# Tutorial: The Time-Synchronization Standard from the AVB/TSN suite

## IEEE Std 802.1AS™-2011 (and following)

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July 2014

# Abstract

This presentation provides an overview of clock and time synchronization across heterogeneous networks using the published standards:

IEEE Std 802.1AS™-2011 and

IEEE Std 802.11™-2012 Timing Measurement

With special focus on wireless / 802.11 links

# Agenda

- **802.1AS goals / applications**
- **Overview**
- **Grand Master selection**
- **Time propagation**
  - Media-independent
  - Media-dependent
- **Time *inside* the system**

# 802.1AS goals

**Distribute a single, accurate, time reference that is optimized for audio/video synchronization**

- **Accurate**
  - 802.1AS time in participating LAN-attached stations is accurate to within 1us
    - If one station thinks it's 09:57:55 AM PST, the others agree within specified # of network hops
    - Assuming +/-100PPM crystal, 1PPM / second maximum frequency drift
    - Accuracy has been physically demonstrated in even near-worst-case LAN environments
- **One time reference for the entire LAN/Subnet**
  - LAN-agnostic architecture
    - Can be applied to any 802-compatible LAN
      - Is explicitly defined for 802.3 (Ethernet), 802.11 (Wi-Fi), MoCA, ITU-T G.hn, and EPON.
    - Contains a Profile of IEEE Std.1588™ -2008 (PTP, or Precision Time Protocol)
      - 1588-2008 reserves a special value for the 802.1AS profile (see Transport Specific in IEEE Std. 1588™-2008)
  - LAN-specific measurements
    - 802.3 measurements follow generic 1588
    - 802.11 measurements leverages IEEE Std. 802.11™ -2012 "Timing Measurement"
      - Formerly known as IEEE Std. 802.11v™ -2011
    - Coordinated Shared Network (CSN) measurements defined also
- **Plug and play**
  - Grand Master (GM) clock is selected automatically
    - Time stabilizes in a fraction of a second
  - Clock tree reconfigures automatically if GM is lost

# These are NOT explicit 802.1AS goals/characteristics

**NO!: Improve the latency of packets/frames**

Time *can* be used to do this, but 802.1AS is silent on the topic (see 802.1 TSN)

**NO!: Improve the delivery jitter of packets/frames**

Time *can* be used to do this, but 802.1AS is silent on the topic (see 802.1 TSN)

**NO!: Constrain delivery jitter of 802.1AS packets**

The protocol is effectively immune to jitter, since each delay is explicitly measured

**NO!: Force every media clock in the [W]LAN to be equal**

…though many times it's desirable. Related media clocks are typically described indirectly by cross-referencing 802.1AS and the samples using presentation times

**NO!: Work over Ethernet 802.3 only (or 802.11 only)**

The application should not care what the physical network is

**NO!: Limited to 7 network hops**

Networks of extremely long chains of bridges/relays have been deployed

# How 802.1AS is used with audio/video

- **First, 802.1AS time-sync is <u>NOT</u> needed where:**
  - *Stored* A/V content is streamed to *one* renderer
    - Renderer can pull content from storage as it is needed
  - *Self contained* A/V system (network isn't in the path)
- **Shared time <u>IS</u> needed:**
  - When there are multiple renderers or sources
  - Where the renderer cannot tell the source to slow down or speed up, yet latency must be very small

- **The "Presentation Time" uses 802.1AS time to port the media rate**
  - "Render audio sample #896 when 802.1AS-time is 8:11:35.023712"
  - Every "presentation time" provides render time of specific sample
  - Every pair of "presentation times" communicates the actual "rate"
    - Nominal media rate (e.g., 44.1KHz audio, or 165MHz for HDMI) is assumed known
    - But the actual media rate always differs by a non-zero PPM, and changes over time due to thermal and other factors

# How 802.1AS is used in industrial/IOT

- **First, 802.1AS time-sync is <u>NOT</u> needed where:**
  - Coordination BETWEEN networked devices is unnecessary
  - *All the data comes from <u>and</u> is acted upon by a single device*
- **Shared time <u>IS</u> needed:**
  - In cyber-physical systems (CPS)
    - For coordination of distributed inputs, outputs, computation, and communication
  - In sensor networks where big-data analytics are applied to the aggregate
    - …without losing temporal information
    - Especially for
      - Low-power, infrequently-communicating devices
      - Cooperative Diversity in wireless communications
      - Devices responsible cooperatively for beamforming or array processing
  - Where communication+computation latency exceeds coordination requirement

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# High level architecture

- **Grand Master selection**
  - GM-capable stations advertise themselves via ANNOUNCE messages
  - If a station hears from station with “better” clock, it does not send ANNOUNCE
    - Configurable “Priority” field can override clock quality
    - MAC address is tie breaker
  - Time relays drop all inferior ANNOUNCE messages
    - Forward only the best
  - Last one standing is Grand Master for the domain
    - GM is the root of the 802.1AS timing tree
    - GM periodically sends the current time
- **Propagation of time**
  - Non-leaf devices in the tree propagate time toward the leaves
    - Taking queuing delay into account (aka “Residence Time”)

# 802.1AS is not alone

- **802.1AS is one of three core 802.1 AVB standards**
  - The others define a reservation protocol and traffic shaping algorithm
- **802.1AS over Ethernet (802.3) qualifies as a Profile of IEEE 1588-2008**
  - 802.1AS simplifies 1588, adds other media (e.g. 802.11)
  - Also other optimizations
    - Better stability over large networks (no cascaded PLLs)
    - Faster GM failover

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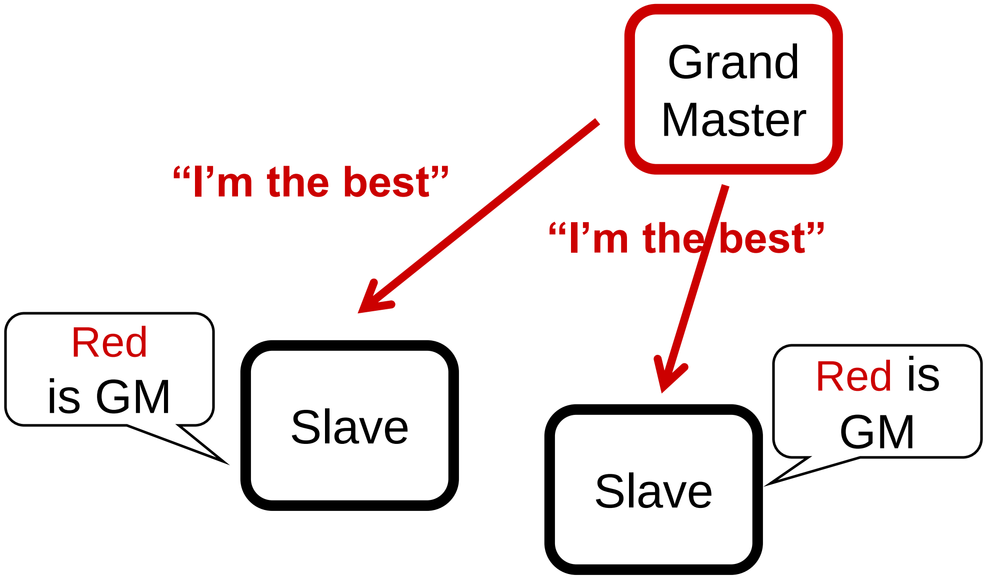
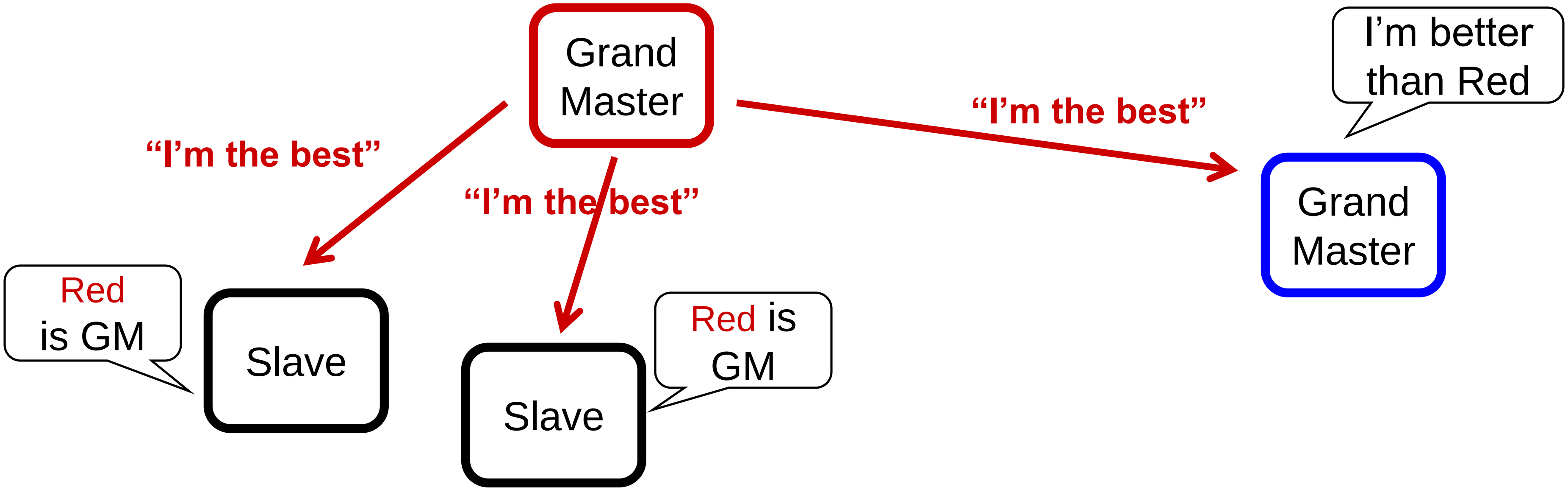
# Grand Master selection – Steady state




**Steady state:**

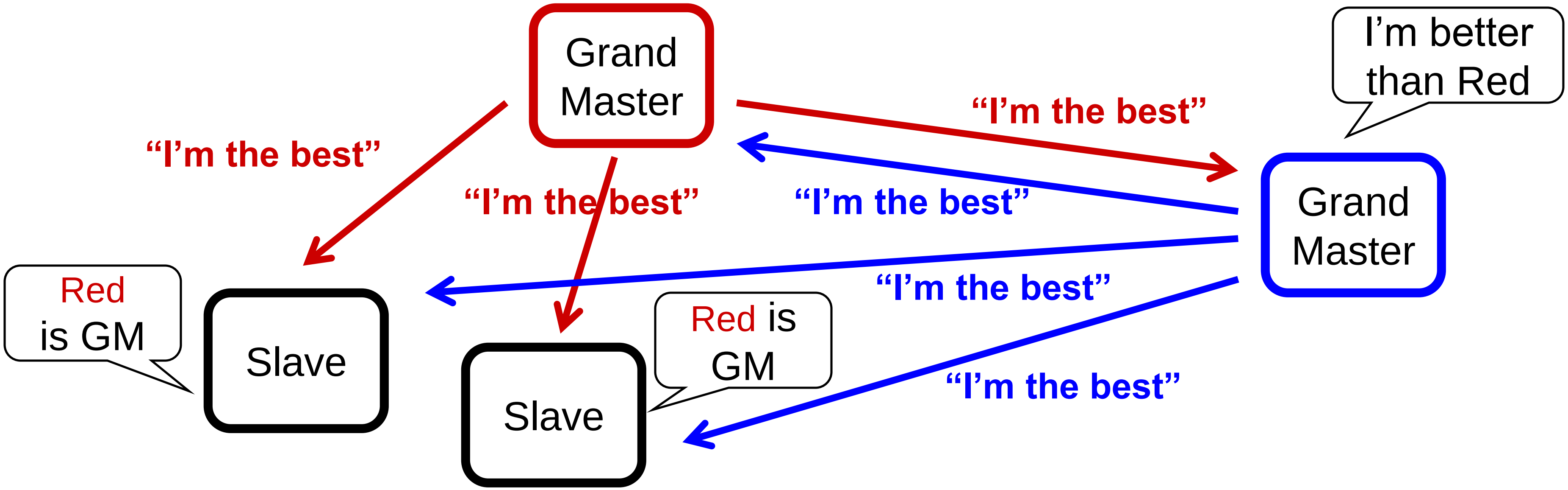
- **The GM sends ANNOUNCE**
- **Slaves acknowledge the GM is best (including self)**
  - …using simple bitwise compare
  - And do not send ANNOUNCE messages
- **Everyone knows their role**
- **Life is good**

# Grand Master selection – New, better GM (1)



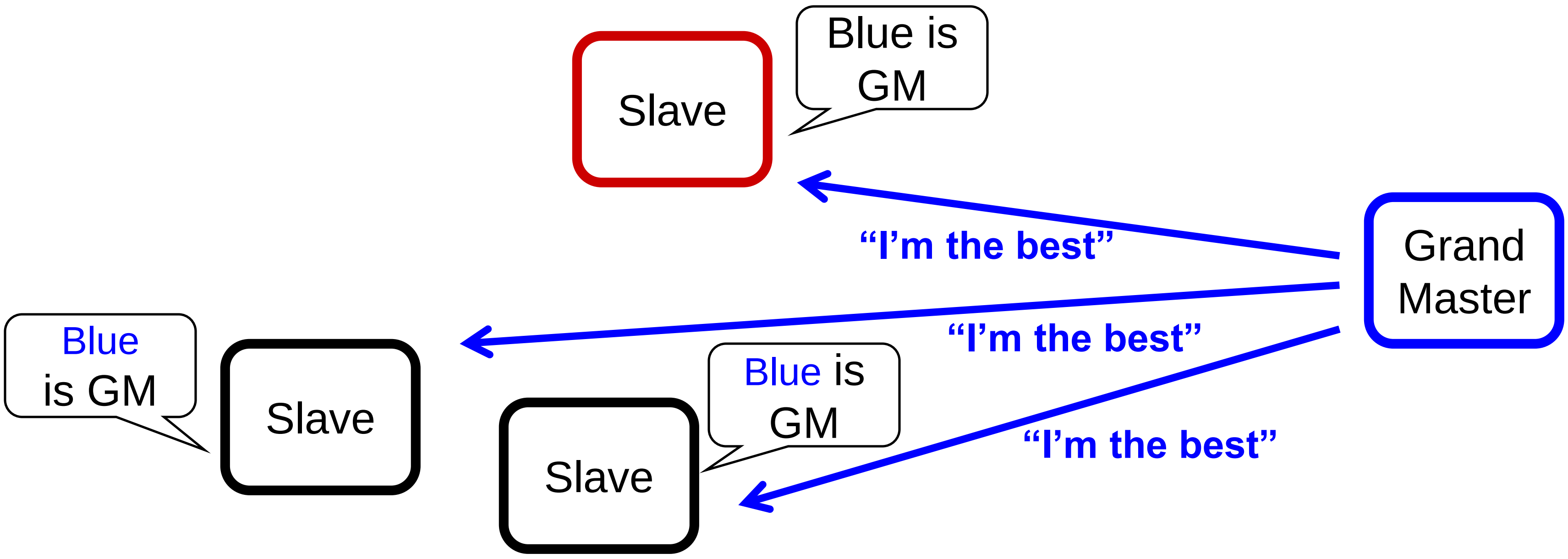

- **Blue station with better clock appears**

# Grand Master selection – New, better GM (2)



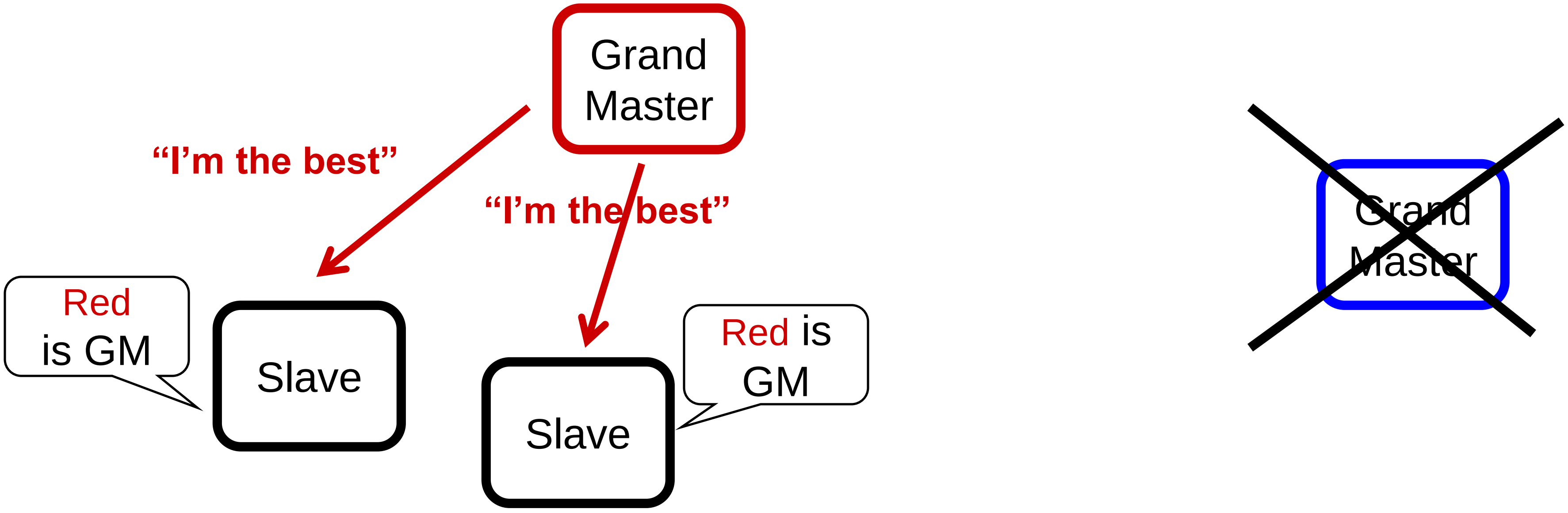

- **Blue station with better clock appears**
- **Blue sends ANNOUNCE**
- **Stations all realize blue is superior**
  - Including Red

# Grand Master selection – New, better GM (3)




- **Blue station with better clock appears**
- **Blue sends ANNOUNCE**
- **Stations all realize blue is superior**
- **Red stops sending ANNOUNCE**
- **Blue is quickly the undisputed GM**

# Grand Master selection – Lost GM




- **If Blue disappears, all GM-capable stations send ANNOUNCE**
- **Eventually, only Red sends ANNOUNCE**

# ANNOUNCE comparison

- **The credentials passed in ANNOUNCE messages are compared (in order of decreasing importance):**
  - Priority (settable by management)
  - Multiple **“quality of my clock”** fields
  - MAC address

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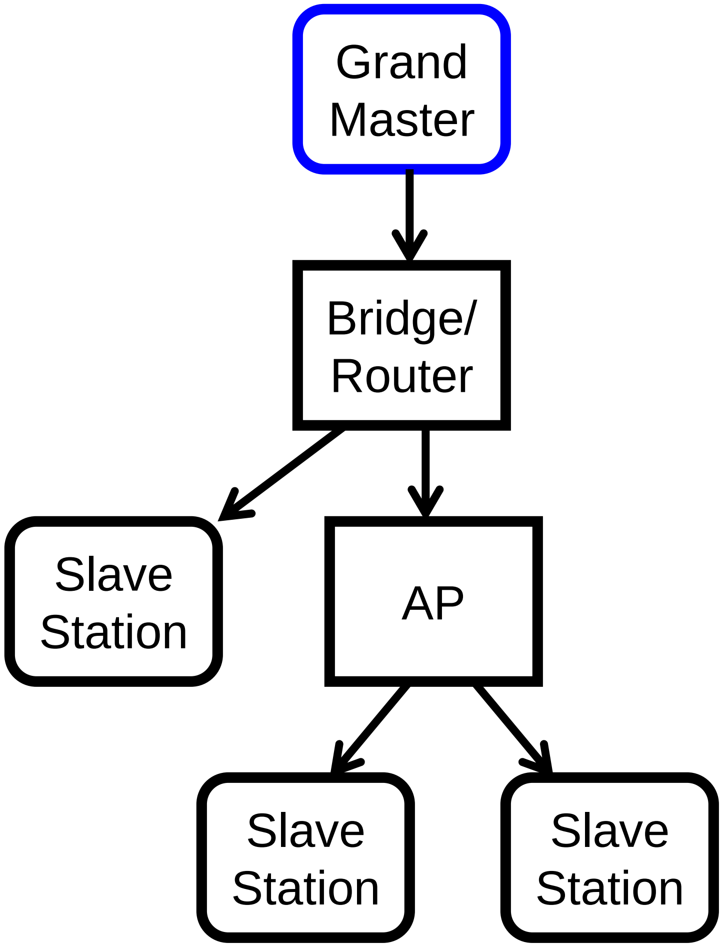
# Time domain is propagated to the "subnet"

- **Time-aware Relays**
  - The best ANNOUNCE
  - The GM's time
- **Relays can be a**
  - Bridge
  - Router
  - Linux computer with 2 Ethernet, a wireless and MoCA NIC(s)
- **Links can be**
  - 802.3 Ethernet
  - 802.11 WiFi
  - Almost anything compatible with IEEE 802

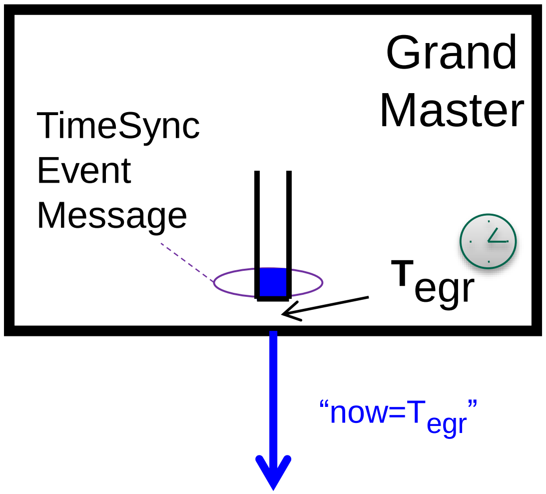



- **Let's look at one relay**

# Grand Master selection – Relays help decide

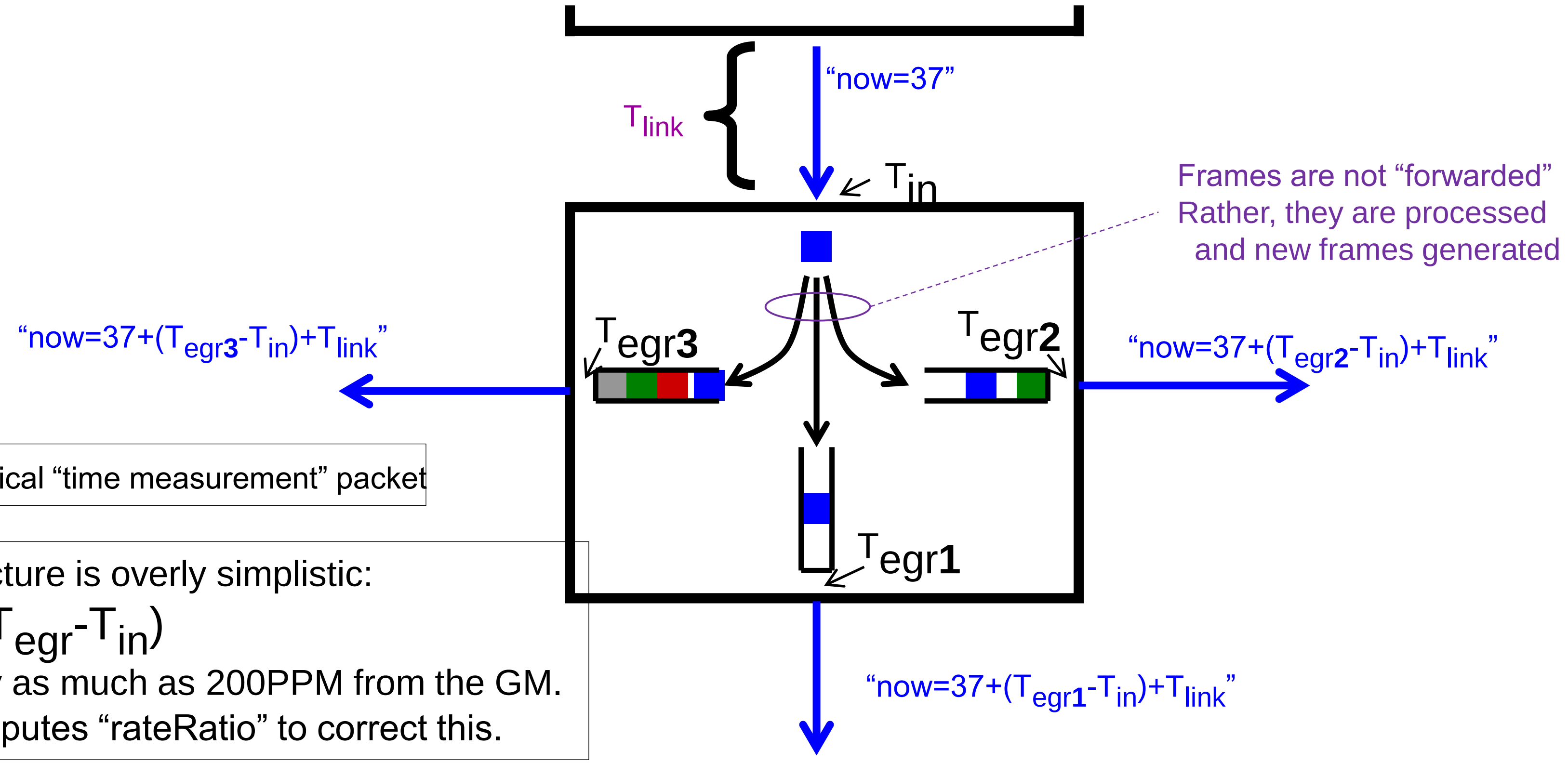

- **Relays filter inferior ANNOUNCE**
  - Relays forward best ANNOUNCE messages
  - Relays drop inferior ANNOUNCE messages
  - Benefits:
    - Reduction in network traffic
    - Faster GM selection
- **Announce messages establish the Clock Tree**

# Grand Master responsibilities




- **Transmit an Event message each Sync Interval**
- **Hardware captures the egress, or Tx time ($T_{egr}$)**
- **Pass $T_{egr}$ downstream**
  - Typically in a Follow-Up message
- **GM time need not be synchronized to atomic time**
  - …for many applications, but UTC offset can also be provided

# Transferring time through a network device




■ is a hypothetical "time measurement" packet

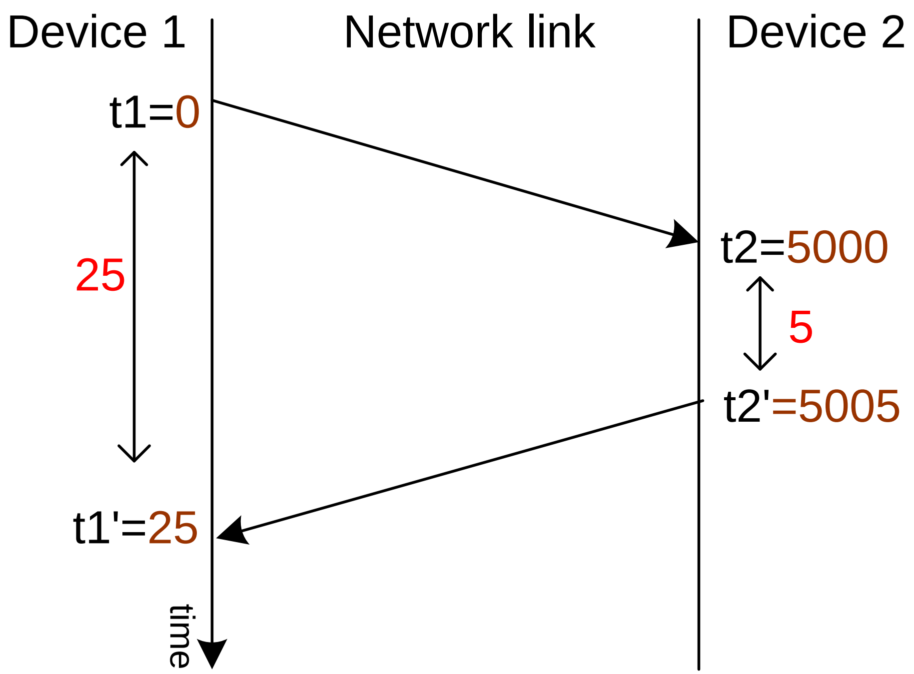
Note: This picture is overly simplistic:

$$(T_{egr}-T_{in})$$

can be off by as much as 200PPM from the GM.
802.1AS computes "rateRatio" to correct this.

- **Time is sent from master over the link with frames that are LAN/media-specific**
  - Illustrated abstractly here by a Blue frame
- **Accurately measure how the long Blue frame is delayed in processing/queueing**
  - Called "Residence Time"
- **Also compensate for link delay ($T_{link}$) and rateRatio**

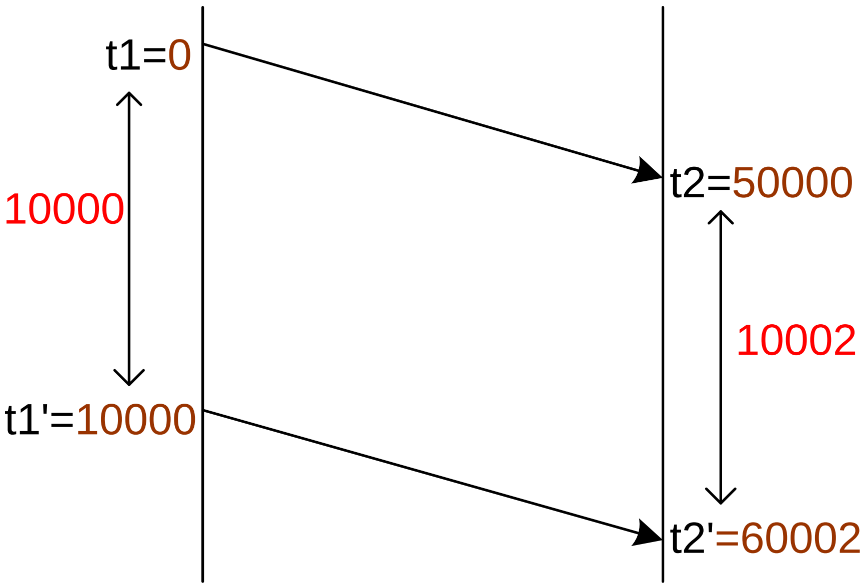
# Example linkDelay measurement




$$\text{linkDelay} = \left( \frac{(t1' - t1) - (t2' - t2)}{2} \right)$$
$$= \left( \frac{(25 - 0) - (5005 - 5000)}{2} \right)$$
$$= 10$$

**If link delay is symmetrical, link delay is 10**

# Example neighborRateRatio measurement




$$\text{neighborRateRatio} = \frac{(t1' - t1)}{(t2' - t2)} = \frac{(10000 - 0)}{(60002 - 50000)} \approx 0.998$$

$\rightarrow$ neighbor is slow by 2000 PPM

**If link delay is constant, station on left is running 2000 PPM (0.2%) slower than station on the right**

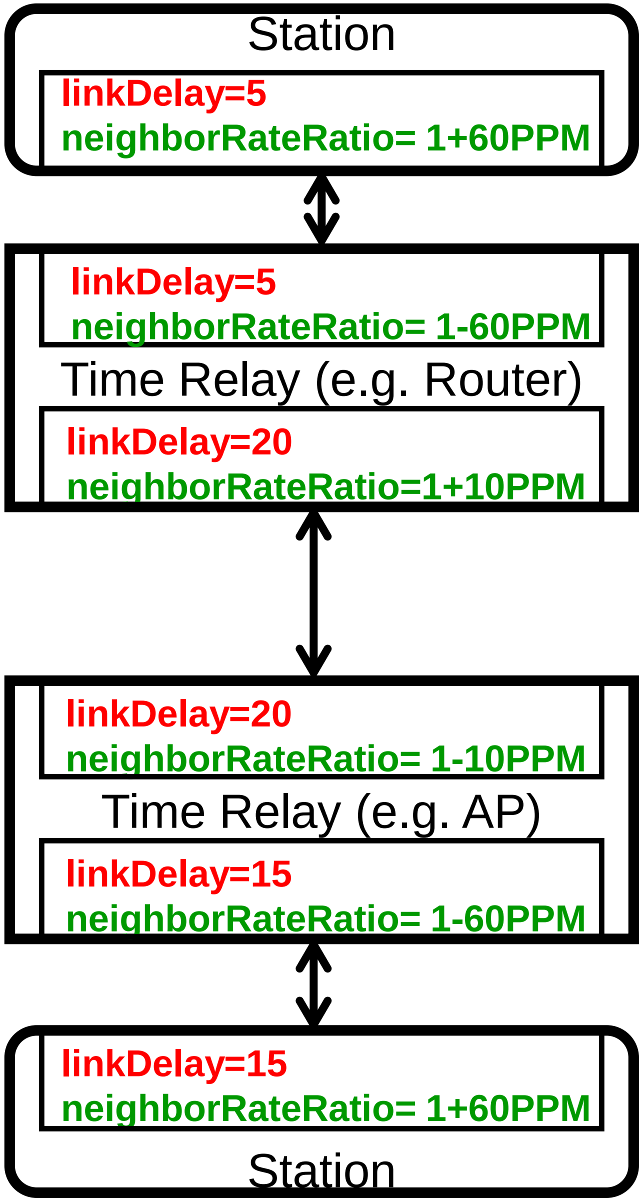
**Note: one *could* measure neighborRateRatio and linkDelay using the same packets (802.11 does, 802.3 does not)**

# Link Delay and Neighbor-Rate-Ratio

**All ports measure**

- linkDelay to neighbor
- neighborRateRatio

**Example values are shown**




Note: No GrandMaster is needed here (yet)

# End-to-end Rate Ratio

**As time is propagated downward, neighborRateRatio is accumulated at each hop**

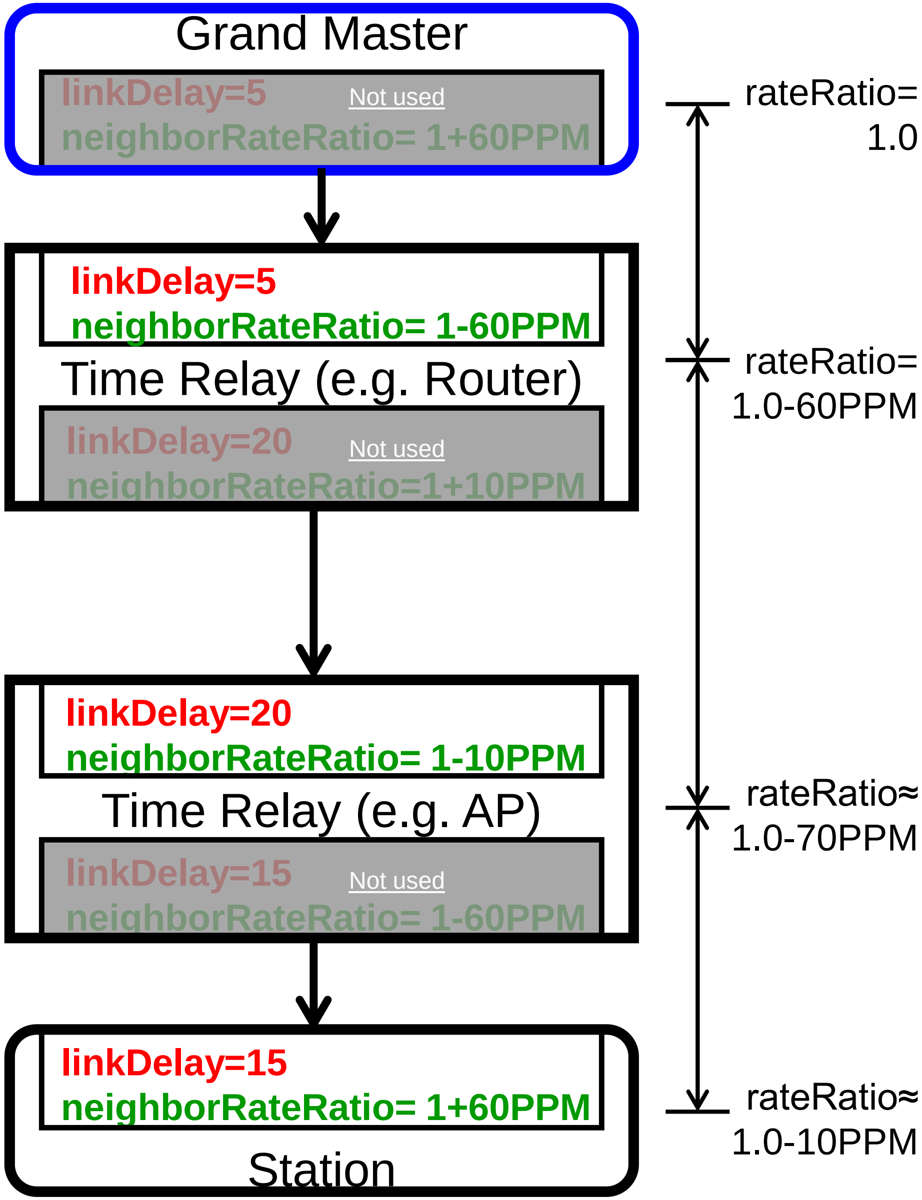
**…using the approximation:**

```
rateRatio +=
        (1-neighborRateRatio)
```

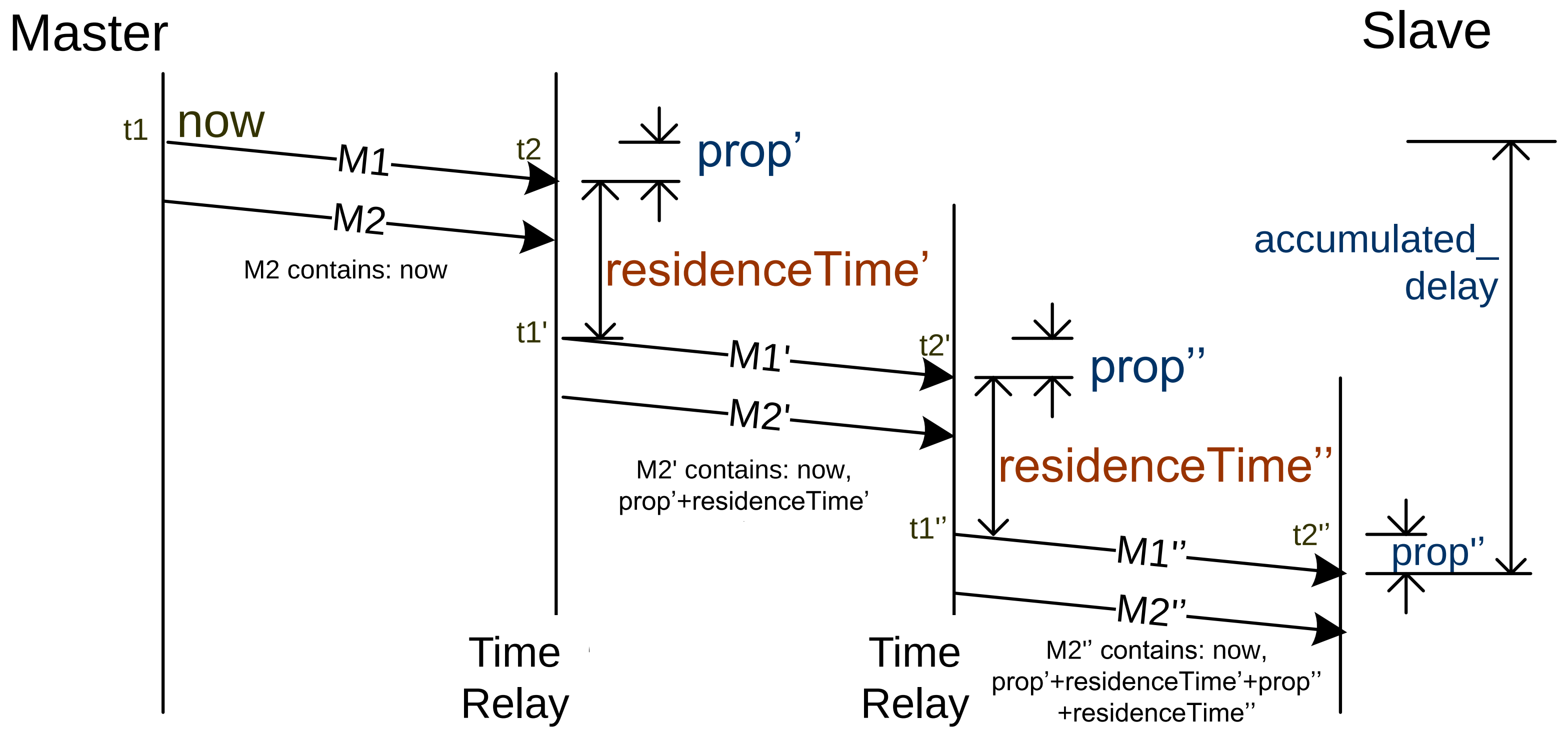
**[Initial rate ratio is 1.0 at the GM]**

**Alternative is to do syntonization per relay, but cascaded PLLs are bad**

**Added benefit: When changing GM, endpoints stabilize quickly because neighbor parameters are already measured**



# End-to-end time synchronization across the LAN




**Grand Master initiates timing message, shown as M1, every Sync Interval**

**At each hop, propagates *now* and measures the actual delay of M1:**

delay = prop + residenceTime * rateRatio

**And carries the *accumulated_delay* in another message, M2**

– Using two messages eliminates real-time processing requirements

**Slaves compute: *currentTime at t2'' = now* plus the *accumulated_delay***

Note: Message interval on each link may be different

# Measurements summarized

**Accurate local egress and ingress timestamps captured in the MAC/PHY**

**Timestamps from special time-measurement frame used to compute:**

- **Link delay (per slave port)**
- **Next-neighbor rate ratio (PPM offset to link partner)**

**When the GM sends “now”, the following are accumulated down the tree:**

- **Residence time (per transmitted time measurement frame)**
- **rateRatio (PPM relative to the GM)**

**These measurements described in 802.1AS:**

- Clause 11: IEEE 802.3 (Ethernet)
- Clause 12: IEEE 802.11 (Wi-Fi)
- Annex E: MoCA, ITU-T G.hn

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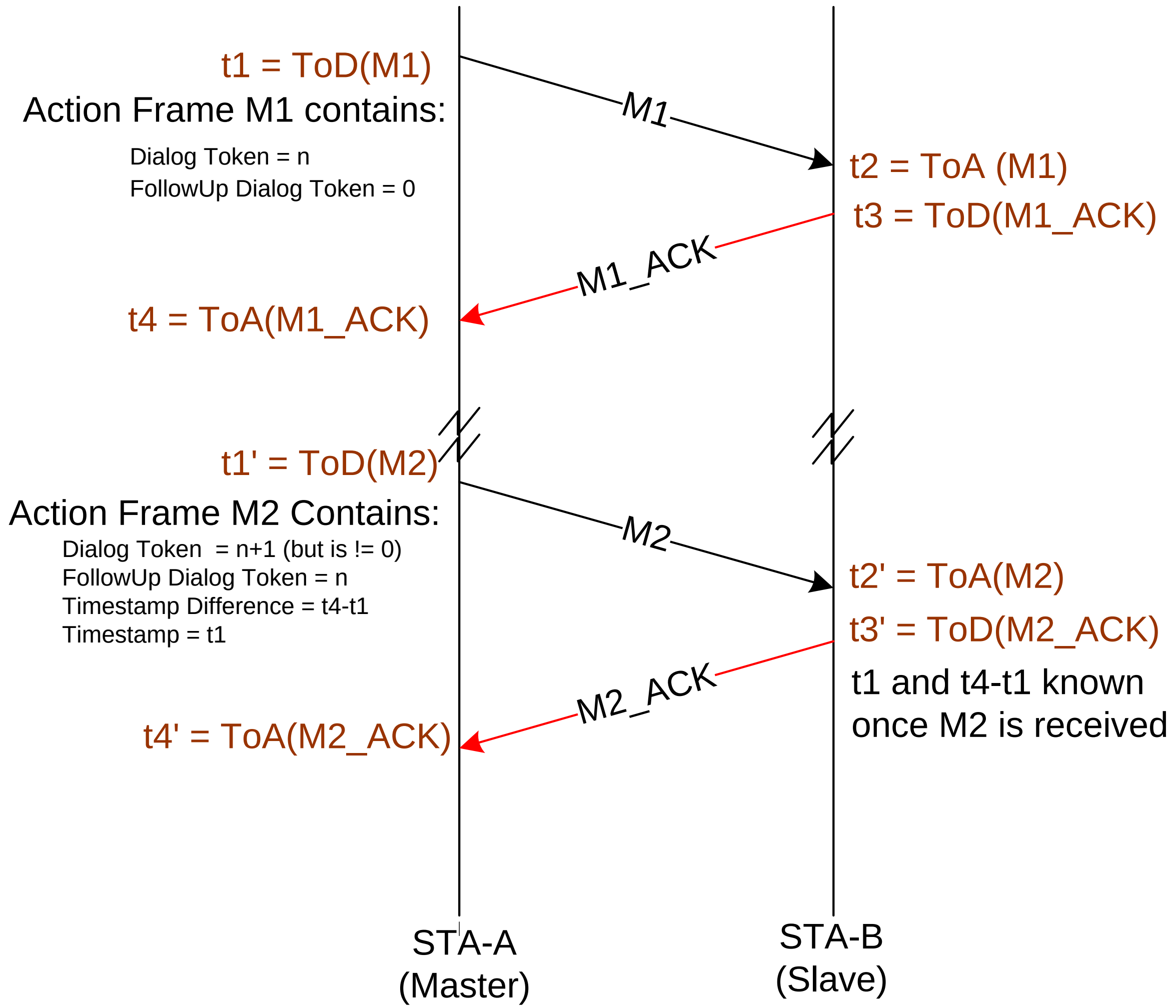
  - Media-independent
  - Media-dependent
    - 802.11 links
    - 802.3 links
    - Other CSN links
- **Time *inside* the system**

# 802.1AS over 802.11 links (Using the 802.11 TIMINGMSMT protocol)




**First exchange:**
- **takes a measurement**

**Subsequent exchange:**
- **takes a measurement**
- **also passes timestamps from prior measurement**

**Free-running counter used for timestamps**

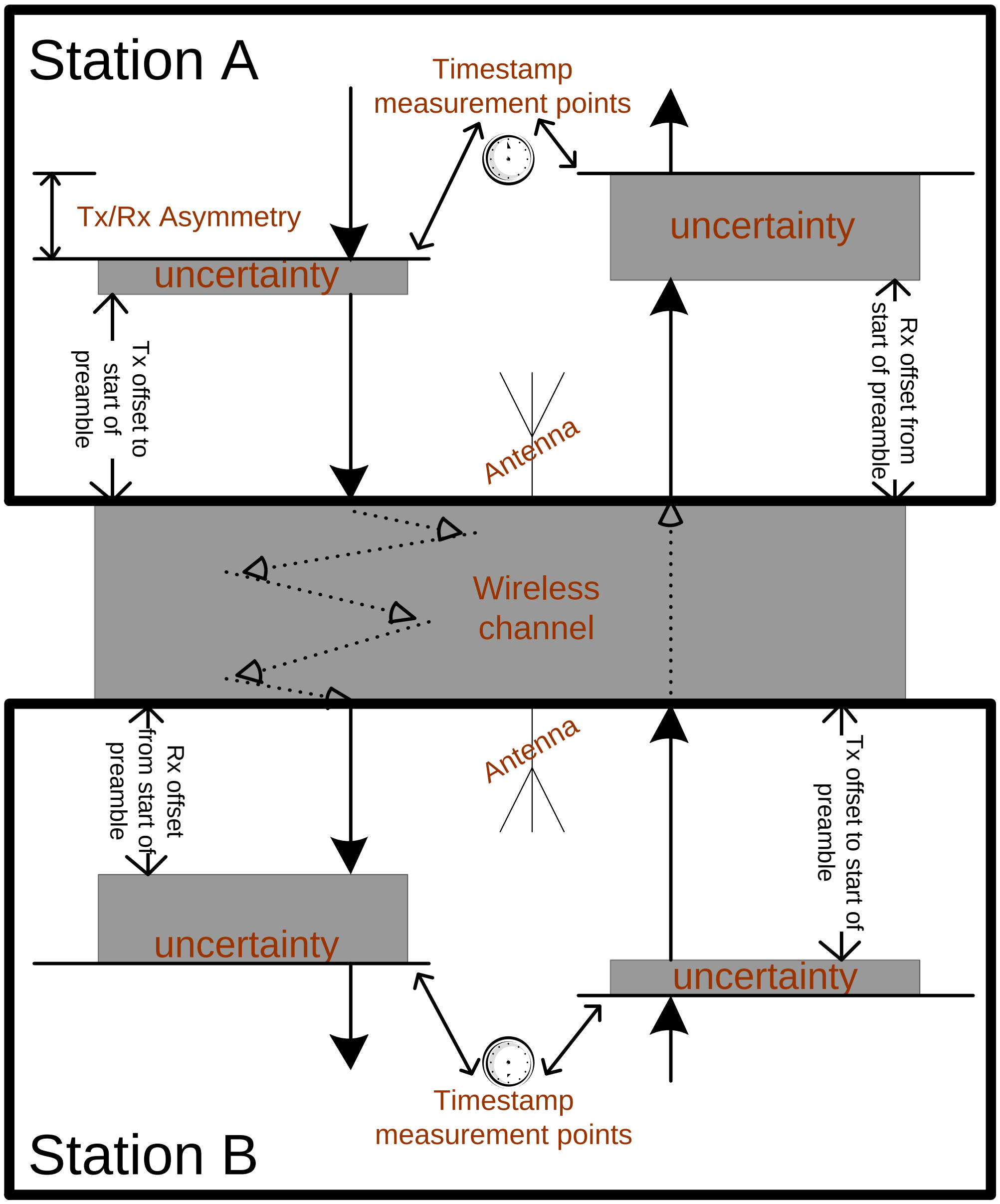
**Allows us to compute:**

```
neighborRateRatio =
    (t1'-t1)/(t2'-t2)

linkDelay =
        [(t4-t1)-(t3-t2)]/2

timeOffset=
        [(t2-t1)-(t4-t3)]/2
```

**[note: rateRatio is also applied]**

NOTE: M1 and M2 have exactly the same format—
they're TIMINGMSMT Private Action Frames (and Unicast, BTW)

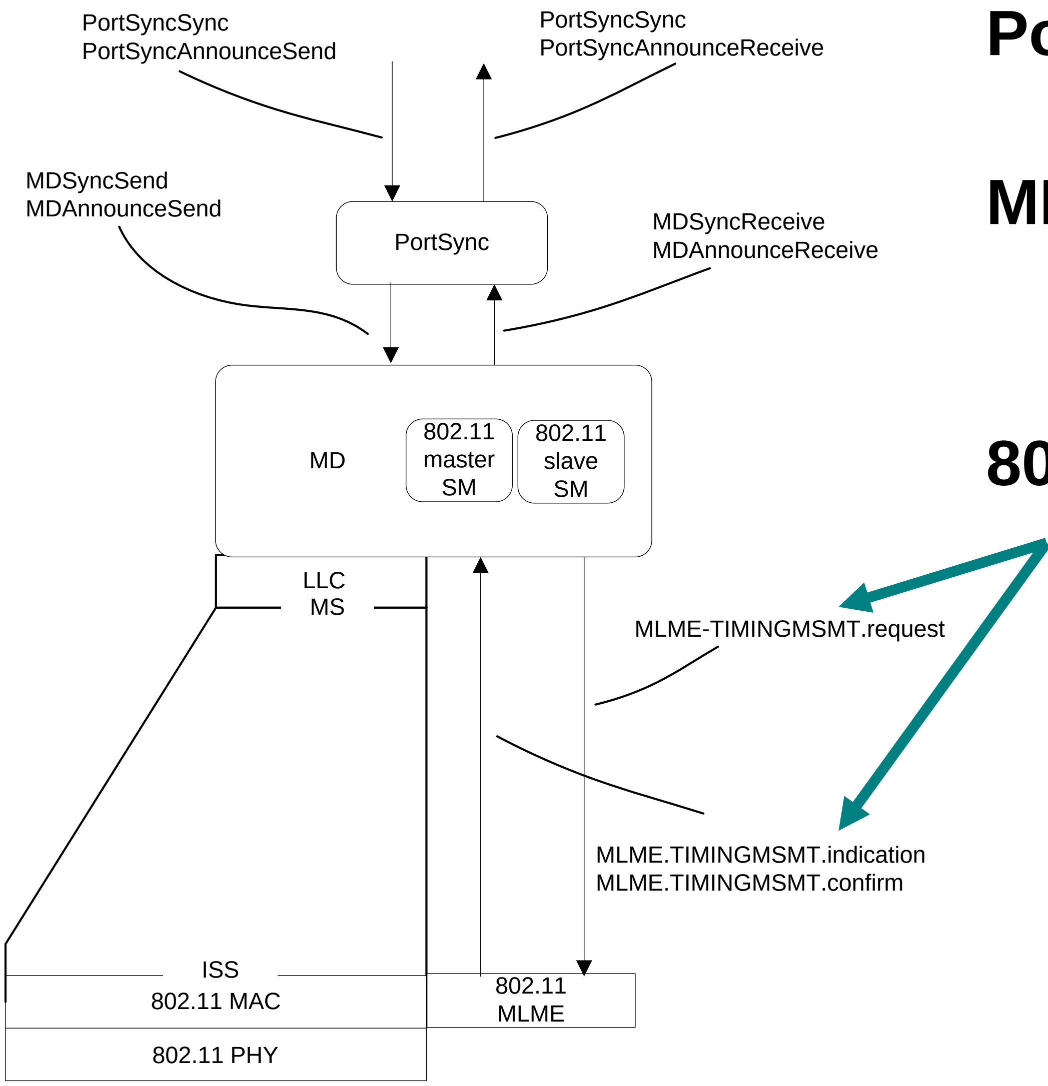
# Accounting for round-trip 802.11 path asymmetry




- **The Antenna is the *reference* for Rx and Tx timestamp measurements**
- **Each system knows the delay between the antenna and where the actual Rx and Tx timestamps are captured**
- **Each timestamp includes some uncertainty**
- **The channel also introduces path asymmetry (and additional uncertainty)**

- **In practice, the difference between the Rx offset and the Tx offset in each system is sufficient information**
  - The rest appears as fixed channel delay and channel uncertainty

# 802.11 links in the 802.1AS architecture




**PortSync is per-port, media-independent**

**MD is per-port media dependent**

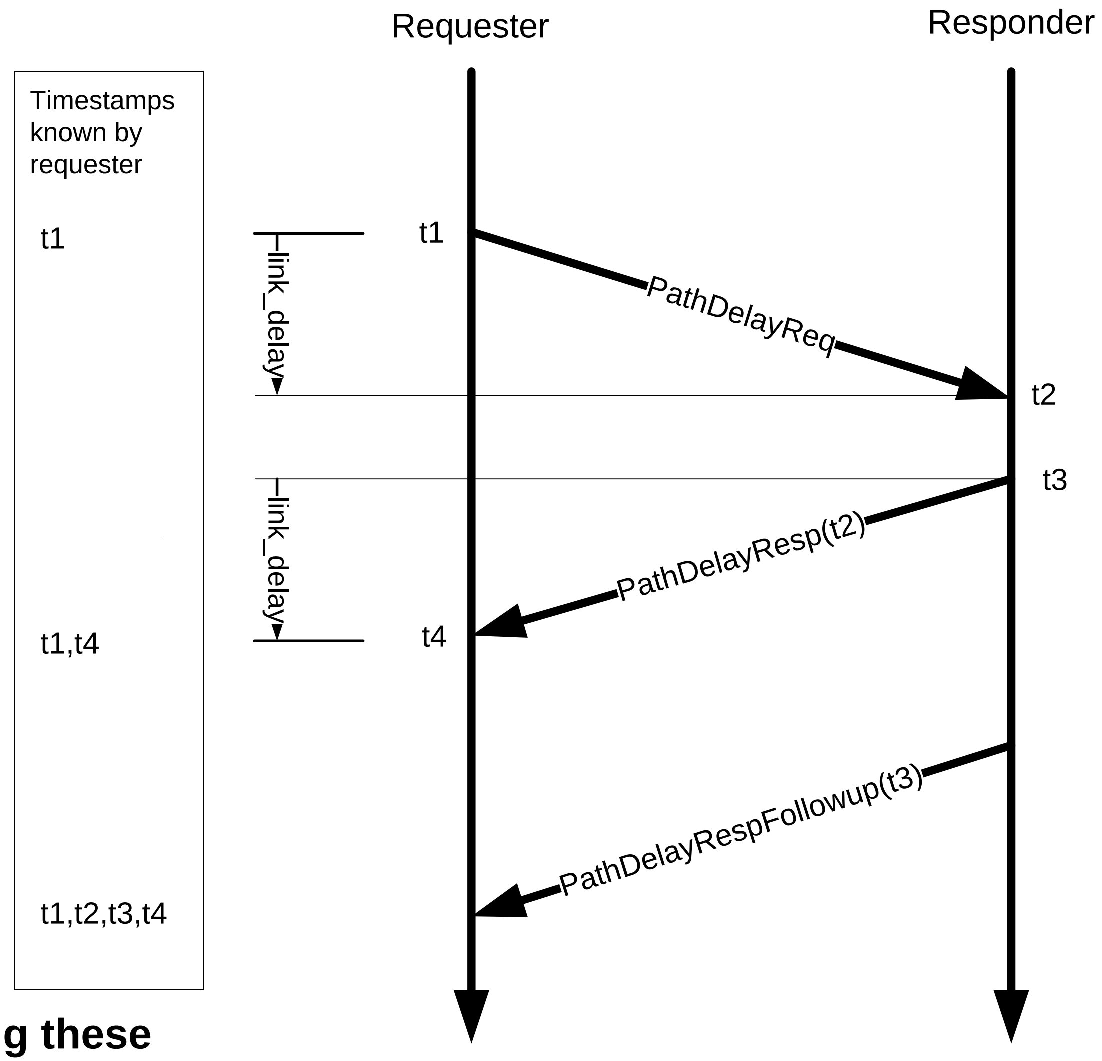
**802.11-2012 defines these MLME.TIMINGMSMT primitives**

# 802.3 protocol (step 1 of 2)

**Measure link delay:**

1. **Requester schedules PathDelayReq for transmission**
2. **As it passes out the PHY, t1 is captured**
   Using the master's free-running clock
3. **Time t2 captured as passes from PHY to MAC**
   Using the slave's free-running clock
4. **Responder schedules PathDelayResp for transmission, sends t2**
5. **Timestamps t3 and t4 captured**
   Using local free-running clocks
6. **PathDelayRespFollowup carries t3 to requester**

**If link delay is fixed & symmetric:**
**link_delay = [(t4-t1) – (t3-t2)] / 2**

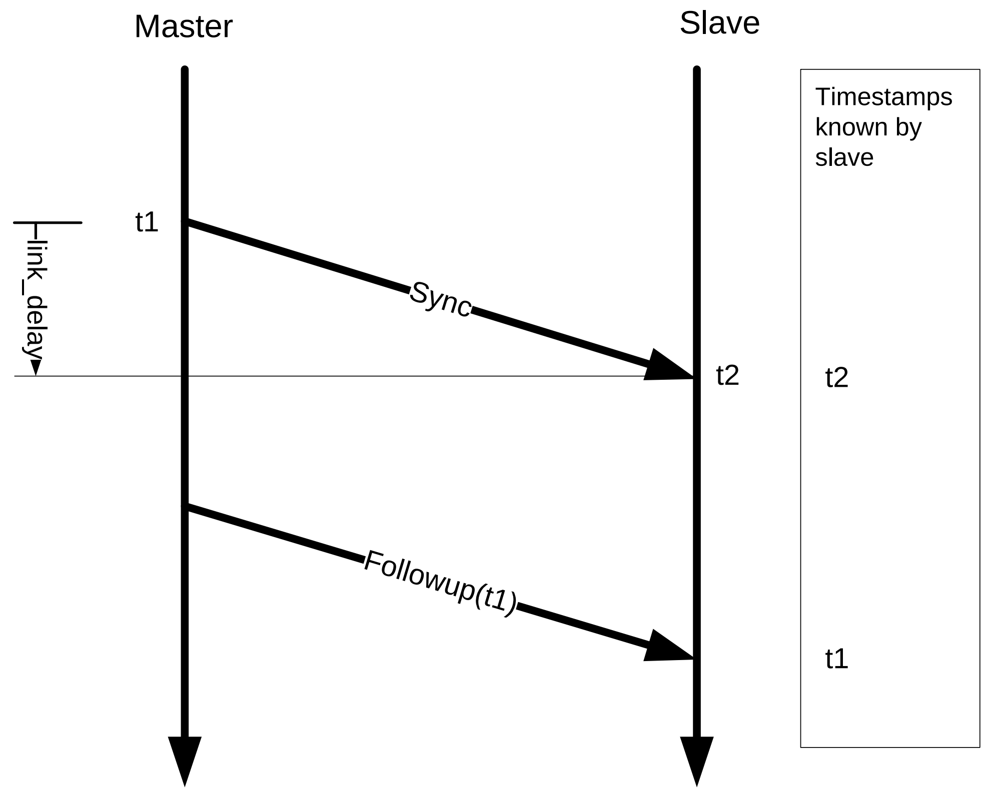



**NeighborRateRatio is computed using these and previous timestamps**

# 802.3 protocol (step 2 of 2)

**Synchronize clocks**

1. **Master schedules Sync for Tx**
2. **As it passes out the PHY, t1 captured**
   Using master's free-running clock
3. **Time t2 captured when it arrives**
   Using the slave clock
4. **FOLLOWUP carries t1 to slave**

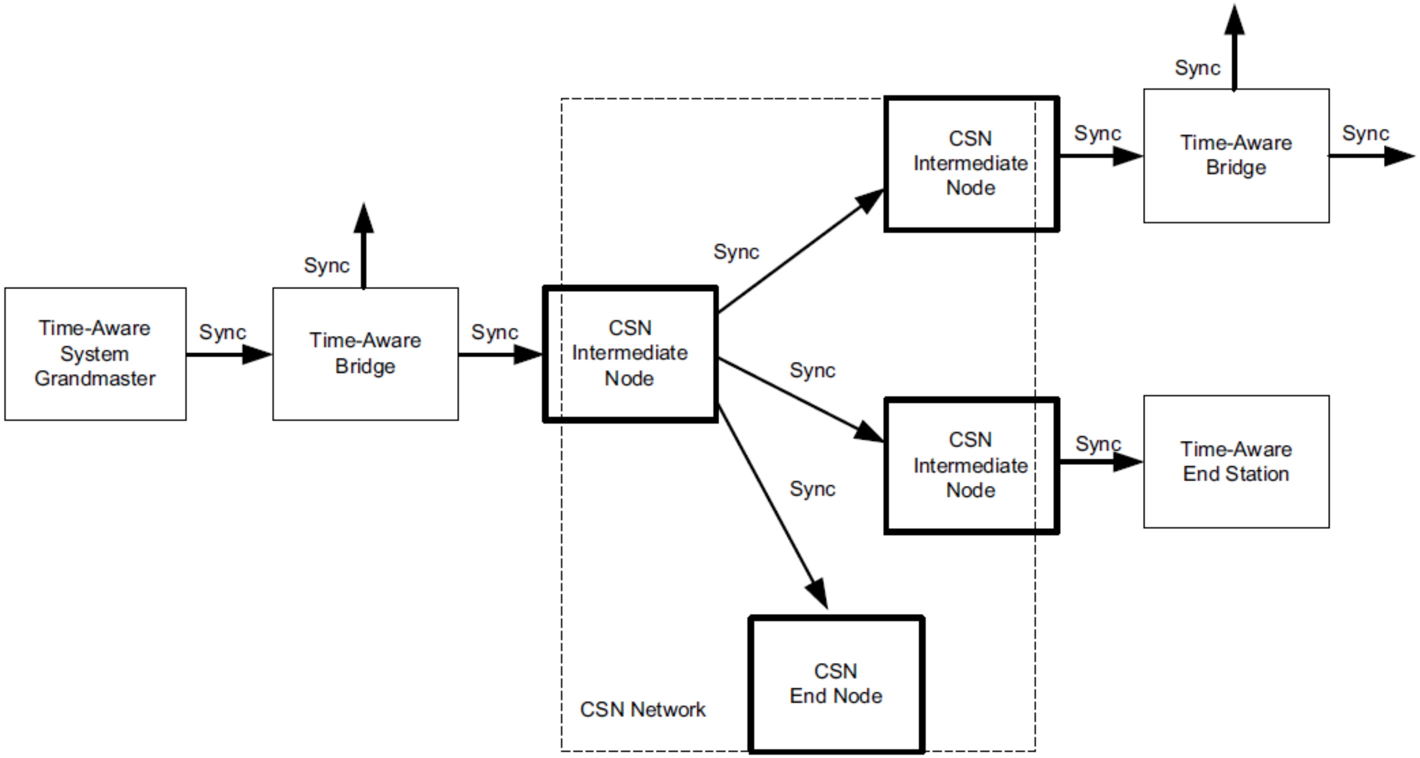



**If link delay is fixed & symmetric:**

**Slave's clock offset**
**= t2 – t1 – link_delay**

**Note: Network infrastructure devices do this too, and communicate the 'residence time' per Sync in the FOLLOWUP frame**

# Coordinated Shared Network (CSN) protocol




- **CSNs use the same protocol as does 802.3 (Ethernet)**
- **Examples of CSNs:**
  - MoCA : Coax networking specification
  - ITU-T G.hn: Coax and power-line networking standard
- **This is described more in Annex E of 802.1AS**

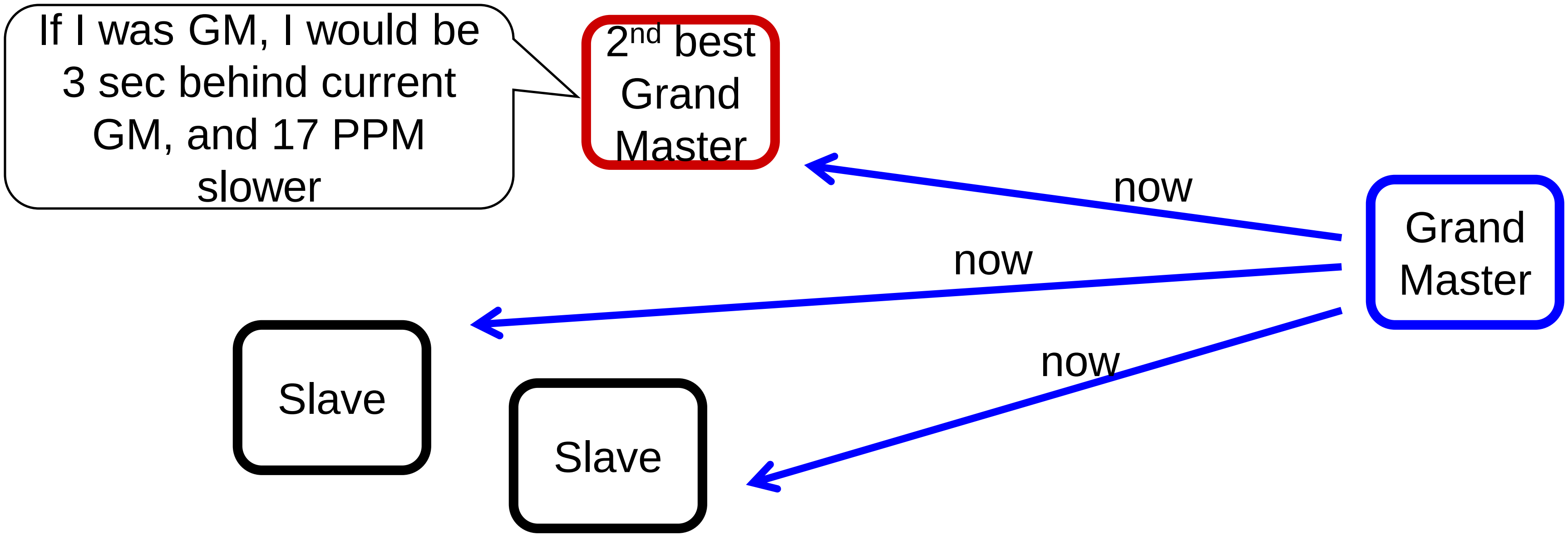
# Message Rates

**Default Message Intervals defined by the standard**

- **Announce sent once per second per Port**
- **Timing Information is sent eight times per second**
  - For 802.11: Eight Action Frames per second (encapsulated Followup)
  - For 802.3 : Eight Sync + Eight Followup frames per second
- **Link delay measured once per second**
  - For 802.3: Three PDelay* frames in each direction per link per second

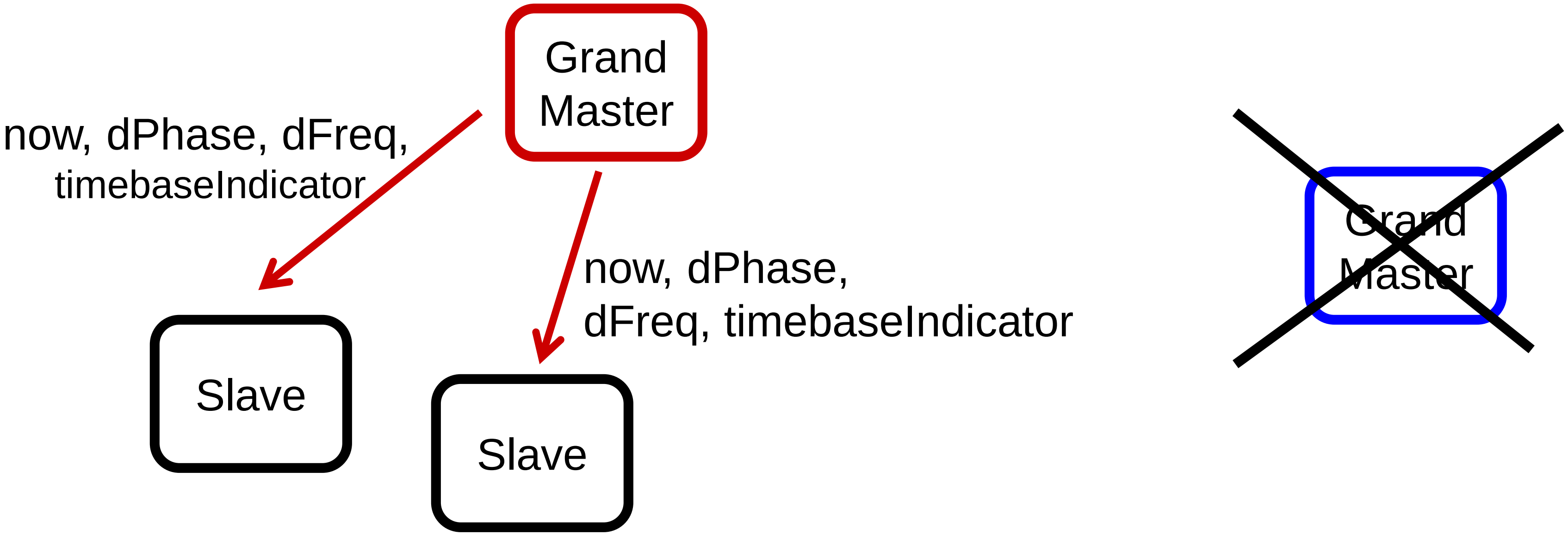
**A different rate can be requested via special SIGNALING messages**

# Handling of discontinuities




- **All potential GMs know their own time offset and intrinsic frequency offset (rateRatio) from the current GM**
- **Time offset may be close to zero (unless it knows UTC-traceable time, e.g., from GPS)**

# Handling of discontinuities – new GM




- **The new GM communicates extra info along with the time**
  - TimebaseIndicator (increments after each discontinuity)
  - dPhase: Last phase change (relative to the previous GM)
  - dFreq: Last frequency change (relative to the previous GM)
- **A GM also does this if it experiences a step change**
  - E.g. GPS regains lock or user manually sets the PTP time in the GM

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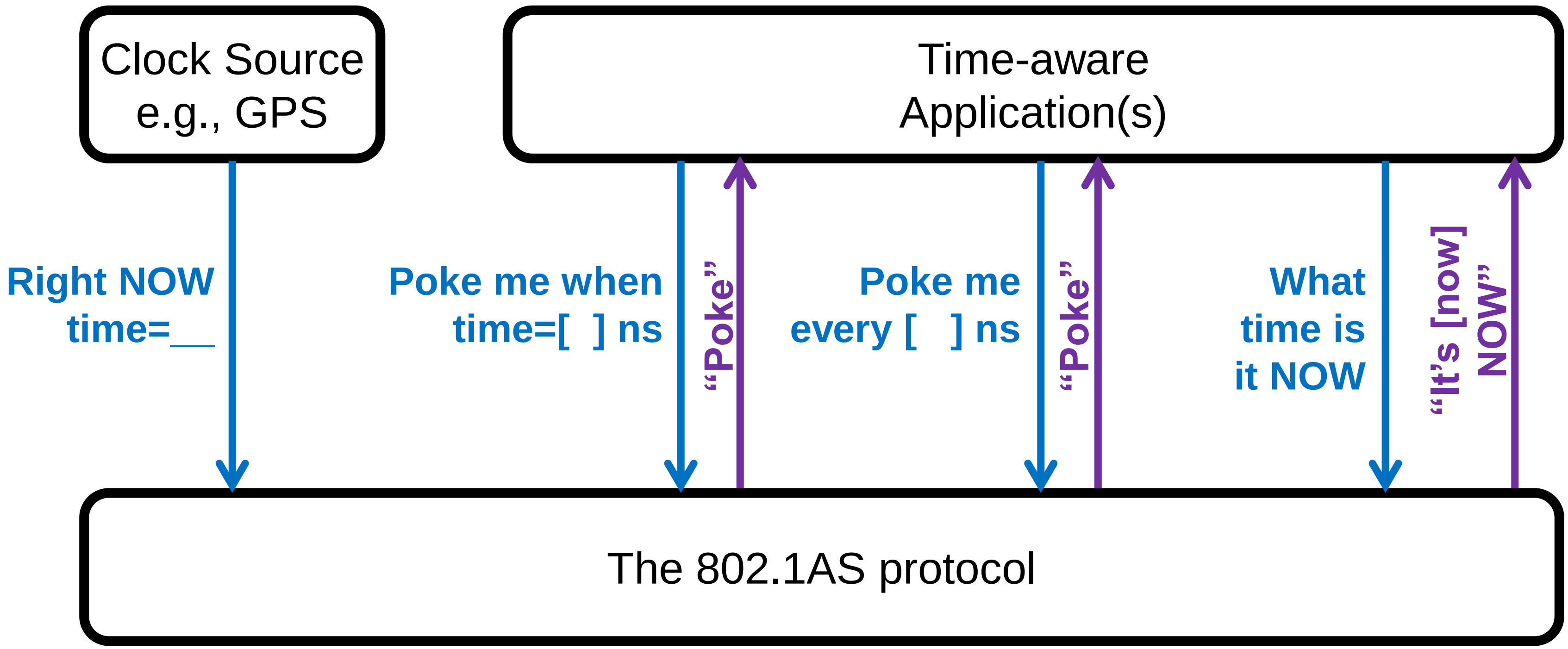
# Four **abstract** application interfaces




In 802.1AS these are defined as…

- ClockSourceTime()
- ClockTargetTriggerGenerate()
- ClockTargetClockGenerator()
- ClockTargetEventCapture()

…respectively

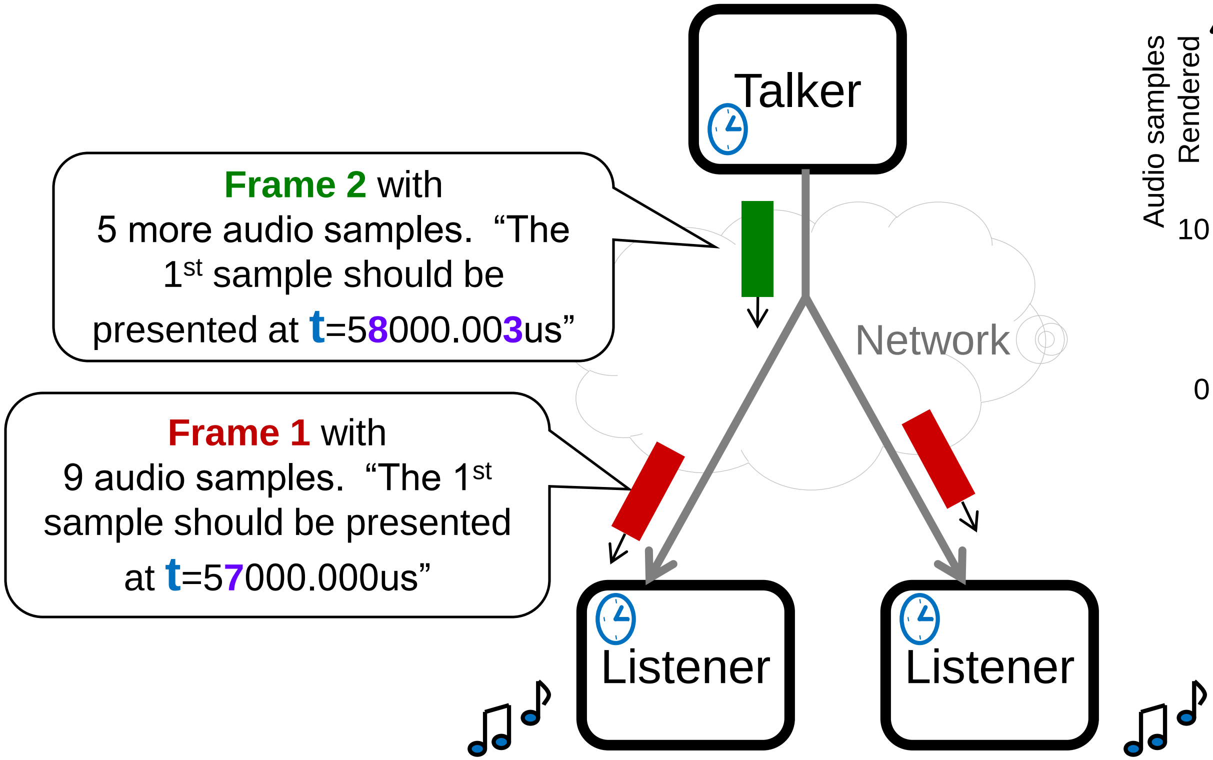
# Perspective on real APIs

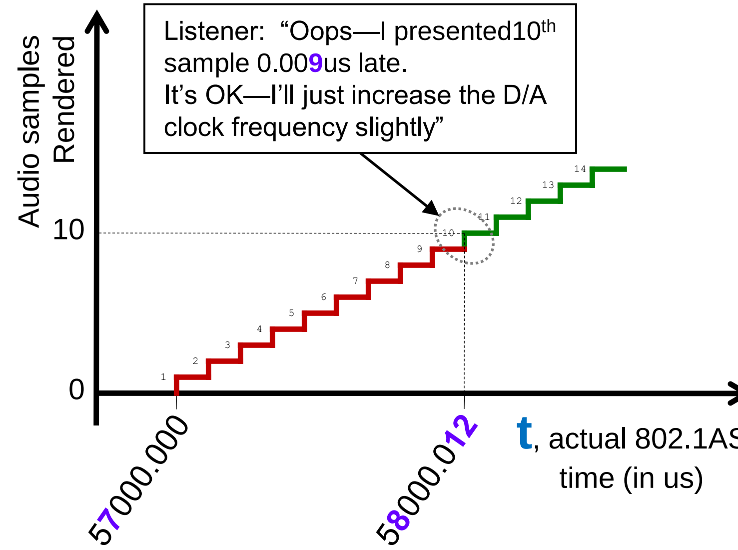
**“Now” is not an ideal software semantic for relating network time to System time within a time-aware systems**

**The preferred fundamental time measurement semantic can be expressed (poetically) as:**

*At the instant*
*when PTP time was X*
*[the other clock] was Y*

# Regenerating the Talker's audio clock




58000.012 us
— 58000.003 us
0.009 us

- **Notes:**
  - Time (t) is 802.1AS time, known to all talkers & listeners
  - Nominal audio sample rate known beforehand, e.g.10KHz, 100us/sample above
  - 802.1AS time is "seconds since Jan 1, 1970 TAI" with precision of 1 nanosecond
  - This allows an ARBITRARY number of independent media clocks <u>simultaneously</u>
  - The Grand Master need not be the Talker

# Relating 802.1AS time to media clock

- **"Presentation Time" added to header of media packets**
  - The Presentation Time is an 802.1AS time
  - Multiple methods for carrying Presentation Time
    - Layer-2: IEEE Std 1722™-2011 (based on IEC-61883)
    - Layer-3/IP: See IETF draft avtcore-clksrc (RTP Extension)
    - Layer-3/TCP/HTTP: TBD
- **Media is buffered in the renderer until the Presentation Time**
  - In some cases, thanks to M*RP and FQTSS (802.1Qat/Qav), Listener buffer size can be minimized
    - But this is out of scope of 802.1AS

# Future work

- **As of July 2014:**
  - An amendment (soon, a revision) of 802.1AS, is under development to add “Enhancements and performance improvements”.  See http://www.ieee802.org/1/pages/802.1ASbt.html
  - More detailed status as of June 2014 is here: http://www.ieee802.org/1/files/public/docs2014/as-mjt-update-for-WSTS-0614-v01.pdf

# References

802 Stds Available Free of Charge
http://standards.ieee.org/about/get/

- **IEEE Std. 1588™-2008**
  - The Definitive Precision Time Protocol (PTP) Definition
- **IEEE Std. 802.1AS™-2011**
  - Clause 12: Media-dependent layer specification for IEEE 802.11 links
  - Also, Technical and Editorial Corrections are published in
    - 802.1AS-2011 Corrigendum 1-2013
- **IEEE Std. 802.11™-2012**
  - Clause 6.3.57: Timing Measurement
  - Clause 10.23.5: Timing Measurement Procedure
- **API definition for use of 802.1AS (and related standards)**
  - http://www.avnu.org/files/static_page_files/C5E0B5F8-1D09-3519-ADB32F1F88E6C057/AVnu_SWAPIs_v1.0.pdf