

IEEE Guide for Designing a Time Synchronization System for Power Substations

IEEE Power and Energy Society

Sponsored by the
Substations Committee

IEEE
3 Park Avenue
New York, NY 10016-5997
USA

IEEE Std 2030.101™-2018

IEEE Guide for Designing a Time Synchronization System for Power Substations

Sponsor

Substations Committee
of the
IEEE Power and Energy Society

Approved 8 March 2018

IEEE-SA Standards Board

Abstract: The design, installation, and monitoring of time synchronization systems in power utility substations is covered. This includes time sources such as Global Positioning Satellite (GPS) and time distribution systems such as Inter-Range Instrumentation Group Format B (IRIG-B), Network Time Protocol (NTP) or Simple Network Time Protocol (SNTP), and IEEE Std C37.238™. The time source and the intelligent electronic device (IED) are assumed to have accurate clocks.

Keywords: IEEE 2030.101™, time synchronization

The Institute of Electrical and Electronics Engineers, Inc.
3 Park Avenue, New York, NY 10016-5997, USA

Copyright © 2018 by The Institute of Electrical and Electronics Engineers, Inc.
All rights reserved. Published 26 July 2018. Printed in the United States of America.

IEEE and IEEE 2030 are registered trademarks in the U.S. Patent & Trademark Office, owned by The Institute of Electrical and Electronics Engineers, Incorporated.

PDF: ISBN 978-1-5044-4637-2 STD22966
Print: ISBN 978-1-5044-4638-9 STDPD22966

IEEE prohibits discrimination, harassment, and bullying.

For more information, visit <http://www.ieee.org/web/aboutus/whatis/policies/p9-26.html>.

No part of this publication may be reproduced in any form, in an electronic retrieval system or otherwise, without the prior written permission of the publisher.

Important Notices and Disclaimers Concerning IEEE Standards Documents

IEEE documents are made available for use subject to important notices and legal disclaimers. These notices and disclaimers, or a reference to this page, appear in all standards and may be found under the heading “Important Notice” or “Important Notices and Disclaimers Concerning IEEE Standards Documents.”

Notice and Disclaimer of Liability Concerning the Use of IEEE Standards Documents

IEEE Standards documents (standards, recommended practices, and guides), both full-use and trial-use, are developed within IEEE Societies and the Standards Coordinating Committees of the IEEE Standards Association (“IEEE-SA”) Standards Board. IEEE (“the Institute”) develops its standards through a consensus development process, approved by the American National Standards Institute (“ANSI”), which brings together volunteers representing varied viewpoints and interests to achieve the final product. Volunteers are not necessarily members of the Institute and participate without compensation from IEEE. While IEEE administers the process and establishes rules to promote fairness in the consensus development process, IEEE does not independently evaluate, test, or verify the accuracy of any of the information or the soundness of any judgments contained in its standards.

IEEE does not warrant or represent the accuracy or content of the material contained in its standards, and expressly disclaims all warranties (express, implied and statutory) not included in this or any other document relating to the standard, including, but not limited to, the warranties of: merchantability; fitness for a particular purpose; non-infringement; and quality, accuracy, effectiveness, currency, or completeness of material. In addition, IEEE disclaims any and all conditions relating to: results; and workmanlike effort. IEEE standards documents are supplied “AS IS” and “WITH ALL FAULTS.”

Use of an IEEE standard is wholly voluntary. The existence of an IEEE standard does not imply that there are no other ways to produce, test, measure, purchase, market, or provide other goods and services related to the scope of the IEEE standard. Furthermore, the viewpoint expressed at the time a standard is approved and issued is subject to change brought about through developments in the state of the art and comments received from users of the standard.

In publishing and making its standards available, IEEE is not suggesting or rendering professional or other services for, or on behalf of, any person or entity nor is IEEE undertaking to perform any duty owed by any other person or entity to another. Any person utilizing any IEEE Standards document, should rely upon his or her own independent judgment in the exercise of reasonable care in any given circumstances or, as appropriate, seek the advice of a competent professional in determining the appropriateness of a given IEEE standard.

IN NO EVENT SHALL IEEE BE LIABLE FOR ANY DIRECT, INDIRECT, INCIDENTAL, SPECIAL, EXEMPLARY, OR CONSEQUENTIAL DAMAGES (INCLUDING, BUT NOT LIMITED TO: PROCUREMENT OF SUBSTITUTE GOODS OR SERVICES; LOSS OF USE, DATA, OR PROFITS; OR BUSINESS INTERRUPTION) HOWEVER CAUSED AND ON ANY THEORY OF LIABILITY, WHETHER IN CONTRACT, STRICT LIABILITY, OR TORT (INCLUDING NEGLIGENCE OR OTHERWISE) ARISING IN ANY WAY OUT OF THE PUBLICATION, USE OF, OR RELIANCE UPON ANY STANDARD, EVEN IF ADVISED OF THE POSSIBILITY OF SUCH DAMAGE AND REGARDLESS OF WHETHER SUCH DAMAGE WAS FORESEEABLE.

Translations

The IEEE consensus development process involves the review of documents in English only. In the event that an IEEE standard is translated, only the English version published by IEEE should be considered the approved IEEE standard.

Official statements

A statement, written or oral, that is not processed in accordance with the IEEE-SA Standards Board Operations Manual shall not be considered or inferred to be the official position of IEEE or any of its committees and shall not be considered to be, or be relied upon as, a formal position of IEEE. At lectures, symposia, seminars, or educational courses, an individual presenting information on IEEE standards shall make it clear that his or her views should be considered the personal views of that individual rather than the formal position of IEEE.

Comments on standards

Comments for revision of IEEE Standards documents are welcome from any interested party, regardless of membership affiliation with IEEE. However, IEEE does not provide consulting information or advice pertaining to IEEE Standards documents. Suggestions for changes in documents should be in the form of a proposed change of text, together with appropriate supporting comments. Since IEEE standards represent a consensus of concerned interests, it is important that any responses to comments and questions also receive the concurrence of a balance of interests. For this reason, IEEE and the members of its societies and Standards Coordinating Committees are not able to provide an instant response to comments or questions except in those cases where the matter has previously been addressed. For the same reason, IEEE does not respond to interpretation requests. Any person who would like to participate in revisions to an IEEE standard is welcome to join the relevant IEEE working group.

Comments on standards should be submitted to the following address:

Secretary, IEEE-SA Standards Board
445 Hoes Lane
Piscataway, NJ 08854 USA

Laws and regulations

Users of IEEE Standards documents should consult all applicable laws and regulations. Compliance with the provisions of any IEEE Standards document does not imply compliance to any applicable regulatory requirements. Implementers of the standard are responsible for observing or referring to the applicable regulatory requirements. IEEE does not, by the publication of its standards, intend to urge action that is not in compliance with applicable laws, and these documents may not be construed as doing so.

Copyrights

IEEE draft and approved standards are copyrighted by IEEE under US and international copyright laws. They are made available by IEEE and are adopted for a wide variety of both public and private uses. These include both use, by reference, in laws and regulations, and use in private self-regulation, standardization, and the promotion of engineering practices and methods. By making these documents available for use and adoption by public authorities and private users, IEEE does not waive any rights in copyright to the documents.

Photocopies

Subject to payment of the appropriate fee, IEEE will grant users a limited, non-exclusive license to photocopy portions of any individual standard for company or organizational internal use or individual, non-commercial use only. To arrange for payment of licensing fees, please contact Copyright Clearance Center, Customer Service, 222 Rosewood Drive, Danvers, MA 01923 USA; +1 978 750 8400. Permission to photocopy portions of any individual standard for educational classroom use can also be obtained through the Copyright Clearance Center.

Updating of IEEE Standards documents

Users of IEEE Standards documents should be aware that these documents may be superseded at any time by the issuance of new editions or may be amended from time to time through the issuance of amendments, corrigenda, or errata. An official IEEE document at any point in time consists of the current edition of the document together with any amendments, corrigenda, or errata then in effect.

Every IEEE standard is subjected to review at least every 10 years. When a document is more than 10 years old and has not undergone a revision process, it is reasonable to conclude that its contents, although still of some value, do not wholly reflect the present state of the art. Users are cautioned to check to determine that they have the latest edition of any IEEE standard.

In order to determine whether a given document is the current edition and whether it has been amended through the issuance of amendments, corrigenda, or errata, visit the IEEE-SA Website at <http://ieeexplore.ieee.org/xpl/standards.jsp> or contact IEEE at the address listed previously. For more information about the IEEE-SA or IEEE's standards development process, visit the IEEE-SA Website at <http://standards.ieee.org>.

Errata

Errata, if any, for all IEEE standards can be accessed on the IEEE-SA Website at the following URL: <http://standards.ieee.org/findstds/errata/index.html>. Users are encouraged to check this URL for errata periodically.

Patents

Attention is called to the possibility that implementation of this standard may require use of subject matter covered by patent rights. By publication of this standard, no position is taken by the IEEE with respect to the existence or validity of any patent rights in connection therewith. If a patent holder or patent applicant has filed a statement of assurance via an Accepted Letter of Assurance, then the statement is listed on the IEEE-SA Website at <http://standards.ieee.org/about/sasb/patcom/patents.html>. Letters of Assurance may indicate whether the Submitter is willing or unwilling to grant licenses under patent rights without compensation or under reasonable rates, with reasonable terms and conditions that are demonstrably free of any unfair discrimination to applicants desiring to obtain such licenses.

Essential Patent Claims may exist for which a Letter of Assurance has not been received. The IEEE is not responsible for identifying Essential Patent Claims for which a license may be required, for conducting inquiries into the legal validity or scope of Patents Claims, or determining whether any licensing terms or conditions provided in connection with submission of a Letter of Assurance, if any, or in any licensing agreements are reasonable or non-discriminatory. Users of this standard are expressly advised that determination of the validity of any patent rights, and the risk of infringement of such rights, is entirely their own responsibility. Further information may be obtained from the IEEE Standards Association.

Participants

At the time this IEEE guide was completed, the H38 Working Group had the following membership:

James Bougie, *Chair*

Galina Antonova	Michael Dood	David Ingram
Farel Becker	Bill Dickerson	Neil McKenzie
Roland Cooke	Kevin Easley	Craig Preuss
Roel De Vries	Doug Gischlar	Joel Sandahl
	Chris Huntley	

The following members of the individual balloting committee voted on this guide. Balloters may have voted for approval, disapproval, or abstention.

Ali Al Awazi	Roman Graf	Pierre Martin
Jay Anderson	Eric W. Gray	John McDonald
Ian Backus	Randall Groves	Jerry Murphy
David Beach	Werner Hoelzl	R. Murphy
Philip Beaumont	Gary Hoffman	Bruce Muschlitz
Wallace Binder	C. Huntley	Michael Newman
William Bloethe	Innocent Kamwa	Charles Rogers
James Bougie	Piotr Karocki	Bartien Sayogo
William Bush	Yuri Khersonsky	Thomas Schossig
Paul Cardinal	Hermann Koch	Nikunj Shah
Stephen Conrad	Boris Kogan	Veselin Skendzic
Ratan Das	Jim Kulchisky	Jerry Smith
Matthew Davis	Marc Lacroix	Gary Smullin
Kevin Donahoe	Chung-Yiu Lam	Wayne Stec
Michael Dood	Robert Landman	Eric Thibodeau
Neal Dowling	Charles Lennon	Michael Thompson
Kenneth Fodero	Albert Livshitz	Joe Uchiyama
Vasudev Gharpure	Bruce Mackie	John Vergis
Jalal Gohari	Kenneth Martin	James Volk

When the IEEE-SA Standards Board approved this guide on 8 March 2018, it had the following membership:

Jean-Philippe Faure, *Chair* **Vacant Position, *Vice Chair*** **John D. Kulick, *Past Chair*** **Konstantinos Karachalios, *Secretary***

Chuck Adams	Michael Janezic	Robby Robson
Masayuki Ariyoshi	Thomas Koshy	Dorothy Stanley
Ted Burse	Joseph L. Koepfinger*	Adrian Stephens
Stephen Dukes	Kevin Lu	Mehmet Ulema
Doug Edwards	Daleep Mohla	Phil Wennblom
J. Travis Griffith	Damir Novosel	Howard Wolfman
Gary Hoffman	Ronald C. Petersen	Yu Yuan
	Annette D. Reilly	

*Member Emeritus

Introduction

This introduction is not part of IEEE Std 2030.101–2018, IEEE Guide for Designing a Time Synchronization System for Power Substations.

Time synchronization is an important part of modern electric utility power system design and operation, but it is critical to the emerging requirements for smart grid operation.

The purpose of this document is to provide guidance in the design of time synchronization systems for electric utility power substations to help ensure that they are adequately designed, tested, and maintained in order to support the present and future applications that rely on accurate and reliable time.

This guide is intended for time synchronization system design and includes many different recommendations that could be implemented, should the designer choose to do so. Manufacturers of satellite clocks, intelligent electronic devices (IEDs), or other time synchronization system components and equipment are not expected to claim conformance to this guide (although this guide may provide manufacturers with product features that might be useful to designers using this guide). There is no planned certification of time synchronization systems to this guide.

Contents

1. Overview	12
1.1 Scope	12
1.2 Purpose	12
2. Normative references	12
3. Definitions	13
4. Time synchronization system design	14
4.1 Introduction	14
4.2 IED information	15
4.3 Accuracy requirements	16
4.4 Time references	19
4.5 Time standards	20
4.6 Time distribution systems	23
4.7 IED internal timing systems	25
4.8 Time reference distribution	27
4.9 Wired time distribution	35
4.10 Network time distribution	46
4.11 Optical fiber time distribution	47
4.12 System power	49
4.13 System availability	49
4.14 System vulnerabilities	54
4.15 Miscellaneous	57
5. System testing	60
5.1 Introduction	60
5.2 Type testing	60
5.3 Routine testing	61
5.4 Factory/site acceptance testing	61
6. System maintenance	64
6.1 Introduction	64
6.2 Monitoring alarm points	65
6.3 Periodic checking/testing of a time synchronization system	65
Annex A (informative) Bibliography	66
Annex B (informative) Time synchronization system configurations	68
Annex C (informative) Time references	73
Annex D (informative) Time distribution options	89
Annex E (informative) Ethernet networks	108
Annex F (informative) Uses of one pulse per second (1PPS) outputs to determine time-base standard performance	112
Annex G (informative) Vulnerabilities of time synchronization systems	114

List of Figures

Figure 1—Example internal timing system of an IED	16
Figure 2—Timing synchronization accuracy across a timing chain	17
Figure 3—Example timing system of a time standard	20
Figure 4—Wireless reception.....	28
Figure 5—Coaxial cable multi-drop transmission line network (end-fed)	36
Figure 6—AC impedance load for a transmission line	39
Figure 7—DC load for a transmission line	40
Figure 8—Simplified diagram of dc loading for a transmission line	41
Figure 9—Transmission line amplifier-splitters and amplifier-repeaters	44
Figure 10—Redundant antenna selector	52
Figure 11—Redundant antenna-splitter selector	53
Figure 12—Redundant wired distribution selector.....	53
Figure 13—Redundant wired reference selector	53
Figure 14—Redundant wired amplifier-repeater selector	53
Figure 15—Redundant wired transmission lines.....	54
Figure B.1—Basic time synchronization system.....	68
Figure B.2—Time synchronization system with time interfaces shown.....	69
Figure B.3—Time synchronization system with time standards	69
Figure B.4—Time standard with multiple output time interfaces.....	70
Figure B.5—Time standard with multiple input and output time interfaces	70
Figure B.6—Multi-drop topology for time distribution	70
Figure B.7—Multi-drop topology with multiple bus drivers, bus amplifiers, and bus repeaters	71
Figure B.8—Star topology with and without switches	71
Figure C.1—Traceability chain for NIST time and frequency services	76
Figure C.2—Simple generic time reference system	77
Figure C.3—WWVB daytime geographic coverage	78
Figure C.4—WWVB nighttime geographic coverage.....	79
Figure C.5—DCF77 geographic coverage area.....	80
Figure C.6—Sky plot of GPS satellites (8 October, 2013 to 9 October, 2013, Kansas City, Missouri, United States)	83

Figure C.7—Time plot of GPS satellites (8 October, 2013 to 9 October, 2013, Kansas City, Missouri, United States)	84
Figure C.8—GLONASS PDOP values ($\text{angle} \geq 5^\circ$).....	85
Figure C.9—BeiDou geographic coverage	85
Figure D.1—1PPS example transmission	89
Figure D.2—IRIG-A through IRIG-H serial time codes	91
Figure D.3—NTP/SNTP time distribution	94
Figure D.4—PTP time distribution.....	96
Figure D.5—Conversion between one-step and two-step clocks	102
Figure D.6—IEEE Std C37.238 steady-state performance requirements.....	105
Figure E.1—Logical Ethernet network	108
Figure E.2—Physical Ethernet network	109
Figure E.3—IP network.....	110
Figure F.1—Time standard, holdover, frequency error.....	113
Figure F.2—Time standard, holdover, time error	113

List of Tables

Table 1—Summary comparison of time distribution methods	24
Table 2—Common transmission line drivers	37
Table 3—Common transmission line receivers	37
Table 4—Common transmission line characteristic impedances	38
Table 5—1PPS fiber-optic distribution parameters	48
Table 6—System elements, risk, failure modes, impacts, and actions for higher availability.....	50
Table C.1—Time reference sources, distribution methods, and accuracy	73
Table D.1—Permissible IRIG-A through IRIG-H variants	90
Table D.2—Comparison between PTPv2 peer-to-peer default profile and the power profile	98
Table D.3—Intervals for power profile messages.....	100

IEEE Guide for Designing a Time Synchronization System for Power Substations

1. Overview

1.1 Scope

This guide covers the design, installation, and monitoring of time synchronization systems in power utility substations. This includes time sources such as Global Positioning Satellite (GPS), and time distribution systems such as Inter-Range Instrumentation Group Format B (IRIG-B), Network Time Protocol (NTP) or Simple Network Time Protocol (SNTP), and IEEE Std C37.238™ plus IEC/IEEE 61850-9-3. This guide assumes that the time source and the intelligent electronic device (IED) have accurate clocks.

1.2 Purpose

Time synchronization is now critical to the smart grid, with substations using legacy systems and new standards for network time synchronization, a guide is needed to help ensure adequate system design is undertaken to support the applications relying on accurate and reliable time.

2. Normative references

The following referenced documents are indispensable for the application of this document (i.e., they must be understood and used, so each referenced document is cited in text and its relationship to this document is explained). For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments or corrigenda) applies.

IEC 61588-2009, IEC/IEEE Precision Clock Synchronization Protocol for Network Measurement and Control Systems.^{1,2}

IEEE Std 1588™-2008, IEEE Standard for a Precision Clock Synchronization Protocol for Networked Measurement and Control Systems.^{3,4}

¹IEC publications are available from the International Electrotechnical Commission (<http://www.iec.ch>) and the American National Standards Institute (<http://www.ansi.org/>).

²This is the adoption of IEEE Std 1588™-2008.

³The IEEE standards or products referred to in [Clause 3](#) are trademarks owned by The Institute of Electrical and Electronics Engineers, Incorporated.

⁴IEEE publications are available from The Institute of Electrical and Electronics Engineers (<http://standards.ieee.org/>).

IEEE Std 1613™-2009, IEEE Standard Environmental and Testing Requirements for Communications Networking Devices Installed in Electric Power Substations.

IEEE Std 1613.1™-2013, IEEE Standard Environmental and Testing Requirements for Communications Networking Devices Installed in Transmission and Distribution Facilities.

IEEE Std 1815™, IEEE Standard for Electric Power Systems Communications—Distributed Network Protocol (DNP3).

IEEE Std C37.118.1a™-2014, IEEE Standard for Synchrophasor Measurements for Power Systems Amendment 1: Modification of Selected Performance Requirements.

IEEE Std C37.238™, IEEE Standard Profile for Use of IEEE 1588™ Precision Time Protocol in Power System Applications.

3. Definitions

For the purposes of this document, the following terms and definitions apply. The *IEEE Standards Dictionary Online* should be consulted for terms not defined in this clause.⁵

accuracy, time-base synchronization: Time-base synchronization accuracy is the typical deviation between the synchronized internal time-base and a reference signal expressed in terms of nanoseconds, microseconds, or milliseconds.

accuracy, time-base: Time-base accuracy is the frequency accuracy that an internal time-base oscillator can maintain relative to a selected incoming reference and is expressed as scalars in scientific notation (e.g., 1×10^{12}).

accuracy, wireless receiver: For a wireless receiver, accuracy is the range of deviation between reference signal outputs from the interface and the reference source signal, expressed in terms of nanoseconds, microseconds, or milliseconds.

central control element: The central control element of an intelligent electronic device (IED) is responsible for the overall operation and control of the IED.

clock: For an intelligent electronic device (IED), the clock serves as the source of time for IED time-based monitoring and control functions. Refer to IEEE Std C37.2™ CLK description.⁶

communications interface: An intelligent electronic device's (IED) communications interface supports centralized monitoring and control for overall time distribution system management.

functional interface: An intelligent electronic device's (IED) functional interface provides data that relies on synchronized time in order to perform the IED's functions.

receiver: Receivers in a time synchronization system receive and demodulate the radio carrier signals, decode the time coded signals, and output time information.

⁵IEEE Standards Dictionary Online subscription is available at: <http://ieeexplore.ieee.org/xpls/dictionary.jsp>.

⁶Modern IEDs use internal oscillators as the basis for their clocks, just as time standards. The use of time distribution to continuously synchronize IED clocks enables them to use lower stability oscillators that can be significantly lower in cost. When free running, these oscillators may not provide the required accuracy for extended periods of time, but with frequent external synchronization these oscillators can meet system performance requirements. Accordingly, modern IED clocks are actually time standards. Fundamentally, they only differ from time standards in their level of performance (stability and accuracy) and their scope of use (individual or limited versus system or site-wide). Today, process clocks and counter-timers can provide very high levels of clock stability and accuracy for negligible cost.

selectivity: The ability of a wireless receiver to reject out-of-band interference.

sensitivity: The ability of a wireless receiver to provide higher quality time signal output for a given radio signal-to-noise ratio (SNR).

stability: Time-base stability is the frequency accuracy over time (including aging) that the oscillator is expected to maintain in holdover mode (when all incoming references are lost). It is a scalar value expressed in scientific notation (e.g., 1×10^{-12}). Stability is usually expressed as a scalar amount per day (e.g., 1×10^{-10} /day).

time distribution interface: A time distribution interface on an intelligent electronic device (IED) accepts a time input from the time reference distribution system. Many IEDs today still have one time distribution interface, but IEDs with multiple time distribution interfaces are becoming more common. A time distribution interface distributes the time information using one or more of the time distribution systems described in 4.6.

time distribution system: The collection of equipment appropriate for localized time distribution information between intelligent electronic devices (IEDs). Localized means site-wide or intranet distribution methods, as opposed to methods used for time distribution information from public time reference sources, which are described in Annex C. Some of the network-based distribution methods that are described here are used for non-local time distribution.

time reference interface: A time reference interface distributes time in a specific time standard time base using one or more time reference distribution methods. A time reference interface recovers the time reference signal from the time distribution medium.

time synchronization system: A system that synchronizes quasi-independent clocks in diverse intelligent electronic devices (IEDs) that are distributed across defined systems of IEDs so that the IEDs all have a singular understanding of “what time it is” over time in order to support the applications supported by the IEDs.

type test: A single, one-time test of individual component models to determine compliance or conformance to one or more identified standards. A type test is valid until the tested model is significantly changed with respect to what was tested. A type test can apply to a single component, assembly, cable, or fully assembled device, such as an intelligent electronic device (IED).

4. Time synchronization system design

4.1 Introduction

This clause outlines a design process for time synchronization systems (refer to Annex B), which addresses:

- 1) Intelligent electronic device (IED)—specific capabilities information (refer to 4.2)
- 2) The applications each IED is supporting and their time synchronization requirements (refer to 4.3)
- 3) Accuracy requirements (refer to 4.4)
- 4) Time standards (refer to 4.5)
- 5) Time distribution methods (refer to 4.6)
- 6) IED capabilities related to clocks and time synchronization (refer to 4.7)
- 7) Time reference distribution considerations (refer to 4.8)
- 8) Wired time distribution issues (refer to 4.9)
- 9) Network (Ethernet based) time distribution considerations (refer to 4.10)

- 10) Optical fiber cable time distribution considerations (refer to 4.11)
- 11) System powering considerations (refer to 4.12)
- 12) System availability to provide acceptable levels of system performance (refer to 4.13)
- 13) System vulnerability considerations to overcome system vulnerabilities (refer to 4.14)
- 14) Miscellaneous items, such as human-machine interfaces (HMIs), security, alarms, time synchronization system management, environmental, mechanical, etc. (refer to 4.15)

NOTE—The organization of this list does not imply a step-by-step process to be followed in the order presented. The order of the tasks may be changed by the designer. Some tasks may require iterative processes. Some steps could be combined with other steps in order to complete. The designer should carefully assess the removal of any tasks.⁷

4.2 IED information

Designing a time synchronization system (refer to [Annex B](#)) requires gathering information regarding the time distribution interfaces for all the IEDs that the time synchronization system is to support. For each IED, the designer should:

- a) Record the IED name and its location, including rack or cabinet information
- b) Identify the number of time distribution interfaces (refer to [Figure 1](#))
 - 1) For each time distribution interface identified, record the following:
 - i) Type of interfaces supported (refer to [Annex D](#)), which can be more than one
 - ii) Type of connector (e.g., Bayonet Neill–Concelman [BNC], screw-terminal, optical fiber connector, etc.)
 - iii) Type of cabling (including communication network connection) (e.g., 50 Ω coaxial cable, shielded twisted pair [STP], Ethernet cable, optical cable, etc.)
 - iv) Signal range or voltage threshold (if any)
 - v) Available impedance options (if any)
 - vi) Available dc load options (if any)
 - vii) Capacitive load

Once all of the IEDs have been identified and characterized, the designer groups the IEDs based on the compatibility of their time distribution interfaces. For example, group all IRIG-xyz IEDs together into protocol-variant compatible groups. Group all one pulse per second (1PPS) IEDs together, etc. These groups are important because they could become the basis for individual time distribution systems.

⁷Notes in text, tables, and figures of a standard are given for information only and do not contain requirements needed to implement this standard.

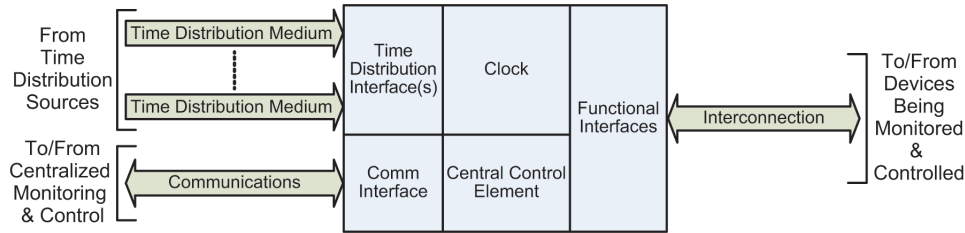


Figure 1—Example internal timing system of an IED

NOTE—IEDs supporting multiple time distribution interfaces or variant synchronization methods provide opportunities to consolidate IEDs into fewer time distribution systems, which could reduce engineering, installation, and maintenance costs because fewer systems result in less equipment and complexity. Fewer time distribution systems also make it easier to increase system availability (refer to 4.13).

4.3 Accuracy requirements

4.3.1 Introduction

Next, the designer determines the accuracy requirements, a critical step in the design process, first and foremost, because the time synchronization accuracy provided by the time synchronization system depends on the requirements for the applications being supported by the IEDs. Some applications may only require timing accuracy on the order of one second. Other applications, like synchrophasors, may require (or desire) timing accuracy on the order of 0.10° at 60 Hz ($\pm 5 \mu\text{s}$) or better. As such, the designer considers what applications are being supported in the IEDs that require accurate time.

First, the designer needs to understand the difference between time synchronization *accuracy* and *resolution* because they are often confused. *Accuracy* defines the measurement of something against an “absolute reference or standard” with an absolute degree of precision and certainty. *Resolution* is the precision with which something is measured and resolved, independent of its accuracy.

NOTE—Many GPS receivers advertise 100 ns “accuracy.” Since GPS is only maintained to 100 ns (refer to C.4.2), this is impossible (GPS typically yields 1 μs accuracy). In reality, these GPS receivers have 100 ns of accuracy to the received time, which is also off by 100 ns. So the total accuracy could be upwards of 200 ns (refer to Figure 2).

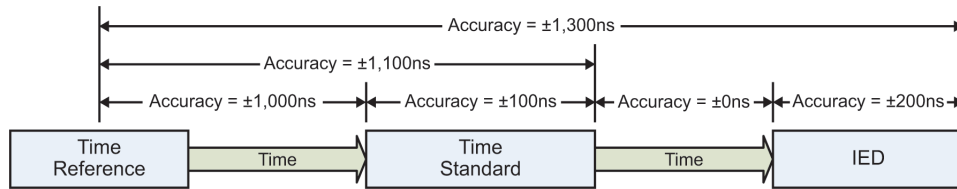


Figure 2—Timing synchronization accuracy across a timing chain

CAUTION

IEEE Std C37.1™-2007 recommends that IEDs supporting applications with required accuracies have their clocks set to 10 times better than that required accuracy. This means that applications requiring ± 1 ms accuracy have their clocks be accurate to ± 0.1 ms. This is not a resolution issue, but an accuracy issue. For example, a 10-digit frequency counter can measure up to 99 999 999.99 Hz. A 10 MHz signal is measured as 10 000 000.10 Hz. The 10 MHz signal has an implied frequency error (inaccuracy) of $+0.10$ Hz with a resolution of ± 0.01 Hz. But unless the frequency counter has been recently calibrated, the *accuracy* is actually unknown. Checking the calibration of the frequency counter may find that its accuracy is 1×10^{-8} ; consequently then the 10 MHz signal that was measured actually had a frequency error of zero with a resolution of ± 0.01 Hz. Although the reading has two digits to the right of the decimal point (resolution), implying ± 0.01 Hz accuracy, there was in fact a 0.10 Hz error in the measurement.

In general, the designer should consider that the time synchronization system supports any applications requiring time-based information and carrying out time-based control actions.⁸ More specifically, utilities use many applications requiring the support of synchronized time and the designer must understand which ones are being supported by the IEDs.

4.3.2 Monitoring and controlling grid power frequency and phase

One of the oldest and most widespread uses of synchronized time is monitoring and controlling grid power frequency and phase (Dickerson [B4]). Grid power frequency and phase monitoring typically requires sub-millisecond level timing accuracy. Over time, the older traditional methods are being supplanted by synchrophasors (see 4.3.6).

4.3.3 Multi-rate billing

To improve power system utilization and efficiency, some utility companies incentivize customers to use power at off-peak times by providing billing rates based on the time-of-consumption (Dickerson [B4]). In the future, this practice may encompass even larger numbers of utilities and customers. To accurately compute billing charges, synchronized time is required to measure and record power consumption over time. Multi-rate billing typically requires sub-second level timing accuracy.

⁸The gathering of time-based information involves the use of remote sensors to monitor and report system states, state-changes, and measurement information back to one or more systems that monitor system status/state, make system measurements, report system anomalies, analyze system performance, and/or control system processes. While sensor information may be useful standing alone, applying timestamps to the information enables the capturing of conditions, events, and information in precise time and sequence, providing powerful insights into root causes for anomalous behaviors, more accurate process controls, and finer-grained operational assessments. But timestamps are only useful when all timestamp clocks are synchronized so that the information from diverse sources can be accurately correlated in time. Gathered information usually diminishes in significance when it becomes more distant in time from significant events. For example, to the extreme, yesterday's high load condition probably has little to do, directly, with the protective switch that just occurred one second ago. The carrying out of time-based control actions involves the use of remote controls to cause system actions. Remote control devices operate under the direction of one or more control systems that use control algorithms to process gathered information and, when required, cause control actions to take place. Often, remote controls must be able to perform their prescribed actions at precise moments in time or in precisely timed sequences with respect to other remote control actions, which can only happen if all remote control clocks are synchronized together.

4.3.4 Power quality billing

Many utility companies and system operators are now considering and, in some cases, implementing financial incentives to customers to assist in maintaining power quality (Dickerson [B4]). Certain types of loads are well known for causing power quality impairments, such as metal refineries that often cause harmful harmonics and flicker. Power quality impairments are defined by international standards. For example, IEC 61000-4-11 and IEC 61000-4-34 are voltage sag standards. Typically, power quality events are measured and recorded with time-of-occurrence and expressed in intensity terms as events occurring within bounded intervals of time. IEEE Std 1159™ provides detailed descriptions for several power quality variation categories, including the phenomena that cause them. Power quality data is transferred using the Power Quality Data Interchange Format (PQDIF) in IEEE Std 1159.3™ and provides a time stamp resolution to 10^{-9} seconds, or nanoseconds. Accordingly, synchronized time is required to accurately record times-of-occurrence as well as the bounding intervals. Power quality billing typically requires sub-second level timing accuracy, while power quality recording may require nanosecond accuracy.

4.3.5 Sequences of events (SOE)

For real time control, as well as diagnosing faults and root causes, IEDs monitor and control key elements across power systems, recording and reporting significant events and information that occur during system operation. This information is only useful if it includes timestamps to establish the sequence and context of the associated information. Without accurate time information, it may be impossible to determine the sequence of events and, therefore, the causal relationships. Synchronized time is required in order to accurately determine the sequence of information. North American Electric Reliability Corporation (NERC) PRC-018-1 requires disturbance and monitoring equipment used by transmission and generator system owners to be synchronized to within ± 2 ms of Coordinated Universal Time (UTC, from the French name Temps Universel Coordonné). IEEE Std 1815™ provides the capability to time stamp data to 1 ms. So, SOE recording typically requires millisecond-level timing accuracy.

4.3.6 Synchrophasors

Synchronized phasor measurement units, also known as PMUs, produce synchrophasors that are used to monitor power systems, determine stability margins, maximize stable system loading, detect islanding, record system disturbances, visualize dynamic system responses, and validate system models. Geographically distributed across power systems, synchrophasors make synchronized real time measurements of electrical quantities (refer to IEEE Std C37.118.2™) and communicate them back (refer to IEEE Std C37.118.1a™-2014) to phasor data concentrators (PDCs) (refer to IEEE Std C37.244™), where the data is processed, analyzed, and visually displayed. As the name implies, synchrophasors require synchronized time with very high precision and accuracy. For IEDs computing synchrophasor data, the maximum allowable time error in IEEE Std C37.118.1a-2014, leaving no additional error margin in computing synchrophasor data, is ± 26 μ s for a 60 Hz system and ± 31 μ s for a 50 Hz system.

4.3.7 Other accuracy requirements

To aid in characterizing accuracy requirements, the designer could use IEC 61850-5:2013 [B7] and IEC 61850-90-1:2010 [B8] as references to characterize typical timing requirements, even when IEC 61850 is not being used. Six classes of timing accuracy TL—T0, T1, T2, T3, T4, and T5—are presented in Table 2 and Table 3 in 11.1.3.3 of IEC 61850-5-2013 [B7], including example applications for each; such as two for synchronized sampling, or process bus. When IEDs provide a time stamp and claim conformance to IEC 61850, IEC 61850-8-1:2011 requires the use of a time synchronization protocol to support the accuracy classes.

Once the designer identifies all of the accuracy requirements of the applications being supported by each IED, the designer adds this information to the groups established in 4.2. That being said, the designer needs to keep in mind that many IEDs only require low precision time, but their time will be used to timestamp events and information that may be communicated and merged with information from IEDs that use higher precision time. There are many instances where merging information from mixed precision timestamps will not matter.

However, when configuring a system, the designer should be mindful of situations where merging information from mixed precision timestamps will matter and configure the system accordingly. So the designer may choose to place some IEDs in higher accuracy groups. The designer then adjusts the groups so that each application's timing requirements are met.

CAUTION

Without considering the timing accuracy requirements for all applications being supported by the IEDs, the designed time synchronization system is unlikely to support each application's time synchronization requirements.

Ultimately, time synchronization accuracy is time distribution system dependent. That is, the accuracy included by the design is that required to meet the needs of all IEDs that are using a particular time distribution system from a particular time reference or standard. Accuracy does not necessarily need to be the same across the power system or even one location. There are at least two approaches to designing the time distribution system:

- The accuracy is better than (preferably much better than) the minimum accuracy required by the most demanding IED (one with the highest accuracy requirement) fed by the time distribution system.
- Separate time distribution systems are used to distribute time at the minimum accuracy required by the most demanding IED on each system. In this instance, IRIG-B may be used for the PMUs, while NTP is used for other IEDs, and IEEE Std 1815 (Distributed Network Protocol 3 [DNP3]) is used for other IEDs.

NOTE—Although IEC 61850 includes an indication of quality associated with a time stamp (refer to “TimeQuality” in IEC 61850-7-2:2010), few other IEDs report the accuracy of their internal clocks and synchronization status at the time that the information is stamped with time (defining a timestamp is ongoing work within The IEEE).

Finally, when the designer configures the time synchronization system for accuracy, it is important to recognize that timing synchronization errors in timing chains are additive. Consider the timing chain in [Figure 1](#).

There is ± 1000 ns of accuracy between the absolute time reference (refer to 4.4) and the input to the time standard. The time standard imparts ± 100 ns of error between its input and output, so the absolute accuracy on output is ± 1100 ns (1000 ns + 100 ns). The IED imparts ± 200 ns of error between its input and output (use), so the absolute accuracy on output is ± 1300 ns (1000 ns + 100 ns + 200 ns). Although it is likely that the accuracy will be better than that for much of the time, statistically speaking, there is no assurance that it is at any particular moment in time, and the IEDs would never know when those moments in time would be. This can be particularly troublesome, for example, with IEDs that have both an IRIG input and IRIG output, which introduces some small delay that may not be well documented.

Once the accuracy requirements (refer to 4.3) and IED information are gathered (refer to 4.2), the designer selects the time reference.

4.4 Time references

The designer selects a time reference to provide the singular source of time (definition of time) for the system so that time can be accurately correlated across and between systems. Time references may be public sources, such as those that are provided by various governmental bodies, or private sources, such as those that might be provided by a utility for itself.

It is strongly recommended to use public time reference sources that are traceable to the International Atomic Time (TAI, from the French name Temps Atomique International)⁹ and/or UTC¹⁰. Both of these sources are coordinated by the International Bureau of Weights and Measures (BIPM, from the French name Bureau International des Poids et Mesures).

UTC and TAI are recommended as the time reference because electric utilities tend to cover large geographic areas. Further, it is often desirable to share time-correlated information between utility entities. This means that all entities must be synchronized to time reference sources that are traceable to a common source. Creating and maintaining reliable time reference sources with broad geographic distribution is very complicated and expensive. There are many challenges in sharing private time reference sources between disparate business entities. Therefore, as a practical matter, public time reference sources are much more cost-effective solutions. Not surprisingly, most systems today are, in fact, synchronized to public time reference sources. Therefore, this guide focuses on public time reference sources and only mentions private time reference sources in the interest of completeness. Refer to [Annex C](#).

4.5 Time standards

4.5.1 Introduction

Next, the designer needs to consider time standards, which provide localized sources of time base (definitions of time) for systems, much like time references do, but time standards do so by synchronizing and disciplining to time references. In doing so, time standards can significantly improve upon the quality and availability of time services relative to what might be available from a time reference at a given site location.

Of necessity, public time references, such as those provided by governmental entities, are usually distributed over vast geographic areas using complex wireless transmission systems. Although the time references are usually pristine at their source, they are often significantly degraded in quality and intermittently available at their destinations due to transmission limitations and impairments that are common to wireless transmission mediums. Time standards address these and other important system issues.

A good time synchronization system design includes one or more time standards that consist of one or more time reference interfaces as inputs, a time standard time base, one or more time distribution interfaces as output, a communications interface, and a central control element. This is illustrated in [Figure 3](#).

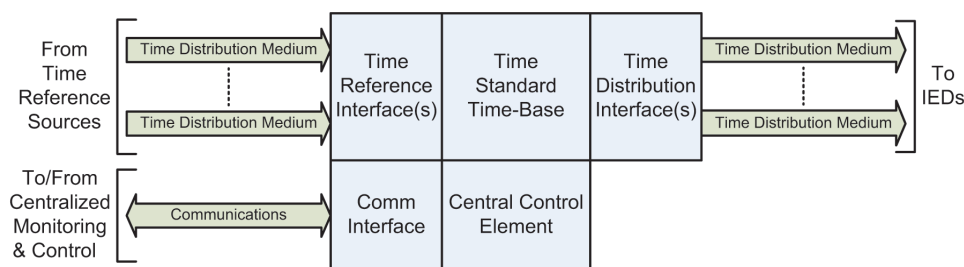


Figure 3—Example timing system of a time standard

⁹TAI is an internationally coordinated, high-precision atomic time standard based on the notion of time passage along the Earth's geoid. It is based on the weighted average of time kept by more than 200 atomic clocks in more than 50 national laboratories worldwide.

¹⁰UTC, which is used for civil timekeeping all over the world, is driven by the TAI time base, but it is adjusted with periodic "leap seconds" in order to keep the time of day close to the mean solar time. Without such a correction, time reckoned by Earth rotation would drift away from atomic time because of irregularities in the Earth's rate of rotation. At the time this document was written, the most recent leap second adjustment occurred on 30 June, 2015, at 23:59:60 UTC. Accordingly, TAI and UTC time differ only by a well-known number of leap seconds that have been added or subtracted since the initiation of TAI. At the time that this document was written, the difference between TAI and UTC stood at 36 s (10 s prior to when this scheme was first implemented in 1972, and 26 s subsequent to 1972).

A time reference interface accepts input from one or more compatible time reference source-distribution pairs, such as those described in [Figure C.1](#). These are used to synchronize and discipline the time standard time base.

The designer needs to understand that time standards impact the system design through the following underlying principles:

- a) By definition, time references provide long-term accuracy.
- b) Time reference distribution methods frequently result in short-term instability (inaccuracy-uncertainty) and lack of availability.
- c) The distribution of time information includes considerable redundant information. That is, the time information is highly repetitive. Most time information messages reaffirm rather than establish time synchronization.
- d) Once a time standard is synchronized, future time information messages are easily synthesized.
- e) By incorporating precision time standards such as high-quality quartz or atomic oscillators, time standards can improve incoming time reference accuracy by averaging out short-term reference instabilities over long periods of time, improve outgoing time distributions by eliminating instabilities, and bridge outages in incoming time references.

Through investigation of these principles, the designer will likely conclude that all time standards are not created equally. They can have many different features and operating characteristics. Some important features and characteristics should be evaluated by the designer:

- a) Number of time reference interfaces
- b) Performance of time reference interfaces
- c) Programmable time reference interfaces
- d) Time-base synchronization accuracy
- e) Time-base accuracy and stability
- f) 1PPS interface

4.5.2 Number of time reference interfaces

Multiple time reference interfaces *can* improve system availability. In the case where the time reference interface inputs use the same time reference, backup is provided for one source and would protect against the failure of one input. In the case where the time reference interfaces use different time references, this may provide redundancy and vulnerability protection by providing consistency checking between the time reference interface inputs. These are the only reasons to have multiple interfaces. Today, most time standards only provide one reference interface (e.g., GPS), but more time standards will have multiple interfaces in the future. That being said, merely having multiple time reference interfaces does not assure that the aforementioned benefits will be realized. The implementation must be effective. Ideally, the designer should confirm that the time standard will:

- Allow the mixing of diverse time reference interface types (i.e., not limited to identical interface types)
- Continuously monitor all time reference interfaces, checking for functionality and consistency, reporting anomalous behavior to a monitoring system, as well as addressing any quality information provided in the distributed time

- Include effective logic for time reference interface selection and switching that appropriately addresses any quality information provided in the distributed time

NOTE—Not all logic is the same, so the designer should understand how to implement the logic to accomplish the desired functionality.

4.5.3 Performance of time reference interfaces

The designer should understand that time standard performance will be limited by the performance of the time reference interfaces, since the reference interfaces drive the operation of time standards. Performance can be particularly variable with wireless interfaces in terms of their sensitivity, selectivity, and accuracy. The technical performance characteristics of the time reference interfaces should be consistent with the current state-of-the-art for any given time reference source-distribution pair.

4.5.4 Programmable time reference interface offsets

Sometimes, interfaces on time references have known uncompensated time errors. Usually, this is a result of transmission cable delays, but it can come from other sources as well. Programmable time reference interface offsets will enable a time standard to compensate for these errors on a per interface basis.

4.5.5 Time-base synchronization accuracy

The designer should consider two accuracies for time-base synchronization:

- The accuracy when an ideal reference signal is used. That is, a reference that does not have any short-term instability. This defines what the time-base synchronizer is capable of achieving.
- The accuracy when time reference interfaces are used under their expected operating conditions (which may vary according to the temperature requirements in IEEE Std 1613™ and IEEE Std 1613.1™), which include short-term instabilities.

The designer should review documentation to help ensure that digital signal processing techniques are used to filter out short-term instabilities, improving upon the accuracy provided by the time reference interfaces. This defines the time-base synchronizer performance for practical implementations.

4.5.6 Time-base accuracy and stability

It is very important for the designer to note that time-base accuracy and stability are usually specified under some specific temperature conditions, which should be appropriate to the utility environment specified in IEEE Std 1613 and IEEE Std 1613.1. Oscillators are greatly affected by ambient temperature. This is particularly true for precision oscillators.

The designer should carefully evaluate time-base standards used in outdoor cabinets and may be subject to wide temperature ranges and fast temperature changes (when cabinet doors are opened).

4.5.7 1PPS interface

Even if 1PPS is not used for time distribution at a site, the designer should confirm that the time standard includes a 1PPS interface for test, measurement, and verification purposes. Refer to [Annex F](#).

The designer should note that different time-base standards will use different oscillators with different levels of stability. They may use phase locking,¹¹ frequency locking,¹² or combined phase-frequency locking techniques to discipline their internal oscillators.

The designer should also note that time-base standards will also use different locking algorithms.

The selection of the oscillator type and locking algorithms will yield different time-base standard performance and operating characteristics.

4.6 Time distribution systems

The designer decides how many time-base standards will be used to synchronize the IEDs and the level of system availability that will be provided. These decisions, in conjunction with the time distribution method, will lead to the selection and configuration of time distribution system equipment (antennas, antenna splitters, antenna selectors, time reference interfaces, time standards, grand masters, time distribution selectors, etc.) to drive the time distribution systems. These decisions may also influence the location of this equipment within the substation. For example, time references conveyed by wireless mediums will require some or all of this equipment to be within acceptable coaxial distances to suitable antenna locations. To help with selection, the designer can use the summary comparison of the time distribution methods discussed in [Annex D](#) and shown in [Table 1](#).

NOTE—Overall, when properly designed and installed, IRIG-B meets most of the accuracy needs for time synchronization in substations. By far, the most common wired time distribution methods for substations are IRIG-B variants, although instances of 1PPS may be found. It would be rare to find an instance of IRIG-J. PTPv2 can meet the emerging higher performance requirements. In the future, over a period of many years, PTPv2 may well emerge as the dominant method for time synchronization in substations.

The equipment selections above will define the capabilities of the time distribution interfaces, which will be the basis for determining whether distribution system loading is acceptable. The distribution system loading should be checked against the associated output interfaces. If there are more IEDs for a given time distribution system than the associated output interface can drive, then the time distribution system will need to be split into multiple time distribution systems. Unless there is a system availability reason to do otherwise, physically adjacent IEDs using the same distribution method should be assigned to the same time distribution system. Another output could be used if available, or an amplifier-splitter or amplifier-repeater can be used to obtain the output interface to drive the new distribution system.

Based on network association and equipment location, cable routing and cables should be designed according to IEEE Std 525™. Each time distribution system's cable runs should be added to the time distribution system load to help ensure that the load does not exceed the output interface drive capabilities.

With the exception of the initial data gathering, all of the foregoing is likely to be a bit of iterative process, seeking an acceptable balance between system availability, complexity, load, margin, and cost.

¹¹In general, phase locking, by definition, produces an integral of time error on output that goes to zero as time goes to infinity.

¹²Frequency locking tends to produce minimum instantaneous frequency error over time, but its integral of error does not drive toward zero.

Table 1—Summary comparison of time distribution methods

Method	Advantages	Disadvantages
1PPS	— Accuracy can be < 10 ns — Simple interface — Commonly used for connecting time reference interfaces to equipment — Best interface for test and verification — Isolated input interfaces provide limited galvanic isolation^a — 1PPS over fiber-optic cable (as specified in UCAIug 9–2LE) provides full galvanic isolation	— Not widely used for distribution in substations, but used for interface to IEC 61850-9-2 merging units and IEDs based on the UCA International Users Group (UCAIug) 9–2LE — Requires separate high bandwidth distribution medium — Requires fiber-optic interface to achieve full galvanic isolation
IRIG-B1yz Modulated	— Accuracy can be < 1 ms — Widely used for distribution in substations (very common) — Balanced transmission interfaces provide galvanic isolation	— Limited accuracy for some future requirements — Requires separate distribution medium
IRIG-B0yz Unmodulated	— Accuracy can be < 100 ns — Widely used for distribution in substations (very common) — Isolated input interfaces provide limited galvanic isolation^a	— Requires separate high bandwidth distribution medium — Requires fiber-optic interface to achieve full galvanic isolation
IRIG-B2yz Manchester	— Accuracy can be < 100 ns — Can drive ac interfaces — Isolated input interfaces provide limited galvanic isolation^a	— Uncommon in substations — Requires separate high bandwidth distribution medium — Requires fiber-optic interface to achieve full galvanic isolation
IRIG-J	— Accuracy can be < 1 ms — Simple interface — Isolated input interfaces provide limited galvanic isolation^a	— Limited accuracy for some future requirements — Not used for distribution in substations — No standard electrical interface — Requires separate high bandwidth distribution medium — Requires fiber-optic interface to achieve galvanic isolation
NTP/SNTP	— Accuracy can be 1 ms to 50 ms — Widely used for distribution in substations (very common) — For network devices, does not require separate wiring — Ethernet over optical fiber cable provides full galvanic isolation	— Limited accuracy for some future requirements — Cannot be used for non-network devices

Table continues

Table 1—Summary comparison of time distribution methods (continued)

Method	Advantages	Disadvantages
IEEE Std 1588™ PTP/PTPv2	— Accuracy can be $< 1 \mu\text{s}$ with PTPv2-compatible network infrastructure (1 ms to 50 ms without compatible network infrastructure) — Not common for distribution in substations; in the long term, likely to become much more common — For network devices, does not require separate wiring — Better performance than NTP/SNTP using same infrastructure; vastly superior performance with PTPv2-compatible network infrastructure — Ethernet over optical fiber cable provides full galvanic isolation	— Cannot be used for non-network devices — Requires PTPv2-compatible network infrastructure to achieve maximum performance
IEC/IEEE 61850-9-3:2016 and IEEE Std C37.238™-2017	— IEC/IEEE 61850-9-3:2016 is a profile of the IEEE 1588 PTP standard providing a “base” set of features, including some performance requirements, for use in power substations — IEEE Std C37.238™-2017 extends the base profile in order to provide support for IRIG-B protocol converters (with local time), support for IEDs requiring real-time updates of the received time quality, and better dependability (IEEE C37.238 clocks and IEDs are isolated [having the exclusive use of a specific domain number] from non-conformant 1588 clocks on the network)	— Same as mentioned in the IEEE 1588 method — The support of legacy IEDs with IRIG-B inputs requires IEEE C37.238 to IRIG-B protocol converters
IEEE Std 1815 (DNP3)	— Accuracy varies greatly between devices, but must be specified by supplier in a DNP3 device profile — Not uncommon for distribution in substations — For substations already using DNP3 on their Supervisory Control and Data Acquisition (SCADA) systems, does not impose additional requirements and does not require separate wiring	— Limited accuracy for some future requirements — For substations not already using DNP3 on their SCADA systems, requires fundamental reconfiguration of systems

^a*Isolated input interface* means that there is galvanic isolation between the IED input interface and IED main circuit. This might be through the use of opto-couplers, digital isolators, or other means.

4.7 IED internal timing systems

As part of the system design, the designer should consider how each IED’s internal timing components impact the time synchronization system design. These components of an IED’s timing system are illustrated in Figure 1.

This design step gathers more detailed information about the IEDs than what is described in 4.2. The designer evaluates whether each IED’s timing system provides the following operating characteristics and attributes:

- a) The designer should avoid IEDs with clocks that use the incoming time distribution interface directly
- b) The designer can use IEDs with multiple time distribution interfaces to:
 - 1) Support diverse time distribution mediums

- 2) Provide for redundant time distribution interfaces
- c) The IED clock should be able to free run and operate in the absence of time distribution inputs for some period of time.
 - d) When multiple time distribution interfaces are available and used, IEDs should compare their internal clock to those inputs, but they should only adjust their time if there is a persistent, fixed offset between the incoming time and the IED's clock. This kind of consistency checking, sometimes called "error bypass," avoids undesirable time jumps caused by occasional time distribution errors from noise or other factors (refer to 4.15.5 and 4.14).
 - e) IED time adjustments should be handled in predictable manners. Some IEDs may prefer adjustments to be immediate "jumps" to the new time. Some IEDs may prefer adjustments to "slew" to the new time with a controlled rate of smaller adjustments. Some IEDs may prefer a hybrid combination of the foregoing, perhaps "jumping" for smaller adjustments and "slewing" for larger adjustments. Ideally, time adjustments made by the IED should be somehow logged by the IED.
 - f) Ideally, IEDs should use time adjustments to determine oscillator frequency error, aging rate, and stability. Further, IEDs should use these adjustments in a control loop to adjust their oscillator frequency and to estimate time accuracy over time when they are free running. The latter can greatly enhance system performance when using protocols that include clock quality indications, such as PTPv2, PTPv2 power profile, IEEE Std C37.118.1a-2014, and NTP/SNTP.
 - g) IEDs should be able to monitor and report their operational status (e.g., never synchronized, synchronized, was synchronized but now free running, was synchronized but now free running and predicted to be within accuracy limits, was synchronized but now free running and predicted to be outside accuracy limits, clock is locked to time synchronization, clock is unlocked from time synchronization, alarms, etc.). This is ongoing work within the IEEE regarding the components of the timestamp. Some IEDs only provide synchronization status for some input signals, like IRIG-B, but not others, like NTP. Some IEDs only provide an indication of clock accuracy when compared to an incoming signal. This is insufficient to support protocols that require clock quality indications, such as PTPv2, PTPv2 power profile, IEEE Std C37.118.2, and IEC 61850. IED vendors should define and document how lock status is determined.
 - h) When the accuracy requirements of an IED requires compensation for the cable delay from the timing source, this compensation must be provided either automatically by the source (IEEE 1588 profiles support this), or using a manual setting at the source or at the IED.
 - i) IEDs should be aware of, and handle to the extent possible, "non-sequence events," such as winter-summer time changes and leap seconds, even when free running. However, the designer needs to consider the impacts of these events on the collected data and the systems depending on that collected data (e.g., use of Daylight Savings Time could cause the overwriting of data when time "falls back" and produce a gap of data when time "jumps ahead") and whether there are any regulatory requirements on how to handle these events.
 - j) Ideally, IEDs should have multiple time distribution interfaces, in number and type. When there are multiple interfaces, there needs to be a deterministic selection mechanism for choosing which interface will be used to synchronize the IED clock. Further, it would be highly desirable for all input interfaces to be monitored all of the time for consistent time information between input interfaces, independent of which interface is actually being used to synchronize the clock. Inconsistent time information should be used as a part of the deterministic selection mechanism for choosing an interface.
 - k) If dedicated time distribution (as opposed to network distribution) is desired or required, unless there is some particular system consideration that requires otherwise, IRIG-B Unmodulated with opto-coupled inputs should be used, rather than IRIG-B Modulated or 1PPS. IRIG-B Unmodulated is low cost and can provide full time information with 100 ns accuracy.
 - l) Optical fiber distribution and interfaces should be used where common-mode voltage differences are so severe that the insulation barrier in opto-couplers can be strained, or where distance is greater

than that supported by other distribution methods. For all other applications, the additional cost and complexity of optical distribution is not typically justified.

- m) For test, measurement, and validation purposes, it is extremely useful for IEDs to provide external access to a 1PPS output from their internal clock (for probative purposes, not distribution).

In addition to the foregoing, the designer should look for the following specific interface characteristics in IED documentation, such as:

- a) IRIG-B Modulated interfaces:
 - 1) Provide galvanic isolation and immunity to transients as defined in IEEE Std 1613-2009 and IEEE Std C37.90™-2005.
 - 2) Tolerate signal level variations from 0.1 V_{pp} to 20 V_{pp} to allow for different time distribution output levels and distribution medium attenuation.
 - 3) Determine zero-crossing to better than 50 μs. It is relatively easy to build hardware to demodulate the IRIG-B Modulated signal with accuracy levels of tens of microseconds. The challenge is to accurately recover the 1 kHz carrier phase angle. Most decoders use simple zero-crossing detectors, which are generally adequate, but the signal slew rate has an inflection point (caused by the change in amplitude) at the on-time mark. For most applications using the IRIG-B Modulated signal, this level of performance (tens of microseconds) is acceptable.
- b) IRIG-B Unmodulated and 1PPS Interfaces:
 - 1) Provide galvanic isolation and immunity to transients as defined in IEEE Std 1613-2009 and IEEE Std C37.90. (For severe application cases, fiber-optics can be used.)
 - 2) Tolerate reflections and other non-ideal behaviors caused by imperfect transmission line connections.
 - 3) Tolerate signal level variations at the receiver from 2 V_{peak} to 6 V_{peak}.
 - 4) Accept repetitive 10 V peak signals (from ringing and overshoot) and IEEE Std 1613 and IEEE Std 1613.1 type transients in excess of 100 V without damage or inappropriate behavior. Time code signals are highly repetitive and redundant with well-known characteristics (pulse shape, repetition rate, composition, etc.). These characteristics can be used to design input interfaces that can deliver excellent performance, even in the presence of communication channel impairments. For example, ringing and overshoot are easily detected by recognizing pulse widths, transition windows, etc. IEDs that fail to reliably decode time codes in the presence of reasonable communication channel impairments can create significant system integration problems.

4.8 Time reference distribution

4.8.1 Introduction

Wireless communication is the primary method for distributing time information from the time reference sources described in 4.4. Because of this, the designer's time reference distribution design includes radio receivers, antennas, transmission lines, and lightning arrestors to receive wireless transmissions mediums including low frequency (LF) and high frequency (HF) radios and global navigational satellite systems (GNSSs), as illustrated in Figure 4.

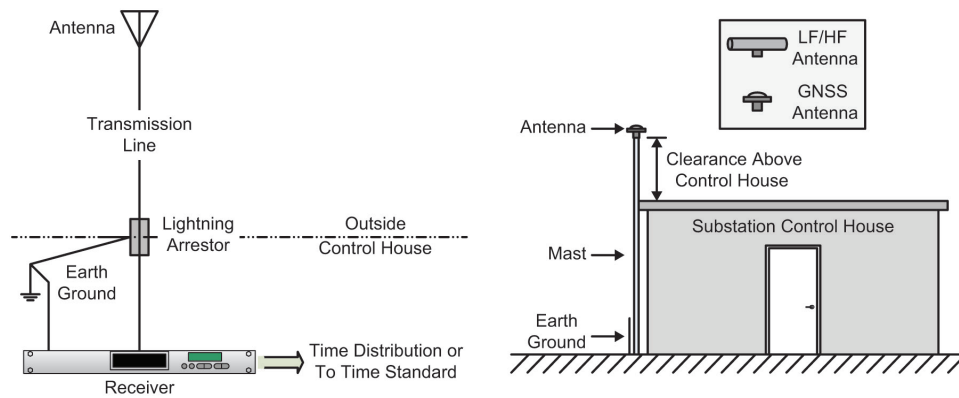


Figure 4—Wireless reception

Successful wireless operation depends on a variety of factors, including, but not limited to, radio wave propagation, radio frequency interference, atmospheric effects, signal strength, signal-to-noise ratios, shadowing, and multipath. For all time reference system design, the following should be considered:

- All components of the time reference distribution system must match in their characteristic impedance: receivers, transmission lines, connectors, lightning arrestors, and antennas. Today, almost all receivers and antennas that might be used in substations have 50 Ω or 75 Ω characteristic impedances. The designer should research and verify all characteristic impedances, and select appropriate components based on the findings. Some help is typically provided when vendors provide receivers with both an antenna and a standard length of coaxial cable, where all components are compatible with each other.
- The connectors on the various components may all be different, where not all connectors can be used with all components. The design should specify the most common connector types, such as BNC, N-type, F-type, and TNC, although many other connector types are also used. This may limit the component choices or cause the specification of different pieces of equipment or different connector options.

These factors influence the designer's equipment selection, system design, and system installation with respect to:

- Receivers
- Antennas
- Transmission lines
- Lightning arrestors

4.8.2 Receivers

The time synchronization system design includes receivers¹³ that deliver time reference sources to IEDs via a time distribution system. Generally, receivers are designed to receive specific wireless systems (e.g., WWVB, MSF, DCF77, BPL, WWV, CHU, BPM, GPS, global orbiting navigation satellite system [GLONASS], etc.). The designer can select any of the following types of receivers:

- *Receiver-interface* devices wirelessly receive time information from time reference sources and feed that information via an interface to another piece of site equipment that does the actual redistribution

¹³Receivers are commonly called satellite clocks when using GNSS, such as GPS.

of time information using site-compatible time distribution methods, such as IRIG-B, NTP, PTP, etc. The distribution equipment might be time standards, time servers, grandmaster clocks, etc. Receiver-interfaces serve as a wireless interfaces for some other piece of equipment.

- *Receiver-distributor* devices wirelessly receive time information from time reference sources and redistribute time information using site-compatible time distribution methods, such as IRIG-B, NTP, PTP, etc. Receiver-distributors serve as freestanding interfaces and distributors, but they do not enhance the redistribution process by inserting a high-quality internal clock between the time input and output.
- *Receiver-standard* devices wirelessly receive time information from time reference sources, synchronize their high-quality internal clocks to the time information, and use their internal clocks to redistribute time information using site-compatible time distribution methods, such as IRIG-B, NTP, PTP, etc. Receiver-standards serve as freestanding interfaces *and* high-quality distributors by inserting high-quality internal clocks between the time inputs and outputs (i.e., it is a time standard with an integrated wireless receiver).

In addition to these receiver types, the designer needs to understand that receivers can come with many different characteristics that can impact their selection. The designer needs to understand that not all receivers are created equally, which may be exacerbated by the substation environment. This means that receivers should be purpose-built specifically for substations. Most substations are remotely located and unattended. All substations have strong electromagnetic fields. Most substations have batteries designed specifically for substations. Some substations are near, or are themselves, potential sources of radio interference and other surges and transients. The designer may consider some of the following additional differentiators to help with receiver selection:

- *Multiple antenna inputs, and multiple GNSS sources.* The designer should move beyond considering just the most basic receiver differentiator, which is the wireless system (e.g., GPS, GLONASS) with which they are designed to operate. So when the designer is concerned about high availability systems (refer to 4.13), the designer should choose receivers designed with multiple antenna inputs. There are a few GNSS receivers that can be used on multiple GNSSs, such as GPS and GLONASS. But they may do so alternatively. That is, they do not concurrently operate using multiple systems, but rather have to ability to select one or more systems. Some may also do this concurrently using one antenna, allowing one time reference to be used to validate the other.
- *Reliable operation.* The designer should select receivers and their associated antennas with high mean time between failure (MTBF) rates, indicating that they are designed to provide years (better yet decades) of maintenance-free operation.
- *Receiver sensitivity.* The designer should select receivers with good receiver sensitivity to receive the very low-level wireless signals.
- *Receiver selectivity.* The designer should select receivers with good selectivity for rejecting (reducing) adjacent channel and out-of-band interference. Selected receivers should be suitable for operation in strong electromagnetic fields.
- *Support for active powered antennas.* The designer should be aware that some receivers provide support for active powered antennas and antenna splitters. Some only provide very limited support for active powered antennas. Some do not support active powered antennas at all.
- *High-quality internal clocks.* The designer's selection of a receiver's oscillator for its internal clock typically depends upon balancing accuracy and stability requirements with cost. Receiver-standards typically include high-quality internal clocks, but there are many oscillators available for those clocks, including temperature-compensated crystal oscillators (TCXOs), oven-controlled crystal oscillators (OCXOs), and atomic (rubidium or caesium).¹⁴

¹⁴In particular, receivers integrating a satellite disciplined oscillator (e.g., an oven-controlled quartz oscillator or a rubidium oscillator)

- *Number and type of time distribution interface outputs.* The design specification of the time synchronization system may require multiple time distribution systems supporting multiple time distribution methods. However, some receivers only provide a single defined time distribution interface output for local time distribution. For example, some GPS receivers only provide 1PPS and a National Marine Electronics Association (NMEA) 0183 serial interface, which is typically only used for interfacing to equipment, not time distribution. Designing redundant operation for these types of receivers may be difficult. Some receivers provide only one time distribution interface output, but allow the designer to select the interface from a set, such as IRIG-B modulated, IRIG-B unmodulated, NTP, SNTP, etc. Some receivers support multiple time distribution interface outputs, which might provide a specific time distribution method or a designer-defined configuration from a set of options specified when ordering the receiver.
- *Redundant receivers.* When the designer is considering redundant time synchronization system design, there are a few GNSS receivers with provisions for integrated redundant operation. That is, the receivers include cross-interfaces to provide redundant operation, typically through multiple antenna connections.
- *GNSS receiver position lock.* The designer may want to consider GNSS receivers which have the ability to “lock in” their position information. Once the GNSS receiver has obtained a good position fix, the receiver can be configured to always use that location (since the receiver is stationary). This can be very useful for the designer because it can allow the receiver to produce accurate timing with as few as only one good satellite in view.
- *Receiver mounting.* The designer needs to verify that the receiver mounting arrangements are compatible with the equipment racks.
- *Receiver power supply.* The designer should connect the receiver(s) to substation batteries and the receiver rated appropriately according to IEEE Std 1613 and IEEE Std 1613.1. The designer should help ensure that the receiver grounds are tied to a local earth ground via low impedance connections.
- *Receiver communication ports.* The designer should select receivers with communication ports that comply with IEEE Std 1613 and IEEE Std 1613.1. Those without communication ports should comply to the standards referenced in IEEE Std 1613 and IEEE Std 1613.1, most notably the IEEE C37.90 series of standards.

When designing time synchronization systems, the designer should consider the following about receivers:

- If multiple input antennas are used, the designer should understand the efficacy of the antenna selection algorithms and the implications of those algorithms on other associated control systems. For example, downstream control algorithms should not respond faster than the switch-and-test time, or system control instabilities can result. The designer should ensure that antenna switching does not adversely affect power to in-line antenna splitters and antennas used by other receivers.
- If the designer is using active powered antennas and/or antenna splitters, the design process should include a check that the receiver is capable of powering the antenna and the antenna splitter (voltage and current), as required.

exhibit improved short-term stability. To avoid perfect lineup between sampling frequency and satellite spreading code, an alternative technique currently adopted in commercial receivers is based on the employment of a temperature-controlled crystal oscillator for down-sampling of the satellite signals. This type of receiver accumulates time errors until the total error reaches a maximum value (i.e., a multiple of the half period of the oscillator), and then generates a phase step that reduces the time error to a minimum. Some receivers step phase in increments of 100 ns (or less) or 1 microsecond (or larger) (Lombardi, et al. [B14]; Orpen and Zwaan [B18]). Consequently, the short-term stability of these receivers could vary significantly (although their long-term performance may be equivalent to models integrating a disciplined oscillator).

4.8.3 Antennas

4.8.3.1 Introduction

The time synchronization system design includes antennas that are designed to work in conjunction with specific wireless systems (e.g., specific LF, HF, and GNSSs), frequently matched with specific receivers. Antennas come in different sizes and shapes with different radiation patterns, depending on the type of system and its operating frequency. The designer may have a choice between antennas that are “active”¹⁵ or “passive”.¹⁶

When designing time synchronization systems, the designer should consider the following about antennas:

- Different antennas will have different mounting and installation requirements. The designer should consult with the manufacturer’s recommendations.
- Appropriate ancillary equipment selection may allow an antenna to be shared with multiple receivers at a site. Antennas are typically mounted on galvanized pipes (called antenna masts) that are attached to physical structures like substation control houses, as illustrated in Figure 4. Attaching an antenna mast to a building or structure may require review by a structural or civil engineer to help ensure that the antenna mast will be structurally safe and that its attachment will not compromise the structure to which it is attached. TIA-222-G-2005 provides guidance and requirements for larger antenna support structures. Antenna masts usually extend some distance above control house roofs. Further, antennas typically require some amount of clearance from surrounding objects, which can detune the antennas, change their radiation patterns, shadow the antennas from receiving signals, or adversely affect their reception of multipath signals.
- If the design includes multiple receivers sharing an antenna, an appropriate antenna splitter is required. The designer should note that not all antenna splitters are created equal. There are *passive* (unpowered, impedance matching) and *active* (powered, amplified) antenna splitters. *Passive* antenna splitters will provide a reduced antenna signal level to all of the receivers, so they should be avoided unless the loss in signal level can be tolerated. An *active* antenna splitter will preserve the antenna signal level to all receivers, so they are preferred. Active antenna splitters may be powered from a separate power supply or, if a receiver provides power, from the dc power provided by the receiver through the coaxial cable. If receiver power is used, the designer needs to check that the receiver is capable of powering both the antenna and the antenna splitter. If the antenna splitter uses the receiver power, understand its method of powering. Often, the antenna splitter will derive its power from a particular receiver interface. This could have availability implications. If the receiver that is used to power the antenna splitter fails or is disconnected, the antenna signal will be lost for all receivers. Also, the designer should also note that all antenna splitters will add some delay ($< 100 \mu\text{s}$), which may or may not be significant (in the context of LF and HF timing accuracies, the delay is usually not significant). For systems requiring microsecond accuracy, the delay can be significant and compensating for that delay becomes an important requirement for the receiver.
- Antennas should be rugged and durable with an IP67 (ingress protection) rating to provide years (better yet decades) of maintenance-free operation.
- When the antenna cable’s attenuation becomes significant, a preamplifier may be included in the antenna housing, with a dc power supply providing current through the cable.
- The antenna mast should be grounded per substation grounding practices.

The following subclauses describe specific considerations in using LF and HF¹⁷ and GNSS antennas.

¹⁵Active antennas include amplifiers in the antenna assembly and the receiver usually supplies low-voltage, low-power dc through the transmission line.

¹⁶Passive antennas do not include amplifiers and are not provided a dc power source from the receiver.

¹⁷For most of their geographic coverage areas, LF and HF systems principally communicate via sky wave signals that are reflected off the ionosphere, although LF systems have stronger ground wave signals closer to their transmission sites.

4.8.3.2 LF and HF antennas

LF and HF antennas come in various sizes and shapes, but the designer's antenna for substation use should be a small loop antenna¹⁸, less than 3 ft (1 m) cubed.¹⁹ The designer should mount the LF or HF antenna atop a galvanized pipe (antenna mast) that has a diameter of 1 in to 2 in (2.5 cm to 5 cm). A mounting bracket attaches the antenna mast to a physical structure like the substation control house, as illustrated in Figure 4. After the antenna has been mounted, but before it is tightened down, it must be rotated so that one of its two main lobes points in the direction of the received signal. This is best accomplished by using a receiver with a signal strength meter (S meter) function, where the antenna is rotated for maximum received signal strength. Once this is accomplished, the antenna should be tightened down.

Multiple LF and HF receivers at a substation can share a single LF or HF antenna by using an appropriate antenna splitter. But only LF or HF receivers operating on the exact same frequency can be shared because each loop antenna is tuned for a specific frequency. For example, two WWVB receivers could share an LF antenna tuned for WWVB. Two 10 MHz WWV receivers could share an HF antenna tuned for 10 MHz WWV. But that same HF antenna could not be used for a 5 MHz WWV receiver.

When designing systems with LF and HF antennas, the following should be considered:

- All loop antennas need to be tuned for the frequency of operation. This can require specialized test equipment and methods. Therefore, it is strongly recommended that LF and HF antennas be purchased pre-tuned for their frequency of operation.
- All wireless systems are subject to the effects of multipath. But LF and HF systems are less susceptible to multipath²⁰ due to their lower frequency (longer wavelength) transmissions. To minimize multipath, the design should have the antenna mast extending at least 4.5 ft (1.5 m) above the building roof. If multiple LF and/or HF antennas are installed adjacent to one another, the antennas should be horizontally separated by at least 12 ft (4 m). All antennas should be installed at the same height. The design should provide a minimum horizontal separation of 12 ft (4 m) between the antenna and any other adjacent vertical structures, particularly taller vertical structures. Even greater horizontal separation is better. Adjacent structures can detune the antenna and alter its radiation pattern.
- The designer should help ensure that no high-power out-of-band signals are nearby to the antenna because LF and HF systems operate at very low signal levels and can be susceptible to high-power out-of-band signals.
- The designer may want to select loop antennas with high-Q to minimize out-of-band interference and perform better in the presence of strong electromagnetic fields.

4.8.3.3 GNSS antennas

GNSS antennas are relatively small disk, dome, or cone-shaped antennas (typically approximately 6 in [15 cm] in diameter and 6 in [15 cm] in height). They have hemispheric radiation patterns, so the design should have the dome pointed directly overhead (skyward) so the antenna can receive signals from the orbiting satellites. The design needs to help ensure accurate operation by providing the GNSS receivers visibility of four or more satellites (although the ability to position lock can lower this to one). Because GNSSs use line-of-sight communication frequencies, the design needs to install the antenna in a location with a clear (unobstructed) view of the sky where the satellites are orbiting, which can include the horizons.

¹⁸Loop antennas have directional radiation patterns with two main lobes that are separated by 180°.

¹⁹The relatively low LF/HF frequencies make non-loop antennas impractically large for substation use. (For example, a LF dipole antenna could be more than 9000 feet (3000 meters) in length. Even an HF dipole antenna could be more than 50 feet (15 meters) in length.)

²⁰Multipath is caused by antennas receiving multiple copies of the signal from the transmission source: zero or one directly from the transmission source and one or more reflections off nearby objects. LF and HF signals can bounce (reflect) off buildings, hills, mountains, water, and other surfaces. The reflected signals arrive at the antenna with arbitrary phase, amplitude, and delay. The final received signal at the antenna becomes the vector sum of the direct and all reflected signals. Out-of-phase signals can sum to reduce the magnitude of the received signal. The longer wavelength tends to limit significant reflection to larger reflective surfaces.

The design should mount the GNSS antennas atop small galvanized pipes (antenna masts) that are attached to physical structures like substation control houses, as illustrated in [Figure 4](#). The antenna masts should extend 3 ft to 6 ft (1 m to 2 m) above a building roof. Many GNSS antennas are designed for mounting on standard 5/8 in UNC (Unified National Coarse) or NC (National Coarse) threaded pipes (as defined in the Unified Thread Standard of ASME/ANSI B1.2-1983). Other antennas come with mounting brackets for top or side attachment to antenna masts. The design should provide a minimum of 3 ft (1 m) horizontal separation between the antenna and any other adjacent vertical structures, particularly taller vertical structures.

The design should include an active antenna, which includes a low noise amplifier (LNA) to boost the received signal in order to overcome transmission line losses. Power for the LNA is supplied by the GNSS using low-voltage, low-current dc via the transmission line.

Multiple GNSS receivers at a substation can share a single GNSS antenna by using an appropriate antenna splitter.

When designing time synchronization systems with GNSS antennas, the following should be considered:

- Almost all GNSS receivers and antennas will have active antennae, it is important that this has enough gain to compensate for the antenna cable loss. But this should be researched and verified, selecting appropriate components based on the findings. The designer may consider using an amplifier when the distance from the antenna to the receiver produces too much signal loss. Amplifiers will introduce a delay whose magnitude may be specified as “group delay” by the manufacturer, which may be in a range of 1 ns to 20 ns. The designer should determine whether this delay is significant for the application(s) being supported. Also refer to [4.9.5](#).
- There are two factors that can limit the amount of horizon that must be visible: 1) GNSS receivers are configured with mask angles,²¹ and 2) GNSS satellites do not always appear on all horizons from all locations. Many GNSS receivers set their mask angle to 10° to 15°, although some will set their mask angle to 5° and accept the less reliable signals.²²
- Some designs may be not be able to achieve an absolute clear sky view, particularly in urban environments. To the extent that there are tall buildings and other obstructions shadowing (blocking) satellite signals from reaching the antenna, for any given height and width of object, the impact to the time synchronization system will diminish with its distance from the antenna.²³ Because GNSS satellites are constantly changing their position in the sky, the impact of obstructions will vary over time. To fully understand the system impact, the designer needs to monitor and measure system performance for an extended period of time, such as one day.
- When designing time synchronization systems using GNSS antennas, the design needs to address multipath because GNSS antennas are particularly susceptible to multipath due to their higher frequency (shorter wavelength) transmissions. Multipath signals can introduce erroneous time inputs into the GNSS receiver calculations, creating positional and time errors. This has particular impact when there are obstructions. When an obstruction is in view, the magnitude of the direct signal goes to zero and the received signal becomes the sum of all reflected signals. There will be a 3 ns contribution of erroneous time for every additional meter that a reflected signal travels. For example, if a reflected

²¹With regard to mask angles, satellite transmissions must transmit through the ionospheric and tropospheric layers that surround the Earth. These layers cause increased signal attenuation, refraction, and delay as the horizon is approached. Further, atmospheric noise and interference increases as the horizon is approached. All of these factors contribute to making satellite signals on the horizon much less reliable. Therefore, GNSS receivers mask (do not use) satellite signals that are below their “mask angle” setting from the horizon.

²²With regard to satellite locations in the sky, each GNSS has its own pattern of orbits for its constellation of satellites (known as ephemeris information). For a given GNSS and a given location on Earth, the possible locations for satellites in the sky might be significantly reduced from a total sky view. For example, a GPS system in the northern hemisphere would benefit from a clear sky view to its mask angle to the southern horizon, but it would only benefit from a clear sky view above 30° elevation to the northern horizon. But without specific ephemeris information for the GNSS, it must be assumed that a total clear sky view to the mask angle for all horizons is required.

²³For example, a skyscraper that is 1 mi (1.5 km) away will have much less impact than the same building that is only 300 ft (100 m) away.

signal traveled an additional 100 m, it would add 300 ns of time error to the calculations. If it traveled 1000 m, it would add 3 μ s. Because GNSS satellites are constantly changing their position in the sky, the impact of multipath will vary over time. To fully understand the system impact, the designer needs to measure and monitor the GNSS receiver for an extended period of time, such as one day or several weeks. Refer to 4.15.3.

- If the design includes multiple GNSS antennas installed adjacent to one another, the antennas should be horizontally separated by at least 1 m, preferably 2 m.

4.8.4 Transmission lines

Transmission lines (typically coaxial cables) are used to connect receivers to their antennas, including an intermediate transit connection through lightning arrestors. Antennas have connectors for connecting the transmission line from the receiver. The design may run the transmission line inside the antenna mast. If this is done, the designer should specify that the minimum bend radius of the coaxial cable is not violated and that the coaxial cable is protected from chafing caused by any sharp edges on the mast.

When designing time distribution systems with transmission lines (coaxial cables), the following should be considered:

- The designer should select transmission lines very carefully. There are wide variations in performance, characteristic impedance, and quality. This is true even for coaxial cables with the same nomenclature but from different manufacturers. The designer should select a cable that is compatible for the environment it is being used in. One simple approach is to use outdoor-rated coaxial cable for the portions of the transmission line installed outdoors because indoor-rated cables will rapidly degrade if exposed to outdoor environments. The designer should evaluate whether the cable's temperature rating is appropriate for the installed environment, which may be a wider temperature range than what would be expected for typical environmentally-controlled areas. The designer may also need to investigate any requirements to install plenum-rated cables to meet electrical or fire protection codes for the installation of indoor cable. Refer to IEEE Std 525.
- The design should attempt to maximize the received signal strength and time accuracy, to the extent practical, by minimizing the transmission line length between the receiver and the antenna. This is particularly important for GNSSs where transmission line losses are higher per unit of linear length because they operate at very high frequencies (1 GHz to 4 GHz). Increased losses reduce the received signal strength. GNSS receiver manufacturers typically recommend limiting transmission line lengths to 15 m (50 ft). Transmission line length also adds signal delay, which creates positioning errors and consequently timing errors. Some GNSS receivers can compensate for this, so if long transmission lines are expected, the designer should carefully review the receiver's specifications during selection.
- The designer should select low-loss transmission cable to maximize received signal strength. This is particularly important for GNSSs where transmission line losses can be 10 dB/100 ft or more.
- The designer should help ensure that the actual installation does not violate the minimum bend radius for the coaxial cable specified by the manufacturer. Not doing so can significantly increase transmission line loss and voltage standing wave ratios (VSWR), adversely impacting the performance of the transmission line and the time synchronization system.
- Unless the designer is very skilled at making coaxial cable assemblies for very high frequency operation, cable assemblies should be purchased pre-assembled (made to length with the appropriate connectors). Good high frequency coaxial cable assemblies are difficult to make. If done poorly, they will have higher losses and VSWR. Poorly assembled cables are difficult to detect without specialized equipment and skills.
- If the transmission line length must be longer than 15 m (50 ft), then a higher gain antenna or inline amplifier will need to be used to boost the received signal and overcome the additional loss. Both

of these approaches have limited effectiveness and side-effects, so this should only be done when absolutely necessary.

4.8.5 Lightning arrestors

The designer needs to address the application of a lightning arrestor in the time system synchronization design. Lightning arrestors minimize the probability and severity of damage from lightning near-strikes. As such, lightning arrestors are an essential consideration of wireless reception depending on the characteristics of the location where the time synchronization system is being installed. Although transmission substations are designed with lightning protection, wireless receivers are particularly sensitive and their external antennas increase the likelihood of harmful impulses being induced in the antennas and conducted into the receivers. The designer needs to understand that when a receiver is damaged from a lightning strike (or otherwise damaged), the receiver's associated time reference source will be lost. The designer should consider lightning damage in determining equipment holdover requirements and redundancy.

When designing systems with lightning arrestors, the designer should consider the following:

- Lightning arrestors should be selected very carefully. There are wide variations in performance, characteristics, and quality.
- GNSSs almost always require GNSS receivers to supply low-voltage, low-current dc power via the transmission line to a LNA built into the antenna (refer to 4.8.3). Not all lightning arrestors pass dc. When designing a GNSS, the designer should help ensure that the selected lightning arrestor passes dc when required.
- To maximize received signal strength, the designer should select lightning arrestors that have low insertion loss and low VSWR at the frequencies of interest: 100 kHz for LF, 1 MHz to 30 MHz for HF, and 1 GHz to 3 GHz for GNSS.
- The design shall have lightning arrestors firmly mounted and well-grounded to a solid earth ground where the transmission line enters the control house (or equipment cabinet if there is no substation control house). The well-grounded connection typically results in a separately routed low impedance connection between the arrestor and the earth ground.
- The designer should include in the design lightning arrestors that can handle multiple strikes. If gas-tube protectors are used, the designer should select ones where the gas-tubes can easily be replaced, since gas-tubes are one-event devices. Also, the designer should also be aware that gas-tubes will not generate alarms after they have been triggered. This must be discovered by preventative maintenance or other means (such as loss of lock detection in the receiver, refer to 4.8.2).

4.9 Wired time distribution

4.9.1 Introduction

The designer's wired time distribution provides for the local distribution of time and typically consists of multi-drop transmission line networks, whose design is discussed in this clause. Refer to 4.10 for the design of wired *network* time distribution methods.

4.9.2 Multi-drop transmission line networks

4.9.2.1 Introduction

The designer's multi-drop transmission line network design is recommended to be *end-fed*²⁴ and comprise the following components:

²⁴When the transmission line driver is placed at one end of a transmission line, and a transmission line terminator is placed at the opposite