OPNT
Optical Positioning, Navigation and Timing

Feasibility of a Nationwide Fiber-Optic Sub-Nanosecond Timing Infrastructure for Terrestrial PNT and GPS Backup Systems

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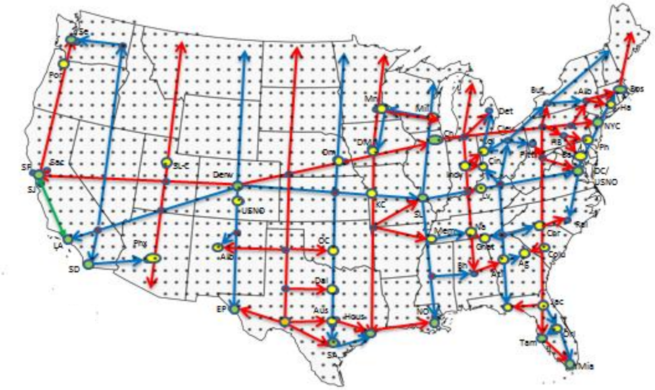
Also affiliated with VU University Amsterdam

opnt. TIME PROVISIONING

Outline

- PNT wishlist - space-based PNT with terrestrial back-up/augmentation
- The (sub)nanosecond time synchronization problem in wide-area telecom networks, and how to overcome it
- Possible terrestrial PNT back-up/augmentation solutions
  - Sparse grid (CONUS)
  - Dense grid (CONUS)



- Outlook

Space-based PNT: GPS

- Building GPS and keeping it operational with such excellent up-time statistics is an amazing and outstanding feat!

- GPS has become the cornerstone of an increasing number of technologies, including critical infrastructure (mobile telecom, electrical power, finance, transportation and aviation, military)

- Looking toward the future, better/more reliable PNT solution is required (in some cases even by law), to overcome
  - Threats of jamming/spoofing/meaconing
  - Extreme space weather conditions
  - Limited coverage and accuracy in urban environments and indoors

PNT performance wish list

Wish-list item	Target performance	Current bottleneck	Solution (Dr. Koelemeij's two cents)
GPS timing backup	<10 ns	Lack of alternative wide-area ns-level timing technology*	Space + Terrestrial
GPS positioning backup	<10 m	Lack of wide-area alternative with fully GPS-equivalent performance	Space + Terrestrial
Improved positioning accuracy & coverage	<0.1 m (urban areas, indoor environments)	▪ Clock accuracy ▪ Multipath	▪ Space + Terrestrial ▪ Terrestrial
Improved time accuracy	<0.1 ns (to support TOA ranging at 0.1 m)	▪ Clock accuracy ▪ Multipath	▪ Space + Terrestrial ▪ Terrestrial

*Note that the accuracy of current network time protocols (NTP - milliseconds, PTP/IEEE1588 - microseconds) is insufficient to provide GPS-independent time

Terrestrial PNT requires a time base with (nation)wide coverage...

- For several PNT back-up and augmentation approaches, a terrestrial system seems the way to go

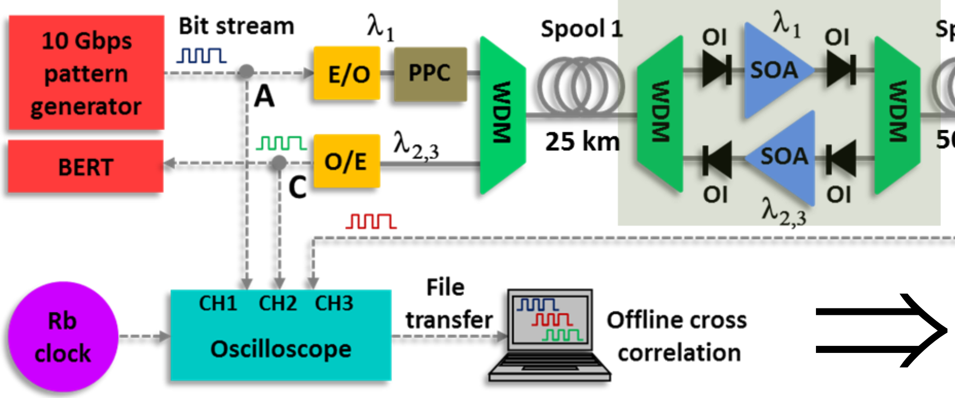
- But any terrestrial PNT system (beacons on Earth) has coverage challenges
  - GPS space vehicle at 20,000 km can cover entire continent
  - Beacon/pseudolite at 600 m tower, distance to horizon: 87 km (54 mi)
  - Would require ~1500 pseudolites to cover CONUS

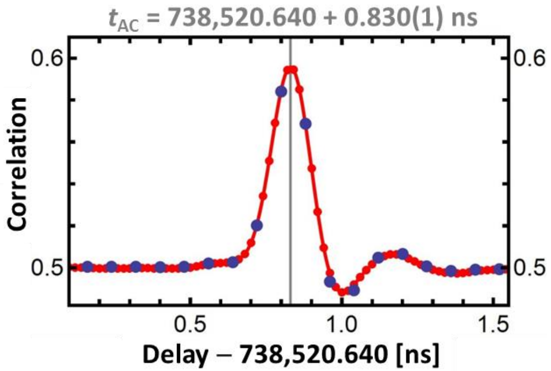
- Literally copying "GPS on Earth" would require:
  - About 1500 atomic clocks ($100MM+)
  - Keeping all clocks in sync (<10 ns) essentially independently of GPS (TWSTFT, other, $$$, recurring)

- **Alternate solution: accurate and continuous clock synchronization through telecom optical fiber, replacing atomic clocks with low-cost oscillators (i.e. new network time protocols beyond GPS)**

Fiber-optic time & frequency transfer

- Over the past decade, scientific research has produced new methods to distribute time and frequency with high accuracy over long distances (>1000 km) through telecom optical fiber*
- Our research: **maximize compatibility with existing fiber-optic network infrastructure**
- Example: two-way exchange and cross correlation of 10 Gbps optical data streams over 75 km**



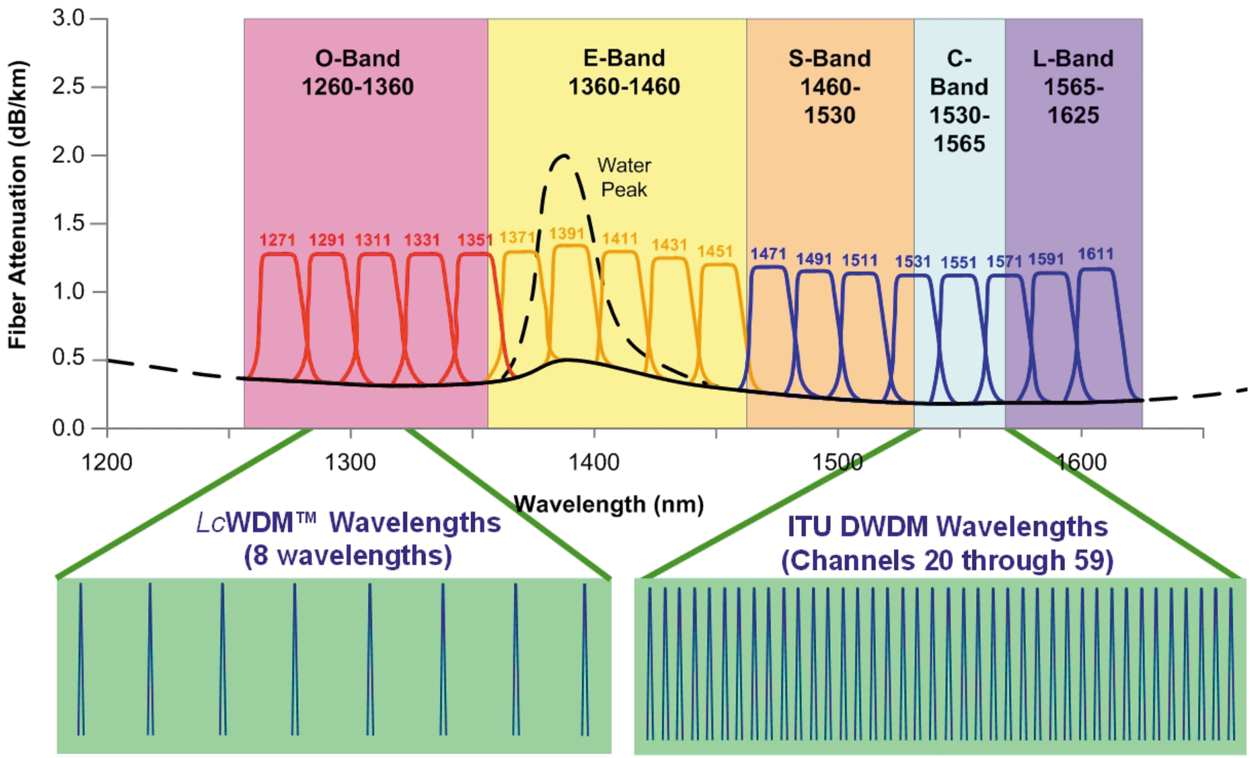


150 km round-trip delay A→C :
1 ps precision

75 km one-way delay A→B :
4 ps uncertainty

* Dozen groups in US, EU, Japan, Australia, China, incl. NIST/JILA, USNO
Sotiropoulos *et al.*, Optics Express **21, 32643 (2013)

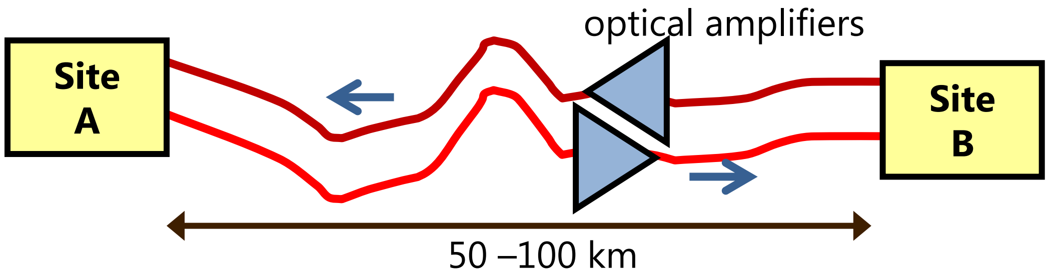
Compatibility with telecom networks: WDM



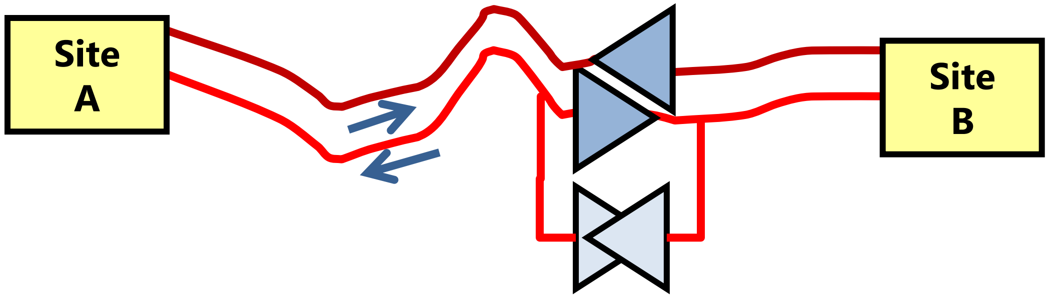
- Wavelength Division Multiplexing (WDM): allows simultanoues transmission of many wavelengths, each carrying its own data
- Can use WDM to transmit “time and frequency wavelengths” along with regular data traffic
- Time & frequency signals don’t require much spectrum
  - Less than 1% of total capacity
  - Fibers always have more than 1% capacity available

Uncalibrated delays and time errors

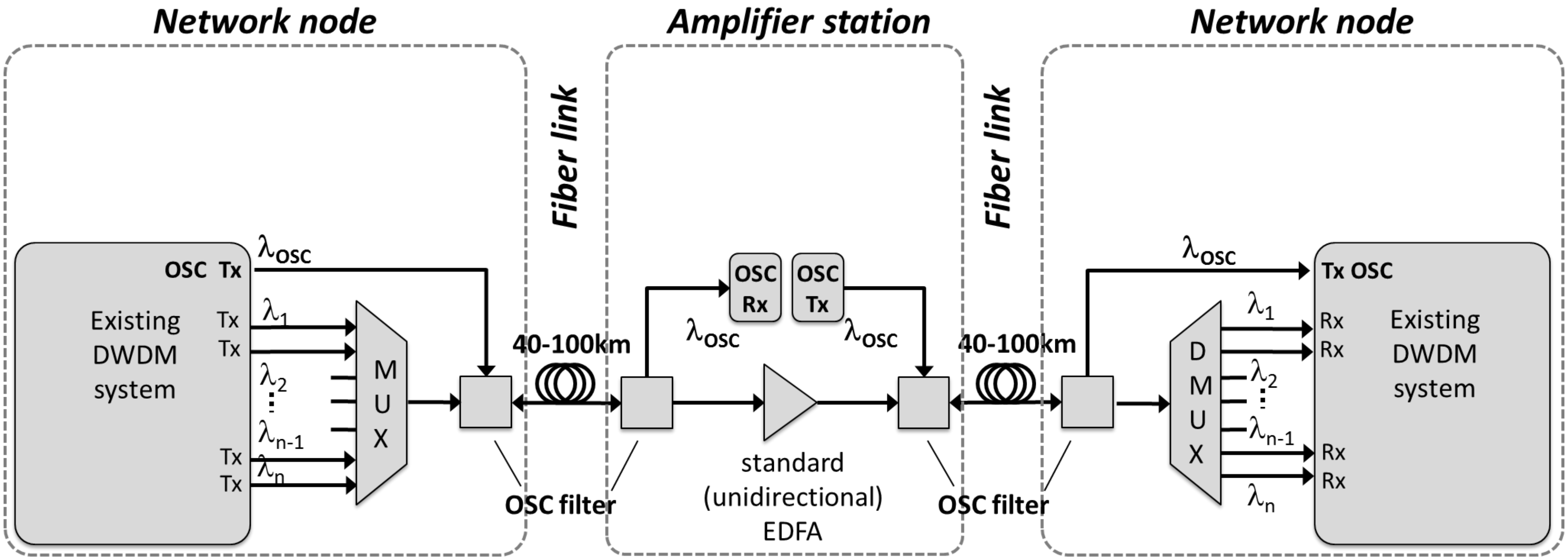
- Fiber-optic communication usually occurs over fiber pairs (but can measure round-trip delay)



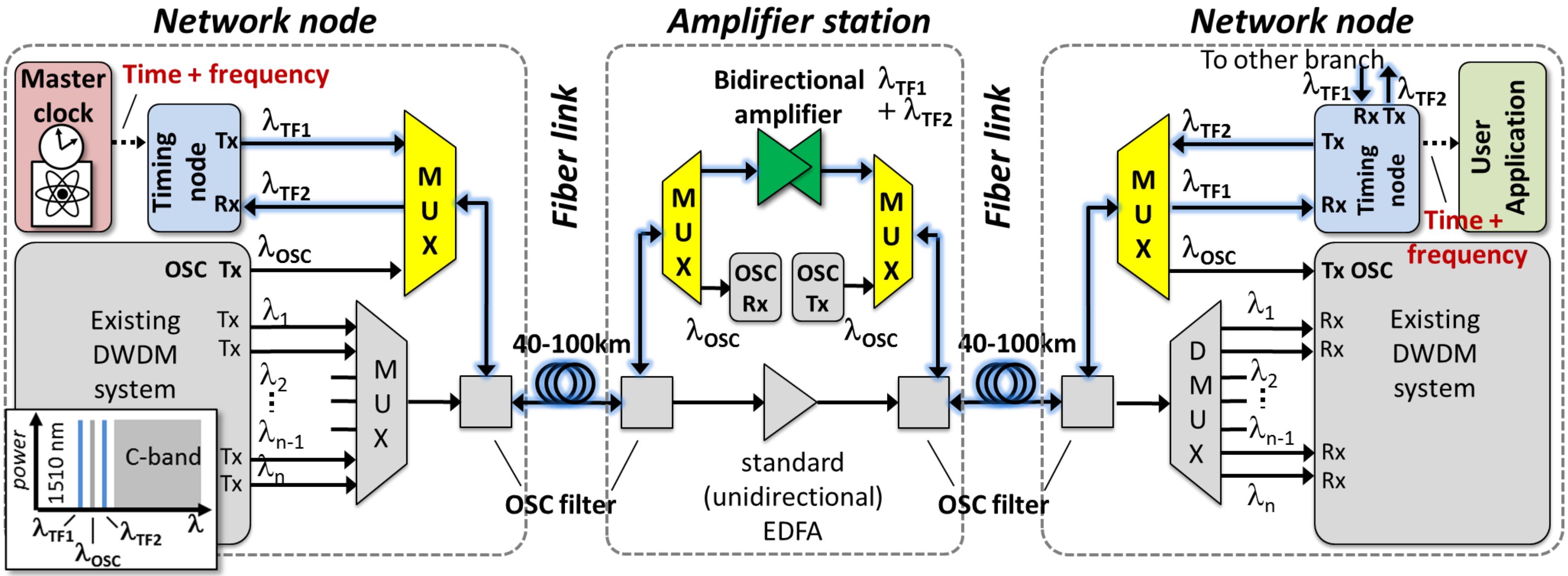
- **BUT difference between fiber delays is typically unknown and can be many microseconds**, leading to similar **time errors**
- Solution 1: use GPS timing receivers at both ends to calibrate and remove time error...
- Solution 2: create bidirectional optical path in fiber (including bypass amplifier)



Timing through C band DWDM systems



Timing through C band DWDM systems



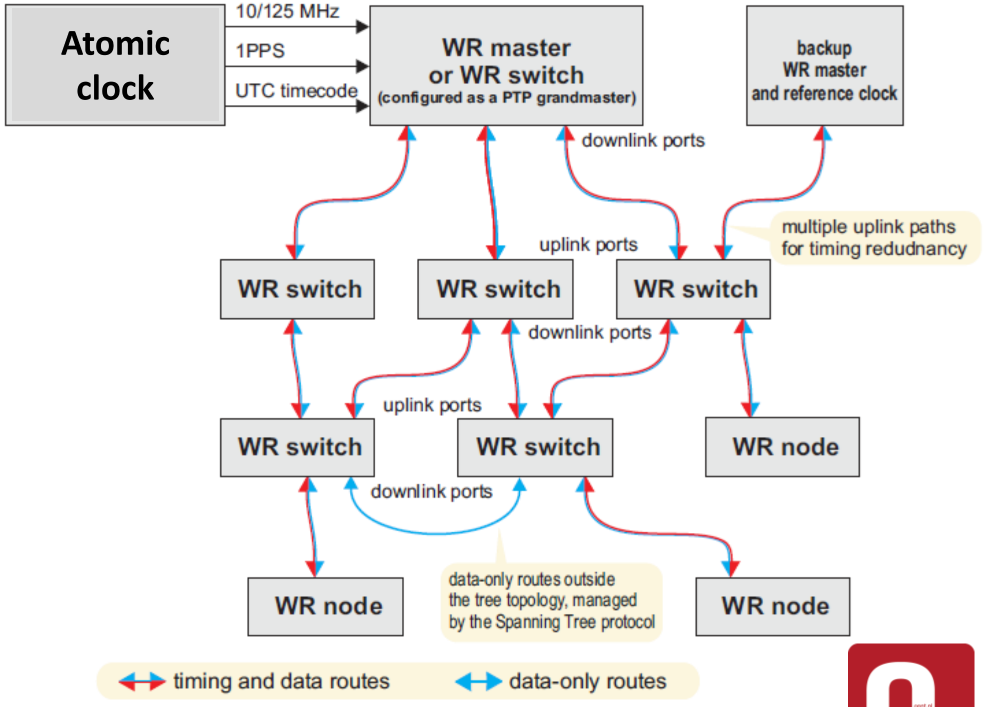
US Patent 9331844 B2
R. Nuijts, JK

Similar WDM solutions demonstrated by others, e.g.
LPL and Observatoire Paris, France
http://www.refimeve.fr/index.php/en/ressources/publications/partners-of-refimeve.html

Research at OPNT and VU University Amsterdam

- In collaboration with a dozen partners, mostly academic, mostly in Netherlands
- Developed and demonstrated key elements in installed networks:
  - WDM methods
  - Bidirectional optical amplification outside C band for T&F transfer
- Special interest: CERN's White Rabbit. Remember that for 0.1 m positioning (lane-level), 0.1 ns is sufficient (no picoseconds needed). VU and OPNT have managed to achieve 0.1 ns with WR.
- WR: basically 1 Gigabit Ethernet, very telecom-ish in nature
- OPNT: has own range of WR devices and supporting equipment (bidi's, WDM filters), first carrier-grade WR designs

'Upgrade' of IEEE1588 : **White Rabbit (WR)**
http://www.ohwr.org/projects/white-rabbit



Recent examples

- 2×137 km WR link between VSL Delft and NIKHEF Amsterdam with (sub)nanosecond performance*
- Time and frequency through live core network Vodafone Netherlands (320 km ring, four locations, sub-nanosecond time sync)
- Interoperability tests in lab of US network operator (four different DWDM systems, <0.1 ns time accuracy over ~100 km during 11-day measurement run)
- Low-noise WR: approaching H-maser frequency stability**
- Ongoing: installations for VLBI and VSL/ESA in Europe (Q2/18)
- Preparations for PoC at US global data center operator

OPNT White Rabbit building blocks

Timing Switch

Sub nanosecond level, branching

Timing Node

Sub nanosecond level end-point

Bidirectional Amplifer

Range Extender

+ WDM Filters, Management, etc.

*E.F. Dierikx et al., IEEE TUFFC **63,** 945 (2016); T.J. Pinkert et al. (in preparation)
**C. van Tour and J.C.J. Koelemeij, NRAO ngVLA memo #22 (2017)

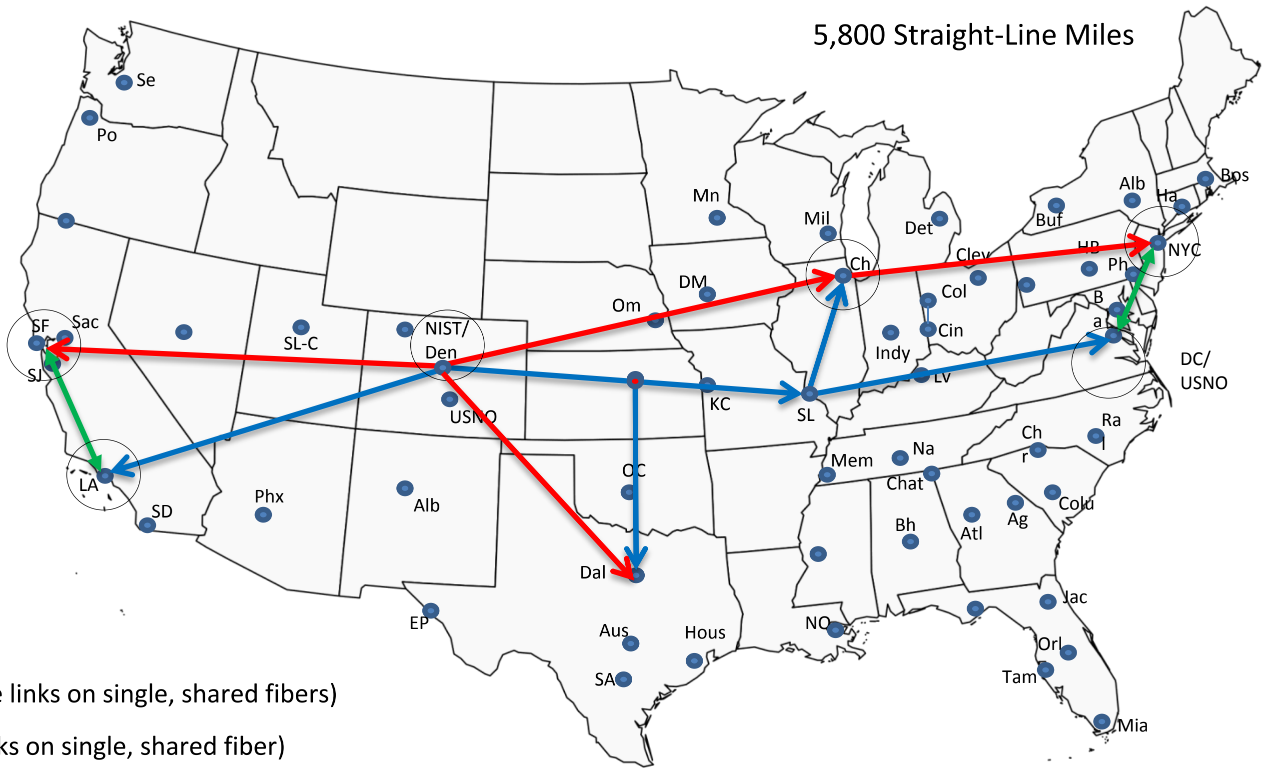
Nationwide terrestrial timing backbone

Several scenarios

US "Coast-to-Coast" Scenario

Metros Served

- NYC
- LA
- Chicago
- Silicon Valley
- DC
- Denver



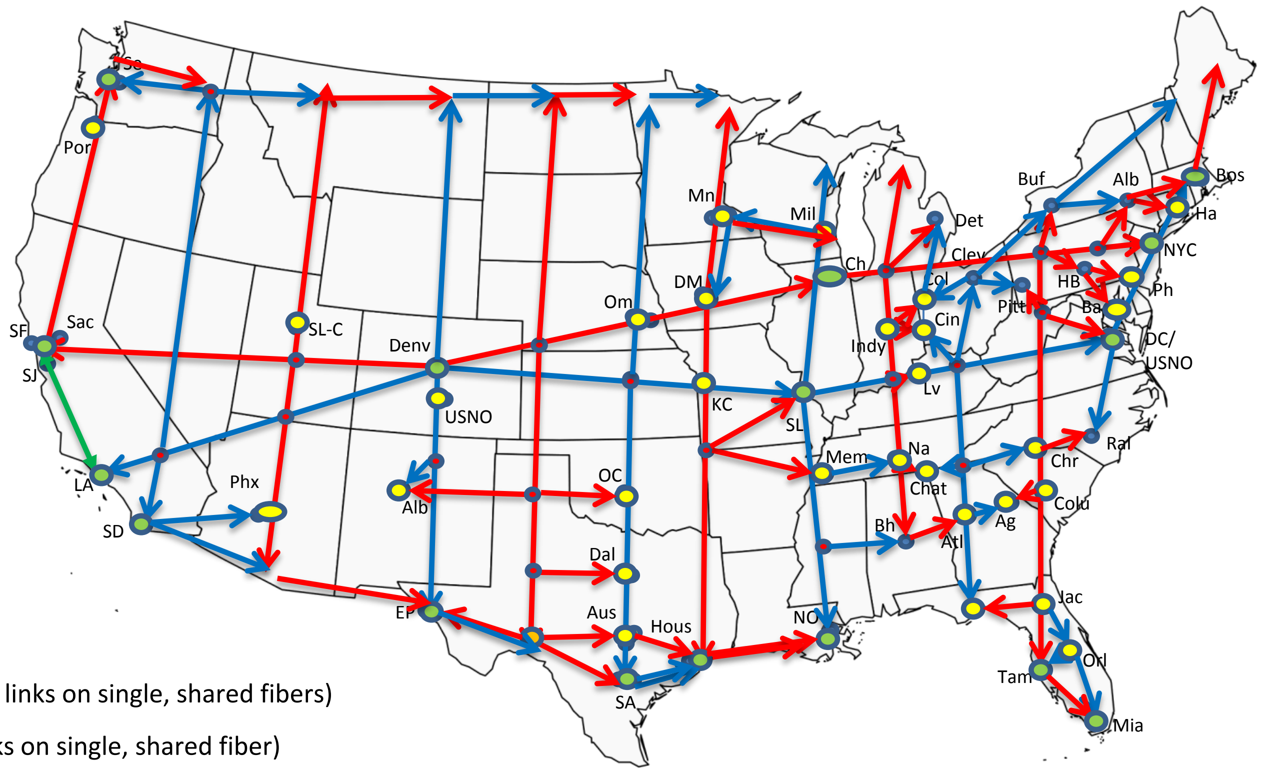
Active and Stand-by (single links on single, shared fibers)

Back-up/Fall-back (dual links on single, shared fiber)

US "Coast-to-Coast Fishbone" Scenario

Metros Served

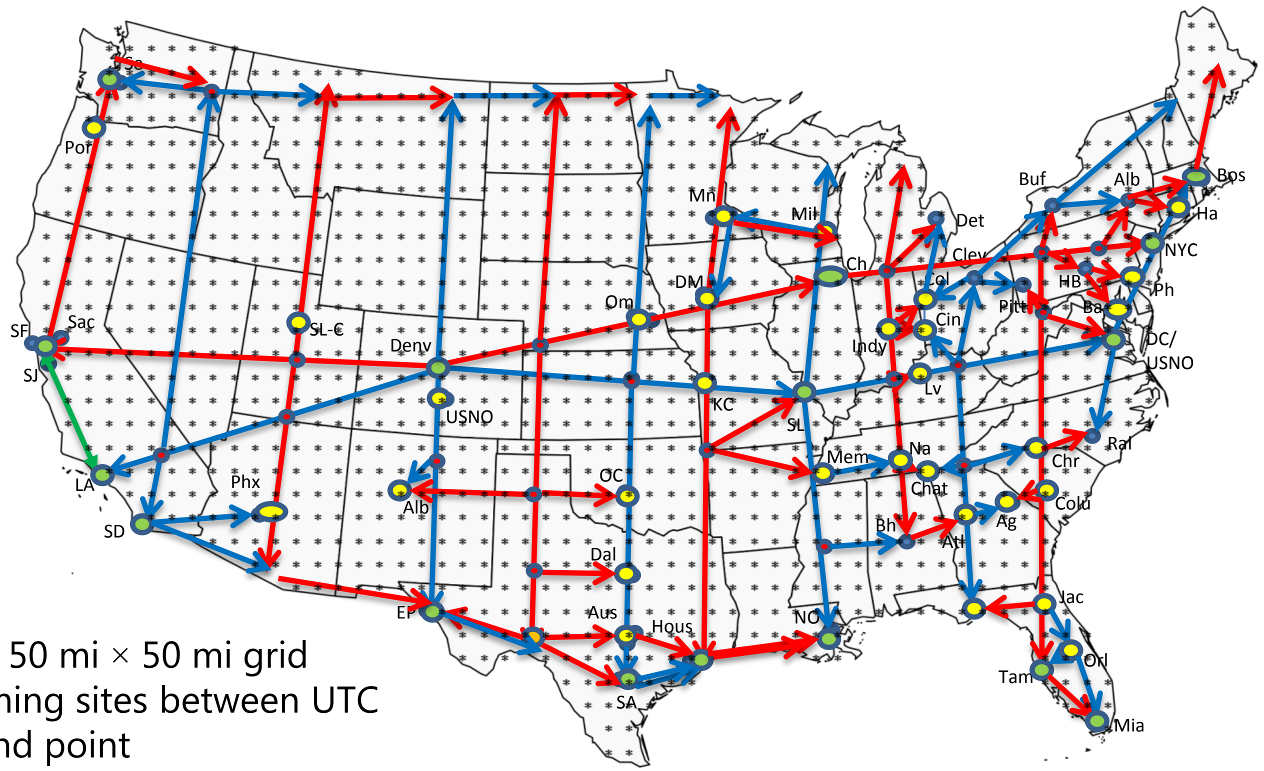
- NYC
- LA
- Chicago
- Silicon Valley
- DC
- Denver



Active and Stand-by (single links on single, shared fibers)

Back-up/Fall-back (dual links on single, shared fiber)

With Full-Visibility, Trilateration Grid



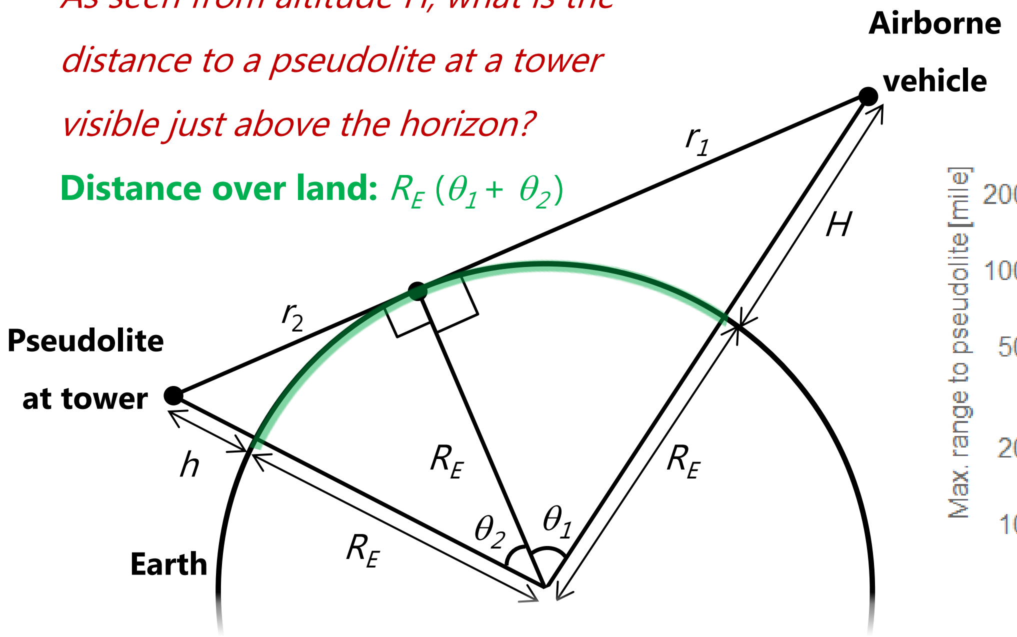
- About 1500 sites on a 50 mi × 50 mi grid
- Never more than 5 timing sites between UTC reference clock and end point
- Target: 1 ns maximum time offset from UTC(NIST) or UTC(USNO)

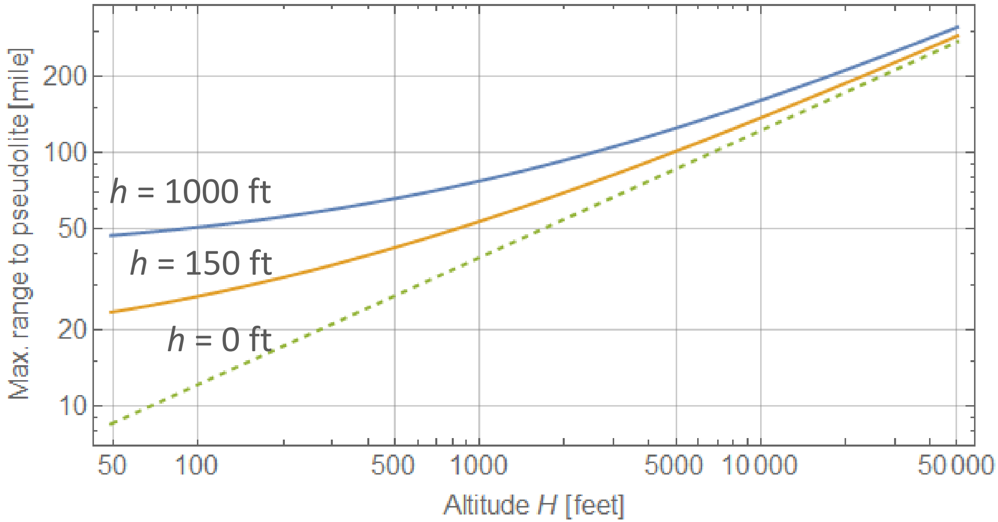
Terrestrial PNT backup system for airborne vehicles?

- Sparse 137 mi × 137 mi grid of 165 pseudolites (could be Lockheed Martin, Locata, NextNav, …)
- Placed at >1,000 ft TV towers
- Support 3D trilateration (≥ 4 sites in view) for altitude H > 10,000 ft
- Denser grid: 1,500 pseudolites on 46 mi × 46 mi grid, 150 ft towers: support PNT for H >1,000 ft

As seen from altitude H, what is the distance to a pseudolite at a tower visible just above the horizon?

Distance over land: $R_E\,(\theta_1 + \theta_2)$





Quick comparison with GPS

- Use same DSSS modulation, but vastly different carrier frequency to avoid interference with GPS (cf. NextNav)
- Requires allocated spectrum
- Higher received power levels possible (higher SNR)
- No transmission through ionosphere
  ⇒ no ionospheric error
- Improved time synchronization accuracy
  ⇒ smaller clock and PNT error
- Stationary pseudolites, well known locations
  ⇒ smaller ephemeris error, simplified PNT algorithm

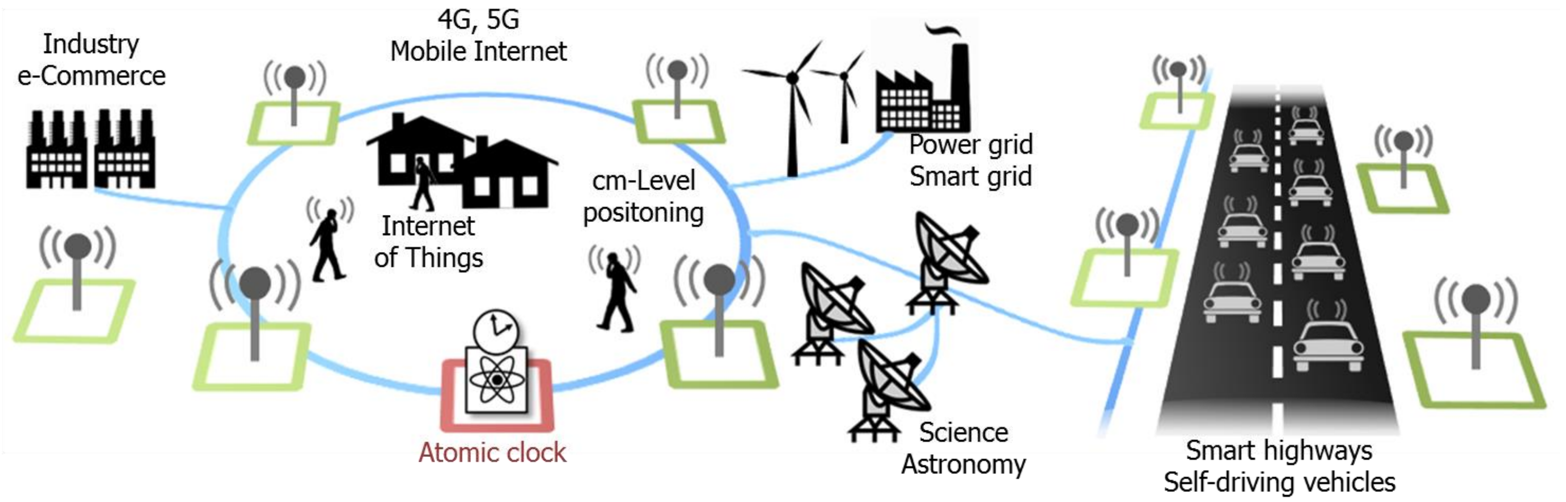
Sources of User Equivalent Range Errors (UERE)*

	GPS	TPS
Source	**Effect (m)**	**Effect (m)**
Signal arrival C/A	±3	±3
Signal arrival P(Y)	±0.3	±0.3
Ionospheric effects	±5	**±0**
Ephemeris errors	±2.5	**±0.5**
Satellite clock errors	±2	**±0.5**
Multipath distortion	±1	±1
Tropospheric effects	±0.5	±0.5
σR C/A	±6.7	**±3.2**
σR P(Y)	±6.0	**±1.3**

* https://en.wikipedia.org/wiki/Error_analysis_for_the_Global_Positioning_System

Outlook: densification and integration into 5G+

- Further densification: integration into 5G+ mobile infrastructure
- National terrestrial time infrastructure also useful for 5G mobile, finance, Smart grids, autonomous driving
- Topics addressed by SuperGPS project (with Delft University of Technology, KPN, VSL, a.o.)



Credits

- **Team @ OPNT**
- OPNT Advisors (Mr. Jeffrey K. Harris, Mr. Jean Pierre Aubry) and independent Board Member (Dr. Niel Ransom)
- Investors (Cottonwood Technology Fund, KPN Ventures)
- Partners and funding agencies:

VU VRIJE UNIVERSITEIT AMSTERDAM

VSL

Nikhef

TU Delft

JIVE Joint Institute for VLBI ERIC

SURF NET

kpn

STW Enabling new technology

NWO Netherlands Organisation for Scientific Research

ASTRON

TU/e

TNO innovation for life

EMRP European Metrology Research Programme Programme of EURAMET

THE FRAMEWORK PROGRAMME FOR RESEARCH AND INNOVATION HORIZON 2020

CERN

university of groningen