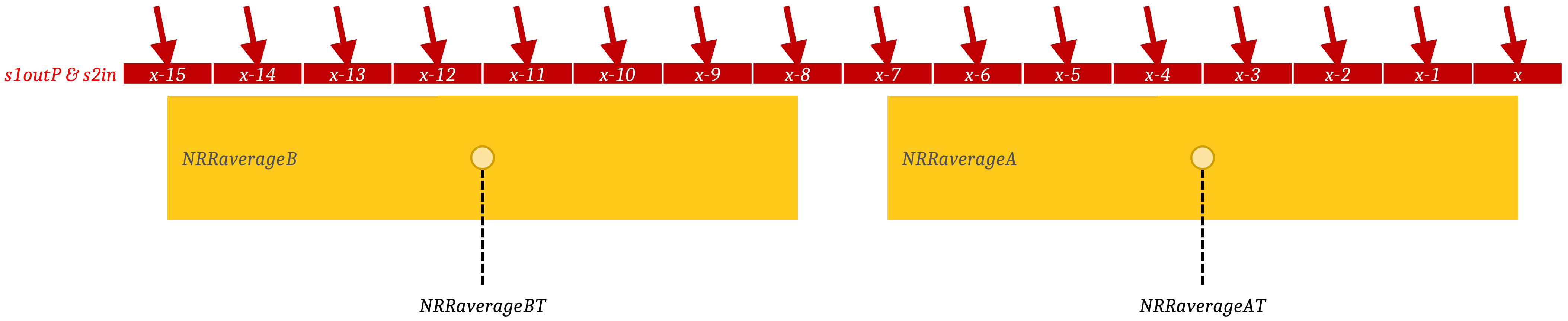
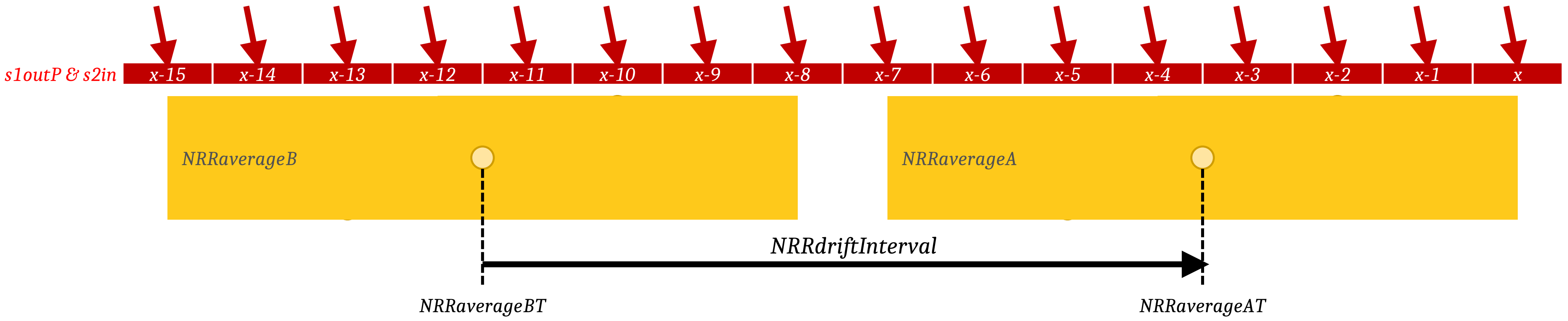
- 4a – NRR Drift Tracking



4. NRR Drift Tracking & Error Compensation

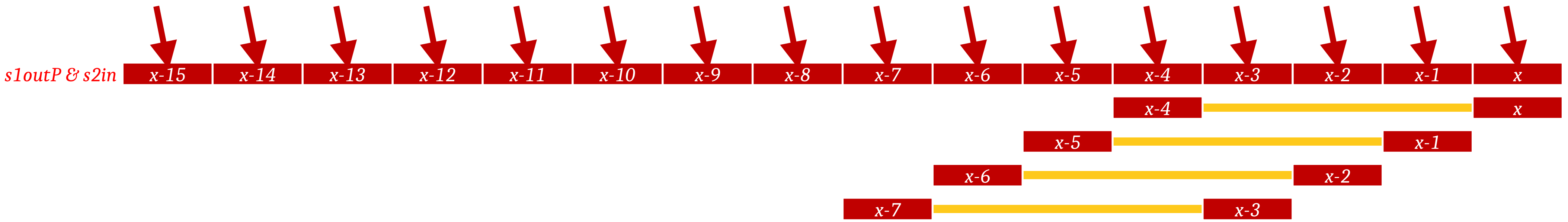
- 4b – NRR Drift Tracking



$$NRRdriftRate(n) = \left(\frac{NRRaverageA - NRRaverageB}{NRRdriftInterval} \right)$$

4. NRR Drift Tracking & Error Compensation

- 4b – NRR Drift Error Compensation



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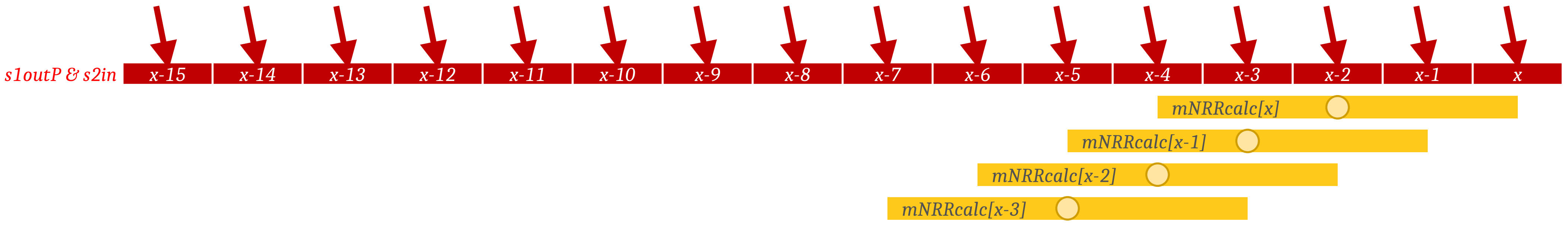

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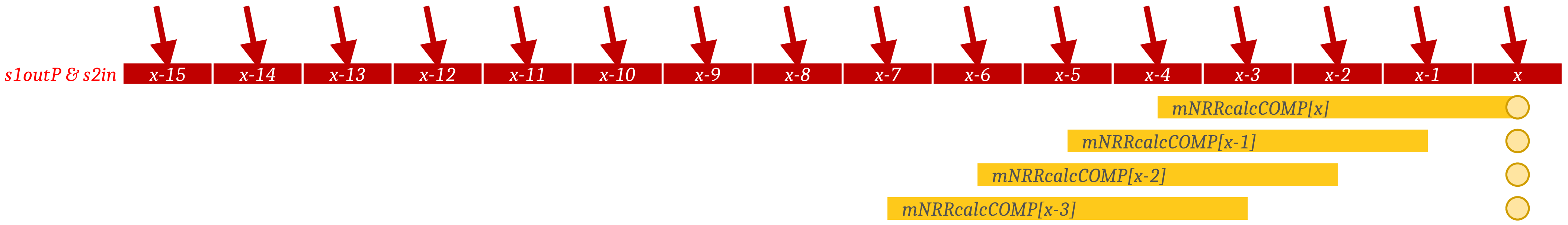

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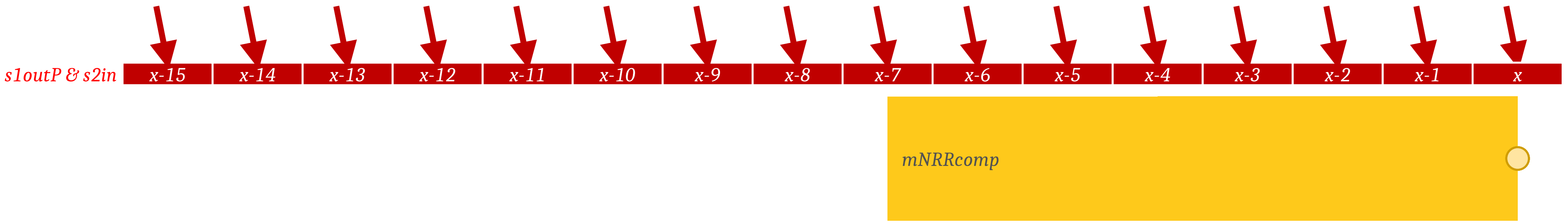

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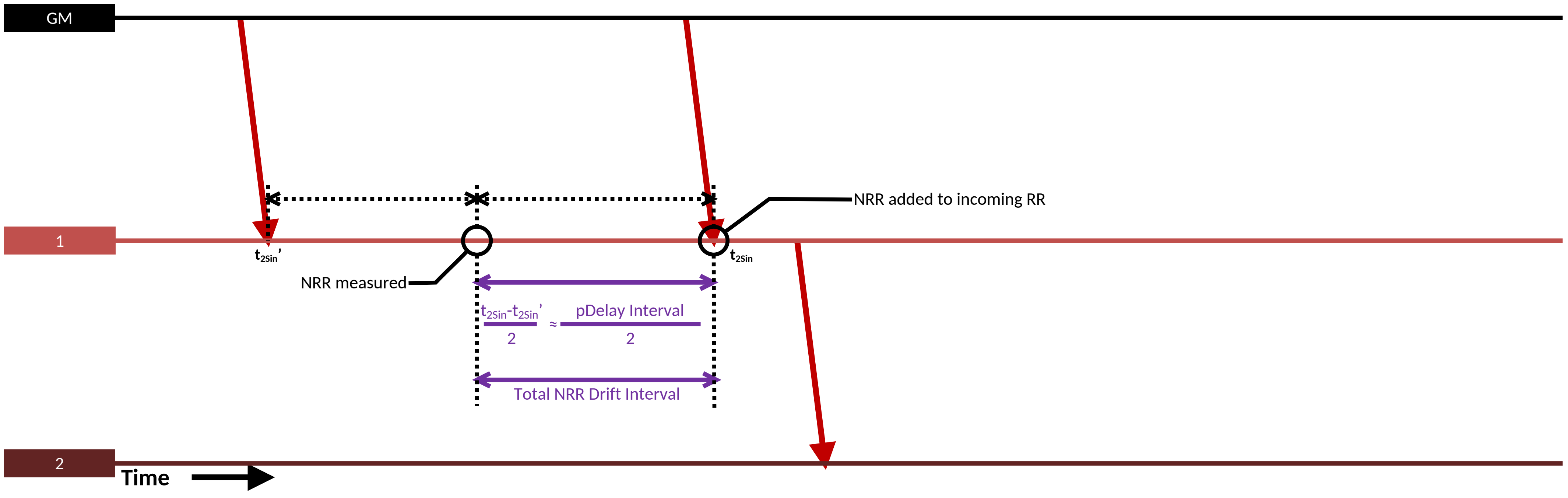
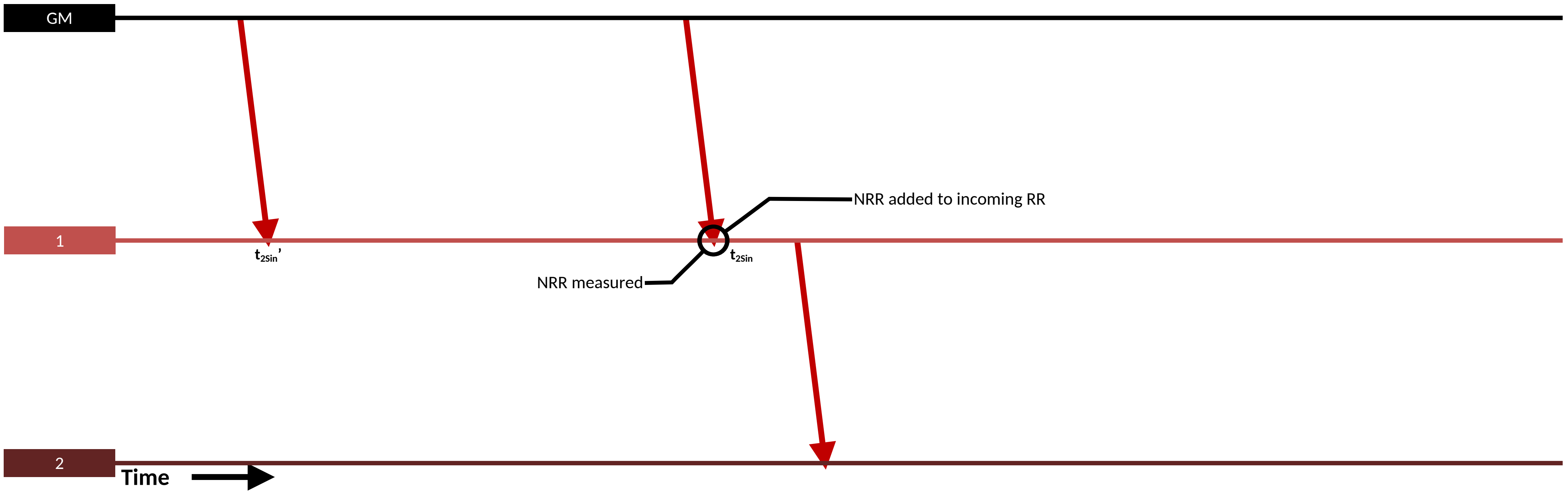
- 4b – NRR Drift Error Compensation



4. NRR Drift Tracking & Error Compensation

- 4b – NRR Drift Error Compensation



3. New “Drift Tracking” TLV
+
5. RR Drift Tracking & Error Compensation

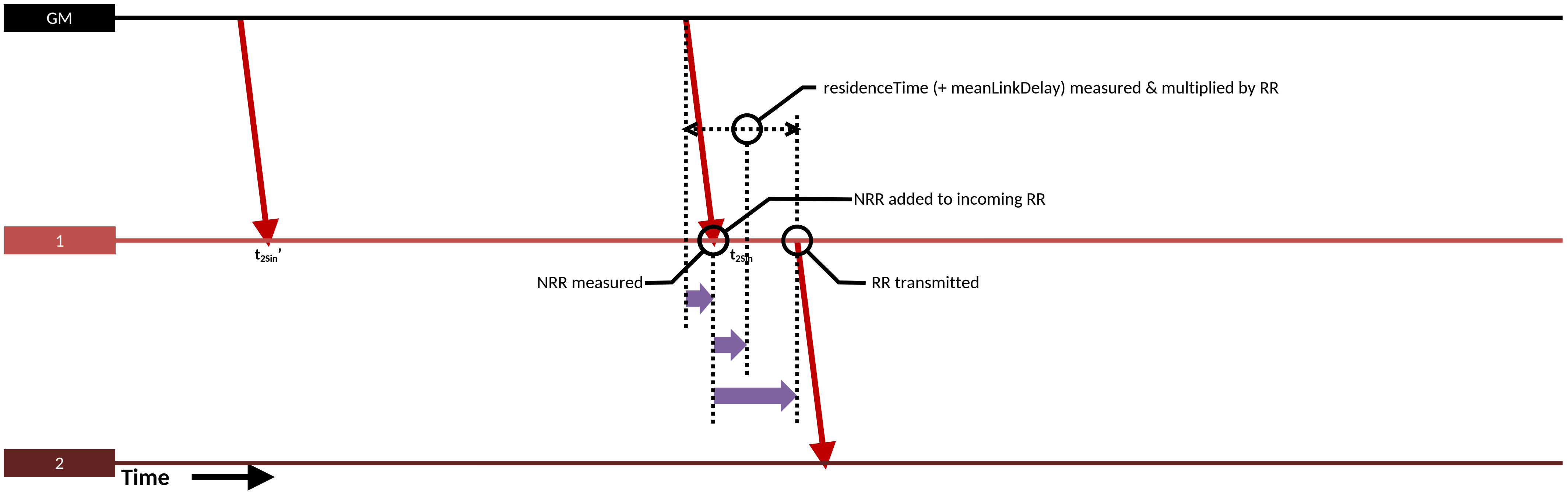
- 3a – rateRatioDrift in Sync or Follow_Up message
- 5a – RR Drift Tracking: NRR Drift added to incoming RR Drift to calculate local RR Drift

5. RR Drift Tracking & Error Compensation

- 5b – RR Drift Error Compensation
  - RR Drift during incoming link delay (usually not significant)
    - Use RR Drift at previous node
  - At Relay Instance: RR Drift from Sync receive to…
    - Effective measurement point between Sync receive and transmit
    - Sync transmit

5. RR Drift Tracking & Error Compensation

- 5b – RR Drift Error Compensation

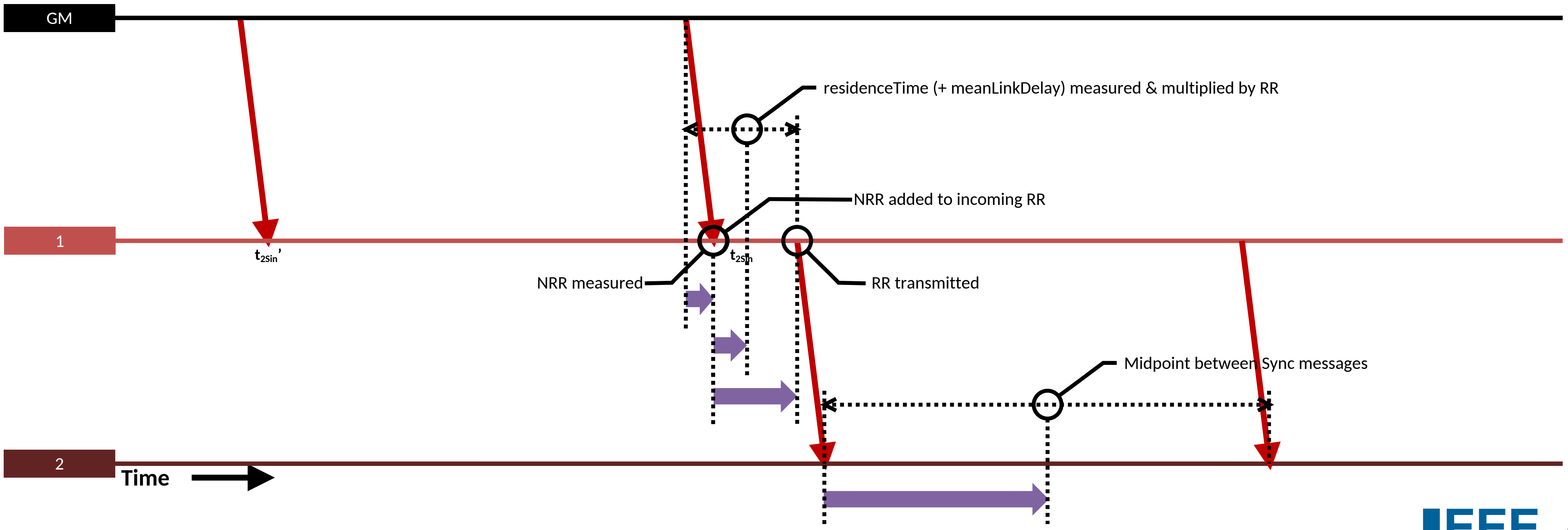


5. RR Drift Tracking & Error Compensation

- 5b – RR Drift Error Compensation
  - – RR Drift during incoming link delay (usually not significant)
    - Use RR Drift at previous node
  - – At Relay Instance: RR Drift from Sync receive to…
    - Effective measurement point between Sync receive and transmit
    - Sync transmit
  - – At End Instance: RR Drift from Sync receive to next Sync receive

5. RR Drift Tracking & Error Compensation

- 5b – RR Drift Error Compensation



6. Mean Residence Time: Max Average 5 ms

- IEEE 802.1AS default maximum 10 ms
  - 100 hops → up to 1 s delay from GM to End Instance
- IEC/IEEE 60802 average 5 ms
  - 100 hops → average 500 ms delay from GM to End Instance

Note: “1. Nominal Sync Interval: 125 ms” already helps reduce the amount of clock drift between Sync messages at the End Instance

7. Consistent Sync Intevals: 119 – 131 ms

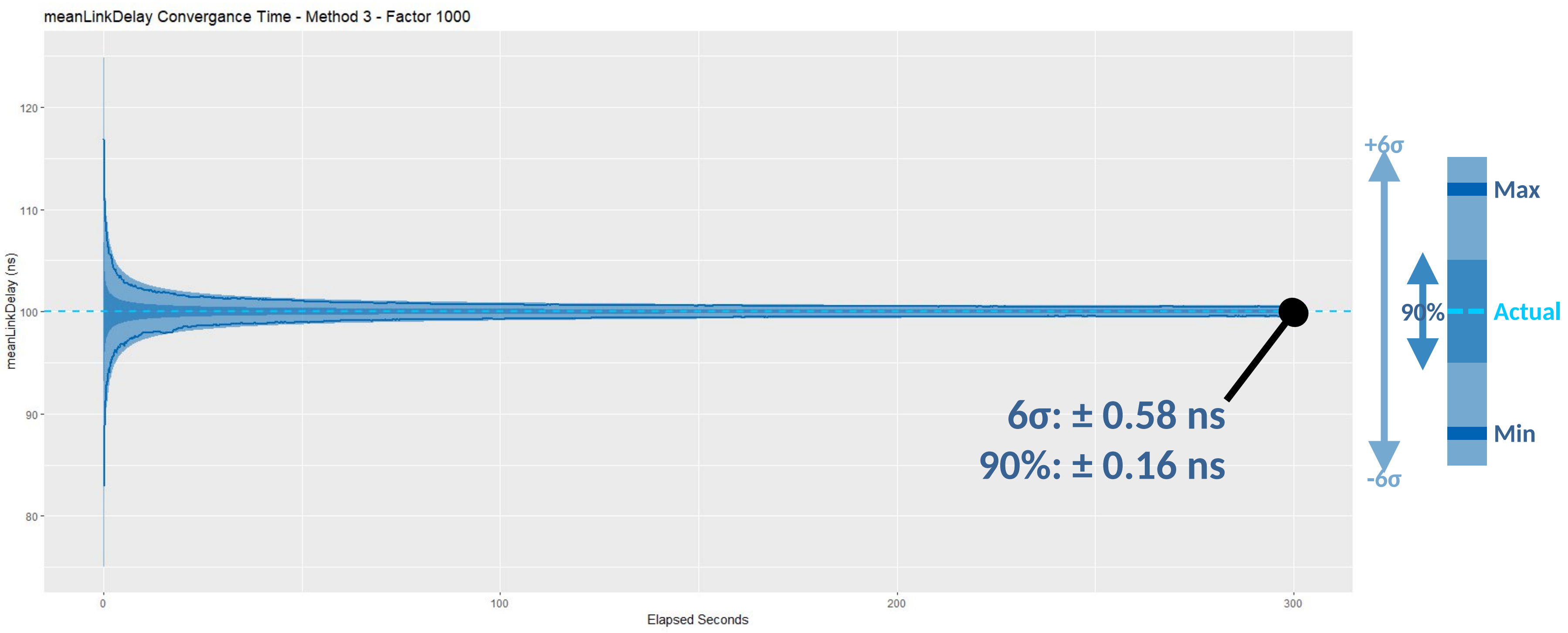
	802.1AS	802.1AS - 125 ms Nominal	60802
Sync Interval	Default **Nominal : 1 s** Mean: Nominal ± 30% (0.7 – 1.3 s) 90% of Inter-message Intervals: Nominal ± 30% (0.7 – 1.3 s) **Maximum: Nominal x 2 (2 s)** (recommended) **No Minimum** (recommended or otherwise) [IEEE 1588-2019 9.5.9.2]	**Nominal : 125 ms** Mean: 87.5 – 162.5 ms 90% of Inter-message Intervals: 87.5 – 162.5 ms **Maximum: 250ms** **No Minimum**	**Nominal: 125 ms** **Minimum: 119 ms** **Maximum: 131 ms**

7. Consistent Sync Intevals: 119 – 131 ms

- 60802’s approach mitigate, but does not eliminate errors due to Clock Drift
- Errors due to Clock Drift tend to cancel out node-to-node
  - Clock Drift causing a positive error at one hop tends to cause a negative error at the next (GM and End Instance are exceptions)
- Tendency to cancel out is greatest if the intervals of interest are consistent

8. Mean Link Delay Averaging

- Example: IIR Filter with a factor of 1,000
  - Converged enough after 15 seconds with 125 ms Pdelay Interval



Error Budget

Error Budget

Network Aspect	Error Type	Network Level Error Budget (ns)
All PTP Instances	Constant Time Error	200
	Dynamic Time Error	600
All PTP Links	Constant Time Error	200
	Dynamic Time Error	

- PTP Link budget is mainly for cable asymmetry. Cables meeting 802.3 specification allows up to 400 m total, GM to End Instance.
- 50 ns dTE budget between Application level and Network level at both GM and End Instance means dTE for 802.1AS layers is **500 ns**

Geoff Garner

Time Series Simulation

Time Series (Time Domain) Simulator

- Event based
  - Each event occurs at a time based on an ideal simulator clock
  - Each message arrival & departure, at each node, generates an event.
- Arrival & departure times are generated based on probability distributions & other assumptions
  - Events are placed on an event list in increasing time order & processed sequentially
  - Successive events are rarely at the same node or port

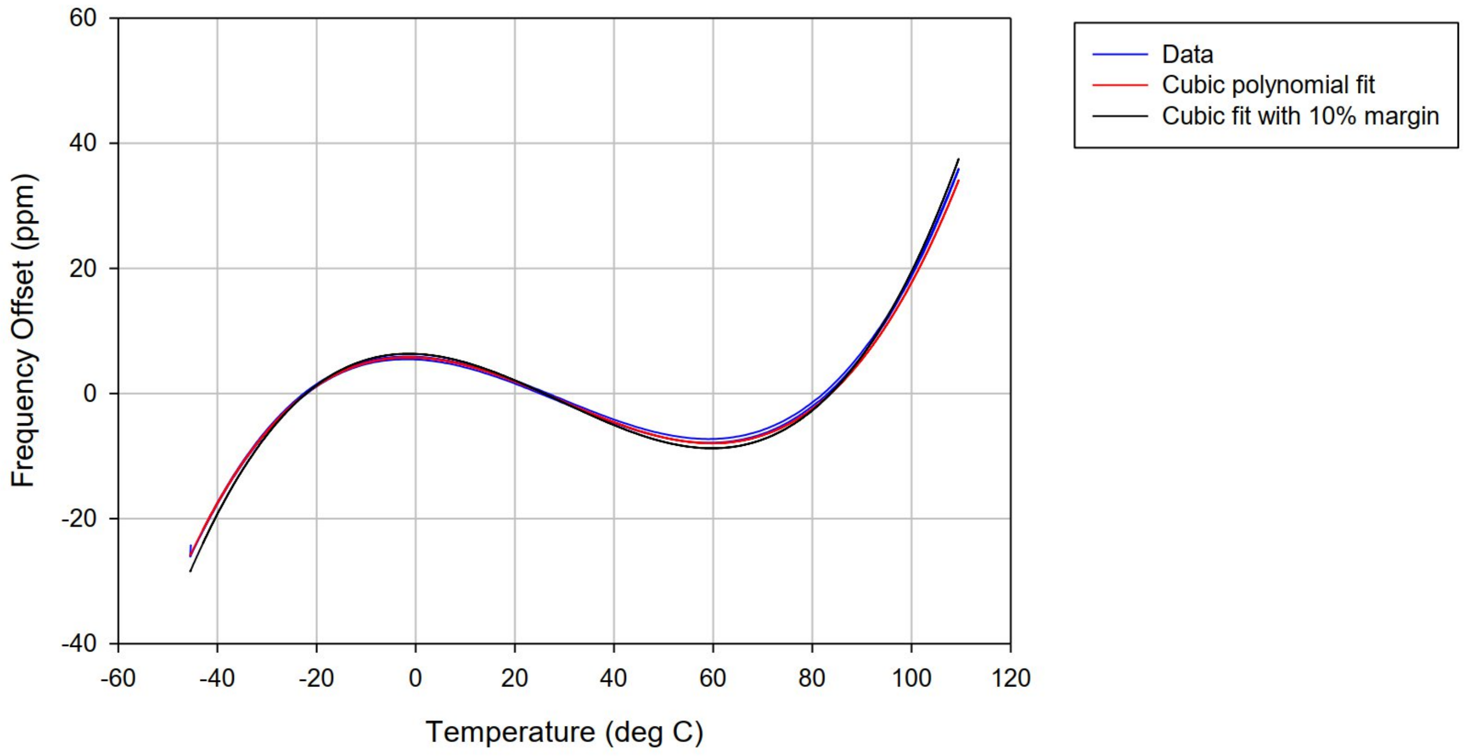
Time Series (Time Domain) Simulator

- Local Clocks, for timestamping, are modelled with respect to the ideal clock
- Model for endpoint filter is based on discretization of continuous-time second-order system with 20 dB/decade roll-off using exact integrating factor (see Appendix IV/ITU-T Rec. G.8251)
- Second-order filter is integrated in discrete time in going from one event to the next
- See "Revised Multiple Replication 60802 TimeDomain Simulation Results…" [IEEE contribution; Geoff Garner, May 2024] and references cited there for details of the simulations

Assumptions – XO Frequency Stability

Cubic Constants	Value
a	0.00012
b	-0.01005
c	-0.0305
d	5.73845

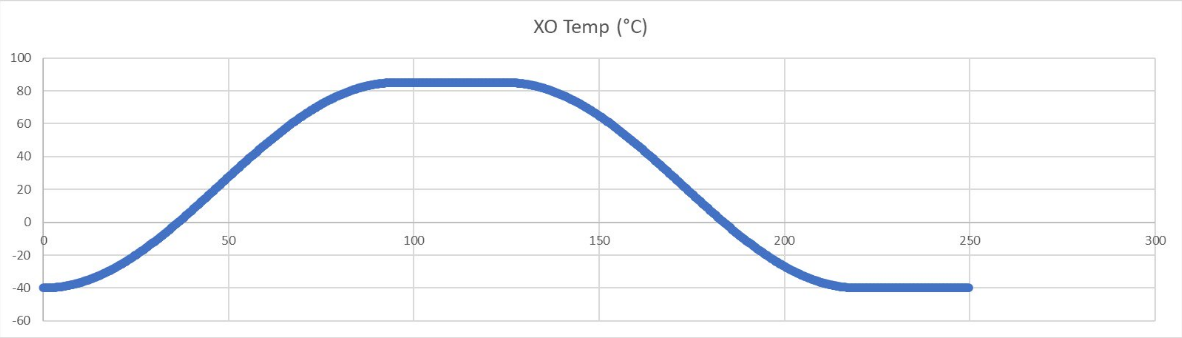
$$freqOffset = a.tempXO^3 + b.tempXO^2 + c.tempXO + d$$

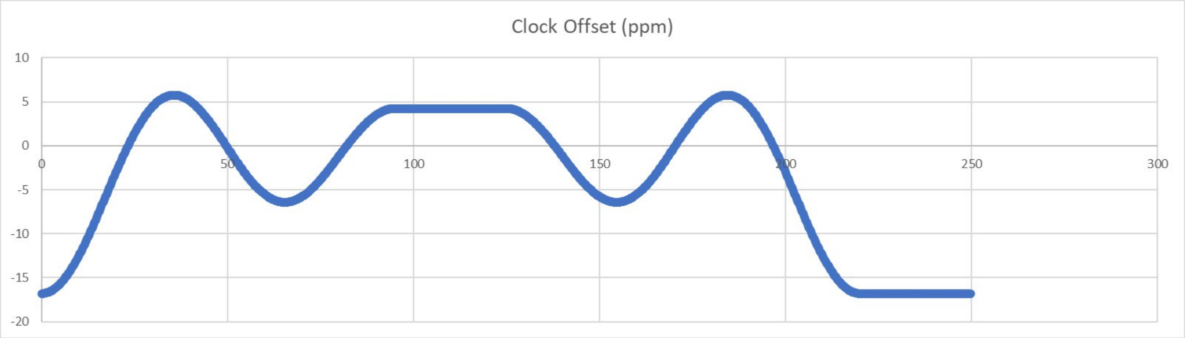


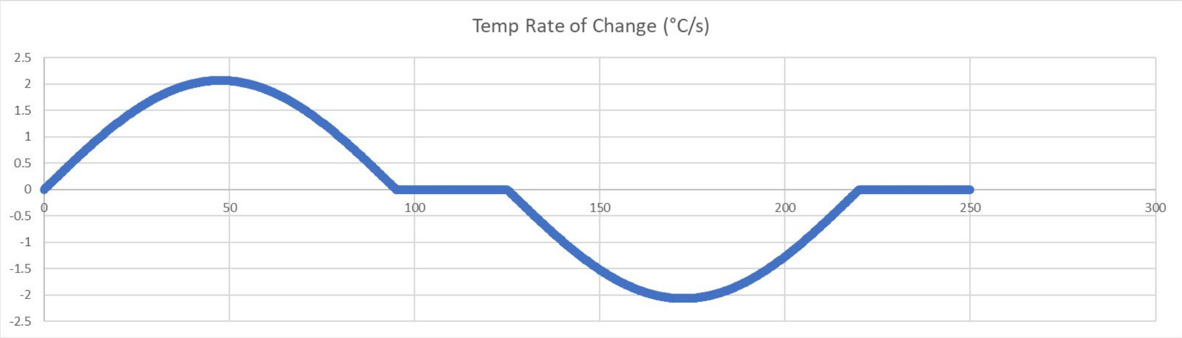
From Geoff Garner, “Phase and Frequency Offset, and Frequency Drift Rate Time History Plots Based on New Frequency Stability Data”, contribution to IEC/IEEE 60802, March 2021
The calculation of freqOffset is not used in the model but is included for completeness and in case the reader wishes to recreate the example graphs.

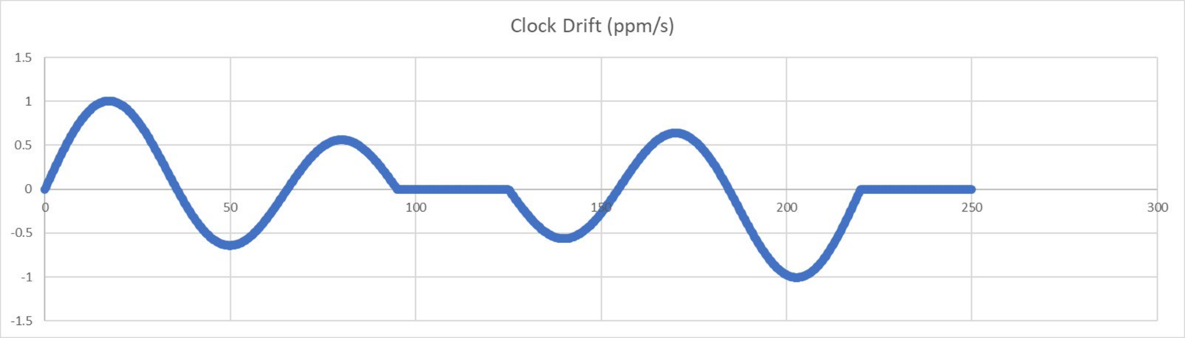
Assumptions – Temperature Profile

Half-Sinusoidal transitions between Min & Max ● Hold at Min & Max between transitions









Inputs		
Temp Max	85	°C
Temp Min	-40	°C
Temp Ramp Period	95	s
Temp Hold	30	s

Temp Rate of Change		
MAX	**2.07**	°C/s
MIN	**-2.07**	°C/s

Clock Drift		
MAX	1.01	ppm/s
MIN	-1.01	ppm/s

Assumptions – Timestamp Errors

- 8 ns Timestamp Granularity
  - Equivalent to 125 MHz clock
  - Leads to Timestamp Granularity Error (TGSE)
  - Truncate to next lower multiple of 8ns, then add 4 ns
- ±6 ns Dynamic Timestamp Error (DTSE)
  - Uniform distribution; added before truncation

Assumptions - Intervals

- Sync & Pdelay Intervals: uniform distribution, 119 ms – 131 ms
  - Relative to ideal simulation clock
- Residence time: truncated normal distribution
  - Mean: 5 ms   σ: 1.8 ms
  - Truncated at 1 ms and 15 ms
- Pdelay turnaround time: truncated normal distribution
  - Mean: 10 ms   σ: 1.8 ms
  - Truncated at 1 ms and 15 ms

Assumptions – Link Delays & Endpoint Filter

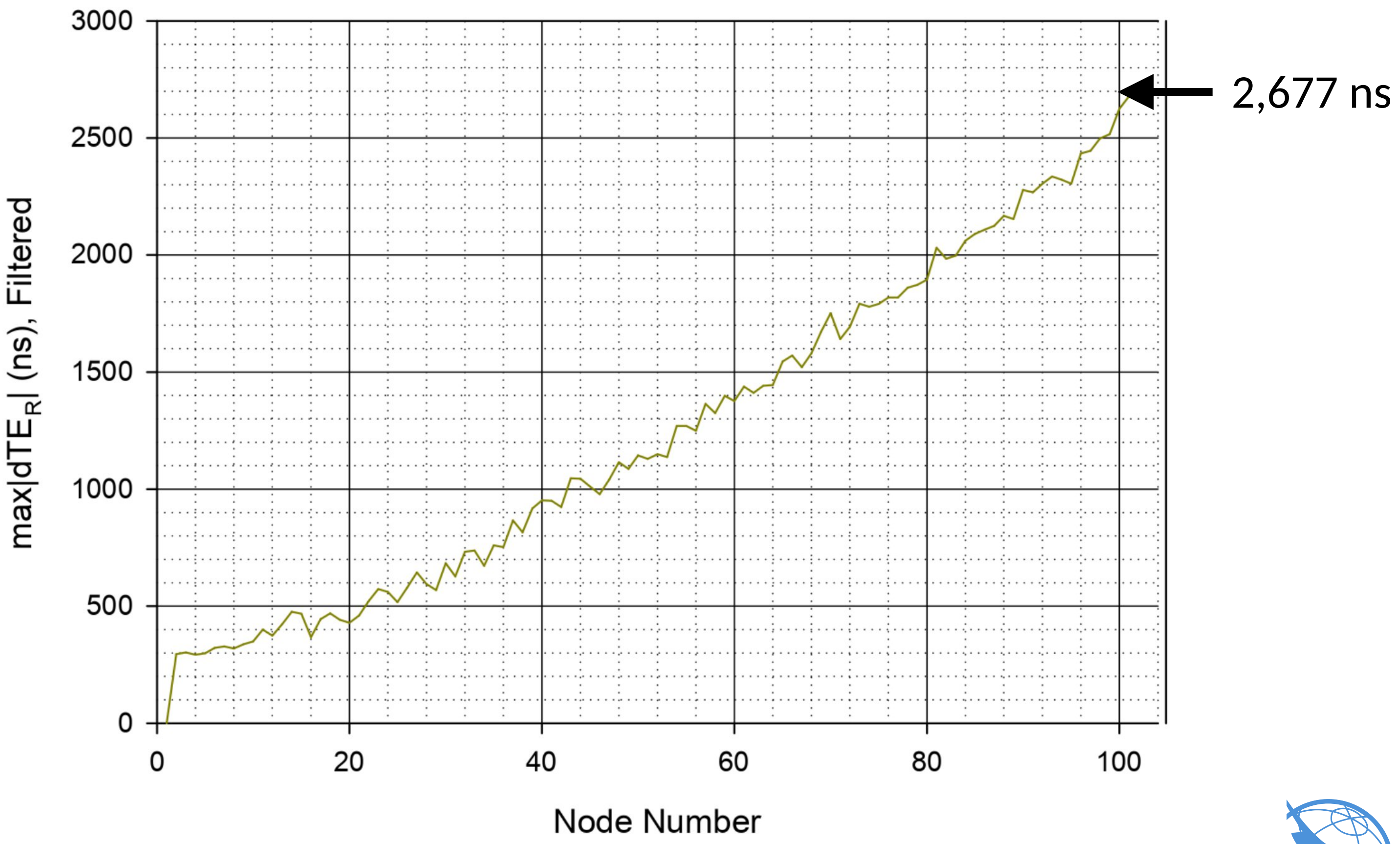
- Link delays are uniform distribution, 5 ns – 500 ns
  - Chosen at initialization of each replication
- Endpoint filter is second-order with 20 dB/decade roll-off and stated 3dB bandwidth and gain peaking

Time Series Simulations – Replications

- Each Replication simulates 1,850 s (just over 30 mins)
  - First 50 s of data are considered “startup” and not used in results
- Certain parameters remain constant through a replication, but change between replications
  - Examples: link delays; nodes’ start positions within temperature cycle
- Usually, when statistically significant data is required, 300 replications are run

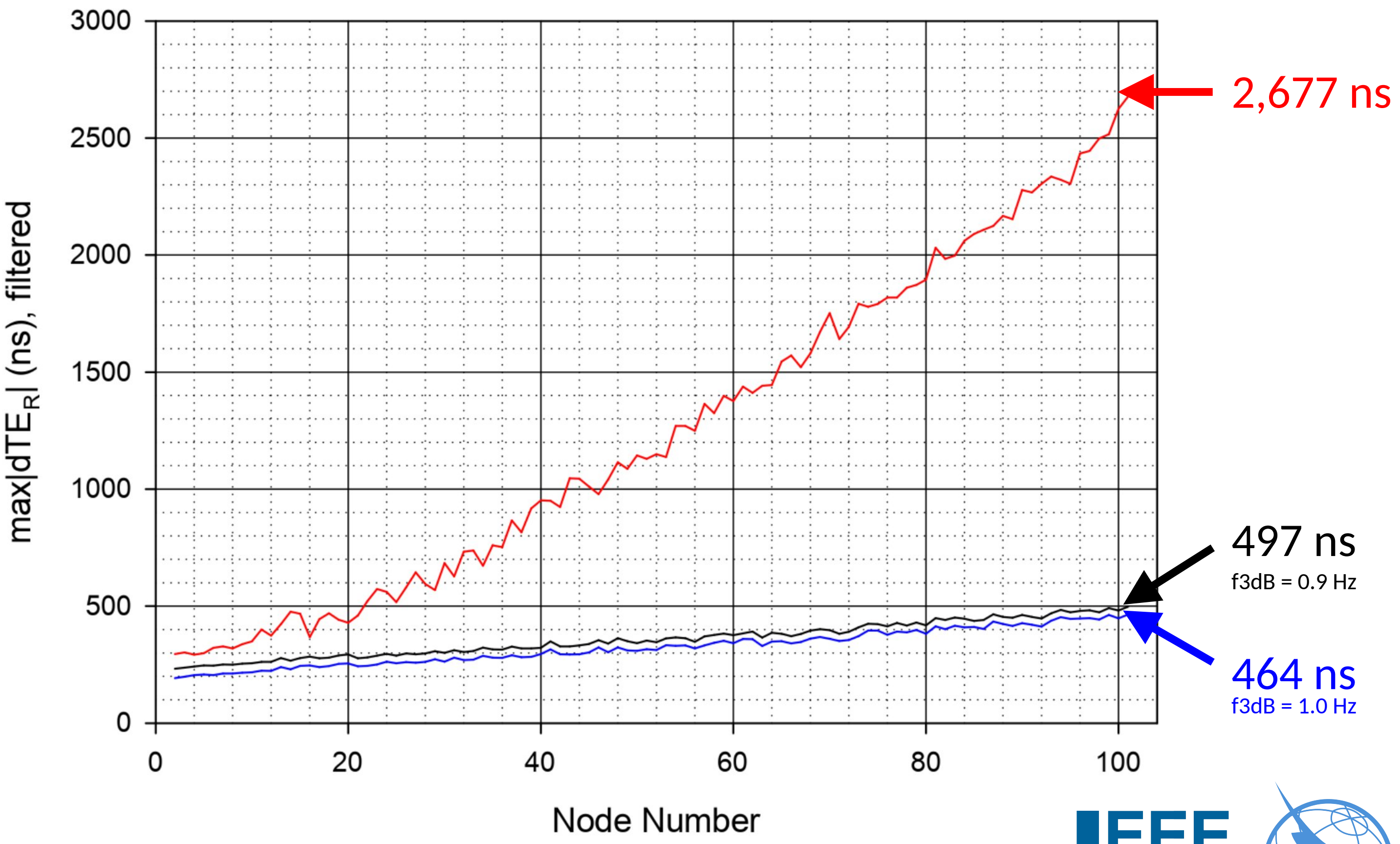
Base Case – Single Replication

	Base
Drift Tracking & Compensation (PTP Relays Only)	û
Mean Link Delay Averaging	û
GM to Other Nodes, Ratio of XO Offset Range	1:1
Endpoint filter	f3dB = 1.0 Hz Gain PK = 1.288 dB zeta = 0.68219
Endpoint filter noise generation modelled (high-pass filtered XO noise)	û



IEC/IEEE 60802 – 300 Replications

	Base	60802
Drift Tracking & Compensation (PTP Relays Only)	û	✓
Mean Link Delay Averaging	û	✓
GM to Other Nodes, Ratio of XO Offset Range	1:1	0.5:1
Endpoint filter	f3dB = 1.0 Hz Gain PK = 1.288 dB zeta = 0.68219	f3dB = 1.0 / 0.9 Hz Gain PK = 0.1 dB zeta = 0.68219
Endpoint filter noise generation modelled (high-pass filtered XO noise)	û	✓



TLDR: It worked!

Too Long; Didn't Read

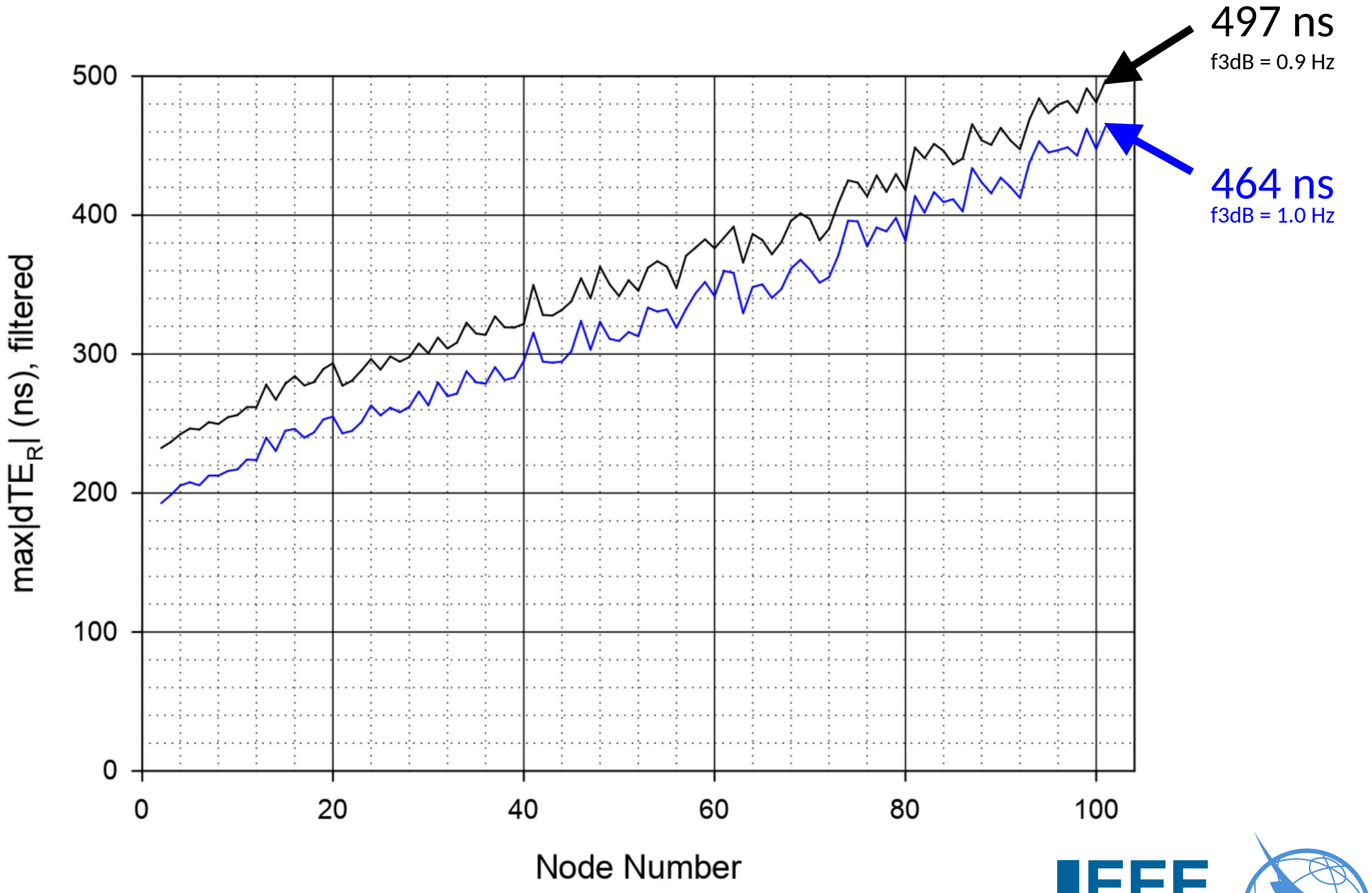
IEEE 802

ITU

Backup

IEC/IEEE 60802 – 300 Replications

	60802
Drift Tracking & Compensation (PTP Relays Only)	✓
Mean Link Delay Averaging	✓
GM to Other Nodes, Ratio of XO Offset Range	0.5:1
Endpoint filter	f3dB = 1.0 / 0.9 Hz Gain PK = 0.1 dB zeta = 0.68219
Endpoint filter noise generation modelled (high-pass filtered XO noise)	✓

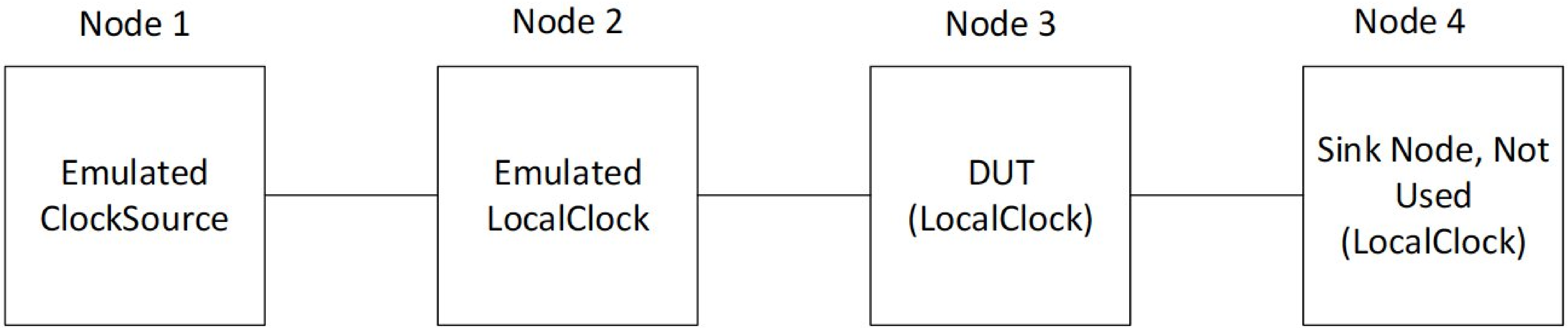


Time Series Simulations for…

Error Generation Normative Requirements

Error Generation Normative Requirements

- Error generation normative requirements are given in IEC/IEEE 60802, Tables 12, 13, and 14
  - Latest draft is D2.4 (modifications of https://www.ieee802.org/1/files/public/docs2024/60802-Garner-McCall-Rodrigues-Planned-Time-Sync-Comments-SA-0524-v01.pdf planned to be included)
- Informative description of testing error generation requirements is given in Annex D, D.3 and D.4 of IEC/IEEE 60802
- Time series simulations were run for a 4-node network that represents the test setup (see backup)
- It was verified that the error generation requirements can be met
  - See 6.2 of IEC/IEEE 60802 for details of the requirements, D.3, and D.4 of IEC/IEEE 60802 for informative description of possible test methodology, and https://www.ieee802.org/1/files/public/docs2024/60802-garner-revised-error-generation-time-series-simulation-results-0424-v01.pdf for details of the simulations


Node 1
Node 2
Node 3
Node 4
Emulated
ClockSource
Emulated
LocalClock
DUT
(LocalClock)
Sink Node, Not
Used
(LocalClock)