Synchronization Measurement and Analysis: TDM and Packet Networks

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Measurement & Analysis: Outline

1. Introduction

2. TDM Measurement and Analysis

3. Packet Measurement and Analysis

Extra slides for reference:

[Appendix 1: TDM Measurement Examples]
[Appendix 2: Packet Measurement Examples]
Some kind of phase detector, phase measurement device, or timestamper is needed for both TDM and Packet timing measurements

- TDM phase measurement: “TIE” (phase deviation)
- Packet phase measurement: “PDV” (packet delay sequence)
“TIE” vs. “PDV”

- **“TIE” vs “PDV”**
  - Traditional TDM synchronization measurements: signal edges are timestamped producing a sequence of samples
  - Packet timing measurements: packet departure/arrival times are sampled and packet delay sequences are formed

- Phase measurements (TIE) can be made using:
  - Frequency/time interval counters
  - Time interval analyzers
  - Dedicated test-sets
  - BITS/SSU clocks with built-in measurement capability
  - GPS receivers with built-in measurement capability

- Packet phase measurements (PDV) can be made using:
  - IEEE 1588 grandmaster/probes
  - NTP servers/probes
  - Specialized network probes
Five Example Measurement Equipment Configurations

1. Cesium/GPS → Counter/TIA → RS-232 or GPIB
   - T1 or E1 Live Traffic

2. Cesium/GPS → Testset → RS-232 or GPIB
   - T1 or E1 Live Traffic

3. Cesium/GPS → BITS/SSU → RS-232
   - T1 or E1 Live Traffic

4. GPS → RS-232 or TCP/IP
   - T1 or E1 Live Traffic

5. PRS ref/GPS → Probe → Laptop
   - T1 or E1 Live Traffic
TIE Measurements: Equipment Comparisons

Phase measurements made simultaneously on two different kinds of equipment. Each plot has two traces.
Packet Measurement Example Configurations

Example Measurement Equipment Configurations

Need (1) PRC TOD reference (2) Precision Packet Timestamping (3) Analysis SW

IEEE-1588

IEEE-1588 Source (Grandmaster) w/ HW packet timestamping
(Timestamps outgoing/incoming packets)

Network

IEEE-1588 Destination w/ HW packet timestamping
(Timestamps packets from all sources)

Analysis SW

NTP

NTP Server w/ HW packet timestamping

Network

NTP Client/Probe w/ HW packet timestamping
(Peerstats/Rawstats)

Analysis SW

QoE Probes

Collector (w/ Database)

Network

Probes
Packet measurements made simultaneously on two different kinds of equipment
“TIE” vs. “PDV”

“TIE” (Single Point Measurement)
- Measurements are made at a single point – a single piece of equipment in a single location - a phase detector with reference - is needed

“PDV” (Dual Point Measurement)
- Measurements are constructed from packets time-stamped at two points – in general two pieces of equipment, each with a reference, at two different locations – are needed
“PDV” Measurement Setup Options

“PDV”

- Ideal setup - two packet timestampers with GPS reference so absolute latency can be measured as well as PDV over small to large areas

- Alternative setup (lab) – frequency (or GPS) locked single shelf with two packet timestampers

- Alternative setup (field) – frequency locked packet timestampers – PDV but not latency can be measured
Are “TIE” Measurements still important? Yes!

- Needed for the characterization of packet servo slaves such as IEEE 1588 slave devices
- There are still oscillators and synchronization interfaces to characterize
- “TIE” measurement/analysis background important to the understanding of “PDV” measurement/analysis
- Many of the tools can be applied to either “TIE” or “PDV” data such as TDEV or spectral analysis
- But there are new tools and new approaches to be applied to “PDV” with some of the traditional “TIE” tools less effective for “PDV” analysis
In most packet network measurement setups, both “TIE” and “PDV” are measured at the same time.
1. Introduction

2. TDM Measurement and Analysis

3. Packet Measurement and Analysis
Making TIE Measurements with a Counter

- **Jitter & Wander Measurement Setup**
  - Computer
  - Software
  - Off-the-shelf counter (or counters)
Measuring Phase with a Counter: T1 1 to 2 ➔ Phase

- Using a reference signal at the same frequency (or sub-multiple) of the signal of interest, a counter can be used to measure phase (TIE) directly.
- Software can take care of data clock recovery (no data clock recovery hardware required), phase rollover, and any other processing required to convert the counter measurements to phase.
- Thus an inexpensive counter can be used to measure phase on signals such as traffic bearing E1s directly.

- Any signal rate
  - T1/DS1 (1.544 M) • 1 PPS
  - E1 (2.048 M) • 10 MHz
  - DS2 (6.312 M) • STS-1/OC-1 electrical (51.84 M)
  - DS3 (44.76 M) • 140 Mb/s Tributary (139.264 M)
  - 64 kbit • STS-3/STM-1/OC-3 electrical(155.52 M)
Synchronization Measurements w/ Phase Digitizing: 3 step process

1. Timestamps

2. Phase

3. Analysis

MTIE, TDEV, Allan Variance, Frequency, PPSD, etc.
A time interval counter is used to time threshold crossings of a signal very precisely. This process is unaffected by amplitude modulation.
Timestamps: 1 MHz signal

Perfect mathematical reference (constant carrier)

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Real signal measurement

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$\phi_{\text{dev (time)/TIE}}$

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$\phi_{\text{dev (degrees)}}$

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$\phi_{\text{dev (UI)}}$

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Phase Modulation Signal Model

\[ v(t) = a(t) \cdot \sin(\phi(t)) \]

\[ \phi(t) = \omega_o \cdot t + \theta(t) \]

\[ \phi(t_i) = \omega_o \cdot t_i + \theta(t_i) = n_i \cdot 2\pi \]

\[ \theta(t_i) = n_i \cdot 2\pi - \omega_o \cdot t_i = \omega_o \cdot (n_i \cdot T_o - t_i) \]
Phase deviation (TIE) is the difference between these two curves
Data Signal Phase vs. Time

Clock

Data

$\phi(t)$

$n_5=7$

$n_4=6$

$n_3=4$

$n_2=3$

$n_1=1$
For synchronization measurements, the measurement analysis used primarily is:

- Phase (TIE)
- Frequency (fractional frequency offset)
- Frequency accuracy
- MTIE
- TDEV

MTIE and TDEV analysis shows comparison to ATIS/ANSI, Telcordia/Bellcore, ETSI, & ITU-T requirements

All are derived from phase
1. **Analysis:** Frequency/MTIE/TDEV etc. derived from phase

2. **Check:** Verify measurement is properly made
   - Sudden (point-to-point) large movements of phase are suspect. For example, if MTIE fails the mask, it could be a measurement problem. Phase will help to investigate this.
   - Large frequency offset is easily seen: Is the reference OK? Is the equipment set to use the external reference?

3. **Timeline:** The processed measurements don’t show what happened over time. Is the measurement worse during peak traffic times? Is the measurement worse in the middle of the night during maintenance activities?

   - Typical reports: 80% - 90% of the plots are phase plots
Analysis from Phase: Jitter & Wander

- **Signal (no filter)**
- **Jitter (low-pass filter)** 1.52 UI peak-to-peak (E1)
- **Wander (high-pass filter)**
Recall the relationship between frequency and phase:

\[ \omega = \frac{d\phi}{dt} \]

Important point: Frequency is the slope in the phase plot.
Dynamic frequency: FDEV/FFOFF
- Instantaneous frequency plotted over time
- Fractional frequency offset is a normalized version of frequency deviation
- Limited resolution as measurement interval decreases

Frequency accuracy
- Derived from longer term measurement
- Phase slope calculation (least-square-fit)
- Example: PRS 1 part in $10^{11}$ requirement

To sum up: a tradeoff exists between precision of frequency result and pinpointing when it occurred
Approaches to Frequency Calculation

- **Point-by-point**
  - 1.5 E-9

- **Point-by-point w/ low-pass filter**
  - 1.8 E-11

- **Segmented LSF**
  - 1.5 E-11
Frequency Offset and Drift

Original oscillator phase measurement (0.7ppm frequency offset)

Frequency offset removed (quadratic shape shows linear frequency drift of 0.2 ppb/day)

Frequency drift removed (shows residual phase movement)
Analysis from Phase: Phase Power Spectral Density

10 kHz modulation

10 kHz component
Allan Variance is a measurement of frequency stability used for characterizing oscillators.

Difference in slope = $\Delta W = W_2 - W_1 \Rightarrow \text{AVAR} = \frac{1}{2} \langle (\Delta W_\tau)^2 \rangle$
Analysis from Phase: Allan Variance (AVAR)

Root Allan variance: No. Ave 6; F0=10.00 MHz; F1=33.33 MHz; *6/19/2000 11:09:59 AM*; *8/2/2000 7:07:14 PM*;
HP 53132A; Test: 28; HP 59503A; 1 PPS; Samples: 130535; Gate: 30 s; Glitch: 100.0 nsec; Ref ch1; TI/Time Data Only; TI 1->2;
Analysis from Phase: MTIE

\[ MTIE(S) = \max_{j=1}^{N-n+1} \left[ \max_{i=j}^{n+j-1} (x_i) - \min_{i=j}^{n+j-1} (x_i) \right] \]
Frequency Accuracy and Stability

Quartz, Rubidium, and Cesium

Quartz:
- Frequency offset: 6.4E-08
- Frequency Drift: 2.3E-11/day
- 02/27/98; 16:54:58

Rubidium:
- Frequency offset: 1.7E-11
- Frequency Drift: 2.0E-12/day
- 05/05/02; 19:22:26

Cesium:
- Frequency offset: 6.6E-13
- Frequency Drift: 3.3E-18/day
- 11/12/99; 07:02:04

Graph showing phase deviation over time for Quartz, Rubidium, and Cesium.
Both MTIE and TDEV are measures of wander over ranges of values from very short-term wander to long-term wander.

- MTIE is a peak detector: shows largest phase swings for various observation time windows.
- TDEV is a highly averaged, “rms” type of calculation showing values over a range of integration times.
MTIE: shows a step in phase

Phase steps upwards 15 μsec about 8 hours into the measurement

MTIE flattens after a certain tau value (moving from left to right)
MTIE: shows a frequency offset

A frequency offset is seen as a constant slope in phase.

MTIE constantly increases with increasing observation time.
TDEV: shows a phase modulation consistent throughout measurement.

Phase shows large swings in the short term but is flat in the long term.

TDEV is elevated for shorter term wander (left) but relatively reduced for longer term (right).
Stability and Accuracy

Fractional Frequency Offset vs. Time

The Allan Variance family of analysis metrics is concerned with the characterization of stability

Diagram from “Time Domain Representation of Oscillator Performance”, Marc A. Weiss, Ph.D. NIST
Systematics and Stochastics

- **Systematics**
  - Frequency offset
  - Frequency drift
  - Environmentals (temperature, humidity, pressure, etc.)

- When systematics are removed, what remains is noise (stochastic processes). Five major noise types:
  - WPM (white phase modulation)
  - FPM (flicker phase modulation)
  - RWPM = WFM (random walk PM = white FM)
  - FFM (flicker frequency modulation)
  - RWFM (random walk frequency modulation)
ADEV to MDEV to TDEV

ADEV

MDEV

TDEV
Measurement & Analysis: Outline

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Packet Network Measurement Setup

- Measurement equipment with precision IEEE-1588 or NTP hardware time-stamping
- GPS time-of-day reference in each unit
  - Required for sub-microsecond end-to-end analysis
  - Log-files of the time-stamp data is post-processed
- Network configurations
  - Basic: crossover cable, hub, switch
  - Baseline: switch, router, multi-hop with no traffic
  - Traffic: load based upon G.8261 “data” profile
  - Production Network with Live Traffic
  - Company LAN and Public Internet
Example Measurement Equipment Configurations

- Need (1) PRC TOD reference (2) Precision Packet TimeStamping (3) Analysis SW
- Probes may be “active” (require master/probe) or “passive” (require master/slave/probe)
- Passive probes also require Ethernet taps or hubs to “see” packets

![Diagram of measurement equipment configurations](image)
Packet Measurement Example Configurations

Alternate Measurement Equipment Configuration for Lab
Source File:
SEQ: 01195 UUID: 00A069012FB9 UTC: DATE 2006:124:01:48:56 NSEC 0650092776
SEQ: 01196 UUID: 00A069012FB9 UTC: DATE 2006:124:01:48:58 NSEC 0649898076
SEQ: 23240 UUID: 000055010016 UTC: DATE 2006:124:01:49:00 NSEC 0372820611
SEQ: 01197 UUID: 00A069012FB9 UTC: DATE 2006:124:01:49:00 NSEC 0649723496

Destination File:
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Example Lab Network Configurations

Network Configurations:
- Crossover
- Hub
- Enterprise Switch A
- Enterprise Switch B
- Enterprise Switch C
- Enterprise Switch D
- Multilayer Switch E
- Wirespeed router M
- Router X
- Router Y
- Multi-Hop: SwA/RtX/SwB
- Multi-Hop: SwA/RtM/SwB
- Multi-Hop: SwA/RtX/RtX/SwB
- Multi-Hop: SwA/RtX/RtY/SwB
For traditional synchronization measurements, the measurement analysis used primarily is:

- Phase (TIE)
- Frequency (fractional frequency offset)
- Frequency accuracy
- MTIE
- TDEV

MTIE and TDEV analysis shows comparison to ANSI, Telcordia/Bellcore, ETSI, & ITU-T requirements.
For packet synchronization measurements, some of the measurement analysis used is:

- Phase (PDV)
- Histogram/PDF* & Statistics
- Running Statistics
- TDEV/minTDEV/bandTDEV

minTDEV is under study at the ITU-T Q13/SG15 and has references in the latest G.8261 draft

* PDF = probability density function
Viewing Phase (Packet Delay Sequence)

When graphing packet delay phase it is often best not to connect the dots.
Performance Metrics

- **Phase (Packet Delay vs. Time)**
  - Basis for all calculations
- **MTIE (Maximum Time Interval Error)**
  - Typically one dimensional for packet delay data
- **TDEV (Time Deviation)**
  - Useful indicator of network traffic load
Performance Metrics

- Standard Deviation (PDV)
- Mean (Latency)
- Maximum Peak Deviation (PDV)

Crossover cable:
Mean: 287.2818 nsec
Peak to Peak: 10.01 nsec
Standard Deviation: 4.450 nsec

Hub:
Mean: 659.7955 nsec
Peak to Peak: 60.01 nsec
Standard Deviation: 12.13 nsec

Switch:
Mean: 16.75112 μsec
Peak to Peak: 310.0 nsec
Standard Deviation: 70.10 nsec

Router:
Mean: 277.6874 μsec
Peak to Peak: 212.5 μsec
Standard Deviation: 20.64 μsec

Switch no traffic:
Mean: 16.75112 μsec
Peak to Peak: 310.0 nsec
Standard Deviation: 70.10 nsec

10% BW Utilization:
Mean: 17.93500 μsec
Peak to Peak: 121.4 μsec
Standard Deviation: 11.53 μsec

25% BW Utilization:
Mean: 19.62525 μsec
Peak to Peak: 122.6 μsec
Standard Deviation: 17.61 μsec

50% BW Utilization:
Mean: 47.99551 μsec
Peak to Peak: 122.8 μsec
Standard Deviation: 50.90 μsec
Raw PDV vs. Running Statistics

Raw packet delay appears relatively static over time.

Mean vs. time shows cyclical ramping more clearly.

Standard deviation vs. time shows a quick ramp up to a flat peak.
Not All Devices are *Equal*

Switch vs. Multilayer switch vs. Router vs. Two Routers

**Switch:**
- Mean: 24.41855 μsec
- Peak to Peak: 334.8 nsec
- **Standard Deviation:** 52.85 nsec

**Multilayer Switch:**
- Mean: 27.02728 μsec
- Peak to Peak: 576.0 nsec
- **Standard Deviation:** 76.19 nsec

**Router:**
- Mean: 277.6874 μsec
- Peak to Peak: 212.5 μsec
- **Standard Deviation:** 20.64 μsec

**Two Routers:**
- Mean: 477.6874 μsec
- Peak to Peak: 369.7 μsec
- **Standard Deviation:** 43.18 msec
Multilayer Switch with Traffic

No traffic:
Mean: 26.9586 μsec
Peak to Peak: 620.4 nsec
Standard Deviation: 73.20 nsec

5% BW Utilization:
Mean: 26.9462 μsec
Peak to Peak: 1.209 μsec
Standard Deviation: 79.12 nsec

10% BW Utilization:
Mean: 28.9450 μsec
Peak to Peak: 34.77 μsec
Standard Deviation: 7.008 μsec

20% BW Utilization:
Mean: 31.2810 μsec
Peak to Peak: 40.41 μsec
Standard Deviation: 9.426 μsec

30% BW Utilization:
Mean: 33.6201 μsec
Peak to Peak: 41.70 μsec
Standard Deviation: 10.88 μsec

50% BW Utilization (2 Traffic Sources):
Mean: 80.8216 μsec
Peak to Peak: 206.6 μsec
Standard Deviation: 47.06 μsec
Multilayer Switch with Traffic

![Graph showing TDEV with No load, 5%, 10%, 20%, 30%, and 50% traffic loads.](image)
Lower levels of noise with the application of a MINIMUM selection algorithm TDEV at various traffic levels on a switch (0% to 50%) converge
Loaded Multilayer Switch: TDEV and minTDEV

Symmetricom TimeMonitor Analyzer
TDEV: No. Avg=1; Fo=10.00 MHz; 2006/10/09; 20:59:40
1 (blue): TDEV; 2 (red): minTDEV
To define bandTDEV, it is first necessary to represent the sorted phase data. Let “x´” represent this sorted phase sequence from minimum to maximum over the range \( i \leq j \leq i+n-1 \). Next it is necessary to represent the indices which are themselves set based on the selection of two percentile levels. Let “a” and “b” represent indices for the two selected percentile levels. The averaging is then applied to the “x´” variable indexed by “a” and “b”. The number of averaged points “m” is related to “a” and “b”: \( m=b-a+1 \).

1. TDEV is bandTDEV(0.0 to 1.0)
2. minTDEV is bandTDEV(0.0 to 0.0)
3. percentileTDEV is bandTDEV(0.0 to B) with B between 0.0 and 1.0
Example bandTDEV Calculation

Phase (Packet Delay Sequence)

Symmetricom TimeMonitor Analyzer
Phase deviation in units of time; Fs=1.000 Hz; Fo=10.000000 MHz; 2006/10/17; 01:30:27
TP5000 Fwd PDV Phase; Samples: 7001; Start: 16000; Stop: 23000; Initial phase offset: 60.3400 usec
MasterUUID: 0080AEEFFF003276; MasterIP: 192.168.1.11; ProbeUUID: 0080AEEFFF013261; ProbeIP: 192.168.2.31

96.0 usec

3.30 usec/div

30.0 usec

0.000 hours

5.83 minutes/div

1.944 hours
Example bandTDEV Calculation

Phase Scatter Plot (Packet Delay Sequence)
Example bandTDEV Calculation

TDEV
minTDEV
bandTDEV (0.4 to 0.6)
Many aspects of traffic generation, from the choice of equipment to the way the equipment is configured, can have a great impact on packet delay variation and by extension on the performance of devices timing from the packet flows, such as IEEE 1588 slaves.
Effects of Different Approaches to Traffic Generation on PDV

<table>
<thead>
<tr>
<th>Total BW</th>
<th>BW Port 1/2</th>
<th>Frame Size</th>
<th>Burst Length</th>
<th>Interburst Gap</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40%</td>
<td>20% / 20%</td>
<td>Different</td>
<td>200000</td>
</tr>
<tr>
<td>2</td>
<td>40%</td>
<td>20% / 20%</td>
<td>Same</td>
<td>200000</td>
</tr>
<tr>
<td>3</td>
<td>40%</td>
<td>20% / 20%</td>
<td>Same</td>
<td>50000</td>
</tr>
<tr>
<td>4</td>
<td>40%</td>
<td>20% / 20%</td>
<td>Same</td>
<td>50000</td>
</tr>
<tr>
<td>5</td>
<td>40%</td>
<td>21% / 19%</td>
<td>Same</td>
<td>50000</td>
</tr>
</tbody>
</table>
Appendix 1

TDM Network
Measurement Examples
Sync Measurement #1: Network Element Cascading

Sync degradation with cascading: PSTN-MSC-BSC-DXX

GSM Mobile Telephone Operator

PSTN → MSC → BSC → DXX → BTS

X: measurement points
Sync Measurement #1: Network Element Cascading

Sync degradation with cascading: PSTN-MSC-BSC-DXX
21 nsec to 48 nsec to 124 nsec to 682 nsec peak-to-peak TIE

Symmetricom Time Monitor Analyzer
Phase deviation in units of time: F0=1.021 Hz; Fo=2.0480000 MHz; 04/16/96; 15:21:37
1: PSTN Input to MSC  2: Output from MSC  3: Output from BSC
Sync Measurement #1: Network Element Cascading

Sync degradation with cascading: PSTN-MSC-BSC-DXX
21 nsec to 48 nsec to 124 nsec to 682 nsec peak-to-peak TIE
Sync Measurement #1: Network Element Cascading

Sync degradation with cascading: PSTN-MSC-BSC-DXX

MTIE

Symmetricom TimeMonitor Analyzer
MTIE, Fc=2.048 MHz, Fs=1.021 Hz; 04/16/96; 15:21:37
1: PSTN input to MSC  2: Output from MSC  3: Output from BSC  4: Output from DXX
Sync Measurement #1:
Network Element Cascading

Sync degradation with cascading: PSTN-MSC-BSC-DXX
TDEV
Sync Measurement #2: SDH/SONET vs. PDH Transport

MSC PSTN timing: PDH vs. SDH transport

x: measurement points
Sync Measurement #2: SDH/SONET vs. PDH Transport

PDH vs. SDH transport

Symmetricom TimeMonitor Analyzer
Phase deviation in units of time: \( F_s = 115.6 \, \text{Hz}; \, F_0 = 2.0480000 \, \text{MHz}, \, 08/22/01; \, 13:08:18 \)
1: Local switch via PDH transport; 08/22/01; 13:08:18
2: Local switch via SDH transport; 08/22/01; 13:08:18
Sync Measurement #2: SDH/SONET vs. PDH Transport

PDH vs. SDH transport

Symmetricom TimeMonitor Analyzer
MTIE, Fo=2.048 MHz, F0=115.6 Hz, 08/22/01, 13:08:18
1: Local switch via PDH transport: 08/22/01, 13:08:18
2: Local switch via SDH transport: 08/22/01, 13:08:18
Sync Measurement #2: SDH/SONET vs. PDH Transport

PDH vs. SDH transport

Symmetricom TimeMonitor Analyzer
TDEV: No. Avg=1; Fc=2.048 MHz; 08/22/01; 13:08:18
1: Local switch via PDH transport; 08/22/01; 13:08:18
2: Local switch via SDH transport; 08/22/01; 13:08:18

SDH

PDH
Sync Measurement #2: SDH/SONET vs. PDH Transport

SONET pointer justifications on DS1

Symmetricom TimeMonitor Analyzer
Phase deviation in units of time: \( F_s = 16.7 \text{ Hz}; F_0 = 1.544 \times 10^9 \text{ MHz}; \) 02/19/98 20:57:50
DS1 transported in SONET VT payload with pointer justifications: \( Y_{max} - Y_{min} = 2.542628883011 \text{ usec} \)
Sync Measurement #2: SDH/SONET vs. PDH Transport

SONET pointer justifications on DS1
Zoom into 8UI phase movement

Symmetricom TimeMonitor Analyzer
Phase shift in unit intervals: \( F_s=167.3 \text{ Hz; } F_o=1.5440\times10^6 \text{ MHz} \), 02/19/98.20:57:50
DS1 transported in SONET VT payload with pointer justifications; MRK1to2: Dtime=1.662 sec; DPhase=0.001 UI; 5.182 us
Sync Measurement #2:
SDH/SONET vs. PDH Transport

SONET pointer justifications on DS1
SONET vs. PDH transport MTIE comparison

Symmetricom TimeMonitor Analyzer
MTIE; Fo=1.544 MHz; Fs=1.481 Hz; 10/13/97; 14:40:33
1: PDH transport; 10/13/97; 14:40:33; 2: SONET transport; 02/19/98; 20:57:50

![Graph showing MTIE vs. Observation Window (Tau)]
Sync Measurement #2:
SDH/SONET vs. PDH Transport

SONET pointer justifications on DS1
SONET vs. PDH transport TDEV comparison

Symmetricom TimeMonitor Analyzer
TDEV: N=0, Fc=1.544 MHz; 10/19/97: 14:40:33
1: PDH transport; 2: SONET transport
Sync Measurement #3: GSM BTS: GPS vs. PSTN timing

Frequency jump from PSTN at GSM base station

Symmetricom TimeMonitor Analyzer
Least square fit fractional frequency offset vs. time; N=100; 02/08/00; 23:57:35
1: PSTN input to GSM base station; 2: GSM base station output; 3: GSM base station output w/ GPS sync.
Sync Measurement #4: NE Reference Switching

Reference switching
Phase deviation ringing and overall phase shift of 2.4 μsec

Symmetricom TimeMonitor Analyzer
Phase deviation in units of time: Fs=499.9 Hz; Fo=2.0480000 MHz; 08-10-1994
SDH switching from line to external 2 MHz; Ymax-Ymin=4.058982028710 usec
Sync Measurement #4: NE Reference Switching

Reference switching
Frequency movement +/- 1 Hz

Symmetricom TimeMonitor Analyzer
Frequency deviation from $F_0$: $F_s = 499.9$ Hz; $F_0 = 2.048$ MHz; 08-10-1994
SDH switching from line to external 2 MHz; $Y_{max} - Y_{min} = 2.006233108997$ Hz
Sync Measurement #5: Oscillator Frequency Jump

Oscillator frequency jump: effect on holdover

Symmetricom TimeMonitor Analyzer
Frequency deviation from Fo: F5 -11.38 mHz; Fo -10.00 MHz; *3/21/97 1:43:35 PM*. *4/25/97 9:50:08 AM*;
Quartz oscillator, Samples: 34259, Gate: 10 s, Freq/Time Data Only.
Sync Measurement #5: Oscillator Frequency Jump

Oscillator frequency jump: effect on holdover
> 150 µsec rather than 1 to 10 µsec

Symmetricom TimeMonitor Analyzer
Holdover vs. time: N=200; Start/Learn/Holdover(h): 0.000.48.00.24.00; *3/21/97 1:43:35 PM*; *4/25/97 9:50:08 AM*;
Quartz oscillator; Samples: 34259; Gate: 10 s; Freq/Time Data Only.
Sync Measurement #6: Microwave Link Down

Microwave link down: 200 μsec over 5 minutes

Symmetricom TimeMonitor Analyzer
Sync while microwave link down during maintenance
Sync Measurement #6: Microwave Link Down

Microwave link down: Frequency offset reaches 1 ppm

Symmetricom TimeMonitor Analyzer
Sync while microwave link down during maintenance.
Sync Measurement #6: Microwave Link Down

Microwave link down: MTIE network limits exceeded by a large margin

Symmetricom TimeMonitor Analyzer
Sync Measurement #6: Microwave Link Down

Microwave link down: TDEV network limits exceeded by a large margin

Symmetricom TimeMonitor Analyzer
Sync while microwave link down during maintenance
Sync Measurement #7:
DSL Synchronization

ATM switch #1
- DS3 out
- DS3 in
- DS1 in
- E1 in
- 8 kHz sync out

ATM switch #2
- DS3 out
- DS3 in
- DS1 in
- E1 in
- 8 kHz sync out

DSLAM
- DS3 in
- 8 kHz sync out

HP 5071A
Cesium Frequency Standard

Symmetricom
TS 2700
CDMA PRS

X = measurement point
Sync Measurement #7: DSL Synchronization

ATM switch internal oscillator
Frequency drifting between –1.2 and 12 parts in $10^8$ over one hour
Average frequency offset: 6.0 parts in $10^8$

Symmetricom TimeMonitor Analyzer
Fractional frequency offset: $F_s$=5.000 Hz; $F_o$=8.000 kHz; 11/10/99; 14:39:16
ATM switch internal clock

[Graph showing frequency offset over time]
Sync Measurement #7: DSL Synchronization

DSLAM internal oscillator
Frequency drifting between –3 and –4 parts in 10^6 over 1 hour
Average frequency offset: -3.4 parts in 10^6

Frequency offset is 2 orders of magnitude worse than the ATM switch internal oscillator.
Sync Measurement #7: DSL Synchronization

ATM switch phase-locked loop affected by daytime temperature swings from air conditioning system (T = 20 degrees F)

Symmetricom TimeMonitor Analyzer
Phase deviation in units of time: Fs=999.0 mHz; Fo=10.000000 MHz; 11/11/99; 17:36:29
1. CDMA PRS Receiver. 2: Primary ATM switch locked to CDMA PRS receiver. 3. Secondary ATM switch (locked to primary ATM).
Sync Measurement #7:
DSL Synchronization

**DSLAM w/ External Sync**

Does not really synchronize to external signal: 2.5 parts in $10^8$ frequency offset!!

Symmetricom TimeMonitor Analyzer
Phase deviation in units of time: $F_s=1.000$ Hz; $F_o=8.0000000$ kHz; 11/10/99, 17:44:52
DSLAM switch locked to ATM switch (with ATM switch locked to cesium clock). $F_o$ offset = 2.529E-8

Graph showing the relationship between time deviation and hours.
Sync Measurement #7: DSL Synchronization

ATM vs. ATM ∆T vs. DSLAM

Symmetricom TimeMonitor Analyzer
MTIE: 1. ATM switch locked to PRS with constant temperature
2. ATM switch locked to PRS with temperature fluctuations due to improperly functioning air conditioning system
3. DSLAM switch locked to ATM switch (with ATM switch locked to PRS)
Sync Measurement #8: IP Synchronization

Modem over IP fails without synchronization

X = measurement point
Sync Measurement #8: IP Synchronization

IP network access server internal oscillator
175 ppm: much worse than stratum 4 requirement of 32 ppm

Symmetricom TimeMonitor Analyzer
Phase deviation in units of time: Fs=10.04 Hz; Fo=1.5440000 MHz; 04/10/00; 12:40:54
NAS free-run: Fo offset = 270.6 Hz; 1.762E-4; Fo reference = 1.5440000000000 MHz
Sync Measurement #8: IP Synchronization

IP network access server locked to external PRS reference

Short-term wander at 1.15 μsec peak-to-peak
Sync Measurement #8: IP Synchronization

IP network access server locked to external PRS reference
Zoom into first 30 seconds: wander pattern observed

Symmetricom TimeMonitor Analyzer
Phase deviation in units of time; \( F_s = 5.089 \text{ Hz}; F_0 = 1.5440000 \text{ MHz}; 04/12/00; 19:02:00 \)
HP E1725 Time Interval Analyzer
Voip1 locked to GPS; \( Y_{max} - Y_{min} = 1.154499045697 \text{ usec} \)
Sync Measurement #9: HDSL: Unsuitable for Sync Transport

HDSL DS1: 15 μsec phase steps every 30 minutes

Symmetricom TimeMonitor Analyzer
Phase deviation in units of time: \( f_s = 49.66 \text{ Hz}; f_0 = 1.5440000 \text{ MHz}; \) *4/1/2002 4:40:20 PM*; *4/1/2002 6:06:15 PM*
HDSL at 9000 feet
Sync Measurement #9: HDSL: Unsuitable for Sync Transport

HDSL DS1: ANSI T1.101 DS1 MTIE requirement exceeded by a large margin.

Symmetricom TimeMonitor Analyzer
MTIE, Fo=1.544 MHz; Fs=49.86 Hz; *4/1/2002 4:40:20 PM*. *4/1/2002 6:06:15 PM*.
HDSL at 9000 feet

Graph showing MTIE and comparison between ANSI DS1 and ANSI PRS.
Sync Measurement #9: HDSL: Unsuitable for Sync Transport

HDSL DS1: ANSI T1.101 DS1 TDEV requirement exceeded by a large margin

Symmetricom TimeMonitor Analyzer
TDEV: No. Avg=1; Fo=1.544 MHz; *4/1/2002 4:40:20 PM*; "*4/1/2002 6:06:15 PM*; HDSL at 9000 feet
Sync Measurement #10:
GPS: Effect of SA Being Turned Off

Effect of turning off SA on GPS receivers
Effect of turning off SA on GPS receivers: MTIE

Symmetricom TimeMonitor Analyzer
MTIE, Fo=1.000 Hz, Fs=200.0 mHz, 09/06/98; 21:46:54
1: 58603 GPS: 09/06/1998; 21:46:54; *** SA present ***; 2: 58503 GPS: 05/06/2000; 05:34:28; *** SA turned off ***
Sync Measurement #10:
GPS: Effect of SA Being Turned Off

Effect of turning off SA on GPS receivers: TDEV

Symmetricom TimeMonitor Analyzer
TDEV; No. Avg=1; Fc=1.000 Hz; Fs=200.0 mHz; 09/05/98; 21:46:54
1: 58603 GPS; 09/05/1998; 21:46:54; *** SA present ***
2: 58503 GPS; 05/06/2000; 05:34:28; *** SA turned off ***
Measuring cesium clock offset with GPS: \(-2.7 \text{ parts in } 10^{13}\)

24 hour measurement: cesium can be used to measure GPS
45 day measurement: GPS can be used to measure cesium
Sync Measurement #11: GPS vs. Cesium

Symmetricom TimeMonitor Analyzer
Phase deviation in units of time: $f_s = 33.33$ mHz; $f_0 = 1.0000000$ Hz; 06/24/00; 10:38:59
Sync Measurement #11: GPS vs. Cesium

Intersect point at 12.7 hours
Both meet PRS requirements by a large margin
Sync Measurement #12: Packet Delay Variation Measurements

PDV from timestamping at both ends of a network

Crossover cable vs. hub vs. switch
Sync Measurement #12: Packet Delay Variation Measurements

Phase

With traffic

Stats

10% load

25% load

50% load
Sync Measurement #12: Packet Delay Variation Measurements

TDEV comparison

Symmetricom TimeMonitor Analyzer (file=crossover2h.tah)
TDEV: No. Avg=1; Fo=10.00 MHz; Fs=500.0 mHz; 01/31/06; 16:10:21

100 usec

TDEV

100 psec

2.000 sec

Crossover

Hub

Switch

10% load

25% load

50% load

2.401 ksec
Appendix 2

Packet Network
Measurement Examples
Production Network with DSL Access

Network spanning 500 km between two European cities
Packet delay changes over time periodically due to periodic change in network loading (30 minute cycles)
Production Network with DSL Access

Phase power spectral density (PPSD) analysis clearly shows periodicity
Asymmetrical packet delay with DSL

**Upstream Packet Delay**
- Minimum: 22.04297 msec
- Peak to Peak: 4.866 msec

**Downstream Packet Delay**
- Minimum: 17.64111 msec
- Peak to Peak: 11.64 msec
Symmetricom TimeMonitor Analyzer (file=QoSM_large_upstr_2007_03_02.csv)
Phase deviation in units of time: Fs=100.0 mHz; Fo=10.000000 MHz; 2007/03/02; 12:30:50
1 (blue): QoSmetrics Maximum Latency; Short packets; 2007/03/02; 12:30:50
2 (red): QoSmetrics Maximum Latency; Long packets; 2007/03/02; 11:47:40

Short packets vs. long packets
Production Network with Live Traffic
Packet delay changes over time with live traffic in a production network

Symmetricom TimeMonitor Analyzer
Phase deviation in units of time: \( F_0 = 499.7 \text{ mHz} \); \( F_0 = 10.000000 \text{ MHz} \); 2006/07/26 23:41:56
Tahiti Phase; Samples: 384; UUID: 00005501000A; Initial phase offset: 1.25107 msec
In another measurement, minimum packet delay remains constant but packet delay variation (PDV) changes over time (diurnal).
Tracking packet standard deviation over time shows gradual decrease through the night and then large increase during business hours.
IEEE 1588 slave performance can be correlated with PDV variations

Symmetricom TimeMonitor Analyzer
Phase deviation in units of time: $F_s=924.3$ mHz; $F_0=1.0000000$ Hz
HP 53132A; Test: 87; IEEE 1588 Slave
For the entire 24 hour period the IEEE 1588 slave meets G.8261 requirements and nearly meets G.811 requirements.
Production Network with Live Traffic: Playback vs. Live

A powerful combination: network PDV capture measurement with network emulator playback
Production Network with Live Traffic: Playback vs. Live

Live vs. emulator (overlay zoom)
Production Network with Live Traffic: Playback vs. Live

Live vs. emulator: distribution

Measurement of live network

Minimum: 132.8125 usec   Mean: 140.4341 usec
Maximum: 675.0976 usec   Standard Deviation: 11.00 usec
Peak to Peak: 542.3 usec   Population: 49030   Percentage: 100%

Measurement of emulator playback

Minimum: 132.8125 usec   Mean: 140.4764 usec
Maximum: 675.0976 usec   Standard Deviation: 10.99 usec
Peak to Peak: 542.3 usec   Population: 49532   Percentage: 100%
Live vs. emulator: TDEV and minTDEV
Packet delay: 335 usec to 5.08 msec
Mean: 342.8 µsec
Peak to Peak: 4.75 msec
Standard Deviation: 14.03 µsec
Company LAN San Jose

Zoom into 300-1300 µsec

Mean: 342.8 µsec
Peak to Peak: 4.75 msec
Standard Deviation: 14.03 µsec
Packet delay: 29 to 471 msec
Public Internet San Jose-Austin

Symmetricom TimeMonitor Analyzer
Phase Deviation Histogram; Fs=16.66 Hz; Fo=10.00 MHz; 2007/01/05 22:14:35
XLi 1588 PDV Phase; Samples: 5456456; UUID: 00A069012081; Initial phase offset: 35.9679 msec

Mean: 30.28 msec
Peak to Peak: 442.7 msec
Standard Deviation: 2.54 msec
Public Internet San Jose-Austin

Zoom into 20-80 msec

Mean: 30.28 msec
Peak to Peak: 442.7 msec
Standard Deviation: 2.54 msec

Symmetricom TimeMonitor Analyzer
Phase Deviation Histogram; Fs=16.66 Hz; Fo=10.00 MHz; 2007/01/05 22:14:35
XLi 1588 PVT Phase; Samples: 5456456; UUID: 00A0690120B1; Initial phase offset: 35.9679 msec
Timing measurements in packet networks

- Precision hardware timestamping together with UTC traceable TOD provides a precision tool for studying even the fastest networks and network equipment.
- Unicast capability is critical for the study of production networks and certain network devices such as DSLAM’s (upstream multicast messages not provisionable for security reasons - depends on vendor).
- Use of fast sync rates provides a means of characterizing rapid temporal packet network and device behavior (transients and systematics), facilitates selection algorithms both for analysis and servo design, and allows for quick collection of statistics.