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Broadcast Positioning System (BPS)
Time and Position Using ATSC 3.0 Signals

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Member PNT Advisory Board

U.S. Critical Infrastructure Depends on Accurate PNT Service (GPS)

- 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
- Food and Agriculture

Dependency on GPS

The PNT signals and other data from GPS satellites allow these infrastructure capabilities to function reliably.

- 7 billion devices are in use worldwide

Without these capabilities, the US economy would come to a standstill.

- US economy could lose $B per day as noted by several sources. No exact number known.

GPS Vulnerability

Recent outages in Denver and Dallas demonstrate the need to provide resilient augmentation systems.

Our adversaries are aware of this weakness and have implemented augmentations within their national boundaries to mitigate this exact same weakness.

US and its allies need to do the same.

Executive Order by the President

Per Executive Order 13905 [3] on "Responsible Use of PNT," the 16 Sector Risk Management Agencies (formerly Sector Specific Agencies) are directed to develop PNT profiles pursuant to the NIST 8323 master profile to identify and mitigate vulnerabilities.

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Technical Requirements to Satisfy Critical Infrastructure Usability Needs

Name of Industry	Timing Requirements
Mobile Wireless Networks	**1.1 µsec** traceable to UTC
Equity Trading Systems	**Timestamp accuracy to 1 µsec to** UTC NIST (SEC Section 613 rules, MifID II EU)
Power Grid	**1 µsec** to UTC, IEEE 37-238, (Synchro-phasors)
Other CI Industries	**200 ns to UTC or better**

ATSC 3.0-Based BPS is one Solution

- Can meet timing requirements of critical infrastructure
- Broadcast infrastructure is already built
- Based on a global standard
- Nationwide coverage
- Can be made totally independent of GPS
- Passive consumer service – no uplink is required
- Resilient - high power, high tower, frequency diversity, backup generators
- US government agencies are engaged on the idea

What is the Broadcast Positioning System (BPS)?

A system and method of estimating time and position at a receiver using ATSC 3.0 broadcast signals

ATSC ADVANCED TELEVISION SYSTEMS COMMITTEE

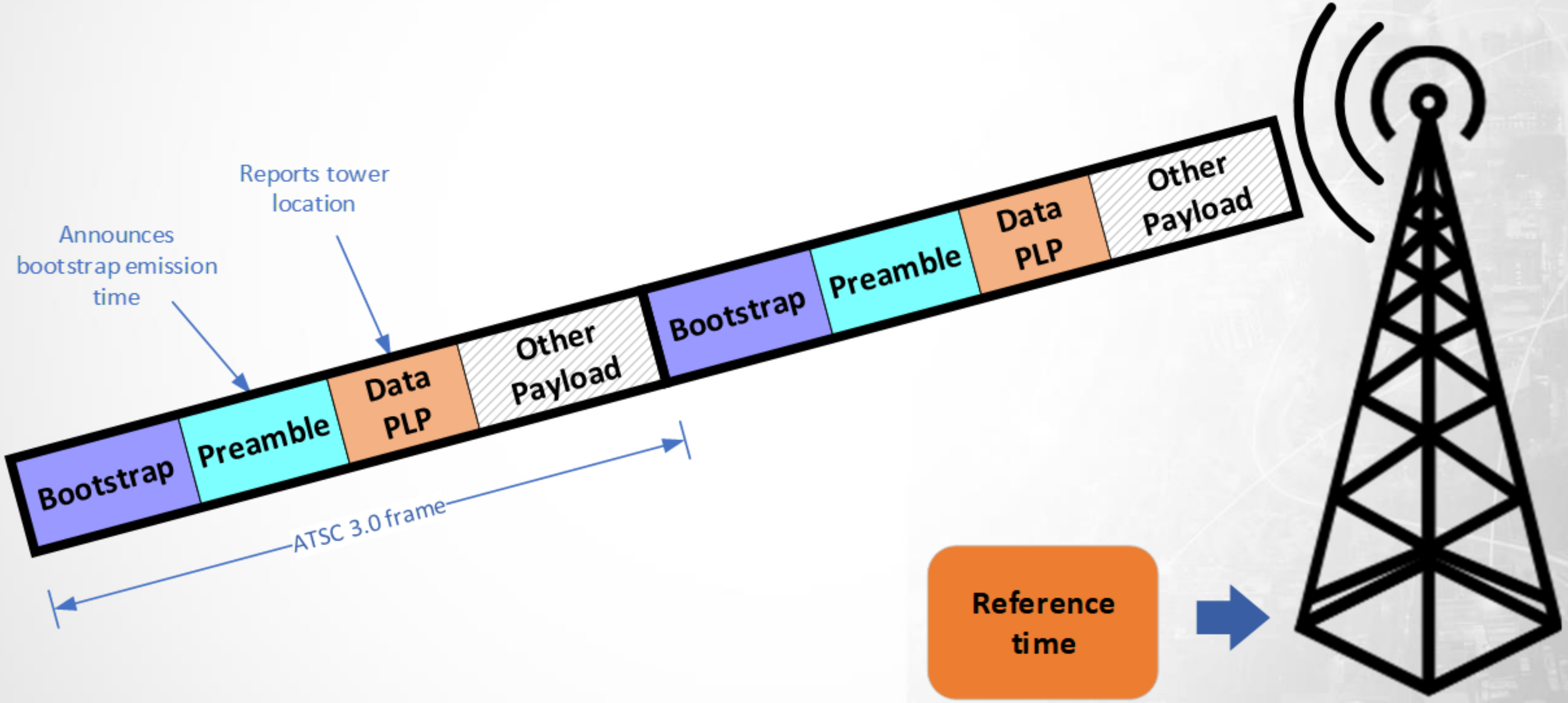
Compliant with ATSC 3.0 standard;

uses datacasting feature

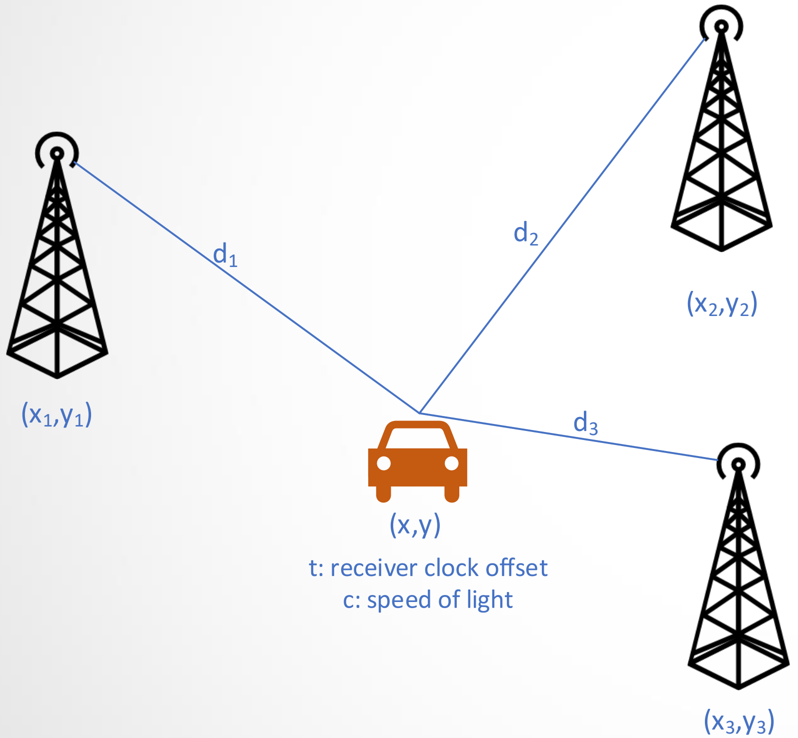
Independent and stand-alone

- GPS, Internet or cellular connectivity not required

Time Delivery



Pseudorange Multilateration Concept



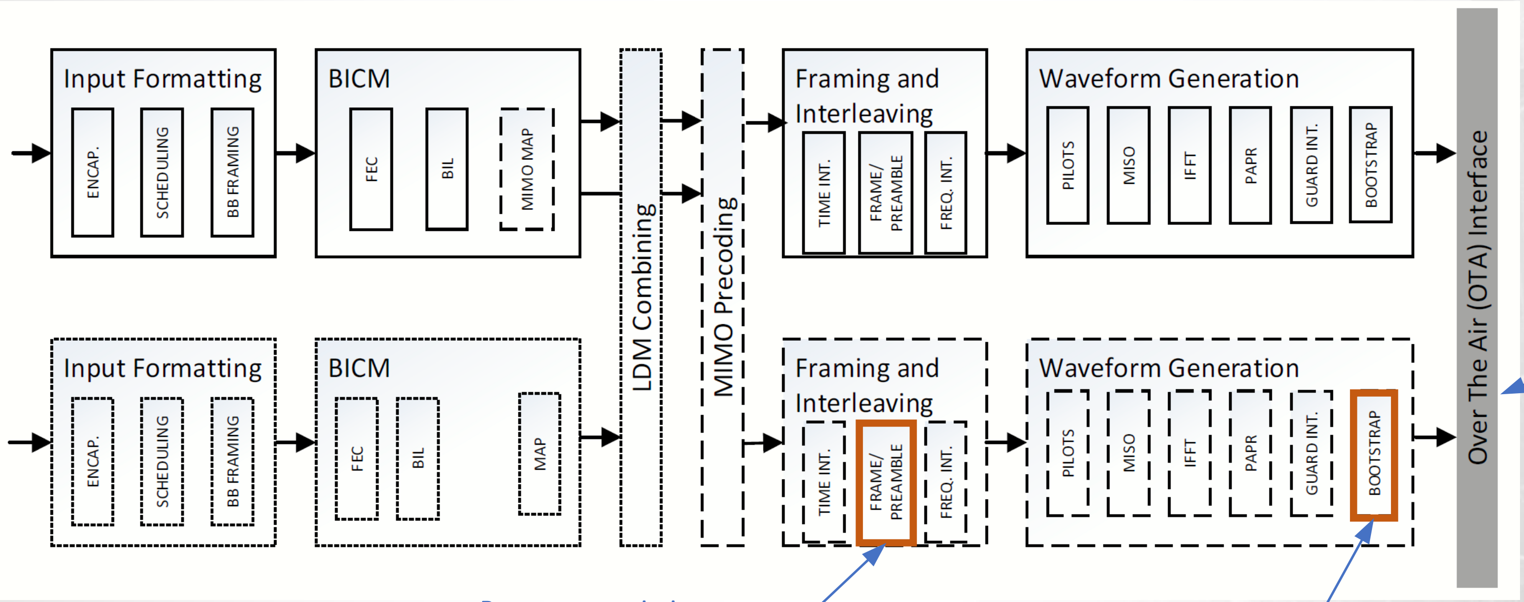
Pseudorange equations:

$$r_1 = \sqrt{(x_1 - x)^2 + (y_1 - y)^2} + ct$$

$$r_2 = \sqrt{(x_2 - x)^2 + (y_2 - y)^2} + ct$$

$$r_3 = \sqrt{(x_3 - x)^2 + (y_3 - y)^2} + ct$$

Preamble Timestamping Challenge



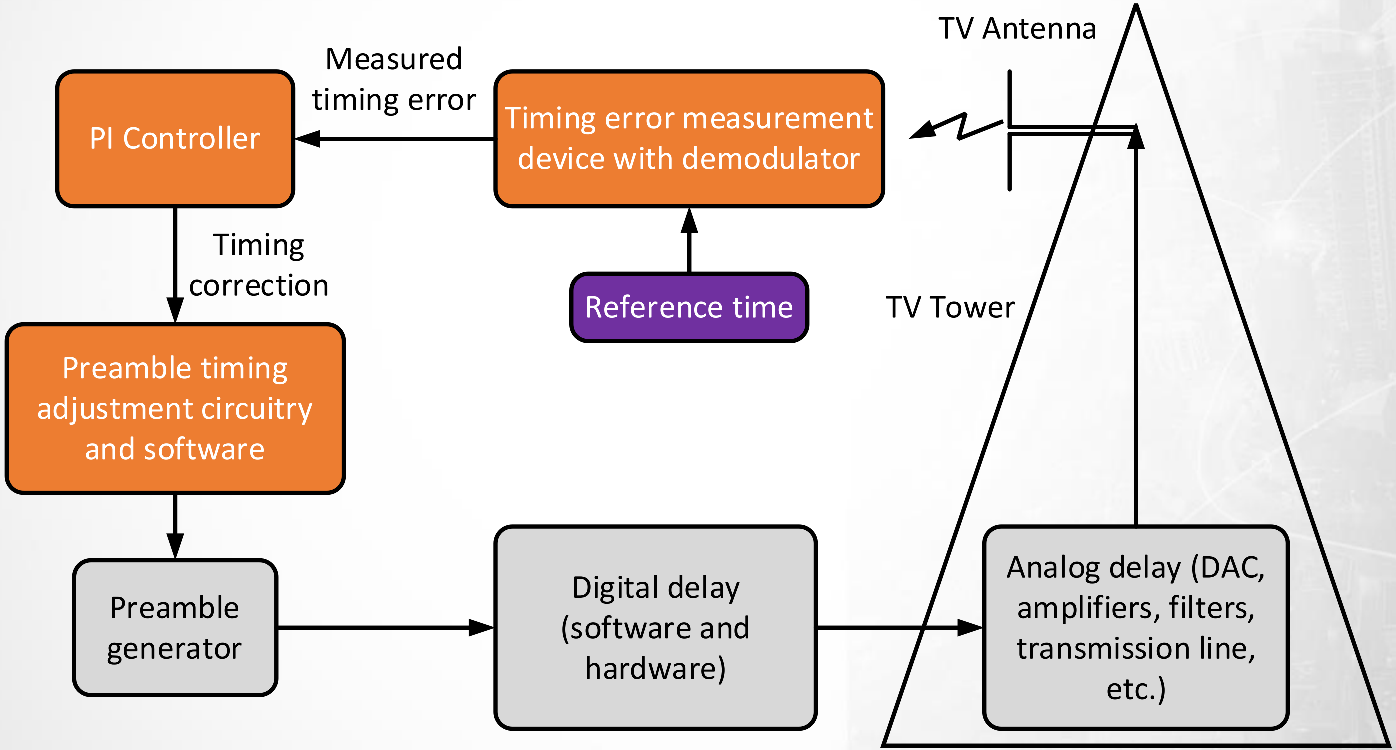
D/A converter, filter, amplifier, and transmission line add additional delay

Bootstrap emission timestamps are created here

Bootstraps are created here

Source: ATSC Standard, Physical Layer Protocol, Doc. A/322:2020

Time Synchronization at the Transmitter



PNT Capabilities of BPS

One TV tower can provide accurate time at a known position

- 100 ns, 95% of the time

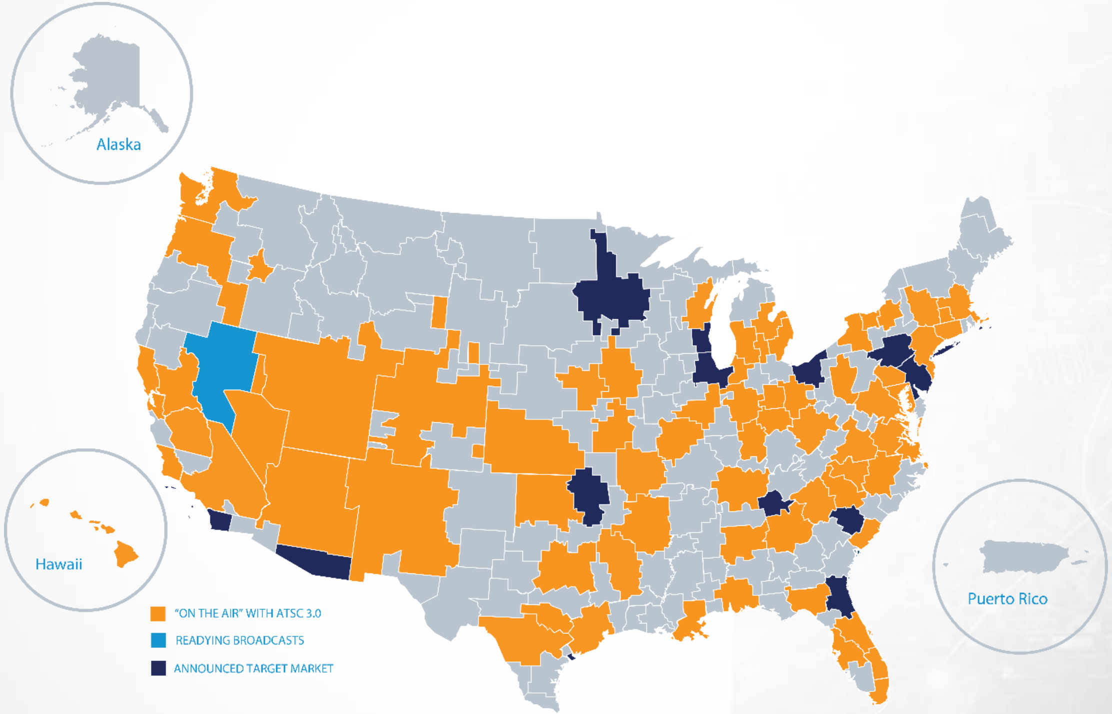
Four TV towers can provide both time and position estimation

- 100 m average accuracy expected

Can detect GPS spoofing

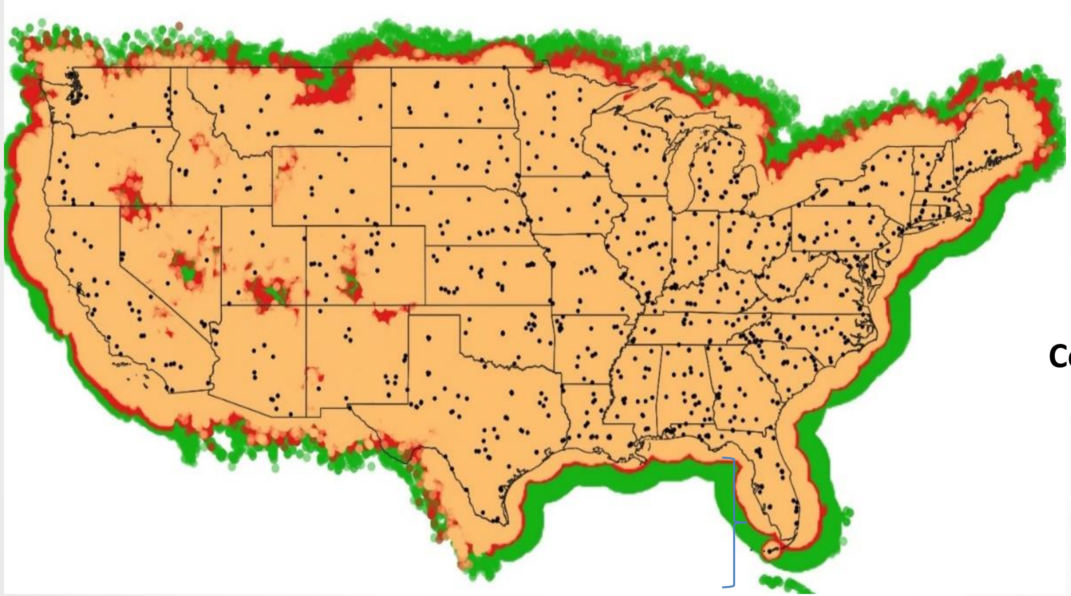
Can enable GPS-BPS hybrid location

Current ATSC 3.0 Market Coverage in US



Source: atsc.org

BPS (UHF & VHF) Coverage at Full Deployment



Average signal reception:

- 17 towers at 1.5 m antenna height
- 70 towers at 50m antenna height

Coverage at 1.5 m antenna height:

- At demodulation threshold (-5 dB SINR)
- Threshold + 10 dB
- Threshold + 20 dB

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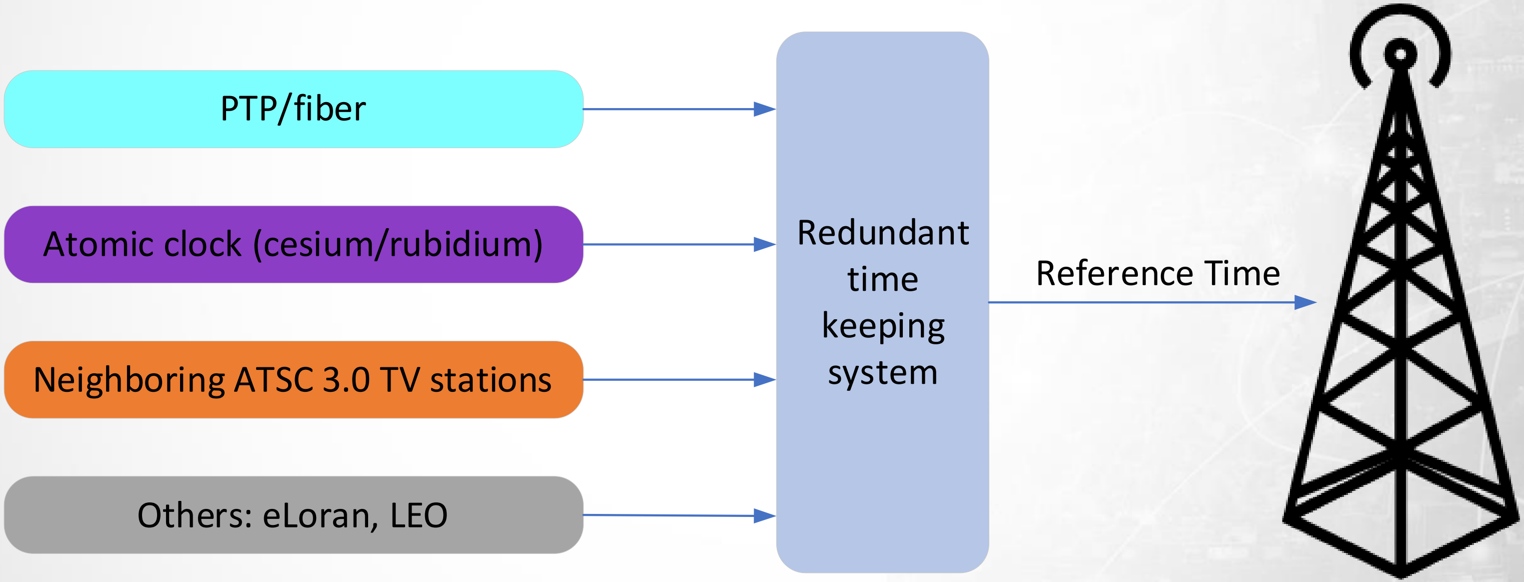
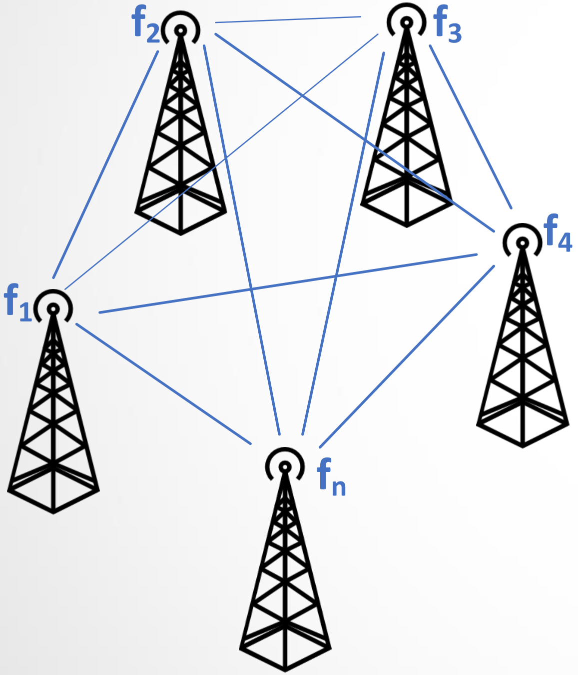
Reliable and Traceable Timing Source

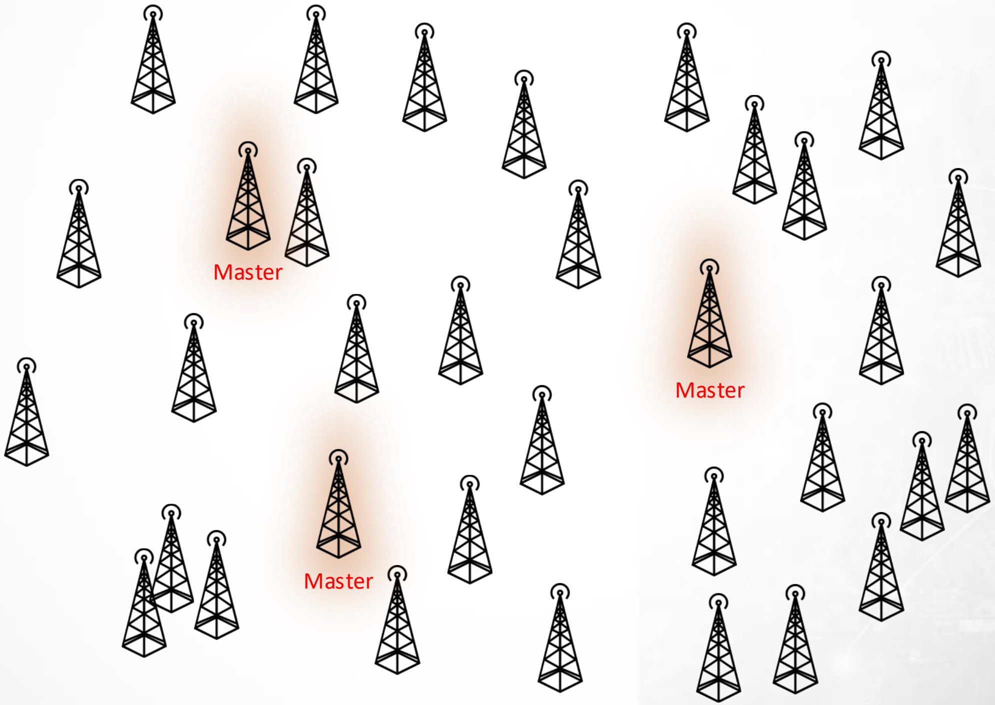


Increasing Resiliency and Accuracy

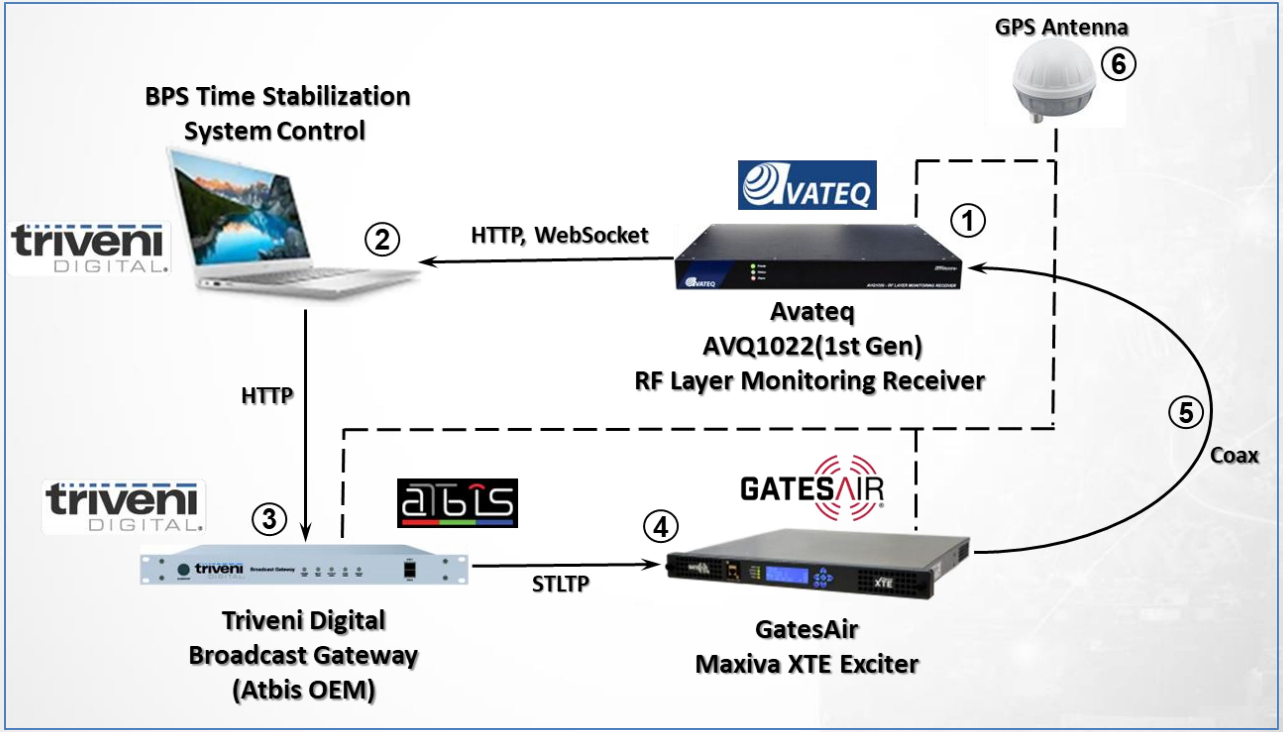


- Report emission time and location of neighboring stations
- Report timestamping errors of previous frames
- Nationwide self-synchronizing network

Self Synchronizing Network with Traceable Time

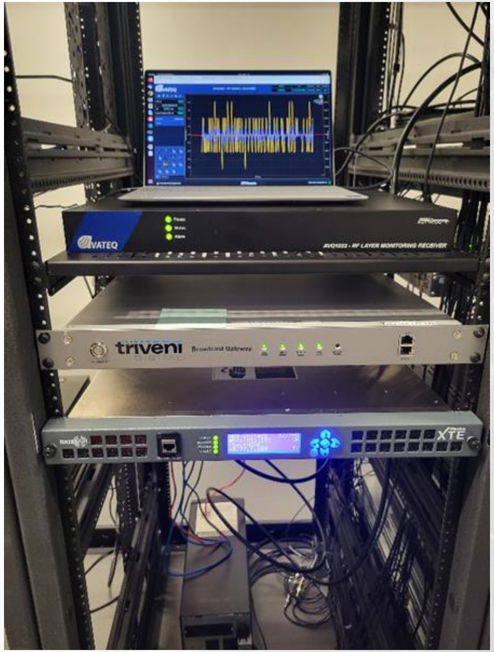


Implementation at NAB 1M Lab



Prototype Running at NAB 1M Lab

ATSC 3.0 Testbed at NAB 1M Lab



Operational BPS Prototype at NAB 1M Lab

Advantages of BPS

- Infrastructure is already built
- Global standard
- Passive consumer service
- Independent
- Frequency diversity
- Nationwide coverage

Development Phases

Phase 1 *2022-2023*

- Build Tx-side prototype
- Demonstrate ATSC 3.0 compliance
- Identify technology gaps
- Measure timing accuracy

Phase 2 *2023-2024*

- Modify equipment/software as needed
- Deploy in a live market
- Build a prototype receiver
- Demonstrate timing at a known location

Phase 3 *2024-2025*

- Add backup timing sources at Tx site
- Demonstrate time delivery in a live market

Phase 4 *2025-2027*

- Deploy ATSC 3.0 based timing for use by the public
- Fund system operations

Phase 5 *2026-2027*

- Build multilateration receiver prototype
- Set up a test area with four TV towers
- Demonstrate joint positioning and timing use case

Phase 6 *2027-2029*

- Add neighbor measurement features
- Deploy BPS (time and position) for use by the public
- Fund system operations
- Plan for future improvement

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Building Coalition for Next Steps

- Upgrade HW and SW for better accuracy
- Deploy BPS at a transmission facility in a live market
- Demonstrate timing use case at a known location
- Funding and large scale deployment

Collaboration with Test Receiver Design

Timing at a known location

- Listen to multiple ATSC 3.0 signals and maintain an ensemble of clocks
- Compute and show the difference between BPS and GPS time
- Show the correlation peaks and effects of multipath to study propagation effects

Positioning (Timing at unknown location)

- Listen to multiple ATSC 3.0 signals and compute location
- Provide traceable timing reference at locations whose coordinates are unknown
- Compare GPS vs. BPS locations errors and display

Stretch Goals

- Use BPS to validate GPS results
- Compute hybrid locations using BPS and GPS psuedoranges

Thank You

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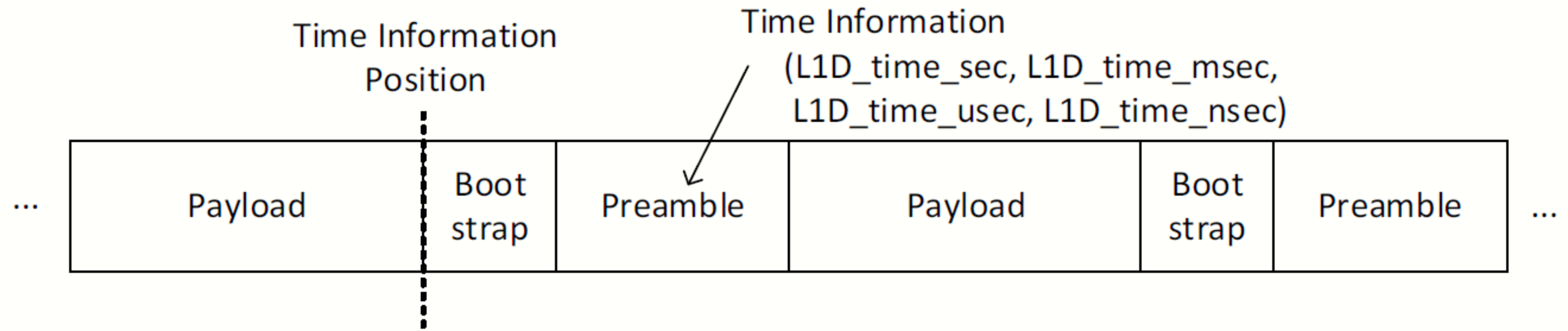
Backup Slides

ATSC 3.0 Signal

Bootstrap – time of arrival (TOA) estimation

Preamble (L1-Basic and L1-Detail) – timing info

Data PLP - tower location and neighbor measurement info



Source: ATSC Standard, Physical Layer Protocol, Doc. A/322:2020

Multilateration Iterative Solution

$$\boldsymbol{\Delta x} = \begin{bmatrix} \Delta x \\ \Delta y \\ -c\Delta t \end{bmatrix} \qquad \boldsymbol{H} = \begin{bmatrix} \frac{(x_1-\hat{x})}{\sqrt{(x_1-\hat{x})^2+(y_1-\hat{y})^2}} & \frac{(y_1-\hat{y})}{\sqrt{(x_1-\hat{x})^2+(y_1-\hat{y})^2}} & 1 \\ \frac{(x_2-\hat{x})}{\sqrt{(x_2-\hat{x})^2+(y_2-\hat{y})^2}} & \frac{(y_2-\hat{y})}{\sqrt{(x_2-\hat{x})^2+(y_2-\hat{y})^2}} & 1 \\ \frac{(x-\hat{x})}{\sqrt{(x_3-\hat{x})^2+(y_3-\hat{y})^2}} & \frac{(y-\hat{y})}{\sqrt{(x_3-\hat{x})^2+(y_3-\hat{y})^2}} & 1 \end{bmatrix} \qquad \boldsymbol{\Delta r} = \begin{bmatrix} \Delta r_1 \\ \Delta r_2 \\ \Delta r_3 \end{bmatrix}$$

Least-square solution: $\boldsymbol{\Delta x} = (\boldsymbol{H}^T\boldsymbol{H})^{-1}\boldsymbol{H}^T\boldsymbol{\Delta r}$

Weighted least-square solution: $\boldsymbol{\Delta x} = (\boldsymbol{H}^T\boldsymbol{W}\boldsymbol{H})^{-1}\boldsymbol{H}^T\boldsymbol{W}\boldsymbol{\Delta r}$ where $\boldsymbol{W} = \begin{bmatrix} w_1 & \cdots & 0 \\ \vdots & \ddots & \vdots \\ 0 & \cdots & w_n \end{bmatrix}$

Simulation Set-up

4 towers at (50000, 0), (0, 50000), (-50000, 0), and (0, -50000) meters on X-Y plane

200 m antenna height

Random TOA estimation error between -5 m to +5 m (uniform dist.)

Standard deviation well above Cramer-Rao bound

Bootstrap sample duration is 48.8 m

Unresolved multipath error at the receiver 0-100 m (uniform dist.)

Assumed that TOA detector will detect the earliest path

Assumed that ambiguity function based joint time-frequency estimation

Receiver clock offset is set to the distance of the nearest tower

Assumed that receiver clock will synchronize with the strongest signal

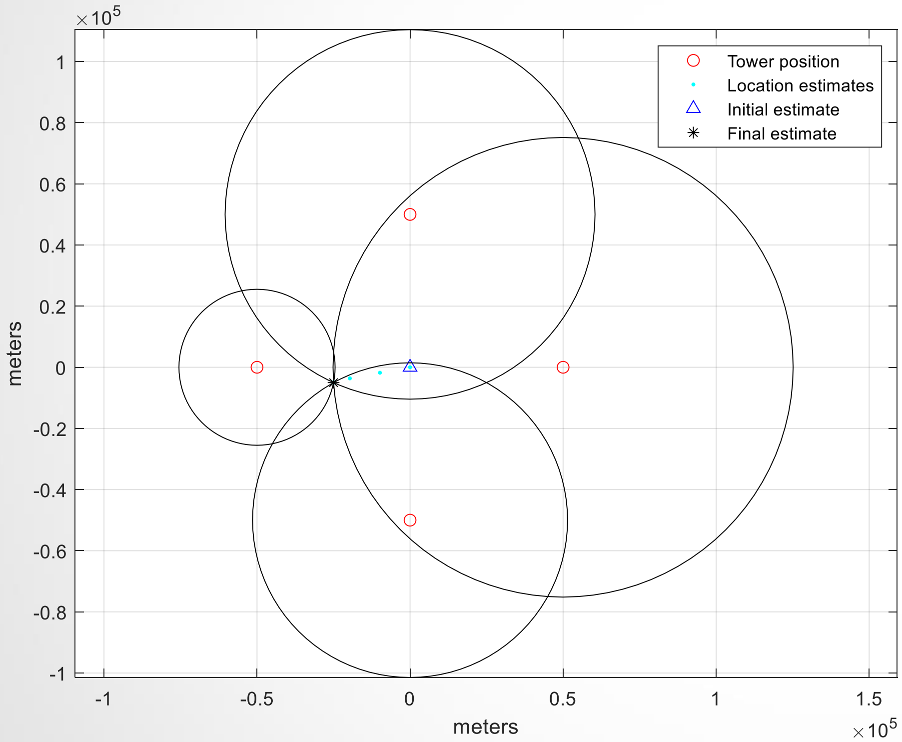
A Typical Simulation Run

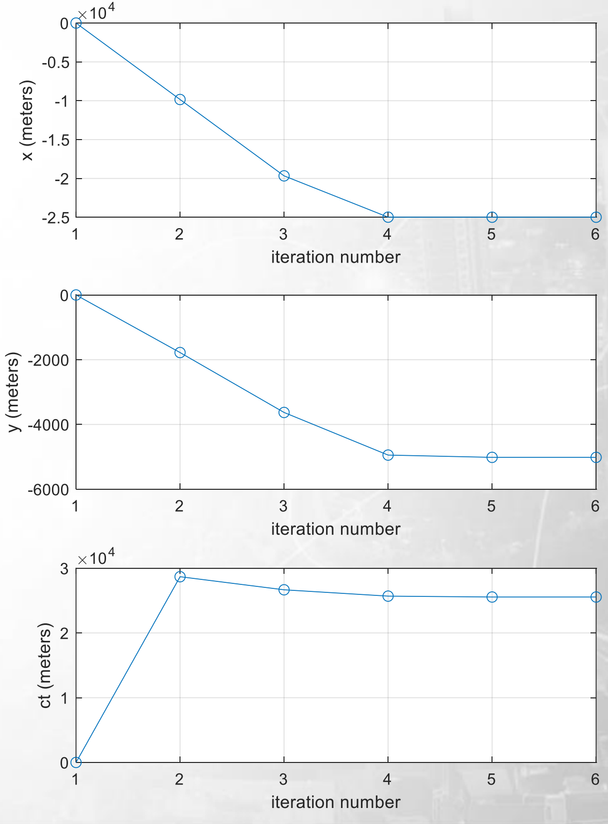
```
TOA estimation error:  4.1 m, -3.2 m, -2.4 m, -3.5 m,
multipath error:      13.6 m, 86.9 m, 58.0 m, 55.0 m,
clock offset:  25495.9 m

true (x,y,t):       x = -25000.0 m, y =  -5000.0 m, t =  25495.9 m
estimated (x,y,t):  x = -24989.9 m, y =  -5015.7 m, t =  25549.6 m
```

estimation error: x =   -10.1 m, y =   15.7 m, t =   **-53.7 m**
estimation error (distance):   **18.7 m**

A Typical Simulation Run





Coverage Planning Factors

Parameter	BPS Value	TV Value	Unit
System Bandwidth	6	6	MHz
Required C/(I+N)	-5	15	dB
Thermal Noise (kTB)	-106.2	-106.2	dBm
Frequency of Operation	539	615	MHz
Antenna Gain	0	12.15	dBi
Antenna Factor	-129.6	-132.95	dBm-dBμV/m
Noise Figure	6	7	dB
Line Loss	0	4	dB
Required Field Strength	**24.4**	**40.8**	**dBμV/m**
Required Power at RX	**-109.05**	**-84.85**	**dBm**
RX Antenna height, AGL	1.5	10	m
Location, Time Variability	50%, 50%	50%, 90%	–

Coverage Definition (Planning Factors)

Nominal Coverage Threshold, dBμV/m

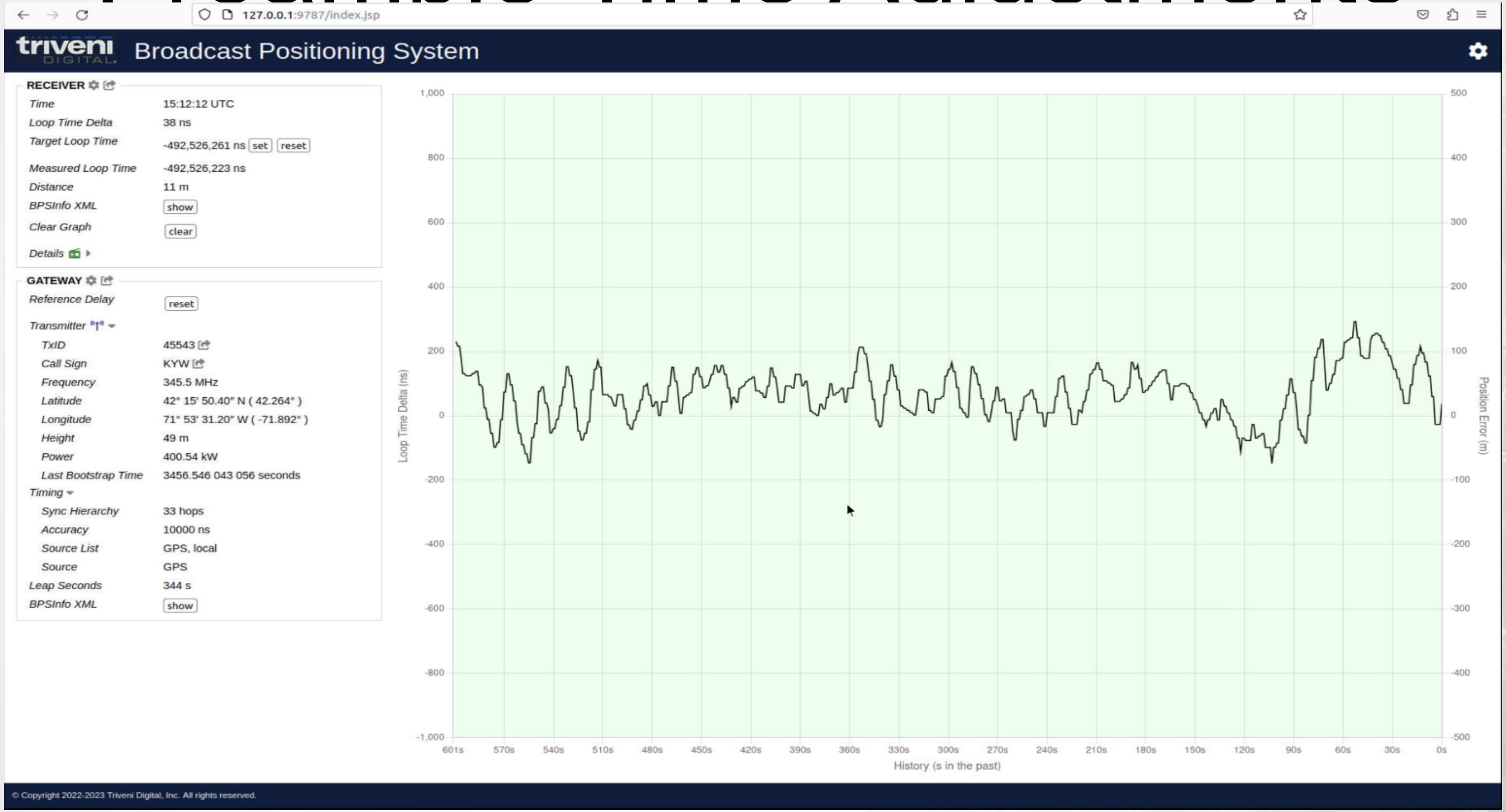
Band	TV	BPS
VHF-L (54-88 MHz)	28	6.6
VHF-H (174-213 MHz)	36	15.6
UHF (470-608 MHz)	41	24.4

Neighbor Measurement (bps_info) Message

Syntax	*No. of bits*	*Format*
bps_info(){		
message_length	16	unsigned integer
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
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
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
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	
bps_crc	32	unsigned integer
}		

Preamble Time Adjustments



Lessons Learned from Prototype

- Proved that Tx-side timestamping can be done without disrupting existing transmission chain
- Demonstrated BPS compliance with ATSC 3.0 standard
- Achieved 300 ns timing accuracy in first implementation
- Developed bps_info message structure that could be standardized
- Discovered technology gaps of existing off-the-shelf equipment
- Identified areas of improvement for future work

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