BPS Mesh Network Initial Deployment Report

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Abstract – The BEIT 2024 paper, ATSC 3.0 Broadcast Positioning System (BPS) Mesh Network [3], provided a description of a notional mesh network intended to manage and monitor a collection of ATSC 3.0 television transmissions intended to provide high precision traceable time. A preliminary network of these Broadcast Positioning System (BPS) transmissions has been constructed in the Baltimore and Washington DC region using two transmitters and a third simulated transmitter in the NAB 1M laboratory. Another BPS transmitter has been deployed in the Denver area to reach the NIST facility in Boulder, Colorado where the signal is being analyzed.

This paper describes the actual systems deployed, how they are operating, and the results of the various experiments being carried out using the first installation of a BPS leader / follower architecture in preparation for a fully operational network deployment.

In addition, the paper describes the initial implementation of a network operating software system which has been developed with the intention of supporting a large, perhaps nation-wide deployment of the BPS Mesh Network.

Background

The BEIT 2024 paper, ATSC 3.0 Broadcast Positioning System (BPS) Mesh Network [3], provided a description of a notional mesh network intended to manage and monitor a collection of ATSC 3.0 television transmissions intended to provide high precision traceable time. This section provides a brief overview of the contents of that paper to supply background information.

Broadcast Positioning System

BPS relies on the preamble of an ATSC 3.0 frame to carry a bootstrap emission timestamp. If this timestamp is accurate, a receiver can synchronize its clock using the ATSC 3.0 signal. Moreover, since the ATSC 3.0 signal can easily carry data because of its IP-based transport, the location of the transmission antenna can be sent with the signal. Armed with the precise bootstrap emission time and the location of the antenna, a receiver at a known location can maintain a very accurate clock.

Previous NAB BEIT conference papers [1] and [3] described prototype systems deployed that achieved accuracy and precision meeting critical infrastructure requirements of the United States. Another BEIT conference paper [2] discussed the potential coverage of a BPS signal at various antenna heights and broadcast robustness. That paper posited that within the continental United States, an antenna mounted on each transmission tower at a height of 50m, would be able to receive as many as 70 transmissions at a broad range of frequencies given the target BPS PLP configuration if all high power transmitters were equipped with the BPS technology.

The new synchronization system along with the potential for receiving the signal from so many neighboring transmitters leads to an opportunity to build an extremely robust time transfer system of multiple transmitters, using multiple disparate frequencies and traceable time sources known as a BPS Mesh Network [3].

Receiver / Synchronizer Overview

The Phase II receiver / synchronizer developed by Avateq Corp. is branded "AVQ1050". It operates in two modes: as a synchronizer, which is used to optimize the local broadcast time transmission or as a receiver to monitor and analyze the BPS signal of neighbor transmitters. The AVQ1050 is based on the Avateq RF front-end with an FPGA-based DSP chain contained within a 1RU box and a second unit for post-processing. Additional development of the FPGA-based DSP core was required to meet the Phase II project objectives. The intention of the AVQ1050 design was:

a) to meet the Phase II project technical requirements in full;
b) to provide more flexibility for development, verification and debugging the synchronization chain and its components at all levels;
c) to introduce a set of standard interfaces for off-the-shelf available instrumental hardware. These were realized as PCIe cards for additional NICs, PTP, I/O, Timing, GPS (if required), etc.; and
d) to deliver a versatile platform suitable for potential applications related to the BPS and not limited to the time synchronization task.

Figure 1 provides a diagram of a notional BPS transmission system that was operated during the proof-of-concept Phase II trials. A description of the various blocks is provided after the figure.

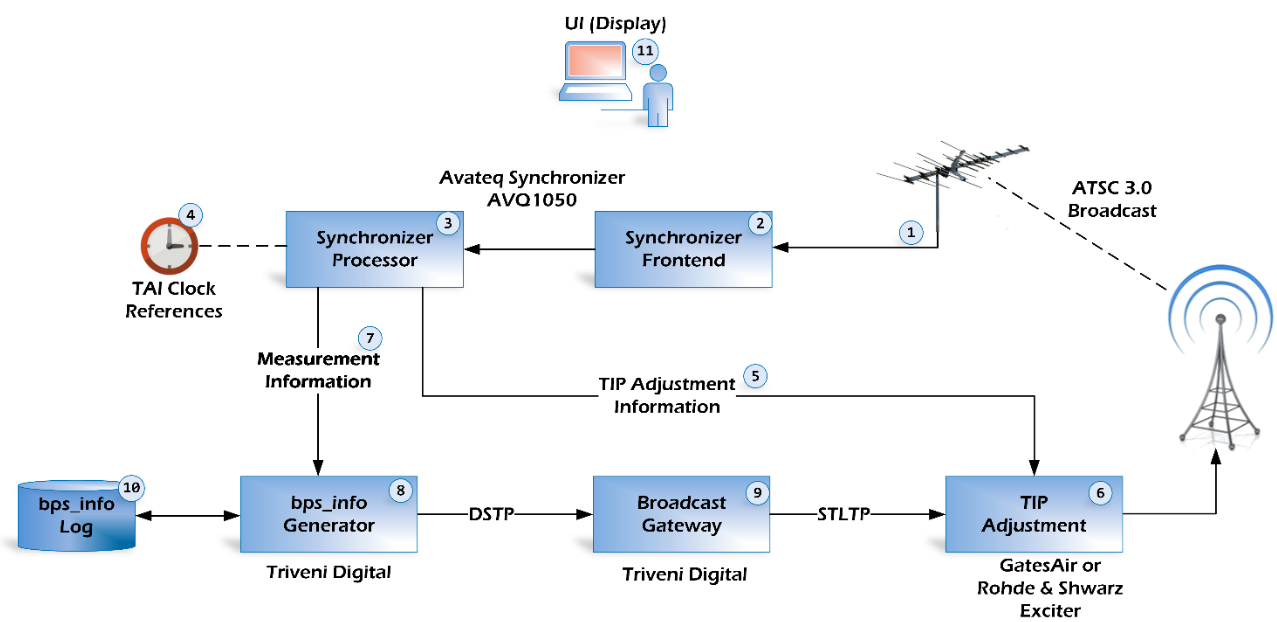


FIGURE 1: BPS TRANSMISSION SYSTEM DIAGRAM.

① The ATSC 3.0 transmission. Compliant transmissions include a time stamp based on the current International Atomic Time (TAI) in the detailed preamble (L1D) according to A/322 [4]. The time represented by the L1D timestamp is referred to as the "Time Information Position" or "TIP" which describes the instant in time at the center of the leading edge of the first sample of the first symbol of the bootstrap when the wave form was emitted from the transmitter antenna.
② The Avateq AVQ1050 ATSC 3.0 BPS Synchronizer Front End. This is a physically separate component that performs the RF signal processing to measure and extract the time signal.
③ The Avateq AVQ1050 ATSC 3.0 BPS Synchronizer Processor is a high-performance computing engine that allows further experimentation to be carried out without constraint. It allows external interfaces through PCIe to high-precision clocks or other devices that may prove useful as the project moves through additional phases in the future.
④ Use of the dedicated processor enables many types of interfaces to reference clocks that were not previously available. Since this system was developed as an experimental platform for the BPS concept, the general-purpose CPU provides more precision clock interface options.
⑤ An adjustment signal is generated by the synchronizer and forwarded back to the exciter to "close the feedback loop". The TIP adjustment interface allows the feedback to be as close as possible to the next emitted frame.
⑥ The TIP adjustment is applied by the exciter to the next available preamble after it receives the TIP adjustment information.
⑦ The Measurement Information is provided to the bps_info Generator function. This information is distinctly different from the information sent to the exciter in step ⑤ above. The information can be a more comprehensive set of data to allow the bps_info structure to carry history and other information helpful to receivers.
⑧ The bps_info Generator uses the latest time differential information along with preset location values to create a bps_info data structure. This data structure is logged and sent to the Broadcast Gateway as a separate data table in a robust PLP.
For Phase II, the bps_info structure was designed as three distinct sections to support different transmission requirements. The timing measurement was separated from the transmitter details and the timing source details to allow higher frequency, dynamic information to be distributed separately from more static data. [3]
⑨ The Broadcast Gateway can operate without knowledge that it is part of the BPS synchronization loop; however, a time adjustment is still available as a lower performance backup.
⑩ The bps_info log function is part of the bps_info Generator. It collects received bps_info structures into a log for post-processing.
⑪ A user interface (UI) is provided via a web interface (HTTP) to allow logging information to be displayed as well as to allow the system to be controlled. Control connections are not shown to reduce diagram complexity. Of particular interest will be a user interface that provides a graph of the time differential value over time to verify that the system is operating correctly. An example of this graphical display is shown in Figure 2.

System Performance

The proof-of-concept developed by the partner companies demonstrated that a feedback control loop can increase the accuracy of the transmitted timestamps of an existing ATSC 3.0 transmission chain. While the Phase I synchronization provided an instantaneous time delay of the stabilized system at less than 300 ns, the Phase II system reduced that number to typically under 10 ns. It was learned that the different exciters had different time response characteristics, meaning they had different transfer functions. It was discovered that the optimal PI controller settings were different in each case.

The Phase II systems included the previous broadcast gateway software used in Phase I but also introduced new firmware into the exciter to allow the synchronizer to control the emitted time directly at its insertion point. The higher performance of the synchronizer / receiver combined with the tighter control loop resulted in an order-of-magnitude improvement in system performance.

The solution demonstrated remains 100% compliant with the ATSC 3.0 standard as was the Phase I system. No change in the standard was necessary for this phase of the BPS project. The solution was demonstrated with transmission equipment from multiple ATSC 3.0 vendors, reinforcing the standard compliance.

Synchronizer Performance

The yellow and blue curves exemplified in Figure 2 correspond to raw measurements of the Bootstrap arrival delay and the filtered and PID-processed TIP adjustment, respectively, provided by the Phase II synchronizer. Note that the scale on the y axis of the graph ranges between ± 0.004 μsec, that is, 4 ns.

It should be noted that the blue line in the graph in Figure 2 shows the variation after PID filtering. This value typically remains below 1 ns.

FIGURE 2: EXAMPLE PHASE II SYNCHRONIZER BPS TIME ARRIVAL GRAPH.

Transmitter "Node" Description

In a nationwide deployment of the BPS network, it is expected that the functionality at each node, that is, each transmitter, would be essentially the same with some "leader" transmitters having time traceable to TAI. It is also expected that by adding additional time-keeping equipment, transmitters can move from "followers" to "leaders" and vice versa. This document assumes that all transmitters within receiving range are on separate frequencies, that is, form a multiple frequency network (MFN).

Figure 3 provides a diagram of an exemplary BPS network using four transmitters. The detailed diagram shown associated with one of the transmitters would apply to all the transmitter nodes in the BPS network. In this case, the node would be designated as a "Leader" since it would have a source of traceable time. Figure 3 provides a logical diagram of the systems and functions developed. The numbered paragraphs that follow the diagram correspond to the callouts in the diagram.

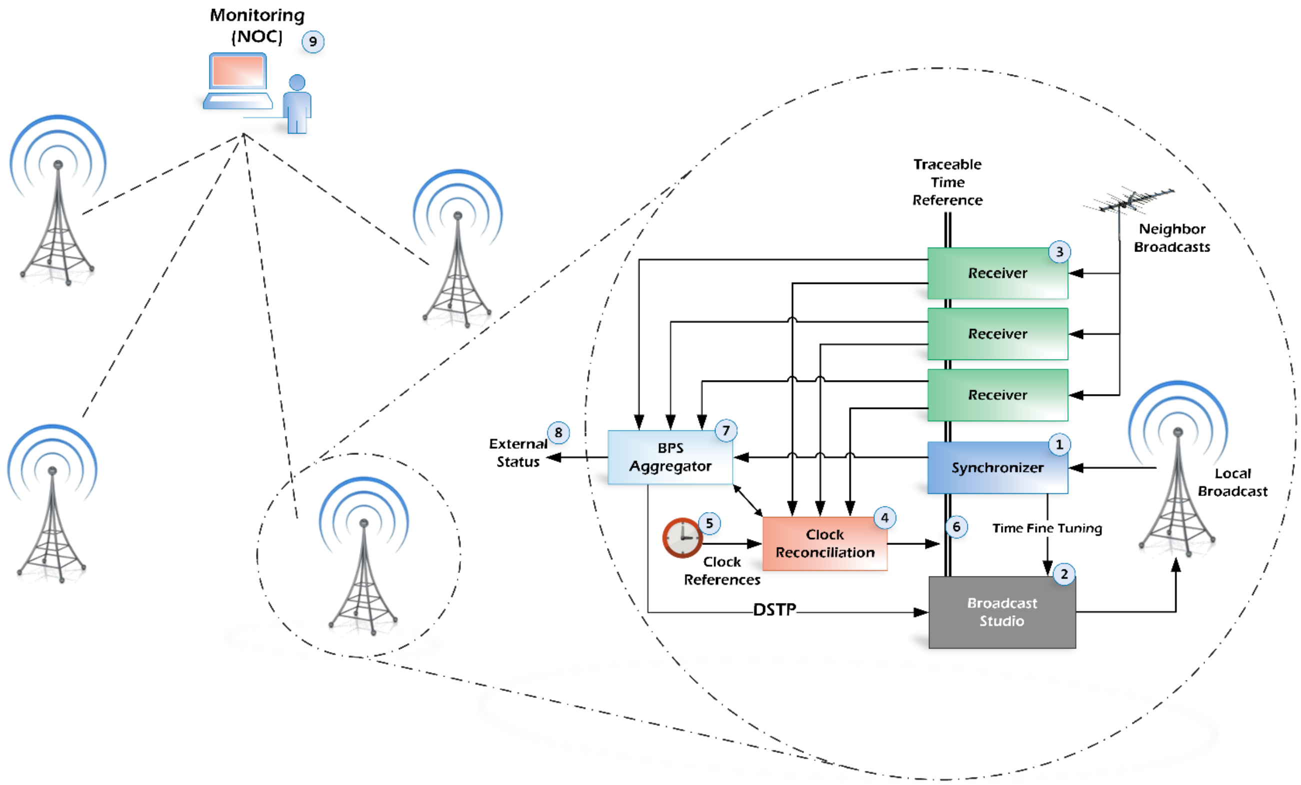


FIGURE 3: BPS TRANSMISSION NODE DIAGRAM.

① This block represents the Avateq AVQ1050 ATSC 3.0 BPS Receiver and Synchronizer described in previous sections. This device, configured to operate as a Synchronizer, receives the local broadcast, measures the bootstrap emission time with the time signaled in the L1D preamble and reports differences. The time difference is passed to the Broadcast Studio air chain ②, specifically, the exciter modified to accept the fine-tuning protocol provided by the synchronizer. Both GatesAir Maxiva XTE and Rohde & Schwarz SDE900/TCE901 exciters provide support for this protocol. All information about the basic processing of the time information is forwarded to the BPS Aggregator ⑦.

② The Broadcast Studio represents an ATSC 3.0 air chain. Internal components of the air chain of primary interest to this document are the Broadcast Gateway and the exciter. The BPS Aggregator function ⑦ provides a multicast or DSTP stream containing bps_info data structure that is formed into a dedicated PLP by the gateway. The output of the gateway is fed, via STLTP, to the exciter which generates the ATSC 3.0 wave form. In addition, the exciter receives fine-tuning information from the Synchronizer to make small adjustments to the emission time of each frame to more accurately generate the time carried in the L1D preamble of each frame.

③ The Avateq AVQ1050 ATSC 3.0 BPS Receiver and Synchronizer can also be used to obtain timing information from neighboring transmitters. In this case, the device is configured to operate as a "Receiver". For this example, three separate devices are required to receive the broadcast from three neighbor transmitters. The number of receivers deployed at any transmitter is limited only by cost since the number of transmissions visible to an ATSC 3.0 transmission tower are likely in the dozens once ATSC 3.0 is fully deployed. The robustness and resiliency of the network increases every time a receiver is added. Like the local synchronizer, these receivers will send all timing information including extracted bps_info to the BPS Aggregator ⑦ function for processing. The clock signals emitted by the receivers are 1PPS and 10MHz reference signals, and date/time info in IRIG-B126 (IRIG-B AM) format. This information is provided to the Clock Reconciliation function ④ for use in determining the best traceable time source.

④ The Clock Reconciliation function will be provided by multiple vendors including Safran, Microchip, and Adtran. This function takes input from each receiver and one or more clock references using them as Input References.

⑤ The Clock Reconciliation function ④ can use multiple clock references to determine the best time reference. The clock icon represents one local clock reference and is backed up by the Input References that can be configured on a priority basis. Additionally, different holdover oscillator options are available.

⑥ The double line represents station synchronized time. This time is sourced from the Clock Reconciliation function ④ and used by all devices as a reference traceable time source.

⑦ The BPS Aggregator function is an extension of the bps_info generator developed in previous phases. It receives information regarding the bps_info from each receiver, the synchronizer and the clock reconciliation system and combines them into a single data stream. There are two types of data reported by the receivers: detailed time information, specifically how each transmitter is varying from the correct time, and static information about each transmitter location and type. The combined bps_info stream along with the detailed timing information are merged into a single multicast IP stream fed into the Broadcast Gateway. This forms the complete data source of a dedicated BPS PLP. This data requires very little bandwidth so the PLP can use a very robust modulation / coding (ModCod) setting.

⑧ In addition to providing bps_info streams to the broadcast gateway, the BPS Aggregator function ⑦ also provides status via an external network connection. This is intended to be accumulated by a central management system which would be used to monitor the entire BPS network operation ⑨. Each device in the diagram also provides a local, web-based command, control, and status user interface as is typically provided by each of these devices today which the NOC can use to configure and control each discrete device if desired if some aberration is detected.

⑨ Ultimately, the entire network will require one or more centralized "Network Operations Center(s)" (NOCs) to monitor the overall behavior of the BPS network. The NOC would identify outages and issues with the various devices across the network. There would likely be multiple NOCs separated geographically perhaps monitoring selected regions of BPS systems. Further, the NOC could manage the various devices in the BPS system by accessing their command-and-control websites. This would likely be done over a dedicated VPN, but these details can be determined once the system becomes operational. For a live market trial, an example interface can be provided to demonstrate the basic NOC functionality.

2024 Development and Implementation

The AVQ 1050 Synchronizer / Receiver exceeded all target performance requirements of Phase II development so that system could be deployed as the core synchronization device in a BPS mesh network, as described in the 2024 BEIT paper "ATSC 3.0 Broadcast Positioning System (BPS) Mesh Network" [3]. The synchronizer and the TIP adjustment protocol connecting it to the local exciter allowed ATSC 3.0 transmitters to be stabilized to the accuracy and precision described in the Synchronizer Performance section above. This synchronization process has become known as the "Local Loop". Since there are currently no receivers aside from the AVQ1050 relying on the bps_info to determine the location of the stabilized ATSC 3.0 transmitters, the Local Loop alone is sufficient to transfer traceable time. This has been demonstrated using the KWGN transmitter in the Denver area to transfer time to the NIST facilities in Boulder and their WWVB radio time transmitter in Fort Collins.

While precise broadcast time is the underpinning of the BPS concept, the bps_info data transmission to support simple BPS receivers and managing the overall network are key features as well. The development efforts over the last year have been focused on enabling that functionality to ultimately support the deployment of a large-scale network comprising hundreds of BPS transmitters. To accomplish this, the BPS Aggregator software needed to be expanded significantly, and a network of these aggregators needed to be developed to allow control and management system concepts to be explored. In addition, the AVQ1050 required extensions and modifications to accommodate the various features needed as the network is being developed.

BPS Aggregator

The initial Phase I and Phase II bps_info generation software took information from the Avateq AVQ1050 and its precursor system and formed the bps_info data structures described in [3]. It also read information from the Safran SecureSync 2400 clock reconciliation system to determine which reference clock source was currently active. This clock source information is used to create a portion of the bps_info data structure. The generation software also logged the information as it was received from the various devices in the local loop.

To enable the functionality envisioned in the BPS Mesh network, the bps_info generation software was extended to enable interfaces to the AVQ1050 operating as a receiver to monitor neighbor transmissions. The information supplied by the AVQ1050 in Receiver mode is slightly different compared to the data supplied by Synchronizer mode. One of the primary differences is the bps_info forwarded from the neighbor transmission. The BPS Aggregator allows selection of the various fragments found in the bps_info data to be forwarded on from the local system. This is expected to be valuable to future receivers since the reception characteristics of the AVQ1050 measurement of the neighbor can be compared to the actual signal if both are received.

The primary function of receiving data from the AVQ1050 receiver is to monitor the performance of the neighbor transmitter from a BPS standpoint. As the mesh network grows, multiple monitoring sites for each transmitter will provide confirmation of the transmission at various points throughout the network, assuming receivers are dispersed. Broad dispersion is highly likely since the preamble and BPS PLP will be receivable much farther from the transmitter than is normally the case because of the highly robust modulation configuration well beyond the normal DMA constraints. The BPS Aggregator was developed to monitor both physical communications with the AVQ1050 as well as the next level functions including reception of the bps_info and validation that the time meets configured criteria. Simple graphs are provided that show when the time of arrival of the frames (as depicted in Figure 2) does not exceed configured limits. The BPS Aggregator logs all information from the connected AVQ1050s whether operating in a Synchronizer or Receiver mode.

Figure 4 provides a snapshot of the user interface of the BPS Aggregator operating in the NAB 1M Washington, D.C. laboratory. This user interface was intentionally developed to correspond to the BPS transmission node diagram shown in Figure 3 above. The user interface is a web site that can be accessed locally or through the BPS VPN as described in the BPS Network section below. The user interface diagram is dynamic, changing as status changes within the monitored network node. For example, the "spark line" above the synchronizer is a live graph of the time-of-arrival of each frame reflecting the information shown in the graph in Figure 2. Data from the AVQ1050 is used as the source of this graph. The lines between the elements in the diagram are active and indicate if communication with a particular element is lost or not performing correctly. Each element also contains a redirect icon which is a link to the user interface of that device. For example, clicking on the Synchronizer redirect launches a separate browser tab containing the interface shown in Figure 2. Using this user interface, a user can conveniently see the status of the local BPS functions on one display and gain access to component user interfaces for troubleshooting purposes.

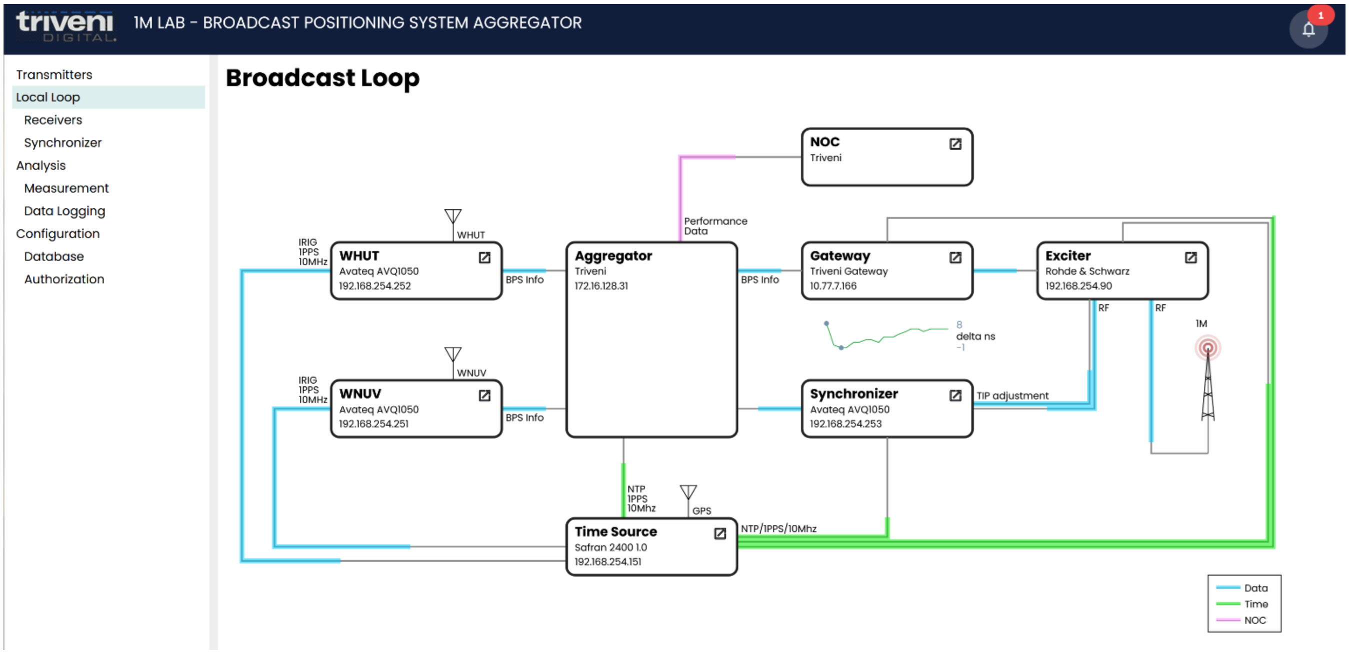


FIGURE 4: BPS AGGREGATOR BROADCAST LOOP USER INTERFACE.

On the left side of the user interface shown in Figure 4 are a list of other pages that the user can access to accomplish particular tasks and see detailed information about monitored functions. For example, the Receivers page, shown in Figure 5, allows the user to add or remove connections to receivers and see detailed information about their connection. Note the panel on the right that shows the BPS Info fragments being received. These are updated when received, typically every second. The user can select which fragments are forwarded to the local broadcast by using the checkbox associated with each fragment. In this case, the fragments from WHUT are being forwarded to the local test broadcast within the 1M lab.

In addition, receivers that cannot be reached are shown with error indicators as is the case with the receiver labeled "Local 1M Receiver" in Figure 5. For this example, the receiver had not been enabled but had been added to the BPS Aggregator to test the failure scenario. The local receiver had also not yet been added to the local broadcast loop diagram. However, the notification that there is a problem can be seen on both Broadcast Loop and Receivers pages as the alarm condition in the upper right corner.

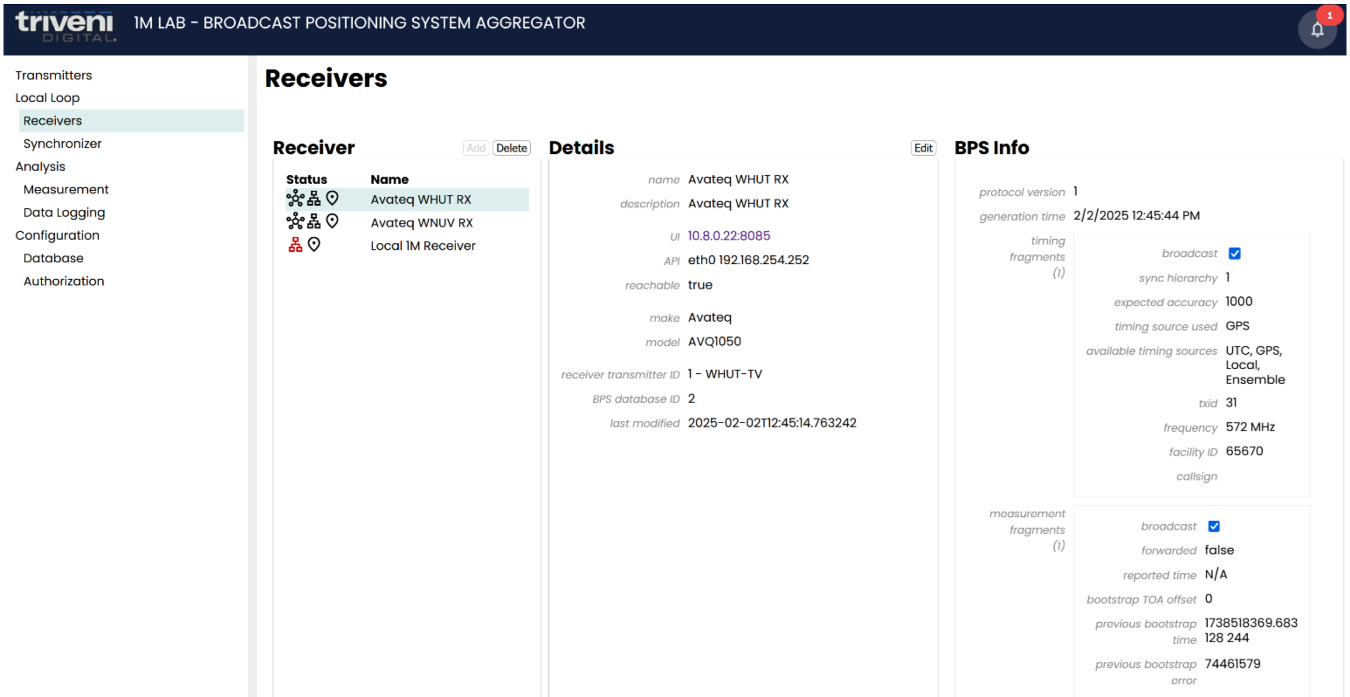
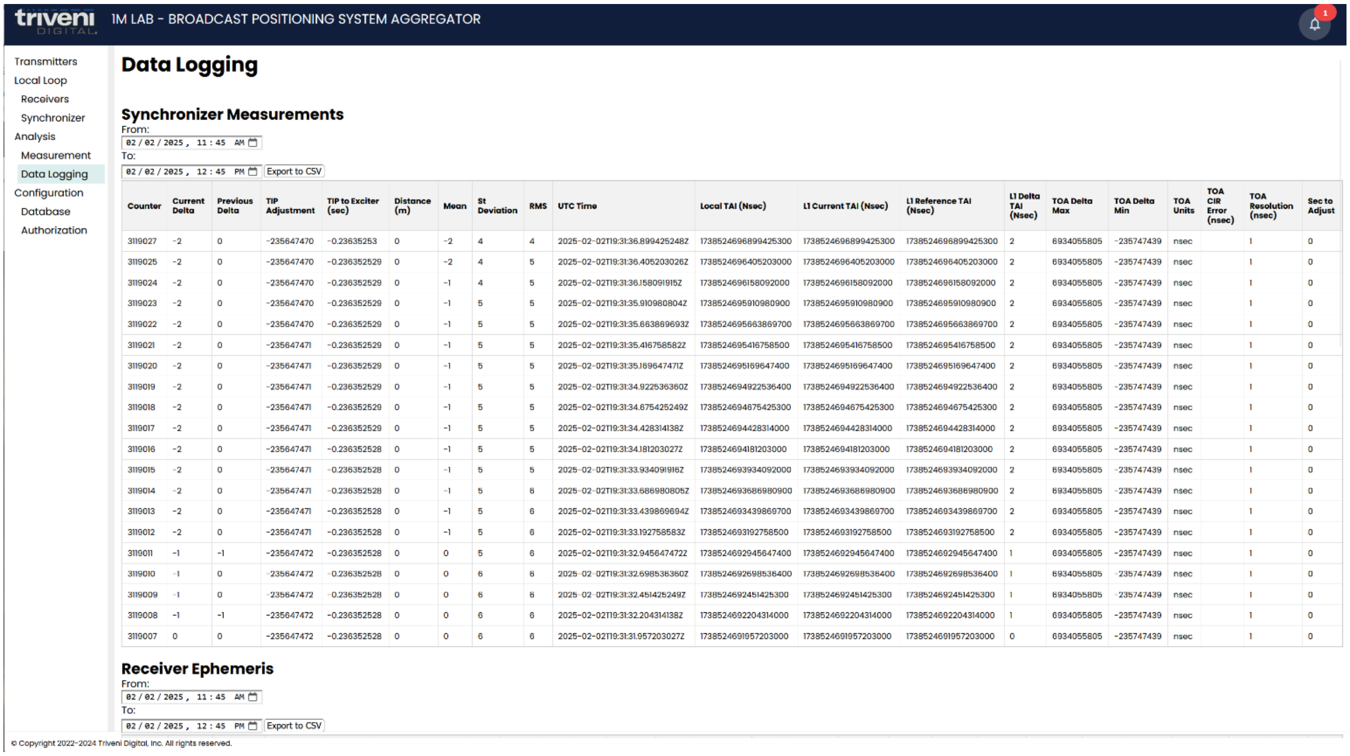


FIGURE 5: BPS AGGREGATOR RECEIVERS USER INTERFACE.

Another key feature of the BPS Aggregator is the ability to log information for export. This capability is found under the "Analysis" section of the menu in the left panel of the user interface. The Measurement page in Figure 6 provides a comparison view of the time of arrival graphs from the local synchronizer and the receivers. This allows comparison between the performance of the local transmission system and the BPS transmissions received with respect to the local reference time.

FIGURE 6: BPS AGGREGATOR MEASUREMENT USER INTERFACE.

The data logging page shown in Figure 7 provides a means for a user to export selected data logs for specific times of day. The data is exported as a CSV file that can then be imported into external analysis tools.



Counter	Current Delta	Previous Delta	TIP Adjustment	TIP to Exciter (sec)	Distance (m)	Mean	St Deviation	RMS	UTC Time	Local TAI (Nsec)	L1 Current TAI (Nsec)	L1 Reference TAI (Nsec)	L1 Delta TAI (Nsec)	TOA Delta Max	TOA Delta Min	TOA Units	TOA CIR Error (nsec)	TOA Resolution (nsec)	Sec to Adjust
3119027	-2	0	-235647470	-0.23635253	0	-2	4	4	2025-02-02T19:31:36.899425248Z	1738524696899425300	1738524696899425300	1738524696899425300	2	6934055805	-235747439	nsec		1	0
3119025	-2	0	-235647470	-0.236352529	0	-2	4	5	2025-02-02T19:31:36.405203026Z	1738524696405203000	1738524696405203000	1738524696405203000	2	6934055805	-235747439	nsec		1	0
3119024	-2	0	-235647470	-0.236352529	0	-1	4	5	2025-02-02T19:31:36.158091915Z	1738524696158092000	1738524696158092000	1738524696158092000	2	6934055805	-235747439	nsec		1	0
3119023	-2	0	-235647470	-0.236352529	0	-1	5	5	2025-02-02T19:31:35.910980804Z	1738524695910980900	1738524695910980900	1738524695910980900	2	6934055805	-235747439	nsec		1	0
3119022	-2	0	-235647470	-0.236352529	0	-1	5	5	2025-02-02T19:31:35.663869693Z	1738524695663869700	1738524695663869700	1738524695663869700	2	6934055805	-235747439	nsec		1	0
3119021	-2	0	-235647471	-0.236352529	0	-1	5	5	2025-02-02T19:31:35.416758582Z	1738524695416758500	1738524695416758500	1738524695416758500	2	6934055805	-235747439	nsec		1	0
3119020	-2	0	-235647471	-0.236352529	0	-1	5	5	2025-02-02T19:31:35.169647471Z	1738524695169647400	1738524695169647400	1738524695169647400	2	6934055805	-235747439	nsec		1	0
3119019	-2	0	-235647471	-0.236352529	0	-1	5	5	2025-02-02T19:31:34.922536360Z	1738524694922536400	1738524694922536400	1738524694922536400	2	6934055805	-235747439	nsec		1	0
3119018	-2	0	-235647471	-0.236352529	0	-1	5	5	2025-02-02T19:31:34.675425249Z	1738524694675425300	1738524694675425300	1738524694675425300	2	6934055805	-235747439	nsec		1	0
3119017	-2	0	-235647471	-0.236352529	0	-1	5	5	2025-02-02T19:31:34.428314138Z	1738524694428314000	1738524694428314000	1738524694428314000	2	6934055805	-235747439	nsec		1	0
3119016	-2	0	-235647471	-0.236352528	0	-1	5	5	2025-02-02T19:31:34.181203027Z	1738524694181203000	1738524694181203000	1738524694181203000	2	6934055805	-235747439	nsec		1	0
3119015	-2	0	-235647471	-0.236352528	0	-1	5	5	2025-02-02T19:31:33.934091916Z	1738524693934092000	1738524693934092000	1738524693934092000	2	6934055805	-235747439	nsec		1	0
3119014	-2	0	-235647471	-0.236352528	0	-1	5	6	2025-02-02T19:31:33.686980805Z	1738524693686980900	1738524693686980900	1738524693686980900	2	6934055805	-235747439	nsec		1	0
3119013	-2	0	-235647471	-0.236352528	0	-1	5	6	2025-02-02T19:31:33.439869694Z	1738524693439869700	1738524693439869700	1738524693439869700	2	6934055805	-235747439	nsec		1	0
3119012	-2	0	-235647471	-0.236352528	0	-1	5	6	2025-02-02T19:31:33.192758583Z	1738524693192758500	1738524693192758500	1738524693192758500	2	6934055805	-235747439	nsec		1	0
3119011	-1	-1	-235647472	-0.236352528	0	0	5	6	2025-02-02T19:31:32.945647472Z	1738524692945647400	1738524692945647400	1738524692945647400	1	6934055805	-235747439	nsec		1	0
3119010	-1	0	-235647472	-0.236352528	0	0	6	6	2025-02-02T19:31:32.698536360Z	1738524692698536400	1738524692698536400	1738524692698536400	1	6934055805	-235747439	nsec		1	0
3119009	-1	0	-235647472	-0.236352528	0	0	6	6	2025-02-02T19:31:32.451425249Z	1738524692451425300	1738524692451425300	1738524692451425300	1	6934055805	-235747439	nsec		1	0
3119008	-1	-1	-235647472	-0.236352528	0	0	6	6	2025-02-02T19:31:32.204314138Z	1738524692204314000	1738524692204314000	1738524692204314000	1	6934055805	-235747439	nsec		1	0
3119007	0	0	-235647472	-0.236352528	0	0	6	6	2025-02-02T19:31:31.957203027Z	1738524691957203000	1738524691957203000	1738524691957203000	0	6934055805	-235747439	nsec		1	0

FIGURE 7: BPS AGGREGATOR DATA LOGGING USER INTERFACE.

Another key feature of the BPS Aggregator is to accumulate and filter performance data on how the local system and its neighbors are operating. This performance data is then forwarded to a module referred to as a "performance data collector" or PDC. This functionality is described in more detail in the BPS Network section below.

Since the BPS technology is still undergoing significant efficacy testing and science, the details of how a local transmission system will operate over time are still being explored. A significant amount of experience with the behavior of the monitored systems has been gathered over the last year but as more BPS transmissions are enabled, more data on potential system failures and failure modes will be accumulated. The BPS Aggregator is architected in a way that allows straightforward expansion and monitoring extensions. This flexibility will be necessary when the BPS network expands and becomes fully operational.

Receiver / Synchronizer Improvements

Based on experimental results obtained during Phase I and Phase II tests, initial implementation of the AVQ1050 Receiver and Synchronizer has been significantly improved thanks to additionally introduced metrics, enhanced accuracy and an integrated set of tools for the BPS signal quality analysis and troubleshooting. A newly introduced BPS Ephemeris© data structure provides real-time estimation of the BPS signal reception and allows integrating the Receiver with the BPS Aggregator.

Figure 8 below presents one channel of the enhanced AVQ1050 BPS Receiver multi-channel architecture. The following numbered paragraphs correspond to callouts in the architectural blocks and provide more details on the supporting functionality.

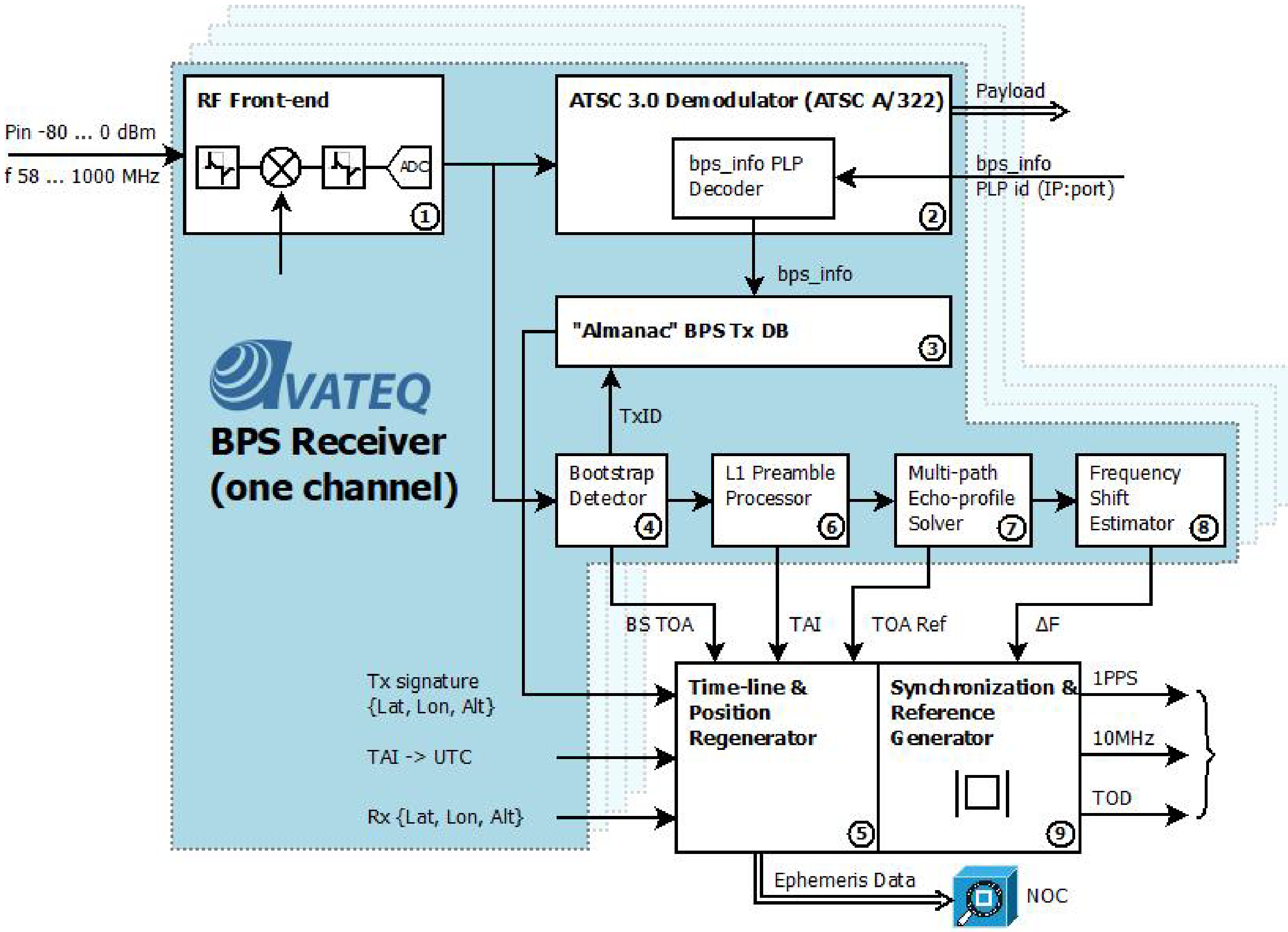


FIGURE 8: AVQ1050 MULTICHANNEL BPS RECEIVER FUNCTIONAL DIAGRAM.

① The AVQ1050 BPS Receiver's RF front-end provides signal amplification, filtering, and sampling. It supports RF signal reception in the frequency range of 50 to 1000MHz with signal levels from -80 to 0dBm.

② The signal is demodulated according to the ATSC A/322 Physical Layer Protocol [4], and the payload, including the BPS-specific "bps_info," is extracted.

③ The Transmitter Identification (TxID) can be obtained from the signal by the Bootstrap Detector or from a global BPS ATSC 3.0 Transmitter Database, similar to the GPS Almanac. Based on the TxID and data from the bps_info, a Transmitter Signature can be defined which includes geolocation and other characteristics to assist in accurate calculation of the time of signal arrival and the receiver’s position.

④ The Accuracy of Bootstrap Time-Of-Arrival (BS TOA) detection directly impacts the signal propagation delay calculation. As the signal-delivered TAI timestamp has a nanosecond resolution, detection of the BS TOA with accuracy comparable to the TAI timestamp resolution is critical for the BPS system performance.

The implemented approach to the BS TOA estimation has been extensively tested and verified over different levels of the signal SNR, modulation and coding schemes creating a basis for the further development of the signal timing information restoration. To improve the BS TOA estimation accuracy for the signals with low SNR, an optimization technique based on the signal statistical characterization over time has been designed and integrated into the algorithm. As the experimental results indicate the design provides the BS TOA estimation accuracy within the units of single-digit nanoseconds.

⑤ The Transmitter Signature is used by the Timeline & Position Regenerator as an initial time point for restoring a whole timeline at the Receiver. The timeline is used for tuning and maintaining the receiver internal clock.

⑥ The Receiver internal clock is synchronized with the TAI timestamp extracted from the ATSC 3.0 signal by the L1 Preamble Processor.

⑦ Another critical characteristic of the Receiver performance is its ability to provide accurate timing information in a multipath operational environment. The multipath propagation environment is a well-known and "hard to fight" real-life phenomena causing multiple signal peaks to appear at the receiver input. Each signal peak (or the main signal echo) can be individually characterized by its time-of-arrival and amplitude. It is critical to detect the earliest peak and use it as a reference for the estimation of the signal propagation delay.

Multiple peaks which are dispersed in a short time interval with small relative delays, i.e. the peaks arriving at the receiver input with small relative delays in their TOAs make the reference peak selection a non-trivial task – several echoes can be seen as a single peak.

The Multipath Echo-profile Solver core is based on an iterative technique for the TOA of the earliest multipath component selection as a time reference for ATSC 3.0-based BPS signals. The technique is based on Channel Impulse Response (CIR) signal processing as the primary source for presentation of a dispersed-in-time received signal. The designed processing provides a signal peak arrival time resolution in a range of 1 to 5 nanoseconds.

Figure 9 provides an example of multiple echoes and automatic selection of a reference peak for the specific Transmitter ID.

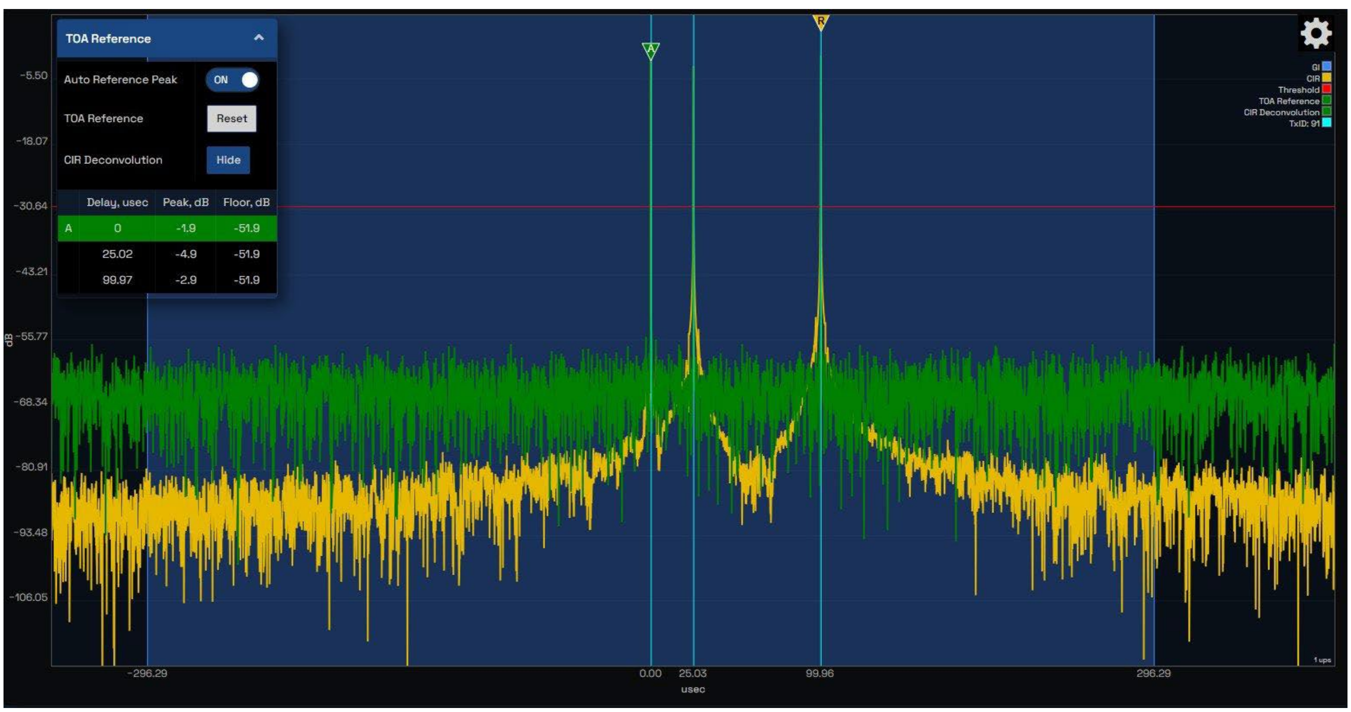


FIGURE 9: AVQ1050 MULTIPATH REFERENCE PEAK SELECTION.

⑧ Frequency Shift Estimator outputs the signal frequency offset for fine-tuning the Synch and Reference Generator core.

⑨ The Synch and Reference Generator is a source of 1PPS and 10MHz references, which are standard signals used for applications and equipment requiring time and frequency synchronization.

The next steps of further improving the Receiver performance include experimental research on the vulnerability of BPS signals to spoofing and jamming, developing methodologies and processing techniques for detection and mitigation of such attacks, and increasing the accuracy and reliability of timing information, especially under dynamic reception conditions.

BPS Network

The BPS network is envisioned to provide a centralized mechanism of monitoring and managing a large number of deployed BPS transmission systems. At the highest level, this is conceptualized in Figure 3 where each transmission node is connected to a centralized, cloud-based Network Operating Center (NOC). This concept requires each transmission node, specifically, the BPS Aggregator in each node, to be connected, in some fashion, with the network management system.

To accomplish this, a BPS virtual private network (VPN) has been deployed. BPS Aggregators connected to this system can deliver performance data to the central management system and can be controlled through that system, if allowed. However, since the BPS local loop involves equipment directly producing the transmission, connecting to an external network, even a secure VPN, is not allowed by many broadcasters. Thus, it has become clear that many modalities of communication from the BPS Aggregator into the BPS network will need to be developed.

Another feature of the mesh network is that each transmission may be monitored not only by the local synchronizer with the local loop but by neighbors, and perhaps multiple neighbors. All this information would be reported to the central system and would need to be presented to the operator monitoring the network in a clear way that could easily identify anomalies and problems.

Current Deployment

The initial deployment of a BPS network was undertaken in 2024. This network involved three transmissions and two laboratories along with a cloud-based server. Figure 10 provides a current connection diagram of these deployed systems across the United States. At present, only the 1M and Triveni Digital labs along with WHUT at Howard University are connected directly to the BPS VPN. Though not currently connected, the KWGN BPS Aggregator will soon be sending performance data through an HTTPS connection to the Cloud Node which is operating as the network center. The numbers within the diagram are described in paragraphs following Figure 10.

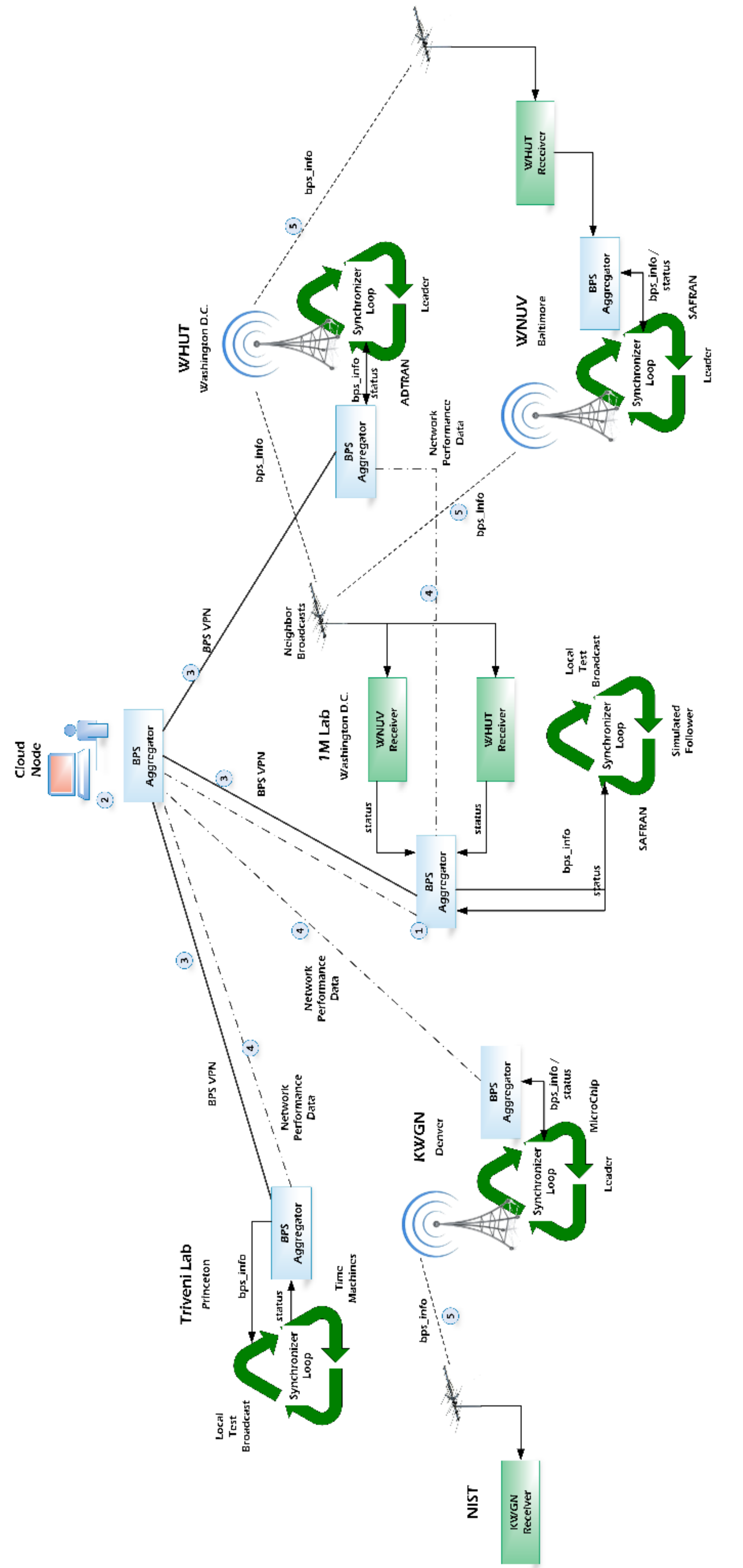


FIGURE 10: BPS NETWORK ACTIVE TEST DEPLOYMENT.

① The BPS Aggregator exists at every node within the network performing multiple functions, sometimes simultaneously.
② The Cloud Node is a single BPS Aggregator configured to operate solely as a performance data collector. It receives data from the 1M Lab and the Triveni Lab over the BPS VPN. It receives data from WHUT through the 1M Lab which is also operating as a PDC. It receives data from KWGN through a one-way HTTPS connection through their firewall. There is no communication allowed back to the KWGN BPS Aggregator. The user interface of the cloud node does not have a local loop or receivers but instead has only transmitters and network monitoring user interface pages. See Figure 11 for an example of the Transmitters user interface page on the Cloud Node.
③ The BPS VPN provides complete access to the various BPS functions within transmission systems. The user can access the BPS Aggregator interface, the interfaces of the Synchronizer and Receivers, and other equipment if enabled. Note that the interfaces of the other equipment are only available if VPN tunneling has been configured on the BPS Aggregator system. This is not required for the system to operate since the BPS Aggregator can communicate with those systems via local networking.
④ The network performance data can be sent to any PDC accessible within the network. In the current deployment, most systems are sending their data directly to the Cloud Node ②. However, the BPS Aggregator at WHUT is sending its performance data to the BPS Aggregator in the 1M Lab which, in turn, is forwarding it on to the cloud node. This confirms that the system can operate in a hierarchy of nodes.
⑤ The bps_info signal as described in [3]. Note that bps_info is intended to be consumed by all BPS receivers deployed while the performance data is only relevant to the BPS network operation.

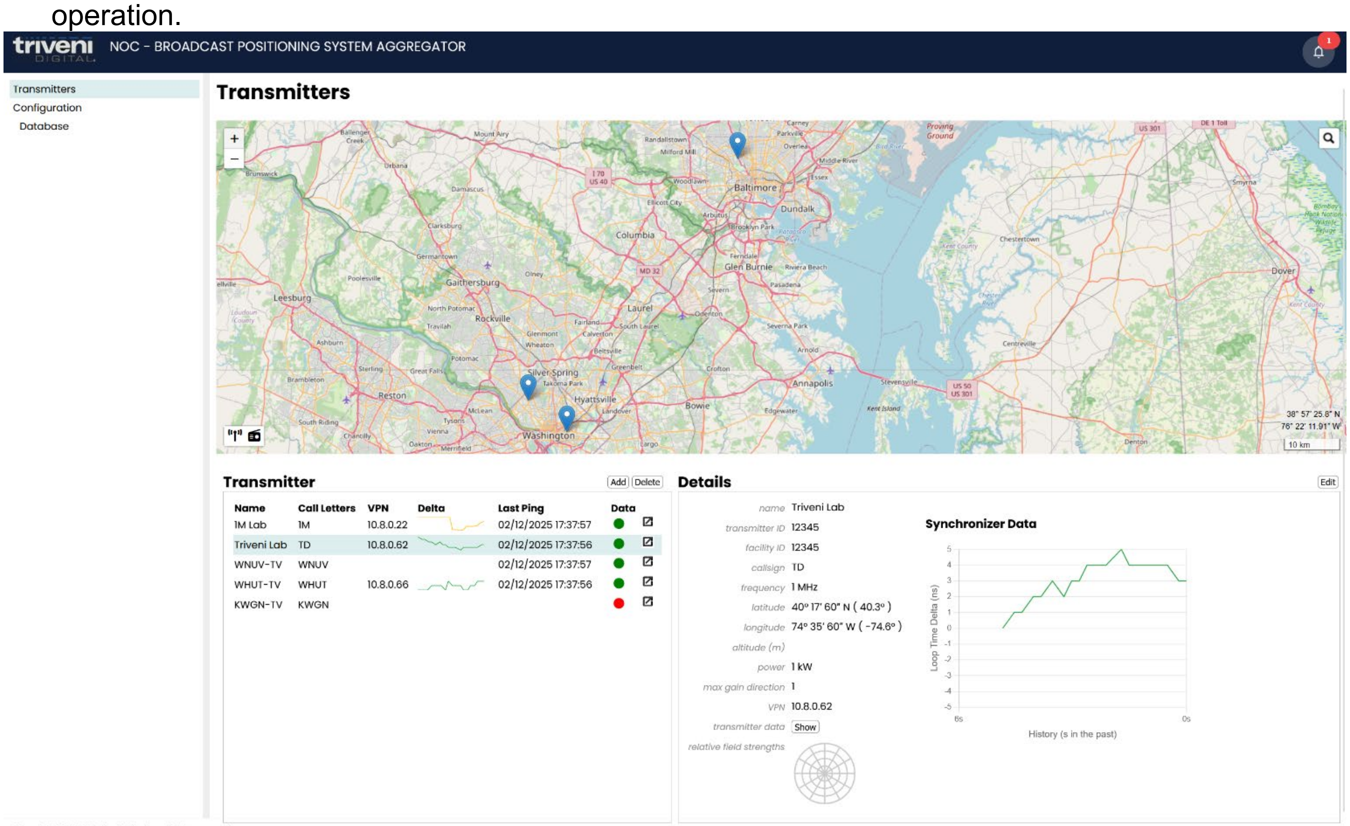


FIGURE 11: BPS AGGREGATOR TRANSMITTERS USER INTERFACE.

Future Development

Because of the limited number of BPS transmissions on air at the current time, there is a limited need for a fully operational network management system. This provides an opportunity to experiment and discover new ways of communicating with the BPS Aggregator and other BPS equipment in anticipation of scaling to an operational network. There are many different network topologies deployed by broadcasters and different nodes may need to be deployed to integrate with those topologies. For example, it may be necessary to establish an intermediate network node within a DMZ that can communicate with the BPS network while also communicating with the BPS equipment in the local transmitter air chain.

The BPS Aggregator will also need to be upgraded to enable certificate management and signing of the bps_info data structure to make it more secure. The bps_info structure will need to be modified slightly to allow a signature to be added. In addition, a notification mechanism will need to be created that will allow the systems to operate in an unattended fashion and notify operators when error conditions occur. Currently, only obvious faults are detected such as device communication failure, channel off-air, BS TOA exceeding thresholds, and missing bps_info. However, as more operational experience is gathered, it is expected that more failure modes will be discovered. It is anticipated that notifications will be either email, SMS messages or even SNMP traps.

Finally, it is expected that additional user interface pages will need to be developed as more transmitters are added to the network. One can envision a display similar to Figure 10 that indicates performance of individual nodes and the relationship of each transmitter node to the network. Also, the user interface pages as currently constructed will not scale well if hundreds or thousands of transmitters are added to the network. New methods of visualizing many transmitters will need to be developed. These will likely be driven by failure modes since only misbehaving systems will demand operator attention.

References

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[4] ATSC: "ATSC Standard: Physical Layer Protocol," Doc. A/322:2022-11, Advanced Television Systems Committee, Washington, DC, 14 November 2022.