Delivering Traceable Reference Time for ATSC 3.0-based Broadcast Positioning System (BPS)

Patrick Diamond
Diamond Consulting
Ayer, Mass., United States

Tariq Mondal, Robert Weller
National Association of Broadcasters
Washington, D.C., United States

Andrew Hansen
Volpe Center
Cambridge, Mass., United States

Abstract – Delivering accurate and traceable time is important for the operation of critical infrastructure industries. A BPS-enabled ATSC 3.0 TV station can meet the requirements of critical infrastructure industries by transmitting precise time. One of the requirements to do so is to have reliable, robust, and accurate timing sources at the TV stations. This paper describes how a variety of timing sources can be used at TV stations for reference. The paper also outlines how BPS-enabled ATSC 3.0 TV stations can evolve into a self-synchronizing mesh network for timing signals.

Introduction

BPS is a system and method of estimating time and position at a receiver using ATSC 3.0 broadcast signals [1]. BPS is compliant with the ATSC 3.0 standard which is currently being deployed in the US [2]. One of the features of BPS is its independence and potential for stand-alone use. That is, it can continue to operate when GPS/GNSS, internet, and cellular connectivity are unavailable. The independence of BPS makes it an attractive solution for providing time transfer information to critical infrastructure supporting safety systems, national security functions, and economic activity.

Although BPS can estimate both position and timing at a receiver, this paper focuses on the timing aspect. Reliable timing information can be derived from a single BPS-enabled ATSC 3.0 signal if the receiver location is known. Timing service coverage analysis here shows that the entire continental US can receive reliable timing information from the existing deployment of VHF and UHF television stations.

To transmit timing information, a TV station must have an accurate and trusted timing reference. BPS-enabled TV stations have the flexibility to invoke one or more timing sources to form a robust reference time, *e.g.*, an ensemble of available clocks, cross-checked time sources, etc. BPS-enabled TV stations receive signals from neighboring towers and under the timing service concept, transmit those neighbor stations' identity, timing, and location and affects a self-synchronizing network. This paper discusses methods and algorithms for synchronizing BPS-enabled ATSC 3.0 TV towers.

High-Precision Position, Navigation and Timing (PNT) as a National Security Concern

U.S. Critical Infrastructure is PNT enabled and per Executive Order 13905 [3] on "Responsible Use of PNT," the 16 Sector Risk Management Agencies (formerly Sector Specific Agencies) are directed to

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develop PNT profiles pursuant to the NIST 8323 master profile to identify and mitigate vulnerabilities. The critical infrastructure sectors include the Energy & Power Grid, Communications, Financial Transactions, Transportation (Aviation, Maritime, Rail, Surface, Pipeline), First Responders, Chemical, Dams, Information Technology, Critical Defense Manufacturing, Healthcare and Public Health, and Food and Agriculture to name several. The PNT signals and other data from GPS satellites allow these infrastructure capabilities to function reliably. Without these capabilities, the US economy would come to a standstill. Our adversaries are aware of this weakness and have implemented augmentations within their national boundaries to mitigate this exact same weakness. The US needs to do the same.

The US Government is aware of this issue. This problem has been recognized as critical since at least 2010 as noted in the release of the National Positioning, Navigation, and Timing Architecture: Implementation Plan [4].

The National PNT Advisory Board [5] discusses this issue constantly and has made several recommendations for developing a national resilient precision timing network. So far, nothing has been done beyond "studying the problem." This paper describes a viable infrastructure-ready solution to this national security weakness: namely, a Broadcast Position System based on ATSC 3.0.

Technical Requirements to Satisfy Critical Infrastructure Usability Needs

Providing an accurate and precise reference clock using ATSC 3.0 is the basic requirement for BPS users. However, critical infrastructure (CI) environments have special needs for this clock signal. The precise clock is used to synchronize critical operations and functions in each CI. A few examples follow:

- **Mobile Wireless Networks** – 4G and 5G radios in the base stations need precise time synchronization to ensure synchrony of their Time Division Duplex (TDD) systems. The requirement for time synchronization in 3GPP radios is a 1 PPS signal, accurate to within 1.1 µsec across the entire network. The 1 PPS signal needs to be traceable to Coordinated Universal Time (UTC).
- **Equity Trading Systems** – Commonly called stock exchanges, there is a legal requirement to apply a time stamp at every step in the processing of a trade. There can be dozens of rapid, independent processing steps in a trade across many systems. In Europe there are Markets in Financial Instruments Directive (MiFID) II rules and in the USA, there are SEC Section 613 rules [6]. A part of each rule set requires time stamps to correlate to UTC within one microsecond. Each trade's entire dataset must be stored for regulatory review for up to 7 years.
- **Power Grid** – Machines called synchro-phasors are used to manage and regulate energy being added to the overall grid from all sources, including conventional power plants, wind farms, and solar panel arrays. Due to the nature of the energy on the grid it is critical to add new energy in a manner that assures it is compatible with the existing energy flow. The technical objective of the synchro-phasor is to ensure the new power is added within one degree of top dead center of the 60 Hz energy carrier. In order for new energy to be successfully integrated, all synchro-phasors need to be time correlated with each other within 1 µsec and correlated to UTC.

These and the other CI industries impose a specific tolerance and accuracy to the time applied to each via the ATSC 3.0 system. This critical level of control requires all ATSC 3.0 clocks to be correlated to UTC. Overall, 200 nanosecond accuracy is adequate for all CI industries, if traceable to UTC.

Time Sources Available at Individual Stations

BPS-enabled ATSC 3.0 transmission systems designed as a trusted timing source will provide for at least three independent timing sources as illustrated in Figure 1. These stations can then operationally leverage a range of robust timekeeping strategies, *e.g.*, clock ensemble algorithms, redundancy cross-checking schemes, or orthogonal source comparison. The BPS transmitter timekeeping system (TKS) can be used to improve accuracy (UTC offset error), resilience by mitigating faults or threats, and other internal performance needs in the broadcasting sector.

In the U.S., the most reliable timing sources would be UTC obtained from the National Institute of Standards and Technology (NIST) or the U.S. Naval Observatory (USNO) and securely delivered to the TV station via optical fiber, satellite link or microwave link. GPS can also provide reference time, as well as Cesium and rubidium clocks located at the station. Additionally, eLORAN signals, if available, can be used. Significantly, signals from neighboring BPS-enabled ATSC 3.0 stations can be used as reference timing sources.

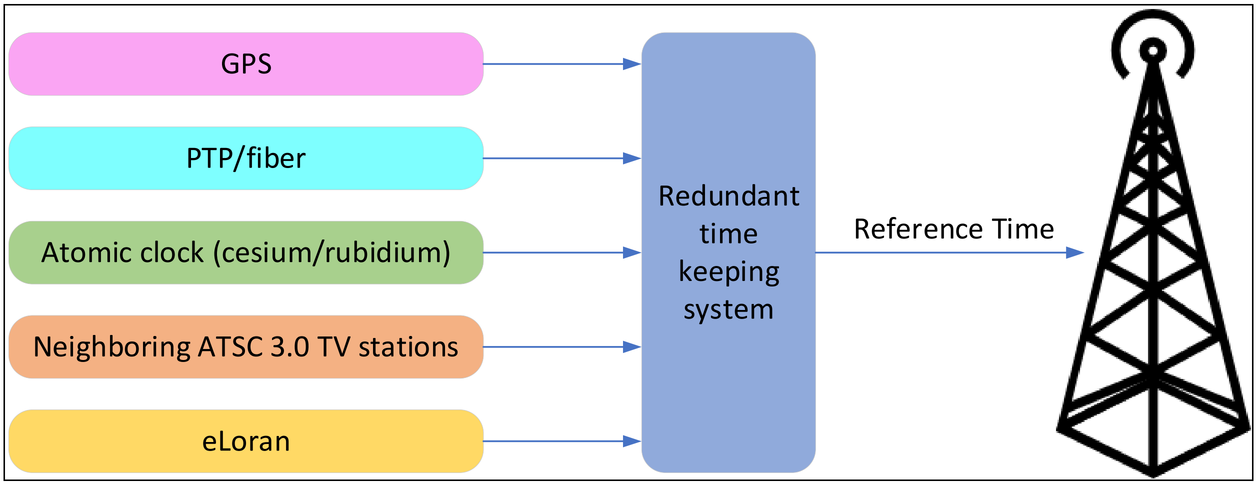

FIGURE 1: MULTIPLE INDEPENDENT TIMING SOURCES CAN PROVIDE REDUNDANCY.

Time Synchronization Using ATSC 3.0 Signals Only

Television transmission towers are tall, and the transmitted TV signals typically travel about 55 miles before attenuating rapidly due to the Earth's curvature. However, a neighboring TV tower will also be tall and may therefore have line of sight to other tall towers located hundreds of miles away. Thus, using directional receiving antennas, one BPS-enabled station may be able to detect signals emitted from many neighboring towers. If those ATSC 3.0 signals are also BPS-enabled, a TV station can use the neighboring BPS signals as timing references.

ATSC 3.0 TV towers can evolve into a self-synchronizing network with traceable reference time if there are enough master clocks in the network. For example, if a few of the towers in the network have redundant timing sources, then other towers in the network can listen to these "master" towers and synchronize their clocks to them. Receiving antennas mounted high on a typical TV tower may be able to detect signals from many neighboring stations. If there are three or more master clocks in the neighbor list, a slave tower can synchronize its clock using only ATSC 3.0 signals.[1]

The BPS self-synchronization network concept is illustrated in Figure 2. Assume that every tower can receive the signals from the three master towers. In this case, all the slave towers can be reliably synchronized using only ATSC 3.0 signals.

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[1] Strictly speaking, only a single master is required for synchronization, but at least three master stations are preferred for reliability and redundancy.

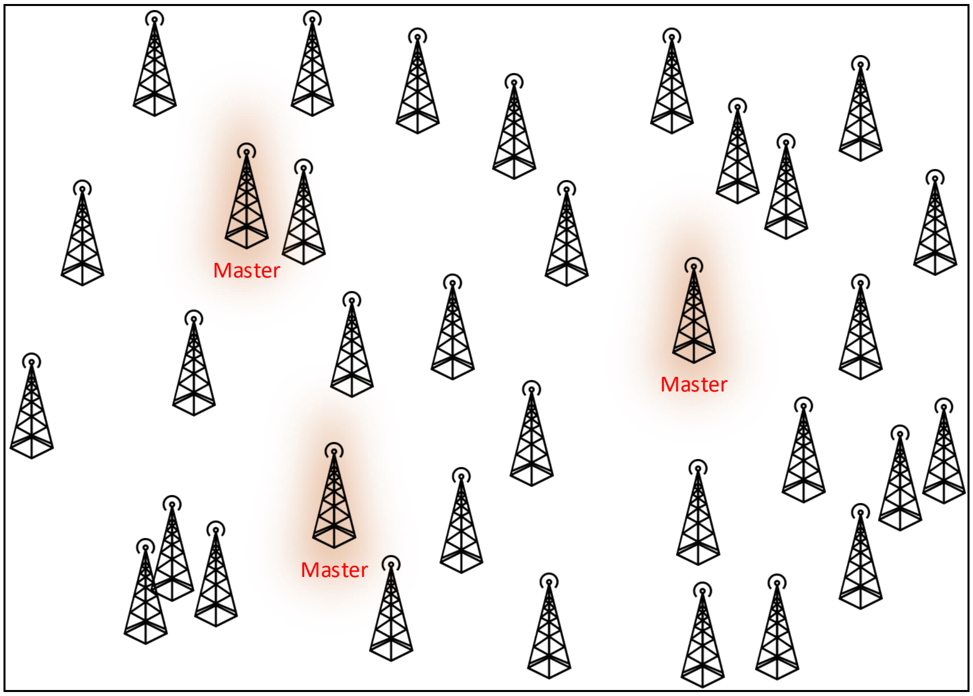

FIGURE 2: IN A SELF-SYNCHRONIZING BPS NETWORK, THE SLAVE STATIONS CAN USE A FEW MASTER STATIONS AS TIMING REFERENCES RESULTING IN ALL STATIONS PROVIDING ACCURATE TIME.

To develop a self-synchronizing network, each ATSC 3.0 broadcast facility will report its clock sources and expected timing accuracy. The `num_independent_sources`, `source_type_list`, and `source_used` parameters, which are described in the Appendix under the `bps_info` message, convey the clock configurations of each BPS-enabled station. The `expected_accuracy` parameter conveys the quality of the timing information. Finally, the `sync_hierarchy` parameter describes the number of "hops" required to trace back to the master clock. Using the described parameters, a synchronization protocol can be developed for the ATSC 3.0 network.

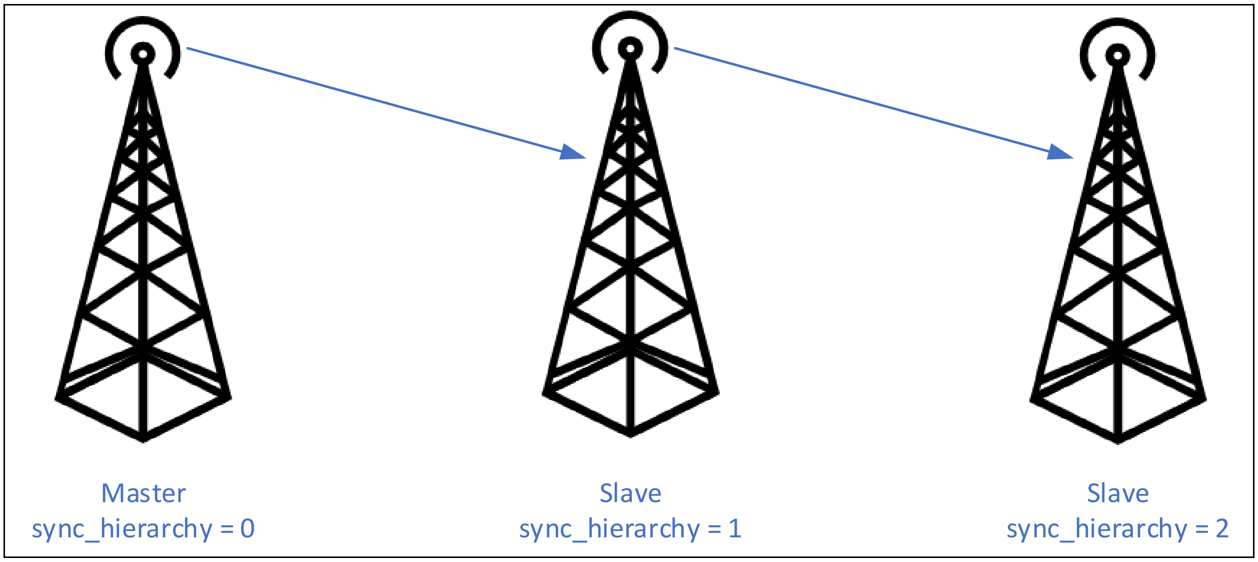

FIGURE 3: EACH STATION REPORTS THE NUMBER OF HOPS IT IS AWAY FROM A MASTER.

Coverage of U.S. Television Stations Transmitting BPS

Coverage Definition

In ATSC 3.0, the most robust physical layer pipe (PLP) operates at -5.72 dB signal to noise ratio (SNR) in a Rayleigh fading channel [7]. Simulations shared by the proponents during ATSC 3.0 standards development showed that the bootstrap and preamble signals can be decoded at about -12 and -9 dB SNR, respectively. Therefore, the data PLP carrying the tower location information is the weakest link, requiring the highest signal level. It is expected that BPS will utilize a PLP having robust characteristics, in order to provide usable coverage at great distances from the transmitter site as well as deep indoors and in other challenging environments. We have used -5 dB as the BPS system SNR threshold. This threshold is about 20 dB below what is typically assumed for DTV reception. Other relevant planning factors used to define BPS coverage are tabulated in Table 1.

Parameter	Value	Unit
System Bandwidth	6	MHz
Thermal Noise (kTB)	-106.2	dBm
Frequency of Operation, UHF	539	MHz
Signal to Noise Ratio	-5	dB
High VHF	194	"
Low VHF	69	"
Antenna Gain	0	dBi
Antenna Factor, UHF	-129.6	dBm-dBµV/m
High VHF	-120.8	"
Low VHF	-111.8	"
Noise Figure	6	dB
Required Field Strength, UHF	**24.4**	**dBµV/m**
High VHF	**15.6**	**"**
Low VHF	**6.6**	**"**
RX Antenna height, AGL (End-User)	1.5	m
RX Antenna height, AGL (TV Tower)	50	"
Location, Time Variability	50%, 50%	–

TABLE 1: PLANNING FACTOR VALUES USED TO DEFINE BPS COVERAGE.

Station Selection

Timing information can be adequately conveyed from a single broadcast station having a primary time reference, but greater reliability and redundancy can be achieved by monitoring signals from several stations. There are a total of 1619 television stations operating 1642 unique transmission facilities licensed and operating in the contiguous United States (CONUS) [8]. U.S. television stations may transmit on low-VHF channels (below 88 MHz), high-VHF channels (between 174 and 216 MHz), and UHF channels (above 470 MHz). All licensed full-power stations are considered in this analysis.

BPS Coverage Determination

Because of its familiarity to the broadcast industry and because reference software has been published by the FCC, the Irregular Terrain Model (ITM, version 1.2.2) was utilized in its point-to-point mode to predict coverage on a uniform grid covering the United States and its territories [9]. A summary of the ITM, including descriptions of some of its features and peculiarities, is given in McKenna, *et al.* [10] The software implementation of ITM used was the FCC's TVStudy, version 2.2.5, with planning factor values adjusted as indicated above. In particular, the software was first configured to predict field strength at the center point of 10 x 10 kilometer "cells" for general users at 1.5 meters above ground. Coverage was defined as indicated in Table 1 (*e.g.*, 24.4 dBµV/m or greater irrespective of the UHF channel involved) and no consideration was given to clutter or undesired stations (*i.e.*, co-channel and adjacent-channel interference was ignored).

Results – Predicted Coverage for General BPS Users

The map of Figure 4 shows the predicted aggregate coverage of BPS for general users if transmitted from all full-power and Class A television stations in CONUS. The coverage shown was calculated at some 103,194 grid points (calculation cells) covering about 10.3 million square kilometers. The total land area of CONUS is about 7.7 million km^2 [11] and the predicted aggregate BPS coverage includes all of that area, as well as all of the Great Lakes and substantial areas offshore and in the border areas of both Canada and Mexico. Even if coverage is required at 10 or 20 dB above threshold (*e.g.*, because of receiver performance limits or reception indoors), there are only a few pockets of CONUS (mostly rural parts of Nevada, Oregon, Utah, Montana, and Colorado) that are not predicted to receive BPS timing service from at least one station.

While Figure 4 shows predicted reception for general BPS outdoor users in CONUS, broadcast television stations are also located in the states of Alaska and Hawaii, as well as Guam, Puerto Rico, and the US Virgin Islands. If BPS is implemented by television stations in those states and territories, full coverage of the land areas, as well as substantial offshore areas, is predicted, except in Alaska where full-power television service is limited to areas near major population centers.

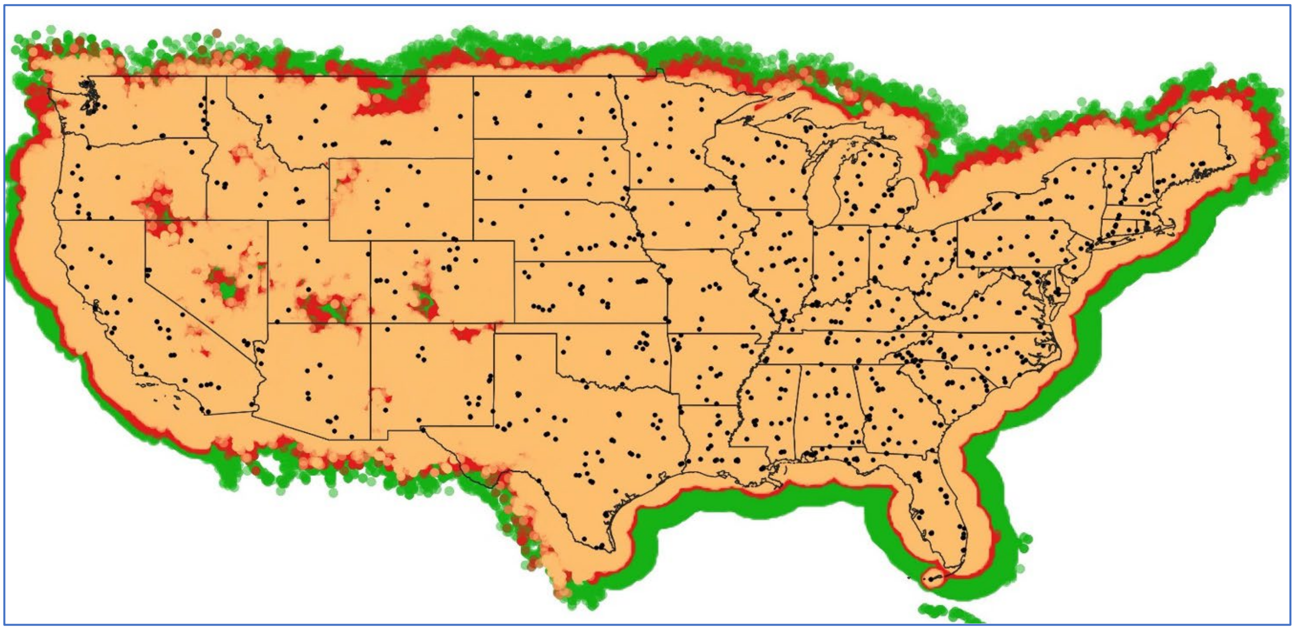

FIGURE 4: BPS COVERAGE FOR GENERAL USERS IN CONUS. SHADED AREAS ARE COVERED BY AT LEAST ONE BPS-EQUIPPED TELEVISION STATION ASSUMING PLANNING FACTOR VALUES GIVEN IN TABLE 1. COVERAGE EQUAL TO OR ABOVE THRESHOLD (TH) IS SHOWN IN GREEN; ≥TH+10 DB COVERAGE IS SHOWN IN RED; ≥+20 DB COVERAGE IS SHOWN IN ORANGE.

While recovery of a single BPS signal is adequate to provide a timing reference at a given known location, more BPS signals can provide improved accuracy and redundancy at that location. With that in mind, each coverage grid point in Figure 4 was examined to determine how many BPS stations are predicted to provide an adequate signal at that grid point. The histogram of Figure 5 shows the number of grid points covered by 1, 2, 3, 4 and more unique BPS signals. Note that the large number of locations (cells) predicted to receive only one or two BPS signals is attributable to offshore locations where only VHF stations provide coverage. UHF television stations are designed to serve their audience and therefore many stations use directional antennas to limit the energy wasted into offshore or other unpopulated areas. In contrast, most VHF stations use omnidirectional antennas that provide usable signals well offshore [12].

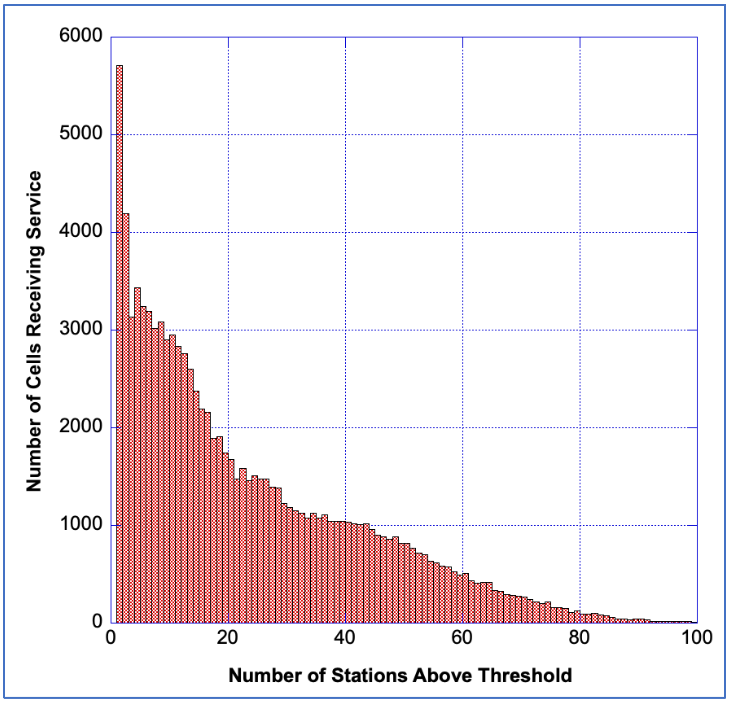

FIGURE 5: NUMBER OF LOCATIONS PREDICTED TO RECEIVE 1, 2, OR MORE BPS STATIONS ABOVE THRESHOLD. THE LOCATIONS (CELLS) PREDICTED TO RECEIVE 1 OR 2 BPS SIGNALS ARE MOSTLY OFF-SHORE. SEE TEXT.

Statistically, Figure 5 shows that a typical (median) location (cell) in CONUS is predicted to receive BPS signals from 17 television stations, although the actual number varies with location, ranging from 1 to 134 stations.

Results – Predicted Coverage for Networked BPS Slave Stations

As discussed in a previous section, a small number of "master" BPS stations can provide timing to "slave" BPS stations, which then can provide a timing signal derived from one or more master stations. If slave station transmitting towers are used to support antennas for reception of BPS signals from master BPS stations, then the probability of reception from multiple stations improves. This is because TV towers are typically very tall and/or located at prominent geographic locations. A second coverage analysis was performed at the specific locations of all television transmitting stations, assuming the BPS receiving antenna is installed 50 meters above ground on the station's tower. As expected, the number of unique BPS signals predicted to be received increased. A typical (i.e., median) receiving antenna at 50 meters above ground on a TV tower is predicted to receive BPS signals from some 70 television stations, with the actual number ranging from 1 to nearly 150. The median reception figure is over four times that of general users at random locations using antennas just 1.5 meters above ground. A chart showing the cumulative distribution of BPS signals predicted to be received at the location of TV transmitting towers is shown in Figure 6.

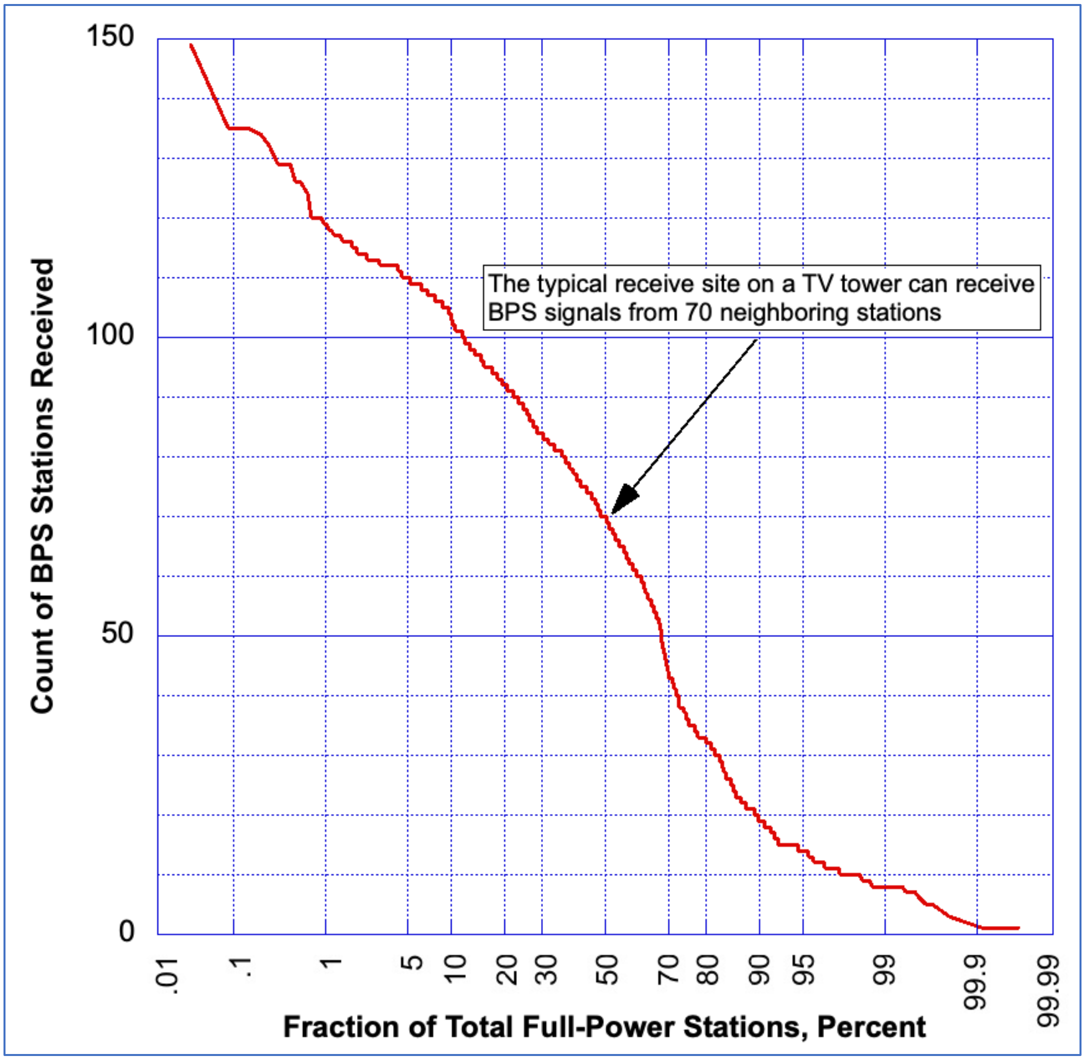

FIGURE 6: CUMULATIVE DISTRIBUTION GRAPH SHOWING THE FRACTION OF TV STATION TOWERS THAT ARE PREDICTED TO RECEIVE THE INDICATED NUMBER OF BPS STATIONS. THE TOTAL NUMBER (100%) OF FULL-POWER STATIONS CONSIDERED IS 1642. SEE TEXT.

Models for Potential BPS Service Adoption

These initial results confirm that there is potential for not only networked time synchronization to provide accurate, precise, and reliable timekeeping function to support the BPS service(s) but also the provision of end user consumable signals for trusted time transfer. Looking forward, the BPS timekeeping function can be implemented along, at least, two paths for adoption.

Where motivated broadcasters desire an affiliation-oriented path, early transmitter technology investment can follow a vertical integration model and form affiliate network timekeeping systems. An affiliate-driven rollout can be conducted rapidly with closely coordinated management decision processes and provisioning of transmitters.

Where broadcasters pursue a service-oriented path to provide timing and positioning in regions with unmet PNT needs, a horizontal integration model is likely to be effective. Investment under regional agreements for equipage at designated timekeeping transmitters to serve as trusted and traceable UTC anchors opens the door to service level agreements for enhanced monitoring and reliability of the time transfer function station-to-station. Those stations “subscribing” to the trusted-and-traceable time transfer service(s) can then serve as BPS transmitter nodes but at a lower level of expected investment.

Regardless of business model choice, the initial objective is to provide an efficient and cost-effective options for secure trusted time to Critical Infrastructure owners and operators, *e.g.*, fintech, energy distribution, communications networks, and transportation operations. Success in this objective will pave the way for increased service provisioning to higher performance (accuracy, precision, etc.) and new functions (positioning, authenticated services, monitoring and cross-checking of other PNT services).

Tower Synchronization Method and Algorithm

As noted earlier, the BPS protocol offers the ability of participating towers to synchronize to each other by exchanging timing information plus configuration and performance information for use in the decision model.

The source type list previously noted offers the basis for deciding whether to utilize a tower in the synchronization algorithm. These source types provide the clock quality level for a tower to use in its combining algorithm. The UTC from NIST or USNO are the highest quality, followed by the GPS source. When BPS is being utilized as a backup for GPS time by a Critical Infrastructure provider, these sources are necessary to maintain the critical operation of that provider.

It should be noted that during normal times in which GPS is not interrupted or unavailable, the BPS towers can be synchronized to the GPS signal. In times of interruption or unavailability the BPS tower will provide near GPS equivalent time from the other sources as noted in the source value table. The USNO and NIST sources will be utilized in these times.

An outline of the self-synchronizing method follows. It should be noted that these steps and expected results need to be confirmed through a thorough prototype testing scenario. Steps and processes will be formalized and documented throughout this “shake down” period. If every tower aligns its clock to the mean clock of the neighboring towers, all of them will converge to a self-synchronized value. If the master towers in this group keep their clocks unchanged, then the self-synchronized time will converge towards the master clocks’ time.

1. Listen to signals from neighboring towers and extract the `bps_info()` message. Adjust for the propagation delay of each tower and estimate the clocks of all the neighboring towers.
2. Using a tower’s own internal clock as a reference, estimate the timing offset of each neighboring tower’s clock. This clock is disciplined to either a Precision Timing Protocol source, a GPS source or a master neighbor source.
3. Compute the mean and standard deviation of the neighboring towers’ clocks. If there are obvious outliers that are not master towers, remove those towers from the neighbor list. For example, clocks with twice the standard deviation of the neighbor group’s distribution can be removed. Do not remove master towers from the list. Let us call the remaining neighboring towers’ list “credible towers.” If master clocks exist within the neighbor group those shall be utilized by the tower performing the analysis and will be called the “Master BPS network reference time.”
4. Using a tower’s own internal clock as a reference, align the credible towers’ clocks so that all of them refer to the same instant in time. This step will be utilized in the event none of the neighbors reports itself as a master. This step is necessary because the bootstrap signals of the towers may not be aligned in time.
5. Compute the mean of the non-master credible clocks; call it the NM BPS network reference time. If a tower is not a master and is using neighboring towers for synchronization, that tower will align its own clock to NM BPS network reference time.

BPS Network Reference Time Network

The actual BPS reference time network will be made up of independent but interconnected time distribution "timing domains." The reason for this is that management of the nationwide BPS time distribution network, if it uses all the towers available, will constitute an extremely large number of timing nodes making management decisions and control unwieldy. For this reason, the BPS time distribution network will be segmented into manageable "domains" each with a size making it practical. These domains will interconnect to provide nationwide uniform resilience of time distribution. This technique eliminates the single point of failure such as found in GPS time distribution. This portion of the BPS network reference time distribution network is a work in progress and will be reported on as it evolves.

Summary

BPS can satisfy the Critical Infrastructure timing needs if GPS becomes unavailable. If all television stations participate, single-tower coverage of BPS signals spans all of CONUS and miles of coastal and border areas. BPS towers can form a self-synchronizing network with a few master stations. A BPS tower synchronization algorithm is proposed to provide the best accuracy to all users throughout the network.

References

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[2] https://www.atsc.org/nextgen-tv/deployments/

[3] Presidential Executive Order 13905 "Strengthening National Resilience Through Responsible Use of Positioning, Navigation, and Timing Services," 18 Feb 2020

[4] National positioning, navigation, and timing architecture: implementation plan. (bts.gov) , July 28, 2010

[5] http://gps.gov

[6] 17 CFR §242.613

[7] "ATSC Recommended Practice: Guidelines for the Physical Layer Protocol," *Doc. A/327:2022-03,* March 2022, Advanced Television Systems Committee, Washington, D.C.

[8] FCC LMS data set, downloaded January 23, 2023. Note that some television stations are authorized to operate multiple transmitter sites in a single frequency network configuration.

[9] "Longley-Rice Methodology for Evaluating TV Coverage and Interference," *FCC/OET Bulletin No. 69*, February 6, 2004

[10] McKenna, P. and Najmy, F., "Evaluation of Two Site-Specific Radio Propagation Models," *Proc. ISART, NTIA Special Publication SP-03-401* (2003)

[11] Henry Gannett, "Areas of the United States, the States, and the Territories," *USGS Bulletin No. 302* (1906)

[12] Weller, R., Colombo, M., and Gao, C., "Statistics of Full Power and Class A Television Stations in the United States as of February 22, 2012," *FCC Report No. TAB 2013-01* (July 16, 2013)

Appendix A

A mandatory presence in the following table means that if the `bps_info` message is transmitted, those fields must be populated within the message.

Syntax	*No. of bits*	*Format*	*Presence*
bps_info(){			
message_length	16	unsigned integer	mandatory
version	8	unsigned integer	
timing_source_info(){			
sync_hierarchy	7	unsigned integer	
num_independent_sources	6	unsigned integer	
for (i=0;i< num_independent_sources;i++){			
source_type_list	4	unsigned integer	
}			
expected_accuracy	16	unsigned integer	
source_used	4	unsigned integer	
}			
self_measurement_info(){			
call_sign	42	array of 7 6-bit unsigned integers	
tx_id	13	unsigned integer	
tx_freq	32	32-bit floating point	
geodetic_lat	64	64-bit double precision	mandatory
geodetic_lon	64	64-bit double precision	mandatory
geodetic_height	64	64-bit double precision	mandatory
radiated_power	32	32-bit floating point	
for (i=0;i<36;i++){			
antenna_pattern_relative_field	252	array of 36 7-bit unsigned integers	
}			
max_gain_direction	10	unsigned integer	
prev_bootstrap_time_sec	32	unsigned integer	
prev_bootstrap_time_msec	10	unsigned integer	
prev_bootstrap_time_usec	10	unsigned integer	
prev_bootstrap_time_nsec	10	unsigned integer	
prev_bootstrap_time_error_nsec	16	signed integer	
}			
leap_seconds	8	unsigned integer	mandatory
num_neighbors	6	unsigned integer	
for (i=0;i<num_neighbors; i++){			
neighbor_measurement_info(){			
call_sign	42	array of 7 6-bit unsigned integers	

tx_id	13	unsigned integer	
tx_freq	32	32-bit floating point	
geodetic_lat	64	64-bit double precision	
geodetic_lon	64	64-bit double precision	
geodetic_height	64	64-bit double precision	
radiated_power	32	32-bit floating point	
for (i=0;i<36;i++){			
antenna_pattern_relative_field	252	array of 36 7-bit unsigned integers	
}			
max_gain_direction	10	unsigned integer	
reported_bootstrap_time_sec	32	unsigned integer	
reported_bootstrap_time_msec	10	unsigned integer	
reported_bootstrap_time_usec	10	unsigned integer	
reported_bootstrap_time_nsec	10	unsigned integer	
bootstrap_toa_offset	32	signed integer	
prev_bootstrap_time_sec	32	unsigned integer	
prev_bootstrap_time_msec	10	unsigned integer	
prev_bootstrap_time_usec	10	unsigned integer	
prev_bootstrap_time_nsec	10	unsigned integer	
prev_bootstrap_time_error_nsec	16	signed integer	
}			
}			
reserved_bits	as needed		mandatory
bps_crc	32	unsigned integer	mandatory
}			

`message_length` – This field indicates the length of the message, including the CRC bits, in units of bytes.

`version` – This field represents the version of the message.

`sync_hierarchy` – This field indicates the number of hops needed to transfer time from a reference ATSC 3.0 tower to the tower that is using neighboring towers' ATSC 3.0 signal as timing reference. If an ATSC 3.0 tower does not use the timing information from any neighboring tower to synchronize its own clock, its hierarchy is 0. For example, towers that receive traceable time from NIST or USNO using satellite, fiber, or other methods but do not use any neighboring tower's signal for synchronization will report 0 in this field. If a tower is using a `sync_hierarchy` 0 tower's signal for timing reference, that tower will report its `sync_hierarchy` as 1. Generally, if a tower is listening to the signals from neighboring towers for clock synchronization, and if n is the lowest `sync_hierarchy` among the received signals, that tower will report n+1 as its own `sync_hierarchy`.

`num_independent_sources` – This field indicates the number of independent timing sources used at the ensemble clock deployed at the tower location for clock synchronization. For example, if a TV station uses GPS, one cesium clock, eLORAN, and 5 neighboring towers as input to the ensemble clock, that tower will report the number 8 in this field. If a tower does not use an ensemble clock but uses another backup clock if its primary clock fails, the reported value will be 1. The corresponding `source_type_list` parameter will be updated accordingly in that case.

`source_type_list` – This field indicates the various timing sources used as reference at the ATSC 3.0 transmission facility. The following table is used to indicate the types:

Value	*Source Type*
0	UTC from NIST or USNO securely delivered to the TV station
1	GPS
2	ATSC 3.0 signal emitted from neighboring towers
3	Local clock, such as cesium or rubidium
4	eLORAN
5	Reserved
6	Reserved
7	Reserved
…	…
15	Reserved

If the transmission facility uses an ensemble of clocks, it will list the most accurate timing source of the ensemble as its source.

`expected_accuracy` – This field indicates the accuracy of the TV station clock 99% of the time compared to UTC. The unit is nanoseconds. A value of 200 means that the TV station clock is synchronized in such a way that the local clock is within 200 ns of UTC 99% of the time.

`source_used` – This field indicates the type of timing source used at the transmission facility. If the tower clock is derived from an ensemble of timing devices, a value of 0 will be reported. If the tower uses just one of the clocks available to it, that source will be reported using the table described under `source_type_list` parameter.

`call_sign` – This field states the 3 to 7-letter call sign of the TV station. If the call letters are shorter than 7 characters, the remaining fields are padded with “space” characters. The mapping of 6-bit unsigned integers and the letters in the call sign follows:

Binary	*Character*
000000	space
000001	hyphen
000010	A
000011	B
…	…
011011	Z
011100	0
011101	1
…	…
100101	9
100110	reserved
…	reserved
111111	reserved

`tx_id` – This field represents the `txid_address` field as it is defined in ATSC A/322 with specific codes assigned according to the table at txid.nabpilot.org.

`tx_freq` – This field indicates the middle of the assigned television channel frequency in units of MHz.

`geodetic_lat` – This field represents geodetic latitude of the midpoint of the transmit antenna in WGS 84 LLA convention.

`geodetic_lon` – This field represents geodetic longitude of the midpoint of the transmit antenna in WGS 84 LLA convention.

`geodetic_height` – This field represents geodetic height of the midpoint of the transmit antenna in WGS 84 LLA convention.

`radiated_power` – This field represents ERP of the radiating antenna in units of kilowatts.

`antenna_pattern_relative_field` – This field represents the antenna pattern by the relative field values reported every 10 degrees. The values are arranged clockwise starting at true north, meaning that the 1st value of the 36-element array represents the relative field strength in the direction north, the 2nd value represents the relative field strength in the direction 10 degrees clockwise from north, and so on. The relative field values are scaled such that the maximum value, which is 1.0, is scaled to the integer 127 in fixed point representation.

`max_gain_direction` – This field represents the direction where relative field strength is maximum, i.e., 1.0. The angle is measured clockwise from north. The angle is reported as a fixed-point value such that 360 degrees is scaled to 1023 in fixed point notation.

`prev_bootstrap_time_sec` – This field will be populated with the `L1D_time_sec` value, as defined in ATSC A/322, of the immediately previous transmitted frame. For `self_measurement_info`, the transmitting tower will provide this information. For `neighbor_measurement_info`, the transmitting tower will receive the value in `bps_info` message from a neighboring tower and report that value in this field.

`prev_bootstrap_time_msec` – This field will be populated with the `L1D_time_msec` value, as defined in ATSC A/322, of the immediately previous transmitted frame. For `self_measurement_info`, the transmitting tower will provide this information. For `neighbor_measurement_info`, the transmitting tower will receive the value in `bps_info` message from a neighboring tower and report that value in this field.

`prev_bootstrap_time_usec` – This field will be populated with the `L1D_time_usec` value, as defined in ATSC A/322, of the immediately previous transmitted frame. For `self_measurement_info`, the transmitting tower will provide this information. For `neighbor_measurement_info`, the transmitting tower will receive the value in `bps_info` message from a neighboring tower and report that value in this field.

`prev_bootstrap_time_nsec` – This field will be populated with the `L1D_time_nsec value`, as defined in ATSC A/322, of the immediately previous transmitted frame. For `self_measurement_info`, the transmitting tower will provide this information. For `neighbor_measurement_info`, the transmitting tower will receive the value in `bps_info` message from a neighboring tower and report that value in this field.

`prev_bootstrap_time_error_nsec` – This is the difference between the actual time when the first sample of the first symbol of the bootstrap was transmitted and the reported bootstrap transmission time in the `L1D_time_sec, L1D_time_msec, L1D_time_usec`, and `L1D_time_nsec` fields mentioned in ATSC A/322. The time difference is measured as actual transmission time minus reported transmission time in nanosecond unit. For `self_measurement_info`, the transmitting tower will measure and provide this information. For `neighbor_measurement_info`, the transmitting tower will receive the value in `bps_info` message from a neighboring tower and report that value in this field.

`leap_seconds` – This field represents the current number of leap seconds expressed as TAI – UTC.

`num_neighbors` – This field indicates the number of neighboring signal measurements reported in the message. If this field is set to 0, no `neighbor_measurement_info` will be populated in the message.

`reported_bootstrap_time_sec` – This field will be populated with the `L1D_time_sec` value, as defined in ATSC A/322, of the most recent frame transmitted by a neighbor tower and received at the transmitting tower.

`reported_bootstrap_time_msec` – This field will be populated with the `L1D_time_msec` value, as defined in ATSC A/322, of the most recent frame transmitted by a neighbor tower and received at the transmitting tower.

`reported_bootstrap_time_usec` – This field will be populated with the `L1D_time_usec` value, as defined in ATSC A/322, of the most recent frame transmitted by a neighbor tower and received at the transmitting tower.

`reported_bootstrap_time_nsec` – This field will be populated with the `L1D_time_nsec` value, as defined in ATSC A/322, of the most recent frame transmitted by a neighbor tower and received at the transmitting tower.

`bootstrap_toa_offset` – This field represents the difference between the time of arrival at the transmitting (self) antenna of the neighboring bootstrap signal and the reported timestamp in `L1D_time_sec`, `L1D_time_msec`, `L1D_time_usec`, and `L1D_time_nsec` fields as mentioned in ATSC A/322. The unit of this time offset is nanoseconds.

`reserved_bits` – This field indicates the number of reserved bits, 0 to 7, that is required to byte-align the message.

`bps_crc` – This field will contain the CRC value as computed according to Section 6.1.2.2 of A/322 over the contents of `bps_info` message excluding the `bps_crc` field.