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Time Distribution Alternatives for the Smart Grid

Workshop Report

Prepared for
Allen Goldstein
National Institute of Standards and Technology
Gaithersburg MD 20899

Prepared by
Chris Kelley
Joan Pellegrino
Emmanuel Taylor
Energetics Incorporated
Columbia, MD 20146

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This report is based on the results of the *Time Distribution Alternatives for the Smart Grid Workshop,* held on March 21, 2017, in Gaithersburg, Maryland. The workshop was sponsored by the National Institute of Standards and Technology (NIST), an agency of the U.S. Department of Commerce.

Appreciation is extended to the NIST organizer as well as the speakers who provided their perspectives. We also appreciate the extensive contributions of the participants (listed in Appendix A); this report would not be possible without their valuable insights. Finally, thanks are extended to the Energetics Incorporated team for their assistance in facilitating the workshop and preparing this report.

Plenary Speakers (in order of appearance)

Lee Cosart, Microsemi Corporation
Stephen Bartlett, UrsaNav
John Lowe, NIST

NIST Organizer

Allen Goldstein, NIST

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1. Executive Summary

Background

The National Institute of Standards and Technology (NIST) hosted the *Time Distribution Alternatives for the Smart Grid Workshop* at its Gaithersburg, Maryland Campus on March 21, 2017. The event, co-hosted by the U.S. Department of Energy, brought together experts from industry, government, national laboratories, and academia to determine research and development (R&D) priorities for alternatives to global positioning system (GPS) time distribution in electrical power systems. The information gained will inform future NIST, DOE, national laboratories and private sector technical programs and strategic planning. The workshop also served to drive discussion for the North American Synchrophasor Initiative (NASPI) working group meeting held following the workshop.

High-Level Findings

Findings from the workshop cover desired future characteristics and targets for time distribution alternatives; challenges and barriers to adoption of time distribution alternatives; and priority R&D areas for time distribution alternatives. Note that when ‘source’ is referenced it refers to the clock at the beginning of the distribution system, while the GPS system is the distribution system. Potential alternative technologies to GPS and GPS backup systems were also discussed. Exhibit E-1 provides a high-level summary of the results in all categories.

Alternative Technologies. Information was presented on the capabilities of Enhanced WWBV, eLoran, Wide Area Precision Time Protocols (PTP) and various GPS backups and enhancements. All have some potential for supplementing GPS, filling gaps, or providing redundancy in the future.

Future Characteristics. Minimal infrastructure, diverse time distribution systems, interoperability, and spoof/jamming/failure resistant, redundancy, precision and resiliency were identified as desirable traits.

Future Targets. Affordability ($500 range for users), greater accuracy (less than 10 µs to 100 µs for distribution), quantified error/performance (1 µs accuracy), no discontinuities, high uptime and integrity (99.99 %), and long time between failures (10 000 years) were identified as primary targets.

Challenges and Barriers. Existing and future solutions face a number of technical challenges. These include the lack of standards for performance and communication and a use case-driven architecture; inadequate capabilities to detect failures/attacks and awareness of the impacts of failures; infrastructure issues such as the development of timing networks, wireless propagation delays, and optimization of data/timing for convergence; breaking the existing dependency on space-based timing systems; and optimizing combinations of timing systems (e.g., wired, wireless, clocks).

Priority Research Areas. As shown in Exhibit E-1, the research priorities address the major challenges identified. R&D efforts needed range from development of standards, use cases and architecture to development of timing networks and other infrastructure. Test beds and demonstrations were identified throughout as necessary for new technology and infrastructure development as well as understanding system needs to help inform standards and architecture.

Exhibit E-1: Timing Workshop Summary Highlights

Potential Alternative Technologies for GPS and GPS Backup

Enhanced WWVB	Enhanced Loran (eLoran)	Wide Area Precision Time Protocol (PTP)	GPS Backups/ Enhancements
NIST time broadcasting station synchronizing radio-controlled clocks in consumer electronics. – Increased broadcast power – Enhanced broadcast format in 2012 with improved performance	Upgrade from Loran-C, a hyperbolic radio navigation system; uses modern technology and low frequency radio signals from fixed land-based radio beacons to determine position. – Can use existing sites and antenna technology used for Loran-C – Designed/tested to meet Non-Precision Approach performance for aviation, harbor entrance/approach, etc.	Allows computers in a local area network to synchronize clocks to within a microsecond of each other. More accurate than Network Time Protocol (NTP) but less accurate than GPS. – Fills need for clock-synchronization between NTP and GPS-based synchronizations with accuracy to 1 µs	Radio KNIT – Radio knowledgeable networked integrated time (Radio KNIT) backs up GPS time by knitting together NIST radio station signals, common view algorithms, and smart internet connectivity applications. On Chip Atomic Clocks – atomic clock accuracy with very low levels of total uncertainty possible Assisted Partial Timing Support – Approach for timing in a wireless long term evolution (LTE)) environment.

Future Ideal Characteristics/Capabilities

- Minimal infrastructure (wireless, fast, open architecture, lower cost/risk, stand-alone)
- Diverse time distribution (terrestrial, wireless/multi-GNSS (global navigation satellite system), communication-based)
- Time transfer through air or fiber, with physical timing virtualized and encapsulated
- Interoperable and backward compatible with legacy systems
- Ubiquitous precise time that is reliable, secure, trustworthy, resilient, and available everywhere
- Spoof proof, jamming resistant, authentication verification
- Redundant systems (triple, source/path, fail over/fail back)

Future Performance Targets

- Affordable – less than/equal to $500 for entry with holdover performance/price
- No discontinuities such as leap second and daylight savings time
- Improved PTP, GPS and ground-based radio
- 1 µs accuracy with known/quantified error, performance, and uncertainty for transmission applications; less than 10 µs to100 µs for distribution
- 1 µs time accuracy at power system facilities (0.5 µs)
- Integrity greater than 99.99 % uptime
- Failsafe, with mean time between failure of 10 000 years

Major Technical Challenges

Standards/ Architecture	Security/Resilience	Infrastructure	Technology
Performance-based complete standards; cohesive use-case driven architectures; lack of communication of requirements and standards.	Detecting failure/attack (subtle); awareness of adverse impacts of failures; agreeing on fail-over/fail-back schemes; lack of cybersecurity requirements for timing and threat models.	Development of timing networks; idea exchange and networking; wireless propagation delays and availability of terrestrial signals; optimal data/timing methods for convergence.	Breaking dependency on anything space-based; optimizing methods of combining different timing systems (wired, wireless, clock); time distribution techniques; solving timing asymmetry in fiber

Priority Research Topics

Develop Standards/ Architectures	Optimize Timing Combinations	Develop Timing Networks	Detect Failure/ Attacks	Break Dependency on Satellite Systems
Conduct standards gap analysis; develop uses cases, architectures for widespread time supporting multiple sources; develop requirements; build smart grid test bed to demonstrate needs/requirements.	Study ensembles of solutions (PTP, GNSS, eLoran, etc) and determine most appropriate; demonstrate transition between FPS and eLoran or fiber on PMUs; build ensemble systems that take the best from each system.	Conduct demonstration projects to show applicability; prove indoor capability of eLoran; develop low cost eLoran receivers and $50 chip-level atomic clock; include timing in infrastructure upgrades; realize one competitive GPS alternative system.	Create attack test cases and revise threat matrix for detection to estimate value of consequences; develop early monitor warning stations; develop methods to detect and protect against failures/attacks in a time distribution system.	Study results of disabling events, enable seamless integration of alternative systems with space-based systems; demonstrate national non-space alternative time scale; study/ develop GPS-like systems and deploy eLoran; develop next-generation on-chip scale atomic clock and devices.

2. Introduction

2.1. Workshop Scope

The National Institute of Standards and Technology (NIST) hosted the *Time Distribution Alternatives for the Smart Grid Workshop* at its Gaithersburg, Maryland Campus on March 21, 2017. The event, co-hosted by the U.S. Department of Energy, brought together over 40 experts from industry, government, national laboratories, and academia to determine research and development (R&D) priorities concerning alternatives to global positioning system (GPS) time distribution in electrical power systems. The objectives of the workshop were to:

- Collect input on industry concerns and ideas regarding research, standards, and metrology-related issues facing time distribution alternatives by developing information on:
  - Measurement science barriers, challenges, and gaps associated with alternatives to GPS for time synchronization
  - Research and development (R&D) needed to address the priority measurement and standards challenges
  - Future measurement- and standards-related targets and goals for time distribution alternatives
  - Actions to overcome the high priority barriers;
- Inform future NIST, DOE, national laboratories, and private sector technical programs and strategic planning; and
- Drive discussion for the North American Synchrophasor Initiative (NASPI) working group meeting held the day after the workshop.

Note that when 'source' is referenced in the report it refers to the clock at the beginning of the distribution system, while the GPS system is the distribution system. The *Time Distribution Alternatives for the Smart Grid Workshop Report* is based largely on workshop discussions and insights provided by speakers and panelists. The report is organized around three significant topic areas:

- **Future Targets for Time Distribution Alternatives**
- **Challenges and Barriers to Adoption of Time Distribution Alternatives**
- **Priority R&D Areas for Time Distribution Alternatives**

The ideas presented here are a reflection of the attendees and not necessarily the entire industry. As such, they should be viewed as a good snapshot of the important perspectives, but not all-inclusive. The participants were carefully selected based on their high level of technical knowledge related to time distribution alternatives and relevant technologies, systems, and practices, and are considered experts in the field.

This report details the findings that identify the most critical technological and measurement science challenges and associated R&D needs for enabling alternative time distributions. The information is useful to both public and private decision-makers interested in furthering the capabilities of time distribution alternatives in a variety of applications. It is hoped that the national research efforts for time distribution alternatives will incorporate some of the needs and challenges detailed in this report.

2.2. Workshop Process

Several key questions and focus areas were posed to gain insights on the important challenges and pathways to address them.

Characteristics of an Ideal Time Solution

- Envisioned future: What capabilities are wanted and needed the most?
- What are the relevant enabling technologies?
- What are the appropriate performance targets and metrics?

Challenges and Barriers for Enabling Alternative Time Distributions

- What technological or other barriers limit development or adoption of alternative time distributions?
- What technology and R&D challenges are addressable today?

R&D Priorities and Pathways to Time Distribution Alternatives

- What are the R&D priorities in the near and distant future that can help enable adoption of time distribution alternatives?

Each group used a real-time voting scheme (5 votes per person, same value for each vote) to indicate which challenges were of most priority to address. When voting, participants were asked to consider the challenges that were most urgent and important to address as well as potential benefits and impacts.

3. Plenary Summaries

Presentations from leading industry experts set the stage for workshop discussions. The presentations of speakers reflect unique opinions of their respective fields. Many of the themes identified were echoed during the breakout sessions and further expanded.

3.1. Alternatives to GPS for Wide Area Distribution of Time: Overview

Allen Goldstein, NIST

Time-synchronized measurements (i.e., phasor measurements/PMU, electronic transformers/merging units) are increasingly being utilized across electrical power systems and are predicted to become mission critical to the proper operation of the power grid. Currently, the Global Positioning System (GPS) is the only means of distributing synchronized time across the power system, despite its vulnerability to short- and long-term outages and intentional or unintentional interference. Many power system experts agree that power system reliance on time-synchronized measurements will require redundant and differently routed sources of synchronizing time.

NIST has a unique mission, and measurement science (metrology) plays an important role in the context of creating critical solution-enabling tools – including metrics, models, test methods, and knowledge – for smart grid owners and operators. This workshop focused on understanding industry concerns, challenges, and the related R&D needs regarding wide-area distribution of synchronized time (within 1 microsecond). The workshop included presentations on important emerging technologies in this area, along with interactive discussions among stakeholders to capture expert perspectives in key areas. Presentations were first given on three emerging time distribution technologies; participants were then split into breakout groups that focused on the aforementioned topic areas:

1. Characteristics of an ideal time solution
2. Challenges and barriers for enabling alternative time distributions
3. R&D priorities and pathways to time distribution alternatives

Each breakout group identified numerous topics and technologies in their respective topic areas and voted on ideas to generate a prioritized list of topics. This content informed the development of this workshop report and its key findings. This document is intended to lay out the high priority research pathways for consideration by NIST, other research agencies such as the U.S. Department of Energy's National Laboratories, academic institutions, and the private sector.

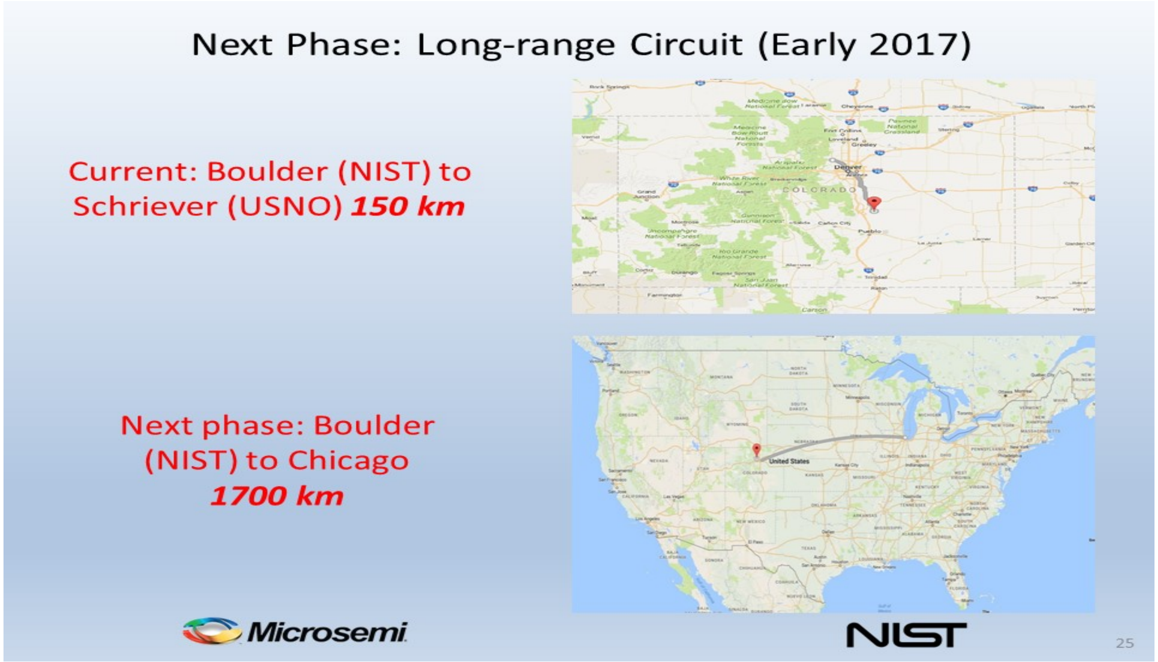
3.2. Wide Area Time Distribution with PTP

Lee Cosart, Microsemi Corporation

Mr. Cosart presented on the potential for using commercial telecommunications optical fiber infrastructure for wide-area time distribution applications. He cited key driving factors such as the need to back up critical infrastructure for time at 1 microsecond or better and the need for a commercially viable method given the present state of technology. Mr. Cosart also discussed researching the use of public telecommunications networks to transfer time.

Mr. Cosart described a project with NIST and two private companies (a vendor and a carrier) to test Precision Time Protocol (PTP) timing signals over two different circuits provided by the carrier. The project tested two-way time transfer using neighboring unidirectional fibers and taking appropriate measurements at NIST and the U.S. Naval Observatory (USNO). Results from a two- to three-month data set shows that the asymmetry between the directions is static and can be corrected for in the measurements as long as the circuit stays up. Meanwhile, a long-term PTP fiber measurement found that two-way time error on a 95-day measurement only showed a 26 nanosecond (ns) error peak-to-peak over that time period, supporting the possibility that this method could provide time holdover below 100 ns indefinitely.

The team used a Modified Allan Deviation (MDEV) to show the capability of frequency transfer approaching 1 part in 10^{15} at ten days. The presentation referenced a new standard published in August 2016 by the International Telecommunication Union called Recommendation G.8275.2 "Precision time protocol telecom profile for time/phase synchronization with partial timing support from the network" which includes assisted partial timing support (APTS), which uses the global navigation satellite system (GNSS) to correct for asymmetry. He then discussed the next phase of the project to test long-range circuits in 2017, shifting from the Boulder, CO (NIST) to Schriever, CO (USNO) circuit – a distance of 150 kilometers (km)– to one from Boulder, CO to Chicago, IL (1,700 km).



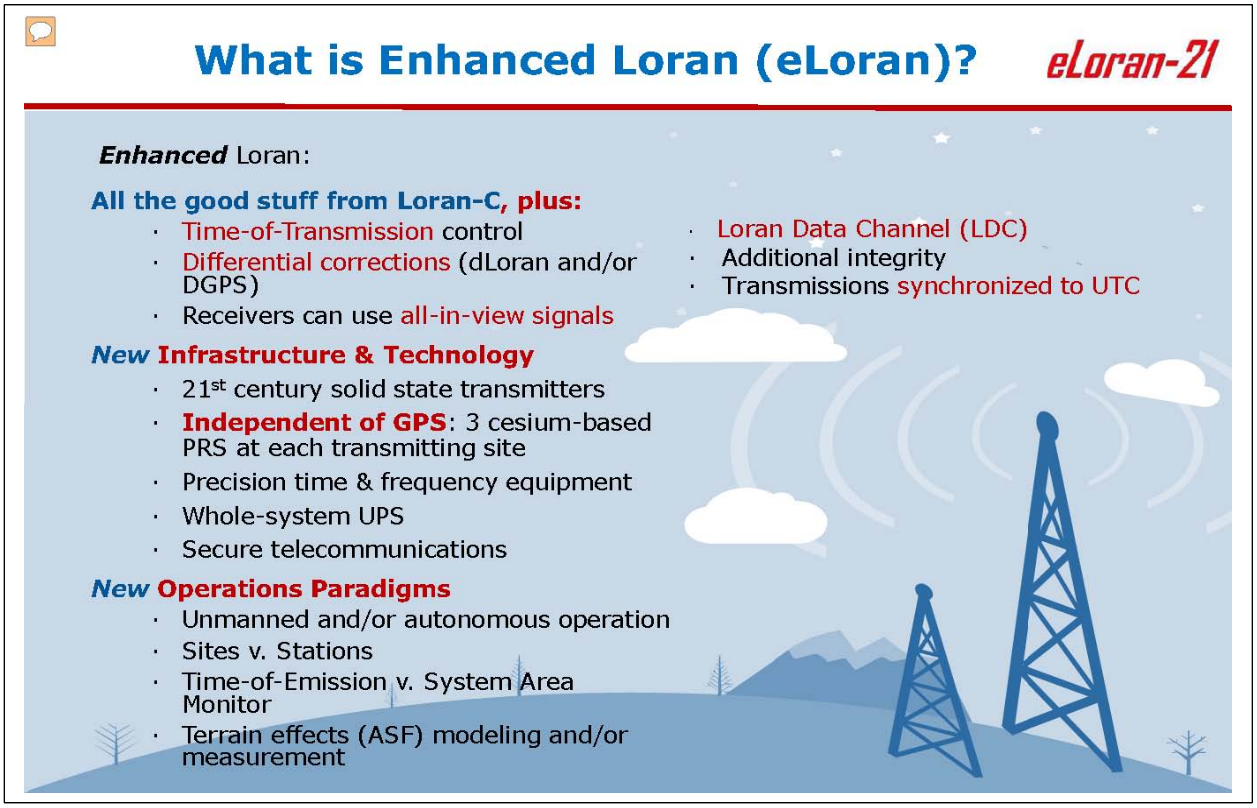
3.3. Wide Area Time Distribution Via eLoran

Stephen Bartlett, UrsaNav

Mr. Bartlett presented on the eLoran technology and provided an overview of eLoran, its capabilities and its predecessor Loran-C; results from a Cooperative Research and Development Agreement (CRADA) on eLoran technology; eLoran timing coverage in the U.S.; and the relevant research opportunities in this space. The CRADA focused on timing evaluations from an eLoran transmitter in Wildwood, NJ, and transmissions to several other sites of varying distance:

- USNO, Washington, D.C. (200 Kilometers)
- Leesburg, VA (225 Kilometers)
- North Billerica, MA (500 Kilometers)
- Rochester, NY (525 Kilometers)
- Gastonia, NC (685 Kilometers)
- Columbus, OH (700 Kilometers)
- Bangor, ME (800 Kilometers)
- Ocala, FL (1270 Kilometers)

Differential eLoran reference sites were located at North Billerica, MA; Leesburg, VA; and Gastonia, NC, for this project. The results showed that without differential corrections or augmentations, eLoran easily demonstrated the ability to meet the (+/-) 1 microsecond timing synchronization requirement proposed in the 2014 Federal Radio-navigation Plan (FRP). Overall, 95 % of all data collected was within 156 ns of UTC without differential corrections or augmentations. The CRADA ultimately found that eLoran proved to be a successful backup to GPS timing in a wide area multilateration (WAM) aviation application, providing equivalent performance to GPS. Additional aviation testing is ongoing, and eLoran proofs-of-concept for smart grid applications are planned for late 2017.



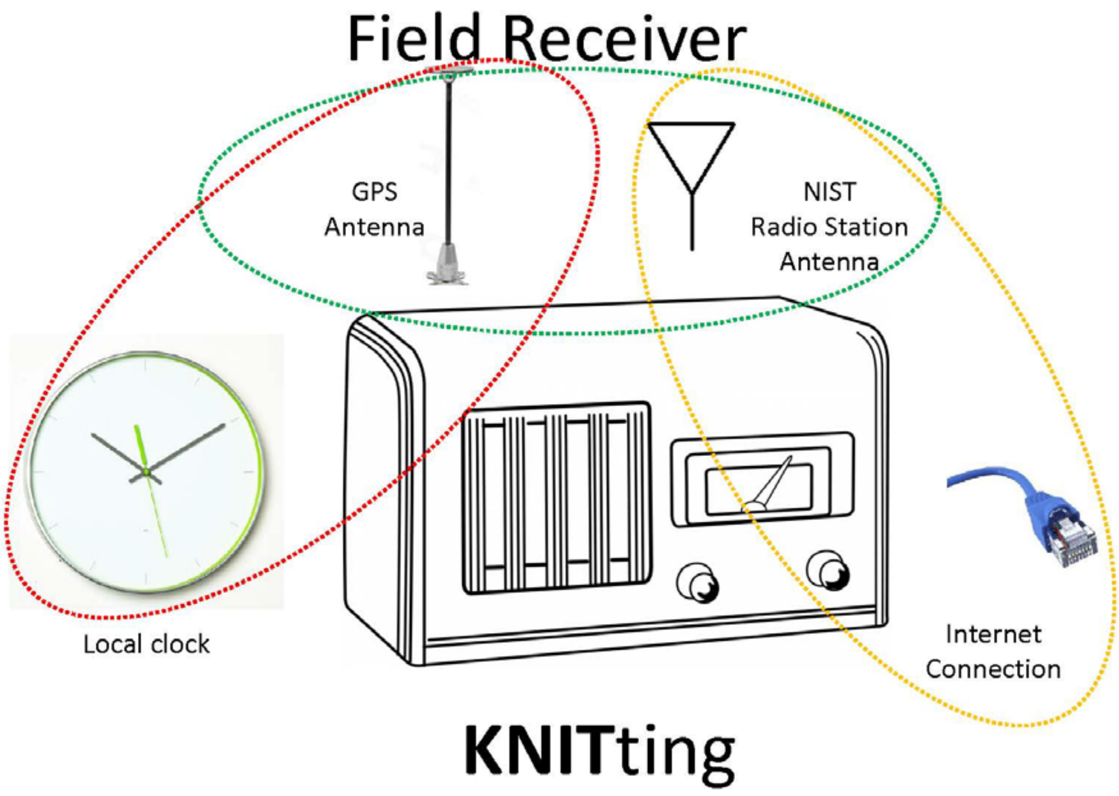
3.4. GPS Time Backup for the Power Industry

John Lowe, NIST

Mr. Lowe presented on the GPS system and the need for time backups for the power grid. He provided an overview of the GPS system and relevant nomenclature, highlighting the importance of the system to critical infrastructure and its vulnerabilities to interference, jamming or spoofing from weather and electromagnetic interference (EMI), among other sources. He then discussed the timing needs of power grid applications (i.e., general purpose, substation monitoring, extended distance applications, etc.), noting the measurement needs for each.

Mr. Lowe then presented on the potential for a GPS time backup via radio knowledgeable networked integrated time (Radio KNIT) that backs up GPS time by knitting together NIST radio station signals, common view algorithms, and smart internet connectivity applications. He then discussed the prospect of connecting monitoring stations and field receivers via the internet to maintain time synchronization in the absence of GPS capabilities, noting the potential for distributed KNIT software infrastructure as a future solution. Lastly, he compared the Radio KNIT solution to the current alternatives of NIST radio stations and GPS, highlighting Radio KNIT's robustness, low energy requirements, and scalability.

Radio Knowledgeable Integrated Time (Radio KNIT) Concept



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4. Wide Area Distributed Time Synchronization Alternatives

Some of the potential alternatives to wide area distributed time synchronization include Enhanced WWVB (radio signal broadcasting), eLoran (hyperbolic radio navigation) and the IEEE Wide Area Precision Time Protocol (PTP – master slave clock synchronization). The general characteristics of each are described in Section 4.1.

4.1. Potential Technologies

4.1.1. Enhanced WWVB

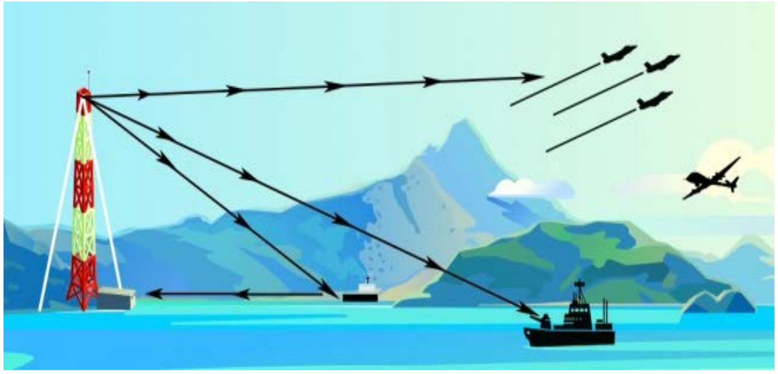
WWVB is a broadcast station – operated by NIST – which has been broadcasting time information to synchronize radio-controlled clocks (RCC) in consumer electronic products like wall clocks, clock radios, and wristwatches throughout the U.S. since 1965. (Liang 2014) WWVB may also be used in other consumer timekeeping applications such as appliances, cameras, and irrigation controllers, as well as in high level applications such as accurate time synchronization. (NIST 2017)

In the early 2000's, there was a significant increase in broadcast power and increases in the modulation factor used for amplitude-modulation to improve reception coverage for existing RCCs and increase their reliability. However, RCCs still had difficulties in reception depending on their geographical location, time of day, type of structure they are placed in, and sources of interference – all factors determining the signal-to-noise-plus-interference-ratio (SNIR) experienced by receivers at a given distance. In order to address reception issues and provide an improved system to the public, NIST introduced an enhanced broadcast format. (Lowe 2013) Since October 29, 2012, NIST Radio Station WWVB has broadcasted a phase modulated (PM) time code that was added to the legacy AM/pulse-width modulation signal. This enhancement has significantly improved performance in new products that are designed to receive it, while existing RCCs and watches are not affected and continue to work as before. (NIST 2017)

The NIST Radio Station WWVB near Fort Collins, Colorado   Photo: NIST

4.1.2. eLoran

Enhanced Loran (eLoran) is a major technology upgrade from Loran-C, a hyperbolic radio navigation system allowing a receiver to determine its position by listening to low frequency radio signals transmitted by fixed land-based radio beacons. Enhanced, or eLoran, was developed in the U.S. in the mid-1990's as part of a U.S. Coast Guard (USCG) program to ensure system efficiency and effectiveness if operated beyond 2000. Although it is a technology more advanced than Loran-C, eLoran can be provided by the same sites and antenna technology used for Loran-C. (UrsaNav 2017)



Enhanced Loran or eLoran uses modern technology and low frequency radio signals from fixed land-based radio beacons to determine position. It meets the accuracy, availability, integrity and continuity performance requirements for maritime harbor entrance and approach maneuvers, aviation non-precision instrument approaches, land-mobile vehicle navigation and location-based services.

As GPS became fully operational in 1994, the U.S. military eliminated its requirement for Loran-C. However, in recognition that Loran-C did not meet the evolving position, navigation and timing (PNT) requirements for the aviation community, a Congressional mandate to continue Loran beyond 2000 was established. From 1997 through 2010, the USCG and Federal Aviation Administration (FAA) executed a program with over $160 million in U.S. government funding to modernize and upgrade Loran-C to eLoran. eLoran was designed and tested to meet Non-Precision Approach (NPA) performance in support of aviation, Harbor Entrance and Approach (HEA) in support of marine, and Stratum 1 time and frequency in support of communications and network operations. Since then, government, academic, and industry studies, nationally and internationally, have overwhelmingly reported positive findings from evaluations of the operational and costs and benefits of eLoran. (UrsaNav 2017)

4.1.3. Wide Area Precision Time Protocol

Precision Time Protocol (PTP) allows computers in a local area network to synchronize clocks to within a microsecond of each other. The standard was originally defined in 2002 and has since resulted in a second and current version that was published in 2008 known as "IEEE 1588-2008" (IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems). (IOL 2012) A further revision is in draft at the time of this report publication (2017)

PTP is more accurate than the Network Time Protocol (NTP) but is less accurate than GPS. The NTP was standardized in 1985 and serves as the most common clock synchronization method used by tens of millions of client computers to synchronize to NTP servers over the internet. Primarily used in a wide-area network where it can achieve accuracy to 10 ms, NTP is accurate to 200 µs on local-area networks,. NTP includes Simple NTP (SNTP), which is stateless (no averaging) and hence suitable for embedded devices but less accurate. GPS-disciplined clocks are the most accurate clocks outside of the atomic clocks used in the international atomic time (TAI) scale. They are accurate to 0.01 µs (10 ns). (IOL 2012)

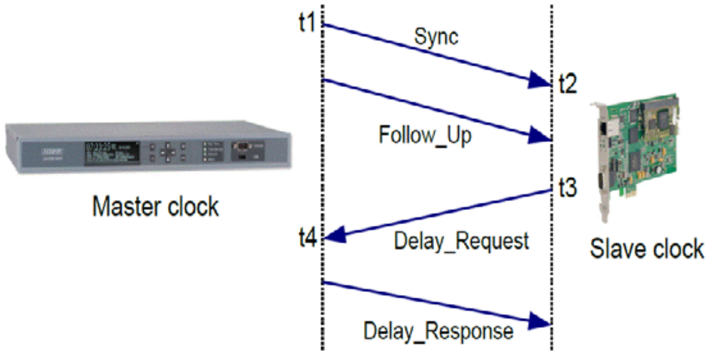


Image: Meinburg Global. https://blog.meinbergglobal.com/2013/09/14/ieee-1588-accurate/ Permissions Pending.

PTP fills a need for clock-synchronization between NTP and GPS-based synchronizations, with accuracy to 1 µs. There are two main reasons why PTP is used instead of GPS: 1) a PTP network only needs one GPS receiver, which is much less expensive than giving each network node a GPS receiver, and 2) in the extreme case that the GPS system becomes inoperable (i.e., during wartime) a PTP-synchronized network will stay synchronized. This latter point is essential for life-critical applications such as the electric power grid and telecommunications services. (IOL 2012)

4.2. Future Needs for an Ideal Time Solution

Developing an ideal time solution to meet future needs for the power grid will require new technologies as well as increased functionality, security and resilience. The desired future technologies and capabilities and potential future performance targets that were identified for time distribution alternatives are described in the following sections.

4.2.1. Desired Future Technologies and Capabilities

Future needs for an ideal alternative time distribution could be met via development and enhancement of new or existing technology (e.g., on chip atomic clocks, timing systems that combine sky, ground and fiber, combinations of multi-path/multi-protocols, etc.); creating open, wide-reaching systems that require minimal infrastructure; and a greater degree of resilience, stability, security, and availability. The desired technology and capabilities identified are shown in Table 4-1, with major concepts summarized below.

Technology – Technologies such as APTS (Assisted Partial Timing Support), on-chip atomic clocks, and PHY (physical layer) are just a few of the potential candidates for enhancing time distribution alternatives. Other innovations that could be advantageous include systems operating from a combination of sky, ground and fiber or that incorporate integration of multiple paths and protocols.

Infrastructure –Wireless technology (5G) could enable minimal infrastructure technology that is easy to access, integrate, establish and maintain and cost-effective to implement and operate. Ideally this technology would be based on an open architecture and specifications and be traceable to a standard UTC (universal time coordinated). The goal would be a low-risk and reliable option that is easy to implement and attractive to utilities and grid operators, plus end-users.

Redundancy – Redundant systems are of major importance for future time distribution scenarios. Redundancy is needed for both source and path, including the ability to know which redundant system is correct. The goal is triple or more redundancy; this could be accomplished using a local clock. Reliable time backup is also needed for all systems and facilities, with fail over/fail back capability and standardized methods for recovery.

Resilience and Availability – Widely-available and precise time that is reliable, secure, trustworthy, and resilient is important to meet future time distribution needs for the grid. A number of characteristics are vital, including the ability to detect and alarm failures; resistance to jamming; embedded security that includes authentication and integrity verification; and inherent traceability and accountability from beginning to end of the timing system. Ideally time distribution systems should be universally usable, globally recognized, and part of a larger time scale beyond the power industry.

Accuracy – Characterization of accuracy becomes increasingly vital for future systems with more distributed power. Time accuracy is needed for the transfer of massive data on networks and in computing platforms. Techniques are also needed to enable self-health reporting of systems (performance) and for systems to self-learn.

Interoperability – Future time distribution alternatives should have a high degree of interoperability with existing timing systems and protocols operating on the grid. Interoperability will allow for ease of integration, reduce costs, and lower potential for errors and failure when systems are combined.

Diversity of Timing Distribution Systems– Another key characteristic for future alternatives is reliance on a diversity of timing distribution systems. These could include, for example, terrestrial, wireless, multi GNSS (global navigation satellite system), and communication-based sources.

Table 4-1. Desired Future Technology and Capabilities
Technologies
• APTS (Assisted Partial Timing Support) • On-chip atomic clocks; ePRTc (enhanced primary reference time clock) with inexpensive CSAC (chip-scale atomic clock) with 10^{-13} uncertainty • Technology-independent communication methods • Systems operating from sky, ground and fiber combined • Technology with multi-path and multi-protocols knitted together • PHY (physical layer), e.g., sync E (Synchronous Ethernet)) and packet protocol (e.g., PTP (precision time protocol))
Technology Characteristics

• Line distribution of time and synchronization
• Minimal infrastructure technology (wireless)
  - 5 G wireless technology
  - 1 TPS network
  - Ease of access; easy to integrate, establish and maintain
  - Open architecture so others can supplement and augment; open technology and specifications
  - Lower cost and risk
  - Stand-alone; traceable to UTC ‘no need to calibrate’
• Ease of implementation for end-user
  - Cable and antenna on building; no pre-surveyed location, calibrations, etc.
• Time transfer either over air or through fiber; physical timing is virtualized and encapsulated
• Threat modeling to understand vulnerabilities and mitigation
• Integrity monitoring of other time services
• Diverse time distribution (terrestrial, wireless/multi GNSS (global navigation satellite system), communication-based)

Table 4-1. Desired Future Technology and Capabilities

Capabilities
• Universally usable, part of a larger time scale, not just the power industry; global • Interoperable (and backward compatible) with existing timing systems and protocols • Portability and mobility to support various applications (e.g., electric vehicles, energy storage) • Ubiquitous precise time that is reliable, secure, trustworthy, resilient and available anywhere - Spoof-proof (or ability to detect and alarm) and jamming resistant (if wireless) - Inherent traceability and accountability - Leap second, distribution failure alerts - Authentication and integrity verification - Beginning to end resilient time system - Ability to maintain performance in harsh environments • Redundant systems - Triple (or more) redundancy using a local clock - Ability to know which redundant system is correct - Redundancy for source and path - Fail over/fail back capability; standardized recoverability - Reliable time backup for all systems and facilities - Different routing options • Highest priority for time signals • Accuracy - Good characterization of accuracy - Better self-health reporting and self-learning (model sources of uncertainty) - Inherent clock accuracy in computing platforms - Guarantees for time accuracy with transfer of massive data over time on networks • Automatic comparison between redundant time distribution means and a method of selecting the most dependable one

4.2.2. Performance Targets

A number of possible performance targets were identified for future time distribution alternatives. To meet future needs identified for non-GPS systems, key targets are that systems be affordable at market entry; accurate to specified micro- and nano-second parameters; provide continuous services levels; and maintain high availability (greater than 99.99 %). The desired future performance targets are outlined in more detail in Table 4-2.

Table 4-2. Desired Future Performance Targets

- Affordable
  - Price target less than/equal to $500 for entry for each end user
  - Vibrant, competitive marketplace
  - Cost-effective; better holdover performance and price; indefinite holdover
- High performance and resiliency
  - Time system without discontinuities such as leap seconds and DST (daylight saving time) changes, etc.
  - Improved PTP, GPS and ground-based radio at 1 nanosecond accuracy
  - Ability to endure disturbances to time synch with immediate recovery
  - Bounded, deterministic latencies
  - Monitoring for accuracy, availability, continuity and coverage
- Timestamps
  - Within target time of event location (TBD)
  - At point of origin – millisecond or better resolution
- Accuracy – always within desired limits
  - 1 μs accuracy with known/quantified error, performance, and uncertainty (even if it is greater than 1 μs) for transmission applications; less than 10 μs to100 μs for distribution; could aid in fault location
  - Target of sub-nanosecond timing accuracy; less than 1 nanosecond accuracy; accuracy 100 picoseconds (10 times better than 1 nanosecond accuracy)
  - 1 μ time accuracy of at all power system facilities (0.5 μs)
  - Accuracy measurement standards
  - Technology error analysis performed on any given solution (stochastic properties)
- Continuity
  - Depends on critical application(s)
  - Varies among users/services, e.g.,99.9 % to 99.99 %
- Availability
  - Integrity greater than 99.99 % to ensure trust, and to support critical infrastructure
  - 99.99 % uptime with reliability, availability, and serviceability
- Known, quantified failure modes
  - Failsafe
  - Recovery
  - Alert to failure happening
  - MTBF (mean time between failure) of 10 000 years

5. Challenges and Barriers to Optimizing Grid Time Synchronization

Both technical and non-technical challenges need to be overcome to enable development and implementation of alternatives to GPS for time distribution on the grid. This section summarizes the challenges identified and those considered to be most important for moving forward.

5.1. Technical Challenges to Time Distribution Alternatives

Standards and Architecture – Standards in general constitute an important challenge for timing alternatives. Current standards are ambiguous and do not necessarily provide complete and measurable coverage or specific performance measures. Use cases are lacking to help justify the reasoning and need for alternatives. Use cases in a number of functional areas as well as applications would be useful to making the case for alternatives and for identifying new uses. It would also enable development of architectures that are cohesive and driven by practical use cases.

Security and Resilience – A major issue impacting resilience is having sufficient capability to detect failures and /or attacks, particularly when the disruption is subtle. A contributing factor and major challenge is insufficient understanding and awareness of the adverse effects associated with the failures of existing GPS timing systems. Raising awareness will in part provide an impetus towards timing alternatives and needed system redundancies. System security is another important challenge. There is lack of agreement on fail-over and fail-back schemes for timing. Best cyber-security practices for timing systems are also lacking.

Technology Issues – Breaking the dependency on timing systems that are space-based that currently exists (e.g., GPS, 2-way satellites, etc.) will be a challenge and require justification and awareness of the real need for accurate timing and redundancies. On the new technology side, optimizing methods of combining different timing systems, such as wired and wireless and clocks is important but also a major technical challenge that will require time and investment. Optimizing and overcoming the limitations of time distribution techniques will be challenging, as major issues such as improving timing and fundamental time distribution techniques, communicating time to equipment, solving time asymmetry in fibers, and others will need to be addressed.

Infrastructure and Development – Some major infrastructure challenges must be overcome to incorporate timing alternatives. These include, for example, the further development of timing networks; optimization of wireless networks; and improved wired time distribution that does not depend on specialized hardware. Wireless networks have many benefits and multiple challenges that must be addressed, including propagation delays, susceptibility to electromagnetic interference (EMI), and the availability of terrestrial signals. Achieving timing convergence is another major challenge, including development of optimal data techniques and capability for ‘ideal’ timing methods that optimize timing closure/convergence.

Table 5-1. Technical Challenges/Barriers to Time Distribution Alternatives
(X) = total number of votes, High Priority = 5+ votes, Medium Priority = 1+ votes, Low Priority = no votes)

Standards and Architecture	
High Priority	• Standards (performance-based, unambiguous, measurable, complete) (8) • Defining clear use case for need (or lack of) (6) - User stories ("As a ____, I want to _____, so that I can _____.") - Use cases (e.g., angular separation analysis, forensic analysis, state estimation, etc) - Application and use – based quality tags and information - Identifying new uses and applications
Medium Priority	• Cohesive architecture that is purpose driven; architecture based on use cases (4) • Lack of communication of requirements and standards (4) - Among different disciplines - Agreement on what a new system should do - Overarching set of "agreed upon" requirements - Consensus building for common solutions
Low Priority	• Adopting common standard across different industries; slow adoption of standards
Security and Resilience	
High Priority	• Detecting the failure/attack, particularly a subtle disruption (12) • Awareness of adverse impacts associated with failures of existing timing systems (6)
Medium Priority	• Agreeing on fail-over/fail-back schemes (4) • Lack of best (cyber security) practices for timing; lack of clarity on security threat model (3) • Clarifying requirements for resilience, reliability, and redundancy (2) - High reliability - Confidence that technology will be available in 10 or 20 years and continuously funded - Understanding impacts and consequences - Addressing changing and evolving threats • Interoperability (2) - Achieving interoperability via standards, plugfest and testing - Availability of equipment to support multi-system interoperability • CIP (critical infrastructure protection) regulations (streaming) (1)
Low Priority	• Wide area transmission with security (and standards); wide area remedial action schemes for control use; synchronized control of distribution equipment • Loss of determinism in operating system, network, and CPU • Limited technology for accurate wide area synchronization • Time delivery methods with low latency and high reliability • Transmission limits (in delivering time signals) • Accurate modeling of physical systems to complement/replace measurements
Infrastructure/Development	
High Priority	• Development of timing networks (5) • Multi-discipline idea exchange and proof-of-concept (5)
Medium Priority	• Wireless (4) – Propagation delays and availability of terrestrial signals • Convergence (4) – Optimal data techniques – Ideal timing methods • Vulnerabilities to distribution media (air, fiber, etc.); each medium has severe restrictions and failure modes (3)

Table 5-1. Technical Challenges/Barriers to Time Distribution Alternatives
(X) = total number of votes, High Priority = 5+ votes, Medium Priority = 1+ votes, Low Priority = no votes)

	• Seven-layered network infrastructure that needs to be rethought for time-sensitive applications (2) • End user access to fiber (for "network" time) (1) • Cost, time and types of technology for infrastructure upgrades (1)
Low Priority	• Wired time distribution that does not depend on specialized hardware • Dealing with environmental locations of equipment • Development of infrastructure, e.g., for eLoran • Capability of existing wired infrastructure and cost of new infrastructure
Technology Issues	

High Priority	• Breaking the dependency on anything space-based (GPS, 2-way satellite, etc.) (10)
	• Optimizing methods of combining different timing systems: wired and wireless and clock (10)
	• Time distribution (8)
	  - Fundamental time distribution techniques, e.g., quantum state transmission
	  - Better timing
	  - Communicating time to indoor equipment
	• Solving asymmetry for time transfer in fiber (6)

Medium Priority	• Accurate, cost effective oscillators that have a long life (3) • High accurate clock-on-a-chip (and inexpensive); small primary reference atomic clock; precise 'wall clock' time to be effective (i.e., for distributed energy); clocks and ensembles (3) • Ensuring time awareness of PTP (precision time protocol) router/switches (2) • Smaller, faster, cheaper devices (2) • Atmospheric effects of RF (radiofrequency) solutions (1) • Inconsistent implementations of technology (1)

Low Priority	• GNSS (global navigation satellite system) challenges
	  - Indoor reception
	  - Intentional and unintentional interference
	  - Large installed base of cheap, inadequate user timing and GNSS equipment (time consumption vs. time provision)

5.2. Non-Technical Challenges to Time Distribution Alternatives

A number of non-technical challenges were identified centered around market demand, economics, user perceptions, and policy and regulation. Table 5-2 provides a complete list; highlights of the most important challenges are summarized below

Markets and Economics – The cost of alternatives and developing a practical business case that is attractive to users is a major challenge. The business case needs to demonstrate that return on investment (ROI) can be achieved, which is difficult when costs and benefits for solutions are not fully defined. The cost of GPS time and its reliability are also inhibiting factors for implementation of new systems (insufficient impetus). This is especially true when the adverse effects of timing failures are poorly understood and leads to limited market demand and drivers for technology (e.g., high demand applications).

User Perceptions and Awareness – Organizational complacency about the urgency of developing alternatives and redundant timing solutions is a key barrier to moving forward. There is insufficient recognition that GPS is inefficient and vulnerable. Leadership is also lacking; a central champion is needed to raise awareness and drive development of alternatives. Alternatively, a disaster may lead to awareness and action but this is a highly undesirable route.

Table 5-2. Non-Technical Challenges/Barriers to Time Distribution Alternatives
(X) = total number of votes. High Priority = 5+ votes, Medium Priority = 1+ votes, Low Priority = no votes)

Markets and Economics	
High Priority	• Cost and a practical business case (9) - Achieving sufficient ROI (return on investment) - Cost of system diversity - Cost of GPS time and its reliability and accuracy limits competition - Cost of GPS PNT loss is considered irrelevant - Cost/benefit for some solutions not achieved yet (e.g., at 1 ps) - Lack of a working business model • Limited market demand and drivers for technology (e.g., high demand applications); limited end-users driving needs; poor understanding/awareness of adverse effects (9)
Medium Priority	• Resources (funds and education) for engineers/scientists, demonstration projects, etc. (4) • Changing the culture of utilities and how to pay for new technology (1) • Corporate, academic and government investment cycles
Low Priority	• Limited historical investment in R&D by power industry • Technologies are available but no clear winners
User Perceptions/Awareness	
High Priority	• Lack of an executive agent to champion, provide leadership and support needed efforts (5)
Medium Priority	• Organizational complacency (2) - GPS has become the default time delivery system; other GNSS systems have followed so as not to fall behind; insufficient recognition that GPS is ineffective and vulnerable - No consensus on the path forward - Limited industry acceptance - Important, but not urgent; no urgency at executive level - Lack of a clear and present danger (status quo perceived as adequate) - Low user expectations
Low Priority	• Limited awareness of importance of precise time; education that timing is different than data • Lack of confidence in a solution
Political/ Regulatory	
Medium Priority	• No policy update for National Security Presidential Directive (NSPD) 39 or Synchronized Multi-Carrier CDMA plus (SMCC -+2004), a candidate scheme of digital terrestrial TV broadcasting in China (2) • Regulatory requirements (1)
Low Priority	• Lack of serious consideration of security, reliability, and resilience • Lack of national performance targets

6. Priority R&D Areas for Grid Time Synchronization

6.1. Technical R&D Areas

Researchers continue to build and improve on alternative timing solutions. However, significant research and development are needed to make some of these solutions a reality and attractive to end-users. New technology and equipment as well as improvements to security and resilience will make alternatives viable as replacements, additions, and/or redundancies for GPS. Standards, protocols, and defined architectures built on realistic use cases and applications will help pave the way for greater development and adoption. Table 6-1 illustrates the various R&D and other activities identified, categorized by the major challenges that need to be addressed.

Table 6-1. Priority R&D Topics for Time Distribution Alternatives (associated challenge votes)

Develop Standards and Architectures (22)	
0-3 Years	• Conduct standards gap analysis and follow-up with actions to resolve • Develop common/consensus use cases, requirements, standards, strategies, priorities; conduct use case analysis • Develop architectures to support widespread time supporting multiple sources • Devise testing for existing standards • Pursue GPS – 1588 integration to achieve time accuracy and security; understand GPS distribution, identification and impact • Convert technical standards to procurement specifications to allow users to know what to specify and a target for vendors to build to (*when new technology is available)*
3-5 Years	• Facilitated, coordinated use cases, requirements development, followed by research coordination (NASPI-like consensus building and information sharing)
5-10 Years	• Conduct projects to validate adopted standards
Detect Failure/Attack (22)	
0-3 years	• Create attack test cases • Revise threat matrix for each detection method to estimate "value" (cost to deploy vs. consequences for each method for an attack) • Understand how different failure modes impact different industries/users • Develop early/timely monitor-warning stations • Find weaknesses to suggest areas of improvement for 'white hat' hacking *(ongoing)* • Determine valid fail over, fail back schemes
3-5 Years	• Create a threat matrix identifying failure and attack modes for each of several time distribution systems and estimating consequences • Develop methods to detect failures/attacks in a time distribution system • Determine the means and measurement systems/standards to detect and/or protect against failures/attack

Table 6-1. Priority R&D Topics for Time Distribution Alternatives (associated challenge votes)	
Break Dependency on Space-Based Systems (GPS, 2-Way Satellite) (10)	
0-3 years	• Study the expected results, compute probability, of a Coronal Mass Ejection (CME) disabling all satellite-based systems (i.e., when sun launches billion tons of electrically-conducting gas (plasma) into space at millions of kilometers per hour, laced with magnetic fields) • Enable seamless integration of alternative time systems with space-based systems • Demonstrate national non-space alternative time scale • Demonstrate the impact of GPS loss on grid of the future (*2 years)* • Develop advanced and low-cost chip scale atomic clock and solutions for holdover
3-5 Years	• Conduct R&D on GPS-like systems; ensure cost to user to adopt is minimal; explore high altitude unmanned aerial vehicle (UAV) atomic clocks • Conduct clock characterization (use a disciplined clock to characterize a free running clock) • Deploy eLoran
5-10 Years	• Develop next-generation on-chip scale atomic clock; devices on a chip
10+ Years	• Deploy chip scale atomic clock in every PMU (phasor measurement unit)/substation clock for under $5, with ultra-low power • Develop inexpensive, small, low-power 10^{-13} accurate atomic clock • Research applicability of Quantum Entanglement for time distribution
Optimize Timing System Combinations – Wired and Wireless and Clock (10)	
0-3 years	• Study ensembles of solutions (PTP, GNSS, eLoran for resiliency and security); determine which clock ensembling techniques are the best/most appropriate • Demonstrate the transition between GPS and eLoran or fiber on PMUs (*1 year)* • Build ensembling systems that take the "best" from each system *(phase I)* • Determine the optimization requirements for combining multiple timing solutions
3-5 Years	• Determine how best to accurately and reliably distribute time to all users/communities • Build ensembling systems that take the "best" from each system *(phase II)*
5-10 Years	• Explore self-aware, self-organizing clocks
Develop Timing Networks and Infrastructure (9)	
0-3 years	• More demonstration projects to show applicability in the field under real-world conditions - *ongoing* • Focus on reliability, accuracy, and trustworthiness • Conduct efforts to improve ease of use from end user perspective; include network reservation schemes • Demonstrate indoor capability of eLoran (*1 year)* • Develop low cost eLoran receivers and $50 chip level atomic clock (*3 years)* • Include timing in infrastructure upgrade efforts • Conduct time availability analysis based on application need
3-5 Years	• Characterize new timing systems; evaluate the quality of delivered time (monitoring/reporting) • Realize at least one operational timing system that is "competitive" with GPS • Develop/realize a free-running clock technology that is as cost-competitive and easy to use as GPS with <100 ns/week drift • Use machine learning to detect time inaccuracies (both intentional and not) • Conduct research on WAN terrestrial timing solutions
5-10 Years	• Investigate the feasibility of a nationwide PTP (precision time protocol) time network for utilities with multiple time sources and geographic diversity; assess the economics of a nationwide time service • Determine how well eLoran or WWBV can be used to support/offset GPS as a time service

Table 6-1. Priority R&D Topics for Time Distribution Alternatives (associated challenge votes)	
	• Create PTP wide area star networks with GPS/eLoran/WWVB APTS • Study better (faster, higher resolution) timing delivery mechanisms and methods
10+ years	• Develop network infrastructure that treats time transmission differently than data transmission
Enable Proof of Concept/Multi-Discipline Idea Exchange for Timing Solutions (5)	
0-3 years	• Pull together experts from multiple domains and examine existing timing requirements, challenges, and solutions • Hold a series of workshops on "time distribution alternatives for the smart grid" and invite presentations from other industries • Establish interdisciplinary group to ponder multi-technology solutions (national laboratory-led) • Develop the business case to ensure that the proposed solution(s) are achievable • Create testbed user facility with open access
3-5 Years	• Continue use of testbed user facility with open access
Develop New Technology/Address Equipment Shortfalls (6)	
0-3 Years	• Asymmetry for time transfer in fiber – Develop network elements with symmetric delays - *3-5 years* • Create algorithms for majority voting in multisource systems • Devise methods for integrity monitoring – Step, Slew (rate) • Investigate techniques to detect time distribution errors using local oscillator; develop holdover controlled oscillators • Study deterministic latency (Network "NASPI Net"); conduct demonstration pilot of capabilities of a deterministic network
3-5 Years	• Develop miniaturized, indoor multi PTP, GNSS and eLoran receiver • Investigate small-inexpensive time source for distribution application (multi-source)
5-10 Years	• Conduct advanced grid modeling that includes precision timing in operations • Conduct uncertainty modeling for sub-ms (millisecond) correction
Conduct Demonstrations and Operate Testbeds	
0-3 Years	• Demonstrate the value of existing timing systems in higher-accuracy uses • Build a smart grid testbed to demonstrate timing needs and requirements • Conduct protection, control and threat demonstration with industry • Time sensitive networking (TSN) microgrid testbed active today from Industrial Internet Consortium (IIC) • Simulate an "incident" to cause adverse event and analyze • Inform policy and regulation with recommendations from demonstrations

6.2. Activities to Drive Markets and Industry Acceptance

***Address Market Issues* –** Market drivers are a key to both development and adoption of alternatives. One way to stimulate the economy is through rebuilding/modernizing old infrastructure. Another approach is to develop a high-priority application that will drive users toward new technology. Conducting demonstrations and developing cost-benefit analyses based on the existing PMU infrastructure could provide a way to show the positive impacts of implementing alternatives. Concentrated funding initiatives, such as the Smart Grid Investment Grant program, could help to drive not just technology development but technology transfer. Such a program could be used for deployment projects that use and text new timing options and systems. An overarching requirement is to study and demonstrate how distributed precision timing would benefit utilities. Understanding the value proposition will go a long way toward increasing market demand from the end-users.

***Industry Consensus Building* –** There is currently a lack of consensus, impetus and leadership in the industry to create and adopt new timing solutions. One suggested approach is to create a roadmap and investment strategy for better timing ensembles and delivery methods. There are also ways to leverage and accelerate technology development among the user stakeholders. Educating users about timing is a critical factor as it will motivate both policy and support for development efforts. One approach is to emphasize that upgrading the timing infrastructure will help to protect the grid from physical and cyber-attack; this is important at the national level. Other ways are needed to persuade business and political leaders that it is important to invest in resilience – even if there is no adverse event at present to reference.

7. Path Forward

7.1. Overarching Themes

The results of this workshop illustrate the need for alternatives to existing GPS timing systems as well as backup systems and many of the challenges that need to be addressed to develop and implement alternatives. Some of the overarching themes that emerged include the following:

- While a number of potential alternative exist, they will require further infrastructure, research and concerted investment to implement and demonstrate their potential to replace, supplement, back up, or fill gaps in existing GPS systems.
- Potential alternatives may need to be combined in ensembles to fill gaps, create the needed redundancies, and supplement GPS-based timing.
- Future alternatives to GPS will need to have the same or better levels of accuracy, resilience, security, trustworthiness, and availability to supplant existing systems; a diversity of timing distribution systems may be needed (e.g., terrestrial, communication-based, wireless, etc.).
- Dependency on space-based systems is currently strong due to their perceived reliability; there is limited awareness of the possible adverse impacts of timing failure events in such systems (and few backups exist).
- Developing and using existing alternatives and new technologies, and integrating these with legacy systems will require standards and use cases to enable new technology, architectures, and interoperability among systems.
- Better understanding of attack and failure threat modes is needed to estimate and demonstrate the true consequences of timing failures in systems based entirely on GPS.

7.2. Path Forward

This report was co-sponsored by NIST, the Department of Energy (DOE), and the Grid Modernization Laboratory Consortium (GMLC). NIST and some of the national laboratories have ongoing programs in advanced timing and related topics, and this report will be used to inform both strategic and tactical planning for these programs. The report shall be used to provide guidance for R&D in the NIST Smart Grid Testbed and also as input to the next revision, R4, of the NIST Smart Grid Framework and Roadmap.

The report will be sent directly to all workshop participants and made publicly available online. Notification of the report publication will be sent to members of the North American Synchrophasor Initiative (NASPI), Smart Electric Power Association Smart Grid Interoperability Panel (SEPA SGIP), IEEE Standards Association members, members of IEC Technical Committees 37 and 94, and members of IEEE 1588 working groups. Many of these members are equipment vendors or policy makers the report may help inform their research and development plans.

8. Appendices

Appendix A. Contributors

Name	Affiliation	Name	Affiliation
Shankar Achanta	SEL Inc.	John Lowe	NIST
Stephen Bartlett	URSAMAX	Dan Lutter	Allied Partners
Lee Cosart	Microsemi Corporation	Sarah Mahmood	Department of Homeland Security, Science & Technology
Robert Cummings	NERC	Ken Martin	EPG
Jeff Dagle	Pacific Northwest National Laboratory (PNNL)	R. Jay Murphy	Macrodyne
Phil Evans	Oak Ridge National Laboratory (ORNL)	Paul Myrda	Electric Power Research Institute
Jerry FitzPatrick	NIST	Mitch Narins	Strategic Synergies, LLC
Allen Goldstein	NIST	Bob Noseworthy	UNH-IOL
Dana Goward	RNT Foundation	Farnoosh Rahmatian	NuGrid Power Corp
Ian Gravagne	Sandia National Laboratory (SNL) /Baylor University	Dan Rippon	Schweitzer Engineering
David Howard	Department of Energy (DOE) Office of Electricity Delivery (OE)	David Schoenwald	SNL
Anthony Johnson	SCE	Alison Silverstein	NASPI
Terry Jones	ORNL	Frank Tuffner	PNNL
Harold Kirkham	PNNL	Harsh Vardhan	General Electric
Kang Lee	NIST	Son VoBa	Sync-n-Scale
Ya-Shian Li-Baboud	NIST	Marc Weiss	NIST
Yilu Liu	UTK/ORNL		

Appendix B. Acronyms

AM	Amplitude modulation
APTS	Assisted Partial Timing Support
CME	Coronal mass ejection
CPU	Central processing unit
CRADA	Cooperative Research and Development Agreement
CSAC	Chip-scale atomic clock
DOE	U.S. Department of Energy
DST	Daylight saving time
EMI	Electromagnetic interference
ePRTc	Enhanced primary reference time clock
EV	Electric vehicle
FAA	Federal Aviation Administration
FM	Frequency modulation
GPS	Global positioning system
GNSS	Global Navigation Satellite System
GW	Gravitational wave
HEA	Harbor Entrance and Approach
IEEE	Institute of Electrical and Electronics Engineers
IIC	Industrial internet consortium
MDEV	Modified Allan Deviation
MTBF	Mean time between failure
NIST	National Institute of Standards and Technology
NASPI	North American Synchrophasor Initiative
NPA	Non-Precision Approach
NSPD	National Security Presidential Directive
NTP	Network Time Protocol
OE	Office of Electricity Delivery and Energy Reliability
ORNL	Oak Ridge National Laboratory
PHY	Physical layer
PM	Phase modulated
PMU	Phase measurement unit
PNNL	Pacific Northwest National Laboratory
PNT	Position, Navigation, Time
PTP	Precision Time Protocol
R&D	Research and development
RCC	Radio-controlled clock
RF	Radio frequency
ROI	Return on investment
SMCC	Synchronized Multi-Carrier CDMA
SNIR	Signal-to-noise-plus-interference-ratio
SNL	Sandia National Laboratory
SNTP	Simple Network Time Protocol
TAI	International atomic time
TSN	Time sensitive networking
TPS	Transactions per second
UAV	Unmanned aerial vehicle
USCG	US Coast Guard
USNO	U.S. Naval Observatory
UTC	Universal time coordinated
WAM	Wide area multilateration
WAN	Wide area network

Appendix C. References

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