IEEE 1588v2 based solutions for VF Backhaul Networks

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Ensuring synchronisation for the next generation of VF cellular IP backhaul

CONTENTS

1. VF backhaul evolution towards Ethernet and sync strategy
2. IEEE 1588v2 performance assessment
3. IEEE 1588v2 roll-out in Portugal
4. Conclusions

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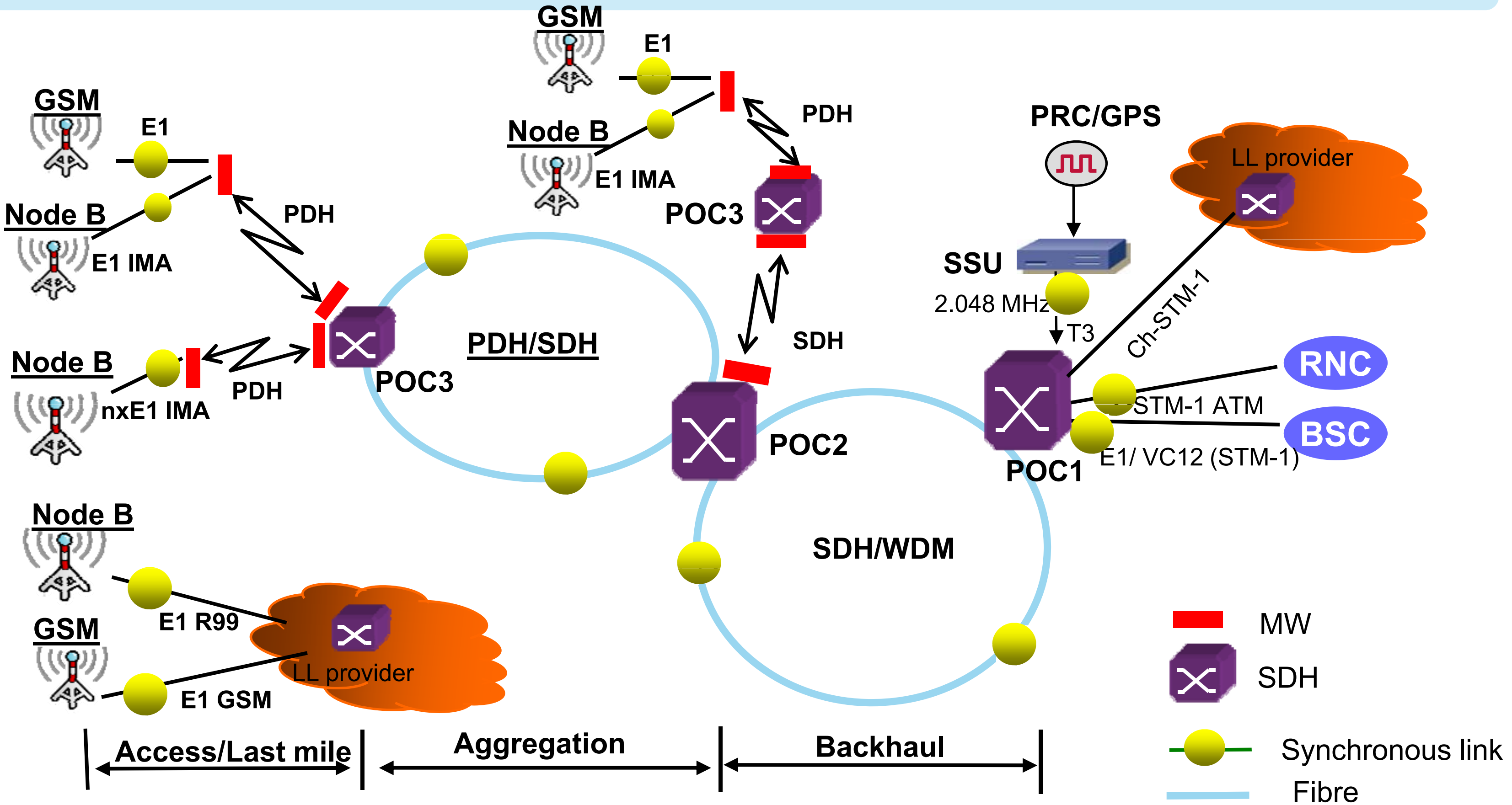
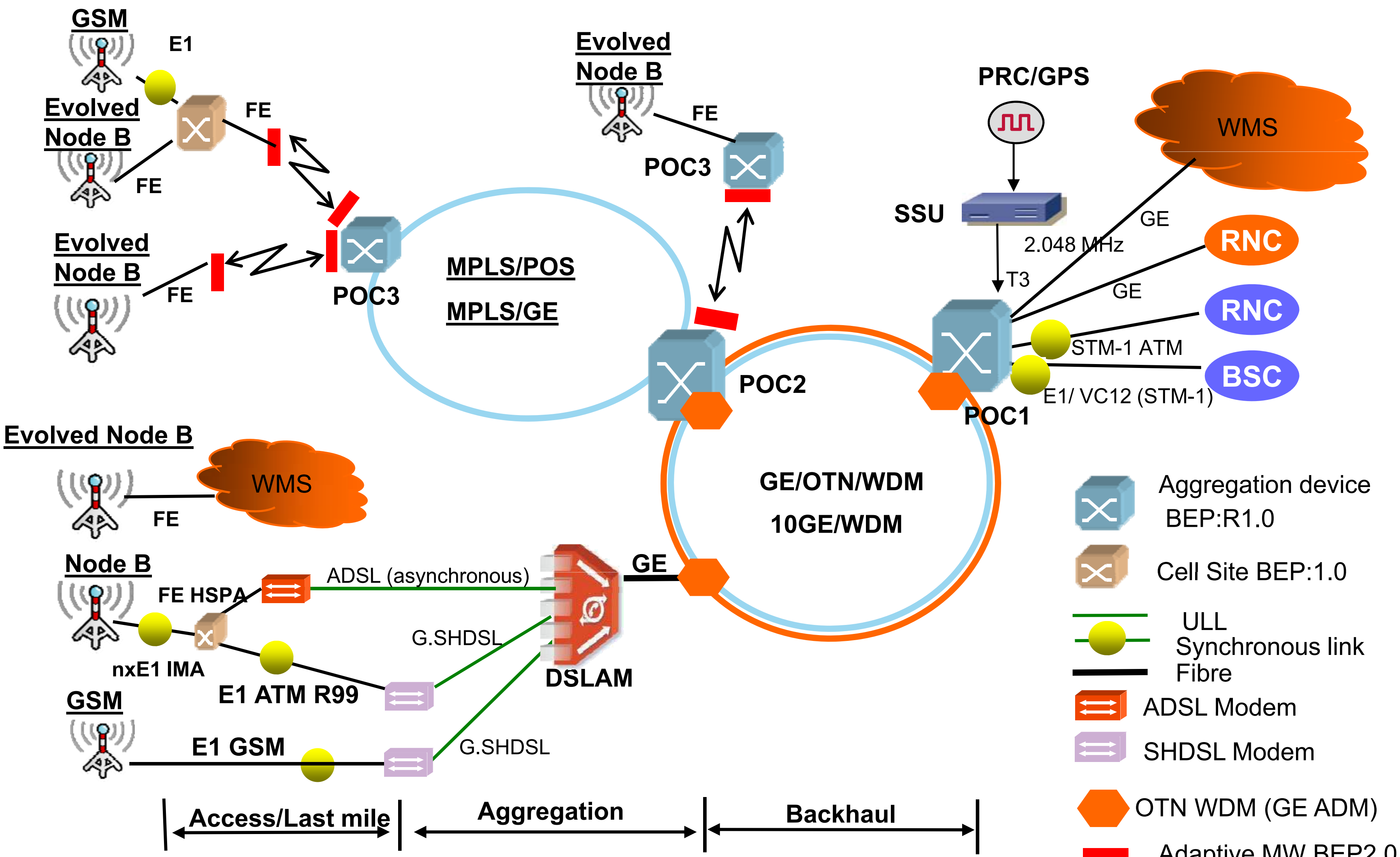
VF traditional backhaul transport network

Traditional backhaul infrastructures rely on SDH/PDH self build and Leased Lines



Ethernet migration critical to mitigate cost penalty given by ever increasing capacity requirements for packet-switched traffic (fixed and mobile broadband)

VF converged backhaul transport



BEP = Backhaul Evolution Programme WMS = Wholesale Managed Services PoC = Point of Concentration

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Synchronization strategy for VF Group

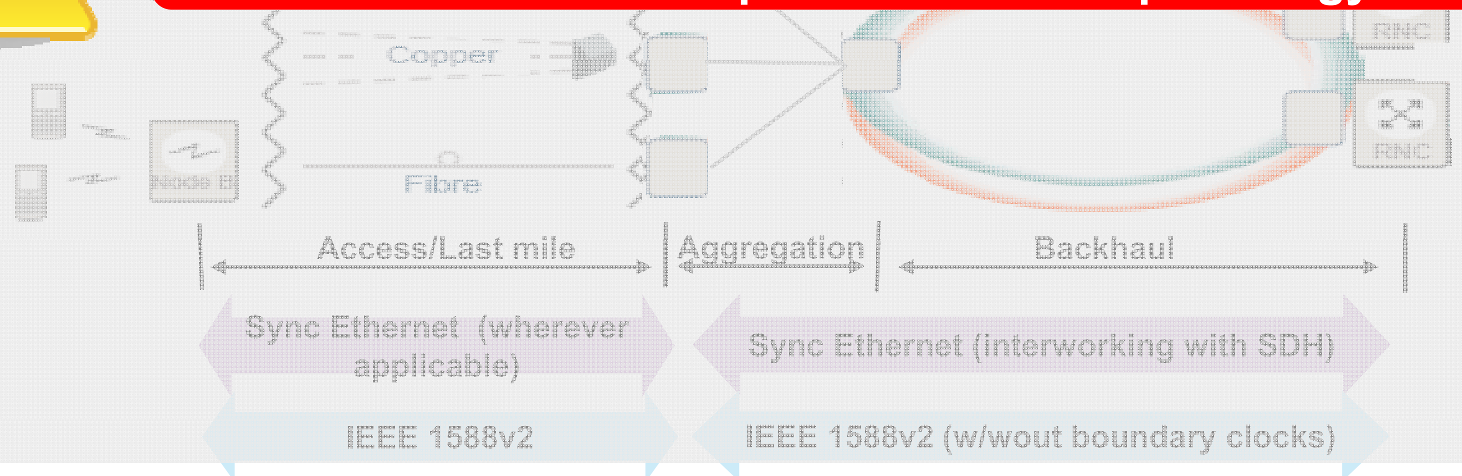
Synchronous Ethernet nodes in the aggregation and backhaul sections for self build networks (as replacement/interworking of SDH)

Synchronous Ethernet for last mile wherever supported (Ethernet MW, Fibre to the NodeB, GPON)

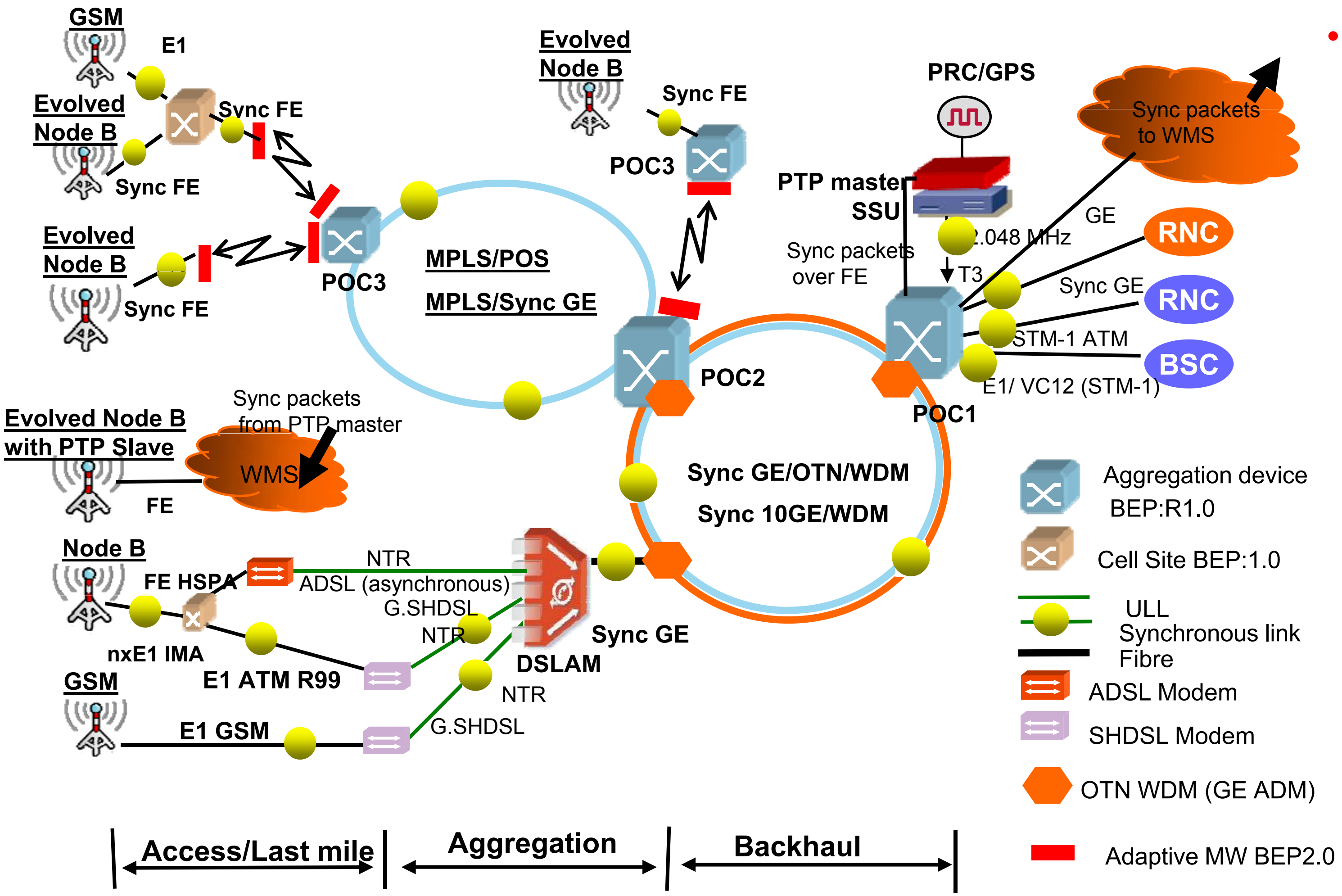
IEEE 1588v2 for

- Managed Ethernet services offering 'plain Ethernet' as replacement of Leased Lines
- Need for phase alignment or timing (1588v2 could be overlaying Sync Eth)
- Need for synchronization on existing metro nodes or when asynchronous DSL links are used
- Boundary clock functionality in core nodes to ensure better phase alignment at RAN sites (MBMS, LTE TDD, WiMAX, etc.)

Deployment of any interim solution such as ACR or NTPv3 NOT contemplated in VF Group Strategy



Example of VF converged backhaul transport network



- Several combinations will be deployed:
  - DSLAM synchronized by PTP
  - PTP in base stations if asynchronous DSL links are used
  - PTP in PoCs driving Sync E lines towards base stations
  - …

BEP = Backhaul Evolution Programme WMS = Wholesale Managed Services PoC = Point of Concentration

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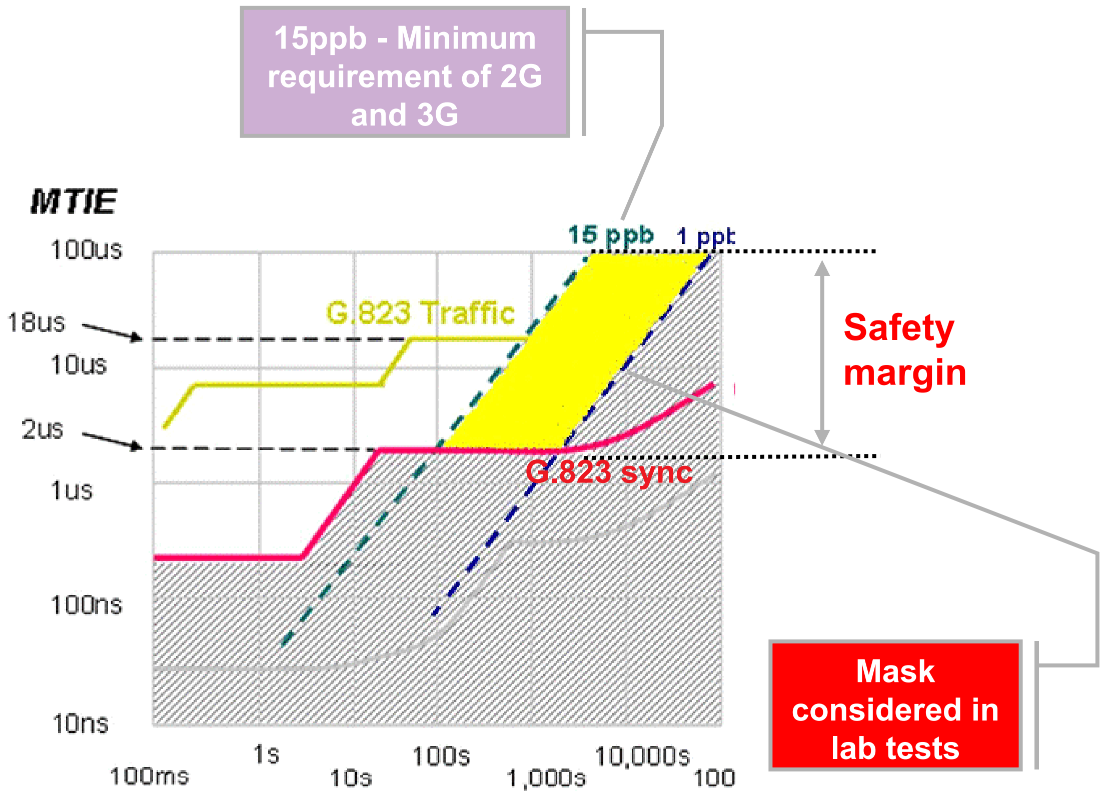
Lab test acceptance criteria

- G.823 sync mask + 1 ppb after 2,000sec
  - To have some safety margins given that lab conditions cannot capture the whole range of situations experienced in a live loaded network



G.823 sync mask

Observation Interval τ (sec)	MTIE requirement (ns)
$0.1 < \tau \leq 2.5$	250
$2.5 < \tau \leq 20$	$100\ \tau$
$20 < \tau \leq 2000$	2000
$\tau > 2000$	$433\ \tau^{0.2} + 0.01\ \tau$

IEEE 1588v2 performance assessment – lab activities

1 Semtech solution Jul 2007 -> Oct 2007 (completed)

- **Objective**: IEEE 1588v2 accuracy in delivering **frequency and phase (relative time)**
- **Equipment**:
  - IEEE 1588v2 - Semtech
  - Reference clock, data analysis - Symmetricom
  - Remote sync monitoring systems - Chronos
  - IP/MPLS backbone, traffic generators – Tellabs

Test results showed at ITSF 2007 – satisfactory performance

2 NSN and Brilliant Telecom Inc. (BTI) Oct 2007 -> Dec 2008 (on-going)

- **Objective**: IEEE 1588v2 theoretical limits and assessment of BTI solution
- **Backhaul**: CE backbone + xDSL (ADSL2+, VDSL2, SHDSL) and AM-MWR in access
- **Equipment**:
  - IEEE 1588v2 master and slave - BTI
  - Data processing – Symmetricom, Matlab, OriginLab
  - CE backbone, xDSL and AM-MWR access, traffic generators – NSN

IEEE 1588v2 performance assessment – lab activities (cont.)

3 Symmetricom solution Jul 2008 -> Oct 2008 (completed)

Objective	IEEE 1588v2 accuracy in delivering frequency	
Backhaul	IP/MPLS network with Ethernet connectivity	
Equipment	IEEE 1588v2 - Symmetricom	
	Reference clock, data analysis - Symmetricom	
	IP/MPLS backbone – Tellabs	Traffic generators – Vodafone

4 Zarlink solution Nov 2008 -> Dec 2008 (to be started)

Objective	IEEE 1588v2 accuracy in delivering frequency	
Backhaul	IP/MPLS network with Ethernet connectivity	
Equipment	IEEE 1588v2 - Zarlink	
	Reference clock, data analysis - Symmetricom	
	IP/MPLS backbone – TBD	Traffic generators – Vodafone

NSN and Brilliant Telecom Inc. (BTI) lab tests

2

Project Objectives

1. Theoretical work
   - Understand the limits of IEEE 1588v2 to characterize whether the network is good enough for packet timing
   - Identification of weak points of existing metrics and possible definition of new SLA (metrics, masks) for estimating worst case frequency and phase stability of a packet based clock recovery mechanism
     - Probe streams and IEEE 1588v2 flow used for detailed network characterization

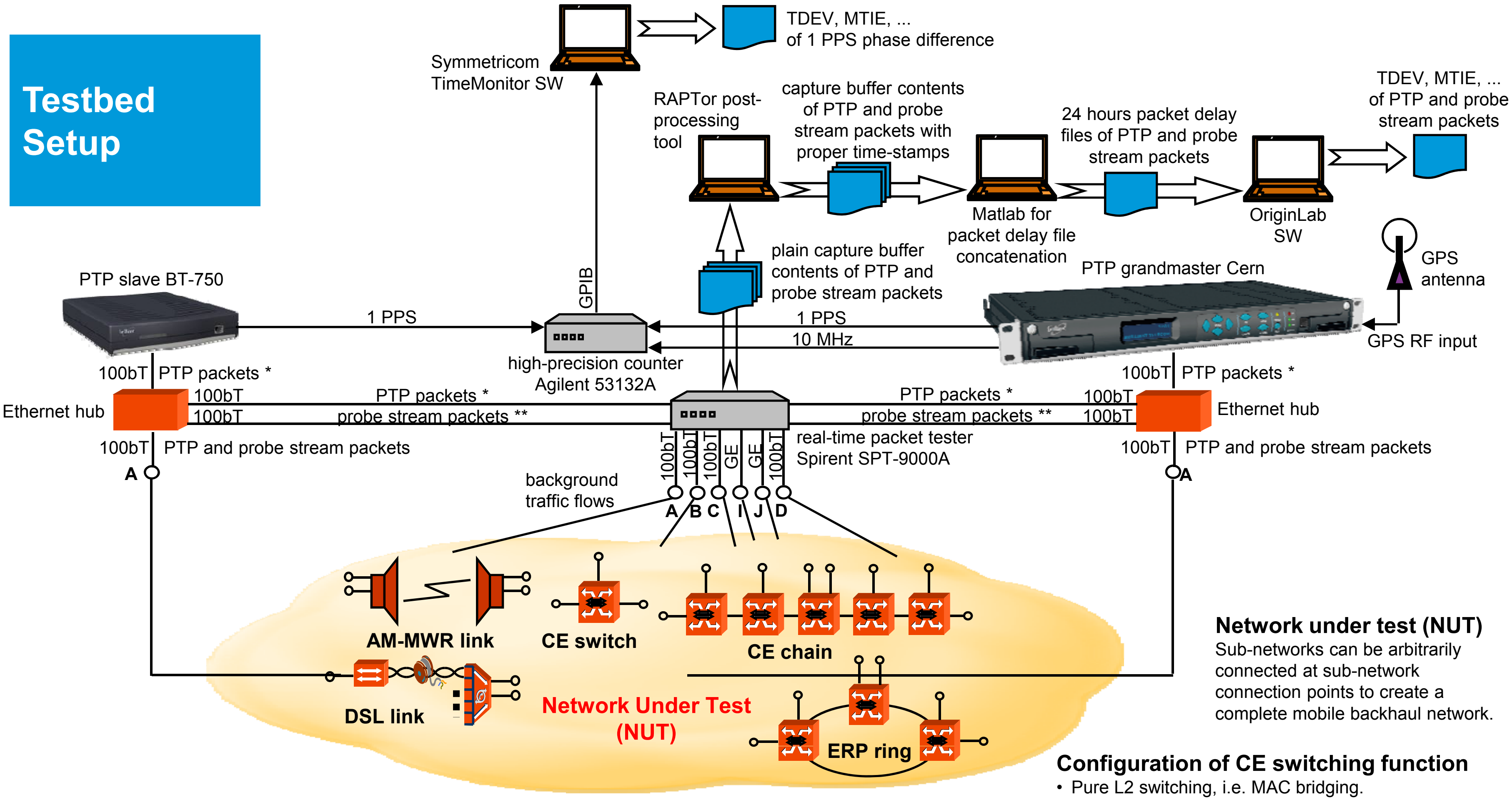
2. Assessment of BTI's IEEE 1588v2 implementation
   - Test BTI IEEE 1588v2 implementation with different traffic load profiles and various access network
   - Carrier Ethernet backbone with following access networks
     - ADSL2+
     - VDSL2
     - SHDSL
     - Adaptive Modulation – Microwave Radio

3. Creation of a network impairment database
   - Collection of delay profiles of packets from probe and PTP streams for each network setup and traffic load
   - Used for analysis of SLA definition (metrics, masks) and
     as an input to network impairment emulator to repeat the tests when no backhaul equipment is available

NSN and Brilliant Telecom Inc. (BTI) lab tests (cont.)

2

Testbed Setup



Network under test (NUT)

Sub-networks can be arbitrarily connected at sub-network connection points to create a complete mobile backhaul network.

Configuration of CE switching function

- Pure L2 switching, i.e. MAC bridging.
- VLAN-based strict priority queuing.
- Policing and shaping disabled on all interfaces.
- No redundancy functions enabled, neither on link nor on module level.

Traffic flows

- PTP packet flow DL = (32 + ~1) pps * 94 * 8 bits per packet
- PTP packet flow UL = ~2 pps * 94 * 8 bits per packet
- Probe stream packet flows = 2 * 100 pps * 94 * 8 bits per packet (1 * EF + 1 * BE)
- Up to 6 interfaces at the Spirent TestCenter SPT-9000A (A, B, C, I, J, D) can be used to generate background traffic flows with well-defined patterns.

* due to hub's broadcast also probe stream packets on this link
** due to hub's broadcast also PTP packets on this link

NSN and Brilliant Telecom Inc. (BTI) lab tests (cont.)

2

Probe Streams and PTP flows

Probe streams	• Probe stream packets at higher packet rate than the PTP sync packets to simulate the ToP behaviour at different PTP sync packet rates • Two streams, best effort (BE) and expedite forwarding (EF) • 100pps, 94 Bytes each (same as PTP packets)
PTP stream	• Best effort (BE) unless specified otherwise • Sync interval 32pps, announce interval 1pps, delay request interval 1 pps

Impairment Flow - Packet size distribution

Random and ITU-T G.8261	• Random: uniform packet sizes from 64 octets to 1518 octets (excluding VLAN tag) • ITU-T G.8261 model 2: 60% of 1518 Bytes, 30% of 64 Bytes, 10% of 576 Bytes

Impairment Flow – Traffic Scenarios*

Constant DL/UL traffic	• 20%, 50%, 80%, 90% and 100% downlink traffic • uplink traffic 25% of downlink traffic (VF PT is experiencing 4:1 DL/UL traffic split)
Ramp traffic with constant DL/UL traffic	• 10% constant traffic. On top every 1 minute 2.5% more up to 75%, then every 1 minute 2.5% less down to 10%. <u>Add traffic both UL and DL (UL = ¼ DL kept constant)</u>
Ramp traffic with variable DL/UL split	• 10% constant traffic. On top every 1 minute 2.5% more up to 75%, then every 1 minute 2.5% less down to 10%. <u>Add traffic only DL</u>
Network overload with constant DL/UL split	• 10% constant traffic. <u>Add 90% of additional traffic (both DL and UL)</u> for 10, 100, and 1000 s

* Due to time constraints only a subset of scenarios are being executed

NSN and Brilliant Telecom Inc. (BTI) lab tests (cont.)

2

Impairment Flow – Traffic Scenarios (cont.)*

Network overload with variable DL/UL split	• 10% constant traffic. Add 90% of additional traffic (only DL) for 10, 100, and 1000 s
Modified ITU-T ramp with constant DL/UL traffic	• Constant traffic at 20% DL and 5% UL for 5 hrs. On top every 3 minutes 1% up to D200% (load that creates 200µs delay shift from initial level). Stay at D200% for 5 hours and then decrease every 3 minutes by 1% down to 20%. Remain at 20% for 6-7hrs to complete 24hrs test (both DL and UL)
ITU-T ramp with variable DL/UL split	• Constant traffic at 20% DL and 5% UL. on top every 12 minutes 1% more up to 80%, then every 12 minutes 1% less down to 20% (only DL)
Network congestion and restoration	• 40% constant traffic. 10 s bursts of 60% (i.e. 100% load) every 100s
Bursty traffic	• 10% constant traffic. Add 5 s bursts of 75% randomly every 2, 5, and 10 s
Network Outage	• Break of network connection for 10, 100, and 1000 s
Routing change	• 10% constant traffic. Activate ERP for 1000 s, then restore
On/Off traffic	• 10% constant traffic. Add_on top 1 hour bursts of 75% every 2 hours
Susceptibility and Immunity tests	• Degrade the recorded PDV profile (using ANUE network emulator or similar) and see when the IEEE 1588v2 slave clock breaches the target synchronization masks

* Due to time constraints only a subset of scenarios are being executed

NSN and Brilliant Telecom Inc. (BTI) lab tests (cont.)

2

Theoretical results

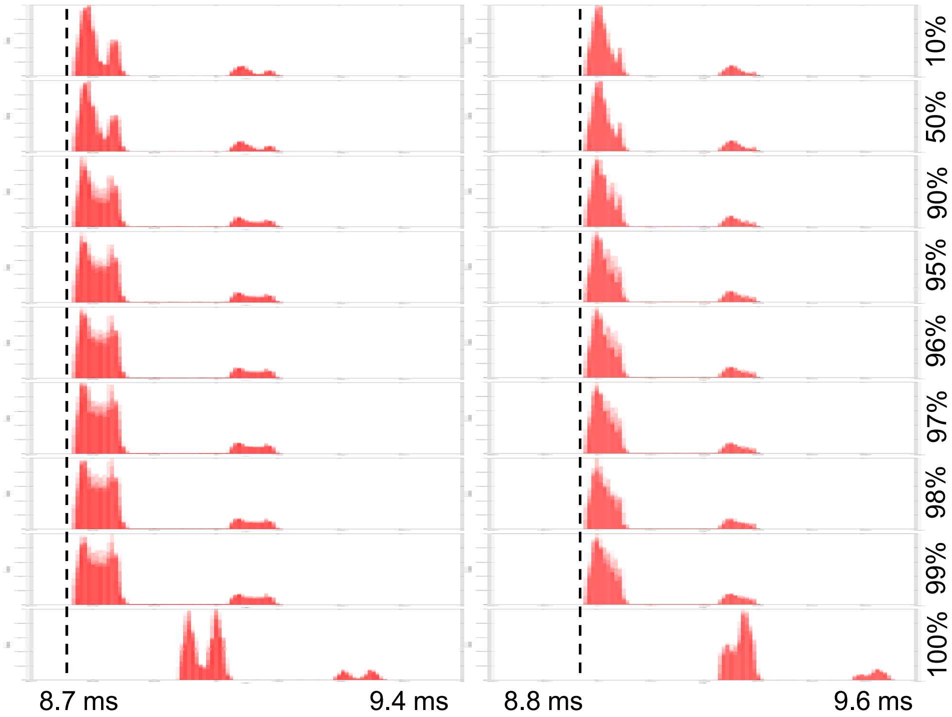
Determining optimal packet rate, percentile, and averaging window length

- The three parameters were varied and the estimated performance compared by means of fixed-averaging-window percentile TDEV and MDEV (modified Allan deviation).
- The performance was analyzed also using packet MTIE. Further, the work contributed to the creation of MAFE (maximum average frequency error), recently proposed in an ITU Q13/SG15 meeting to be included in G.8261.

Measurement results – VDSL2 as access network – single stream with evenly spaced packets

downstream, 94 octet packets, no x-talk (53,652 kbit/s)

downstream, 94 octet packets, 23 self-next VDSL2 + 24 distant ADSL2+ (27,116 kbit/s)



Key findings

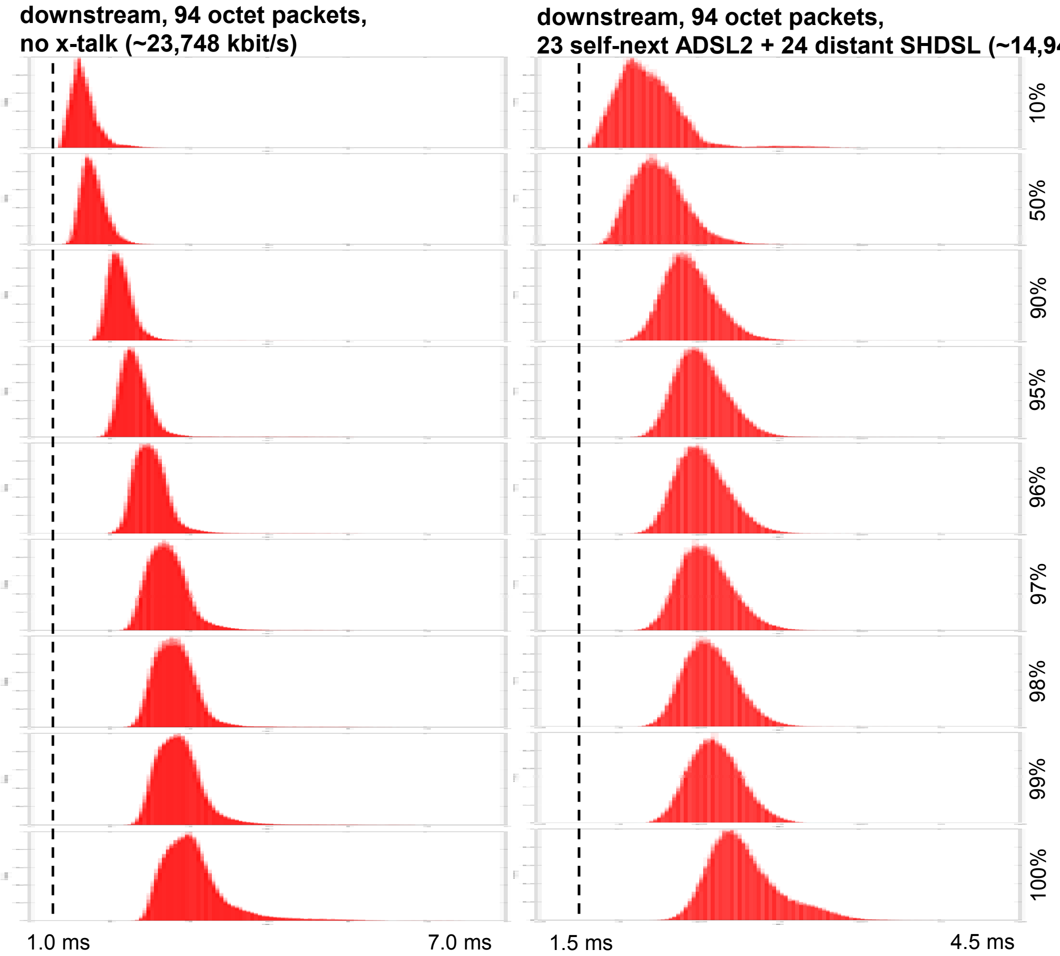
- Delay PDF shape remains quite the same up to 99% traffic load. At 100% it is simply delayed
- The maximum variance of PTD 1% over all measurements is 6 μs
- Higher overall delay with x-talk is due to higher transmission delay at lower data rate

- PTD 1% of VDSL2 without seamless rate adaptation will not be an issue for PTP

NSN and Brilliant Telecom Inc. (BTI) lab tests (cont.)

2

Measurement results – ADSL2+ as access network – single stream with evenly spaced packets



Key findings

- Delay PDF shape remains quite the same up to 100% traffic load with slight widening with increasing load
- Higher overall delay with x-talk is due to higher transmission delay at lower data rate
- Even at data rates clearly below 100% PTD 1% varies considerably
- The maximum variance of PTD 1% over all measurements is at about 1 ms

- PTD 1% of ADSL2+ may become a severe issue for PTP
    - Tests with actual network configurations must be carried out before deployment

NSN and Brilliant Telecom Inc. (BTI) lab tests (cont.)

2

Measurement results – Accuracy of network emulator

Understand the accuracy of network emulators vs real network…

downlink	NUT	Anue	delta	uplink	NUT	Anue	delta
PTD min. [ms]	9.923	9.928	0.005	PTD min. [ms]	11.802	11.808	0.006
PTD avg. [ms]	10.394	10.399	0.005	PTD avg. [ms]	12.859	12.864	0.005
PTD med. [ms]	10.385	10.391	0.005	PTD med. [ms]	12.877	12.881	0.004
PTD 1% [ms]	10.092	10.097	0.005	PTD 1% [ms]	12.014	12.020	0.006
PTD 95% [ms]	10.639	10.645	0.005	PTD 95% [ms]	13.444	13.447	0.003
PTD 99% [ms]	10.754	10.762	0.007	PTD 99% [ms]	13.631	13.637	0.006
PTD 99.99 % [ms]	11.045	11.050	0.005	PTD 99.99 % [ms]	13.819	13.826	0.007
PTD max. [ms]	11.096	11.100	0.005	PTD max. [ms]	13.819	13.826	0.007

Key findings and conclusions

- PTD values over Anue network impairment emulator only slightly higher (3 ... 7 μs) than over real backhaul network

➢ **Anue network impairment emulator can most likely be used as "Network Under Test" in many timing-over-packet applications**

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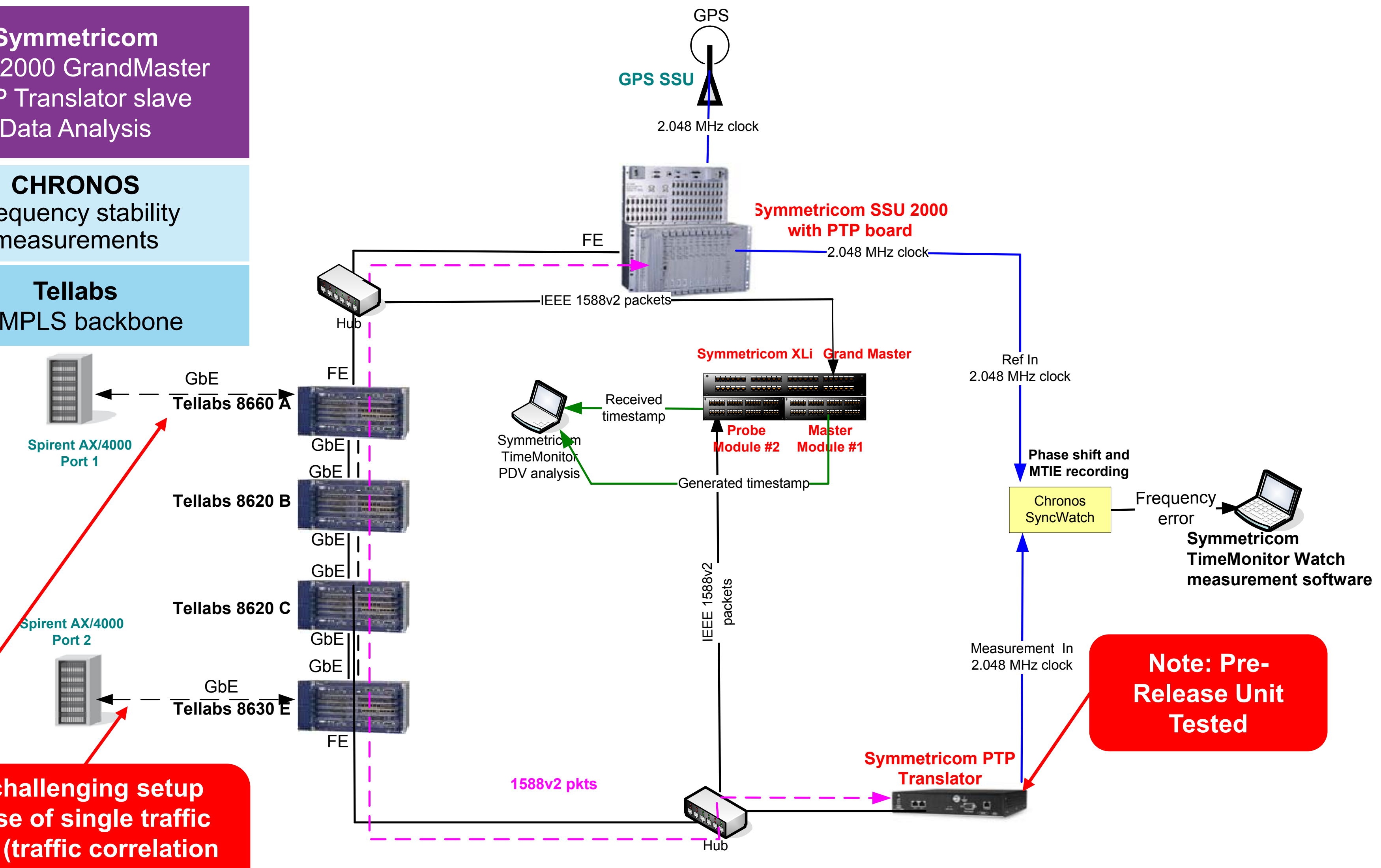
Symmetricom PTP translator lab tests

3

Symmetricom
SSU 2000 GrandMaster
PTP Translator slave
Data Analysis

CHRONOS
Frequency stability
measurements

Tellabs
IP/MPLS backbone



Note: Pre-Release Unit Tested

Very challenging setup because of single traffic source (traffic correlation across all nodes)

Symmetricom PTP translator lab tests (cont.)

3

Quiet network conditions

Long term stability tests	• No additional traffic on GbE link

Challenging network conditions

Different Levels of Constant Traffic	• Constant traffic on GbE link 50%, 60%, 70%, 80%, 90% and 100% of network capacity
Bursty Traffic	• Constant traffic on GbE link at 10% and on top add bursts of traffic at 75% ,65%, 55% and 45% of network capacity for periods of 5 seconds. The time between consecutive heavy bursts will be set at 2, 5 and 10 seconds randomly. (Outcome: 45% burst below sync mask others marginally above)
On/Off Traffic	• Constant traffic on GbE link at 10% and on top add bursts of traffic at 75% (and 65% and 55%) of network capacity for one hour, then 0% for the next hour, then 75% (and 65% and 55%) again for next hour, and so on… (Outcome: 55% burst below sync mask others marginally above)
Ramp Traffic	• Constant traffic on GbE link at 10% and on top add 75% of traffic in 2.5% increments every 1 minute. Once reached the 85% mark, start decreasing the traffic by 2.5% decrement (again every 1 minute)
Network Overload	• Constant traffic on GbE link at 10% and on top add 90% of network capacity (in addition to the 10% of constant traffic) for periods of 10, 100 and 1000 seconds
Routing Change	• Routing change and software switchover (no traffic load)
Network Outages	• Break the network connection for various periods of time (e.g. 10, 100 and 1000 seconds) and restore. Observe accuracy during holdover

Symmetricom PTP translator lab tests (cont.)

3

G.8261 challenging network conditions

G.8261 ramp	• Constant traffic on GbE link at 20% of network capacity and on top add 60% of traffic in 1% increments every 12 minutes. Once reached the 80% mark (i.e. after 12 hours), start decreasing the traffic by 1% decrement (again every 12 minute)
G.8261 congestion and restoration	• Constant load 40% of GbE link. After a stabilization period, increase network disturbance load to 100% for 10s, then restore. Repeat with a congestion period of 100s. (Outcome: PTP translator met sync mask requirement but indicated a bridging state condition)

Extra tests replicating typical conditions and link failures

40% step changes between 20% and 60%	• Constant traffic on GbE link of 20% and on top add 40% step changes with 100s duration every 100 seconds
20% bursty traffic between 50% and 70%	• Constant traffic on GbE link at 50% and on top add bursts of traffic of 20% for random durations of 2, 5 and 10 seconds
Random step changes between 50% - 70% levels	• Traffic varying randomly between 50% and 70% with step changes every minute of 2.5%

Excellent performance with "typical" network conditions (below G.823 sync mask)

Some refinements needed to improve behaviour with unexpected dramatic load change scenarios – even though traffic mask was met for all cases. The 15ppb mask was met except in one overload recovery case

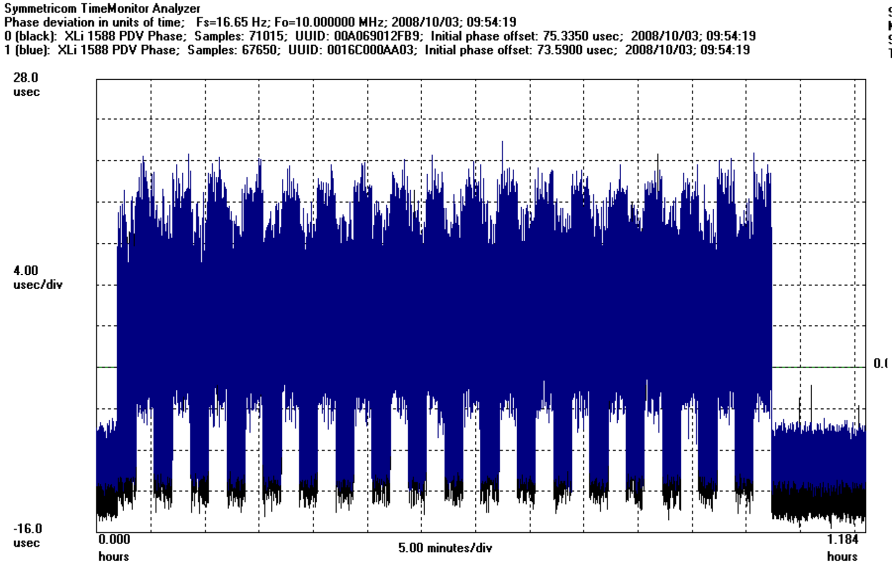
Symmetricom PTP translator lab tests (cont.)

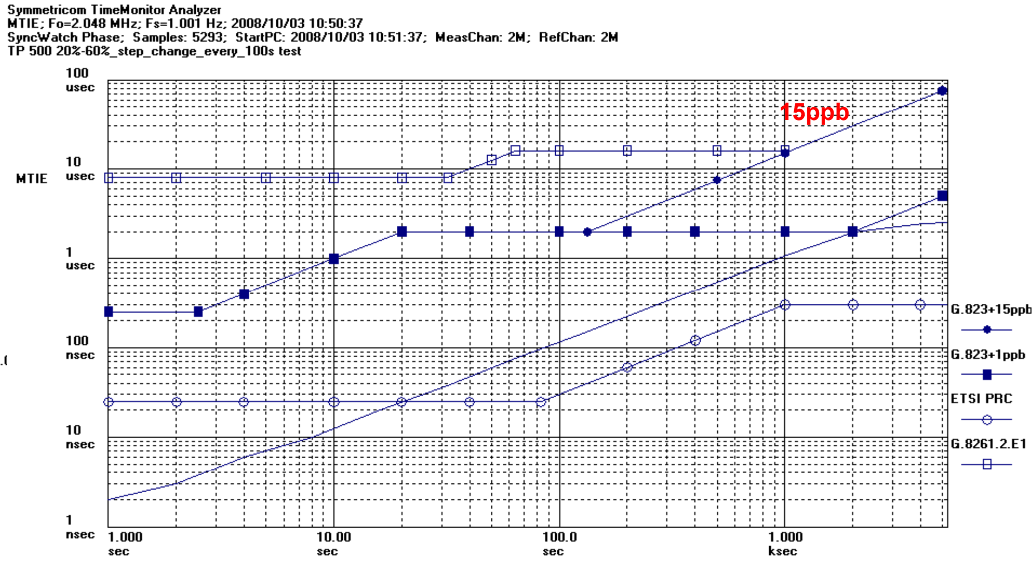
3

40% step changes between 20% and 60%

- Constant traffic on GbE link of 20% and on top add 40% step changes with 100s duration every 100 seconds

PDV	MTIE
• Black: Master -> Slave (36.25us) • Blue: Slave -> Master (34.38us)	• 2.56us (well below 15 ppb mask)





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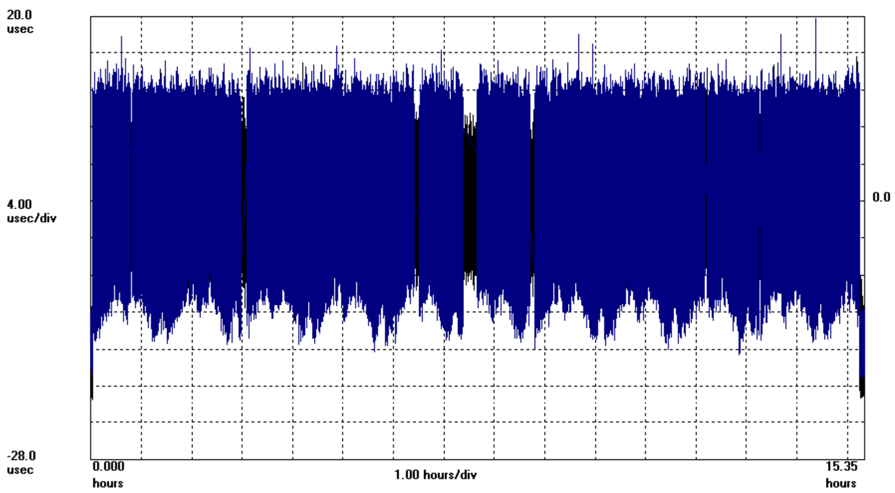
Symmetricom PTP translator lab tests (cont.)

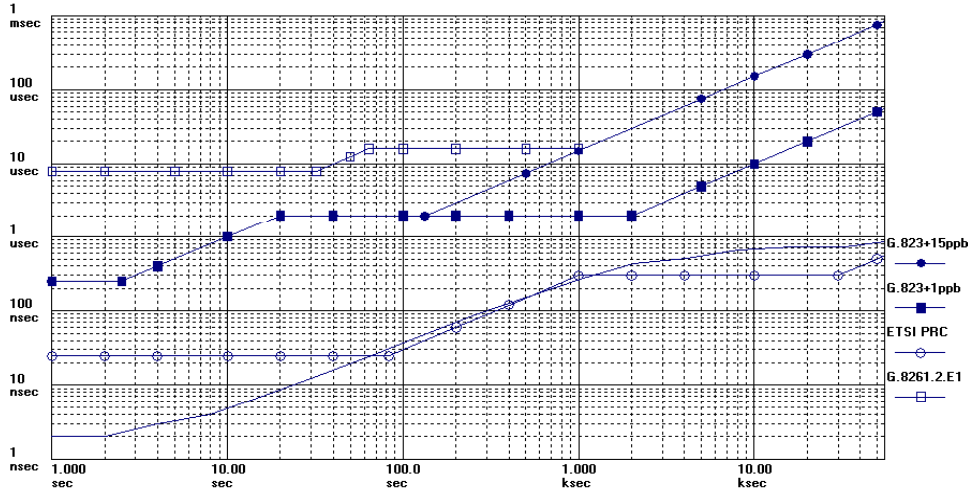
3

Random step changes between 50% - 70%

- Traffic varying randomly between 50% and 70% with step changes every minute of 2.5%

PDV	MTIE
• Black: Master -> Slave (37.00 us) • Blue: Slave -> Master (38.8 us)	• 0.854 us (well below sync mask)





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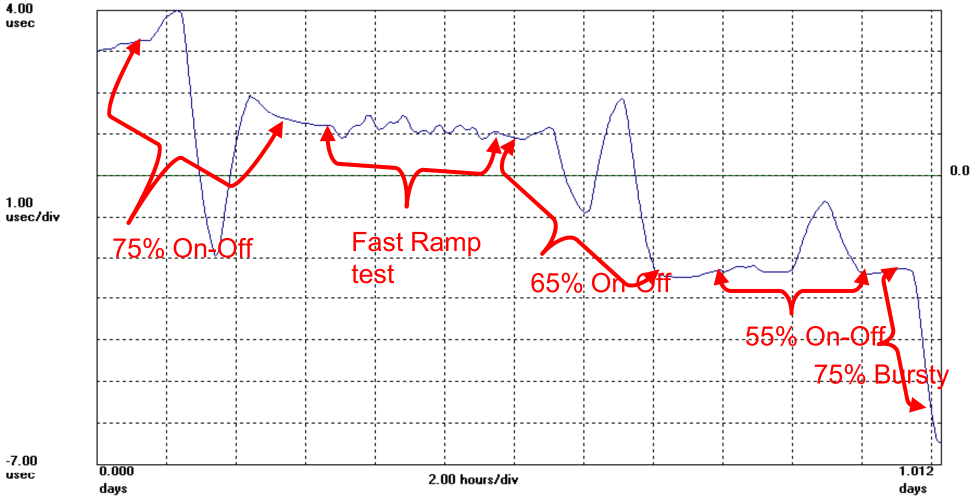
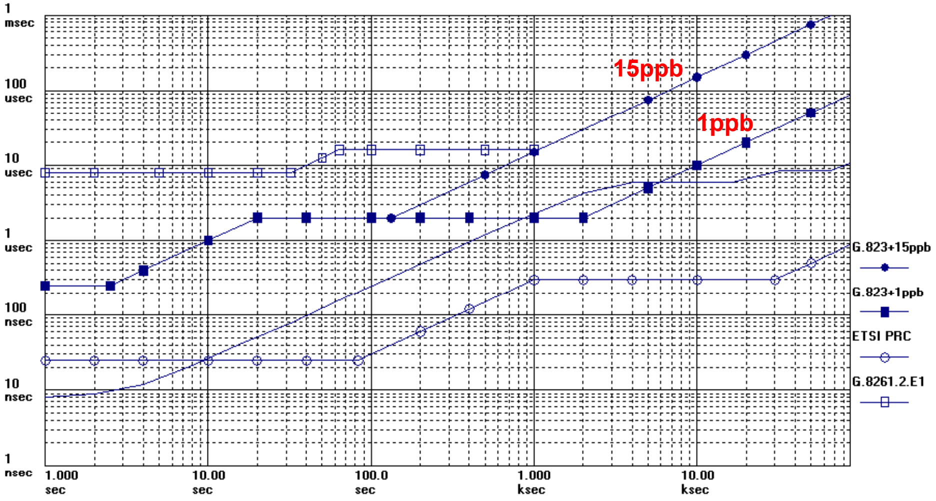
Symmetricom PTP translator lab tests (cont.)

3

24 hrs of consecutive challenging conditions (75% On/Off, Fast Ramp test, 65% On/Off, 55% On/Off, 75% Bursty)

TIE	MTIE
• Overall offset over 24hrs = 10.5us	• 10.5us over 24 hrs (0.12 ppb - well below 15 ppb mask)





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IEEE 1588v2 roll-out in VF Portugal

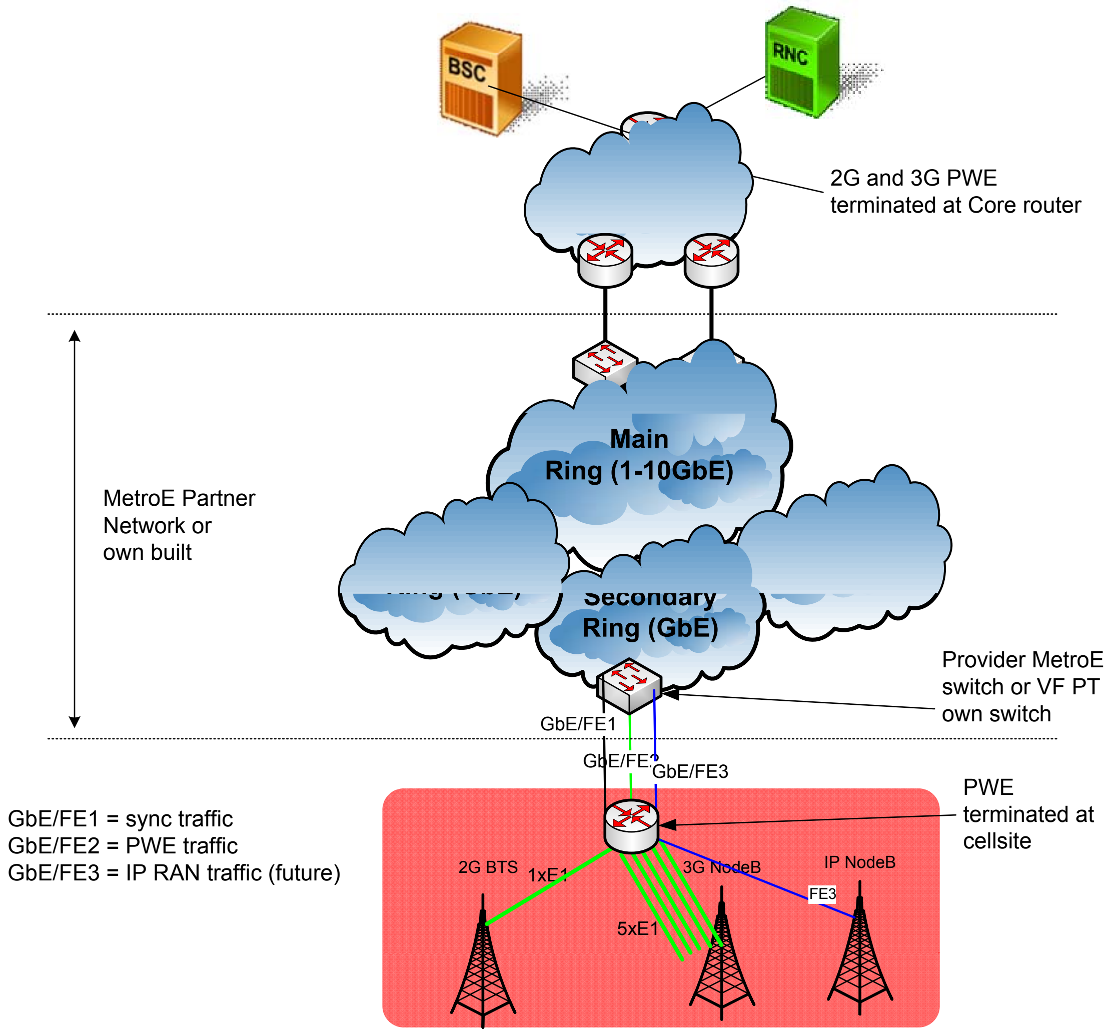
VF PT started the MetroEthernet project beginning of 2008 for mobile backhaul…

VF PT own MetroEthernet (VF PT fibre and switches)	**Leased MetroEthernet Service** (L2 capacity provided by Colt, PT, etc.)
↑ Future proof - fibre infrastructure re-usable for Ethernet services to corporate, fibre in the access (FTTx as post DSL), etc.	↑ More cost effective alternative to leased lines (E1s)
↑ Low OPEX	↑ Fast Rollout (if fibre partner has a good footprint) and low CAPEX
↓ CAPEX intensive	↓ OPEX intensive
↓ Possibly slower roll-out than leased managed services due to fibre/duct availability	↓ Harder to customise for Ethernet services to corporate, no residential FTTx

Both options require synchronization at cell site!

IEEE 1588v2 roll-out in VF Portugal - Architecture

VF PT MetroEthernet architecture similar for both options



- PWE3 (Pseudo Wire Emulation End-to-End) used to transport legacy over MetroE (2G+3G voice and data)
- Primary rings connected to VF PT core nodes
- Secondary rings connected to primary rings
- Switches at secondary rings providing FE ports to each cellsite (GbE future)
- VLANs provisioned
  - Sync traffic
  - PWE traffic
  - IP RAN traffic (future)

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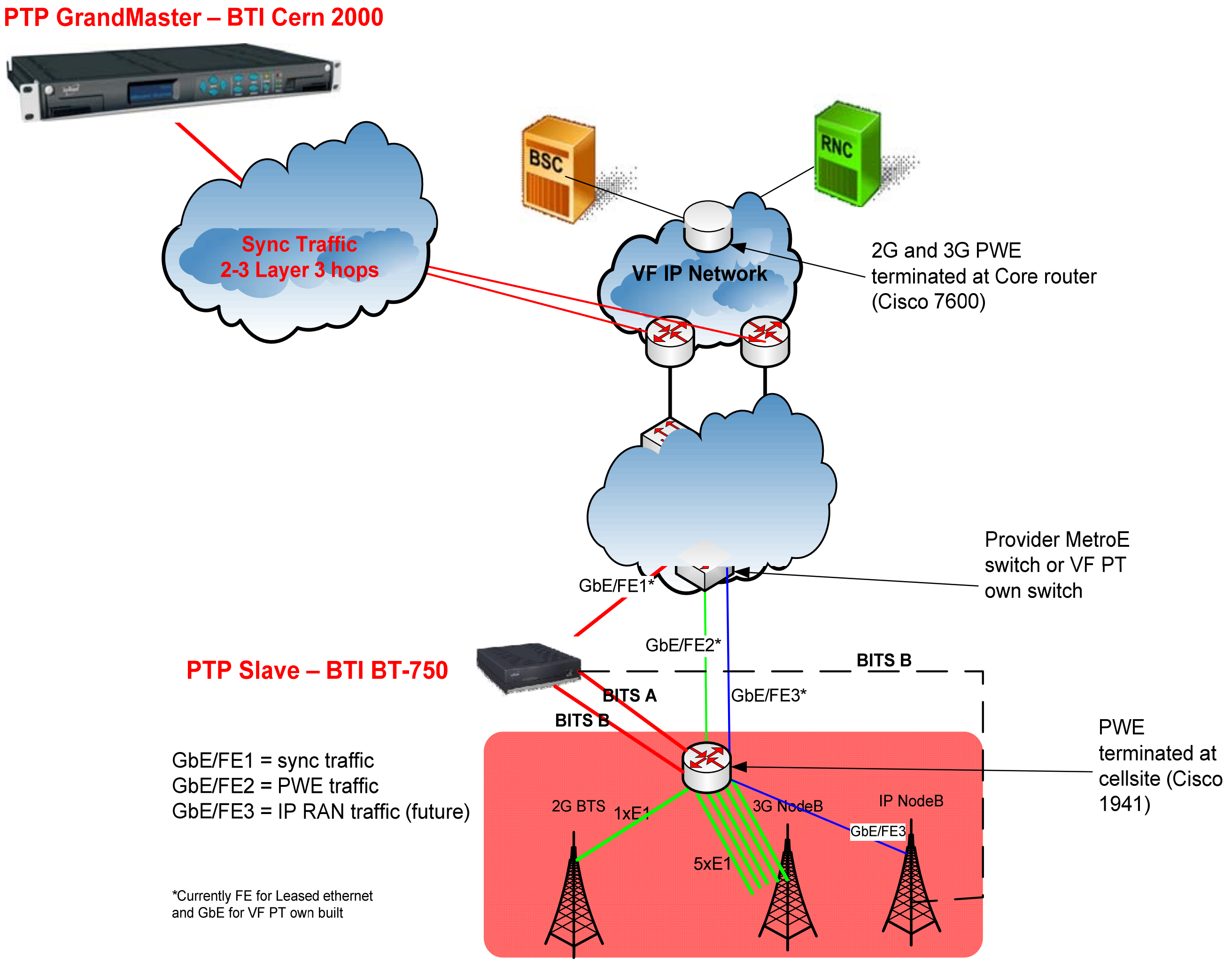
IEEE 1588v2 roll-out in VF Portugal – Sync solution

IEEE 1588v2 only applicable solution given the 'Plain Ethernet' connectivity



- PTP solution end to end
- IP network with 2-3 hops connecting Grandmaster (BTI Cern 2000) to MetroE
- PTP traffic on MetroE is switched (L2). 7-8 hops max
- L2 and L3 QoS enabled
- At provider metroE switch, the port of PTP traffic is connected to PTP slave (BT 750)
- PTP slave provides BITS interfaces for cellsite router (Cisco 1941)
  - Both BITS A and B used for redundancy
- Two ways to synchronize future IP RAN NodeB
  - One E1 from Cisco 1941
  - Splitting solutions of BITS interface

IEEE 1588v2 roll-out in VF Portugal – Sync solution (cont.)

Pros and Cons of a Standalone PTP solution

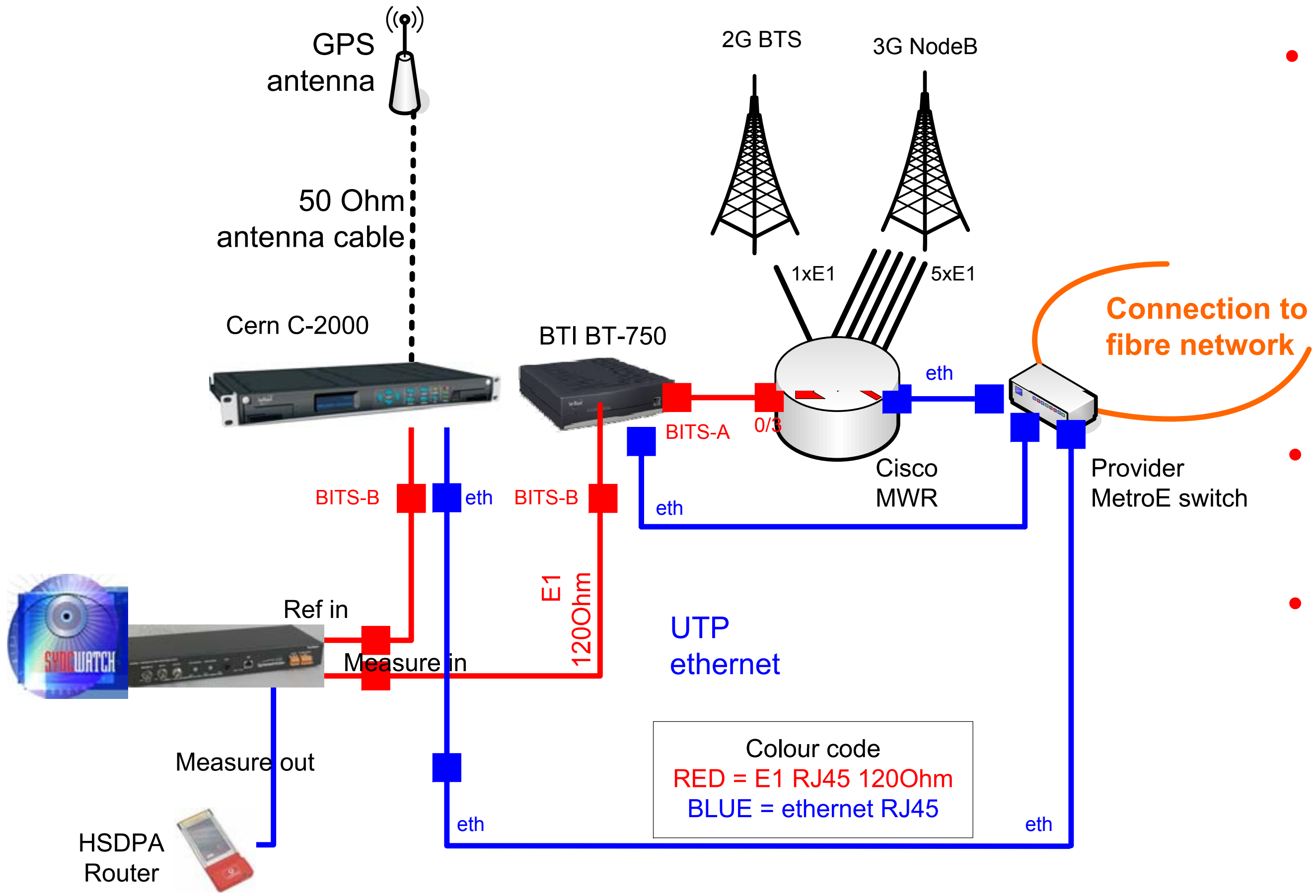
Pros	Cons
• Independent from RAN and PWE vendor • Can synchronize existing and future base stations • Direct engagement operator-sync vendor for product specifications and customization • Independent software upgrades • Easier alarm management and troubleshooting	• Additional vendor to manage besides cellsite router vendor • Additional box to integrate into operator's network • Separate box introduces additional point of failure

IEEE 1588v2 standalone slave excellent solution

Long term solution could be integrated boards and chipsets – VF PT deployment will indicate the preferred option from an operational perspective

IEEE 1588v2 roll-out in VF Portugal – Sync monitoring

Chronos/Symmetricom TimeWatch probe to measure accuracy of PTP at cellsites

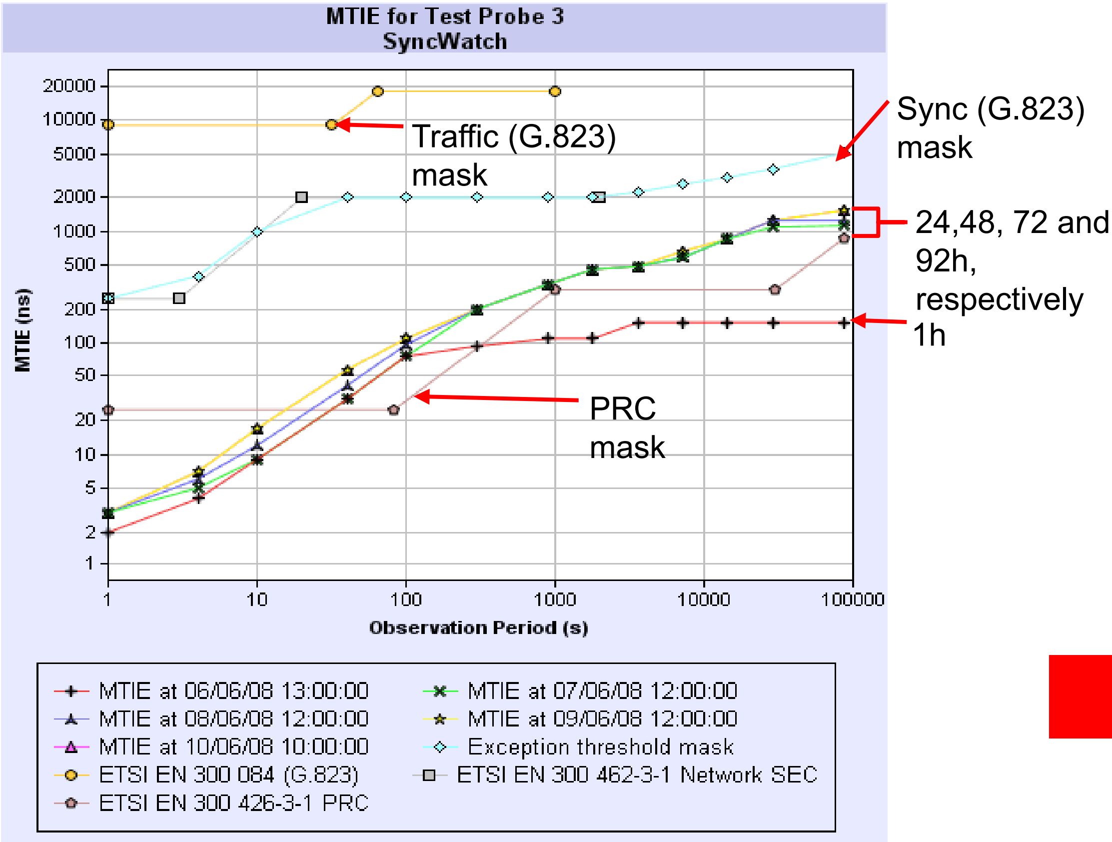


- TimeWatch essential to ascertain the accuracy of sync solution in the initial deployment stage

- TimeWatch probe at the most ‘challenging’ sites
- PDV monitoring (with multiple metrics) essential in every site to estimate clock performance and ‘anticipate’ potential problems

IEEE 1588v2 roll-out in VF Portugal – PTP Performance

Good performance observed so far…



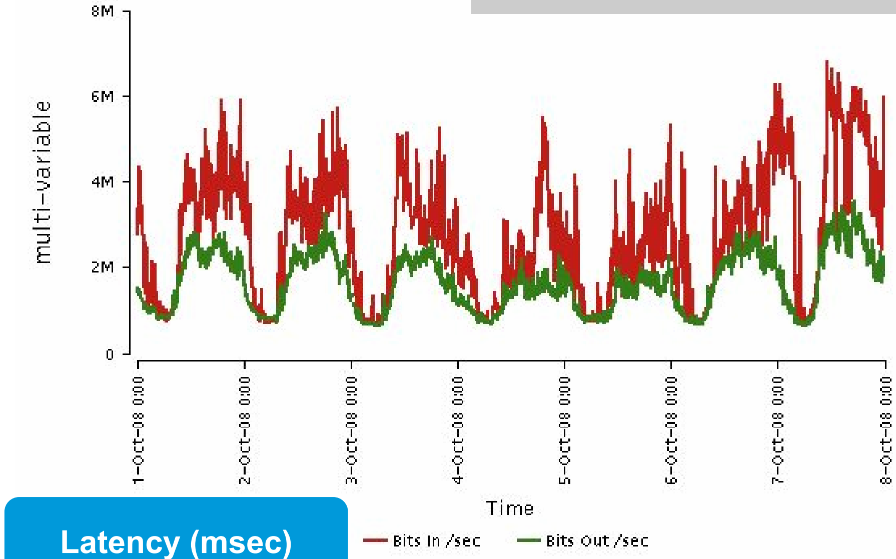
- Accuracy at the cellsite monitored by TimeWatch always better than 1ppb

Live Demo!

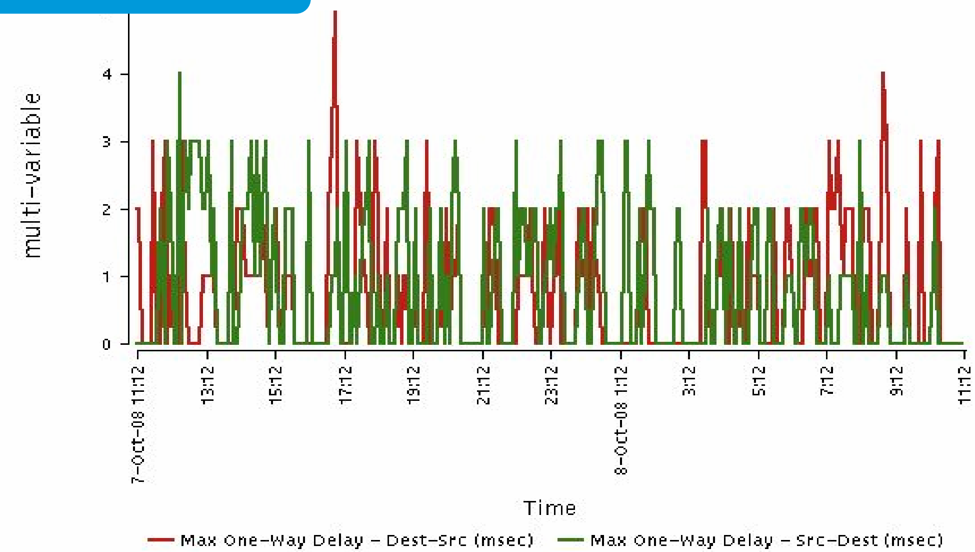
IEEE 1588v2 roll-out in VF Portugal – PTP Performance (cont.)

Throughput (Mbps)

Traffic for the entire cell site
Bits In = Downlink
Bits Out = Uplink



Latency (msec)



- First cellsite went live 4th June 2008
- Currently around 100 sites being served by metroE (mix of leased and own metro)
  - Plan to reach 250 by FY 2008/09 (March 2009)
- Traffic per site averaging around 2Mbps, with peaks of 5-6Mbps
  - Will increase with HSDPA 7.2Mbps roll-out
- Latency in the region of 1-4 ms

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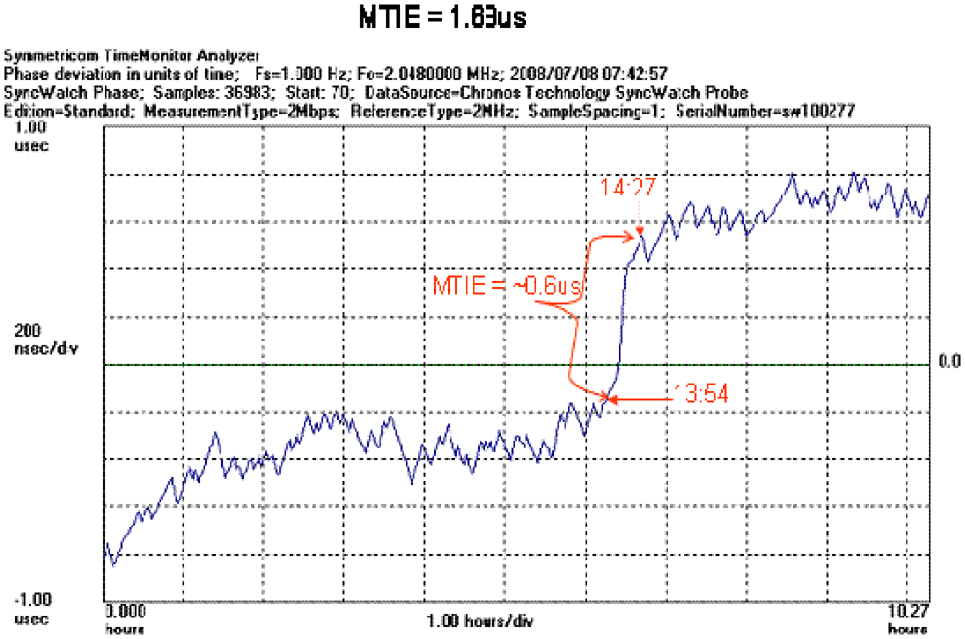
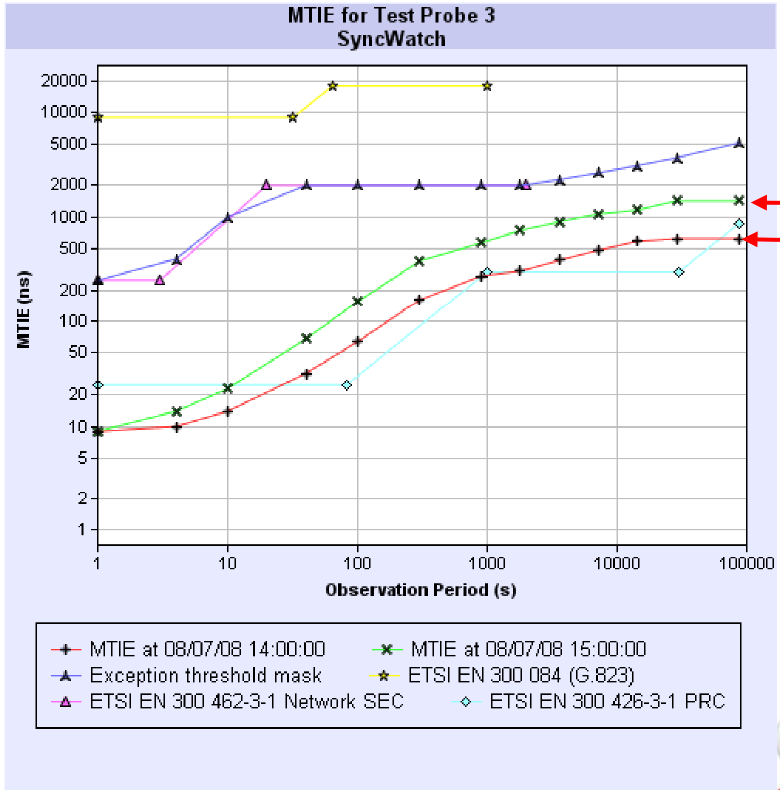
IEEE 1588v2 roll-out in VF Portugal – PTP Performance (cont.)

Fibre cut event had a minor impact on PTP performance…

- Break in fibre ring in Lisbon occurred on 07/07/2008 around 13:53 -> protection mechanisms kicked in as expected
- BTI slave went into holdover for around 3m 15sec. After moving to ACQUIRING mode it took around 9 minutes to move back to LOCK mode
- PDV variation caused by new path has a slight impact on PTP performance (less than 1µs)
  - Overall accuracy kept well below G.823 sync mask





IEEE 1588v2 roll-out in VF Portugal – Conclusions

Before live roll-out…

Close collaboration with PTP vendor to produce a PTP-based SOLUTION (features, operational, support, management, etc. aspects)

Lab tests with actual network configuration and challenging network loads necessary for protocol tuning/optimization and ascertain performance

Experience from live roll-out…

Operational and dimensioning aspects are critical (master redundancy with BMC is essential, number of slaves per master, 1588v2 domain boundaries, alarm management, etc.)

Even with reasonably high loads, PTP has NO major issues with MetroEthernet environments (no pressing requirements for boundary/transparent clocks)

Despite the work necessary before roll-out, end-to-end PTP solution is much less expensive then hybrid approach (Ethernet for traffic and SDH/PDH for sync)

Other PTP deployments…

As shown by VF tests in NSN lab, deployments over xDSL access networks (and possibly over AM-MWR) will require additional tests and protocol tuning

It is important the vendors and operators community share experience to create 'deployment guidelines' (PTP profiles + PDV database for PTP algorithm tuning)

Ensuring synchronisation for the next generation of VF cellular IP backhaul

CONTENTS

1. VF backhaul evolution towards Ethernet and sync strategy
2. IEEE 1588v2 performance assessment
3. IEEE 1588v2 roll-out in Portugal
4. Conclusions

Final thoughts - Take away points

1

IEEE 1588v2 confidence boost given by Vodafone Portugal rollout

- Pre-deployment lab tests still required ahead of deployment for tuning purposes given the non-deterministic nature of packet-based solutions
- Planning challenges of IEEE 1588v2 are rewarded by a simpler solution compared to a hybrid network

2

Avoid IEEE 1588v2 market fragmentation

- Considerable effort and time to develop a robust solution -> telecom vendors should liaise with sync vendors rather than trying in-house solutions
- Vodafone intends to work closely with all major sync vendors

3

Continue Standardization work – profile definition a top priority

- Sync requirements for specific applications/networks
- Transport network requirements (size, max number of L2 and L3 hops, load, load variation, etc.)
- IEEE 1588v2 network dimensioning (boundaries of 1588v2 domains, slaves supported by a grandmaster, boundary clocks, transparent clocks, Sync E interworking, etc.)

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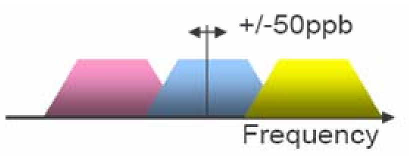
Synchronization requirements for cellular networks

Frequency Sync

Reduce Handover Failures
Drive oscillators in the base station to produce accurate frequency signal over air interface (FDD systems)

FDD



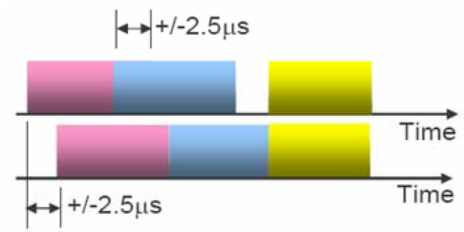
Requirements

- **3G FDD, GSM, LTE-FDD**
  - **+/- 50 ppb** (macro cells)
  - **+/- 100-250 ppb** (pico/femto)
- **DVB -H/-T**
  - **+/- 5 ppb** @ 706MHz (TBD)

Phase Sync

Increase System Efficiency
Frame alignment to minimize timeslot interference (reduce guard interval) in adjacent base stations (TDD systems)

TDD



Requirements

- WCDMA **TDD** systems
  - **+/-2.5 μs** (micro second) between base stations is required **(+/- 1.25 μs between ref and BTS)**
  - CDMA 2000: +/-3 μs time alignment
- Mobile WiMAX
  - **< +/-1.4 μs** (**+/- 1.0 μs for some WiMAX profiles**)
- LTE TDD
  - **~ +/-1.4 μs** (TBD)
- DVB -H/-T
  - **~ +/-5 μs** (1/20 of guard band is +/-7.5 μs)

Frequency Sync for Real Time Applications

Guarantee good user experience
Avoid pixellation, waves, video freeze, etc.

Requirements

- Voice – 32 ppm
- Two way video – 50ppb
- HDTV – 100 ppb