MICHIGAN STATE
UNIVERSITY

High Accuracy Wireless Timing Synchronization Using Software Defined Radios

2023 GNU Radio Conference

High Performance SDR Applications

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delta
Distributed Electromagnetics
Theory and Applications

emrg
Electromagnetics Research Group
Michigan State University

Outline

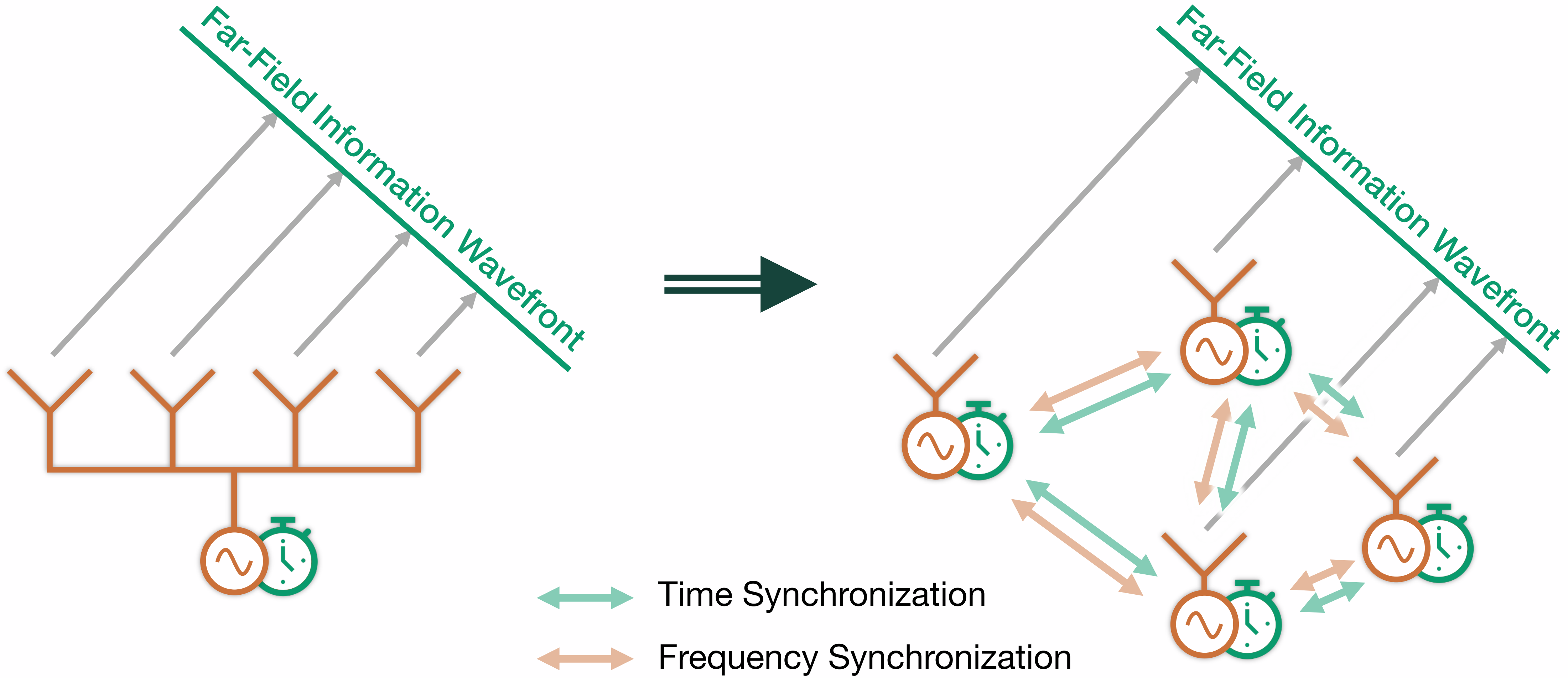
1. Motivation and Applications
2. Synchronization Technique
3. Software Overview & Demo
4. Experimental Results

1 | Motivation and Applications

Motivation // Coherent Distributed Antenna Arrays

Traditional Phased Array

Distributed Phased Array



Time Synchronization

Frequency Synchronization

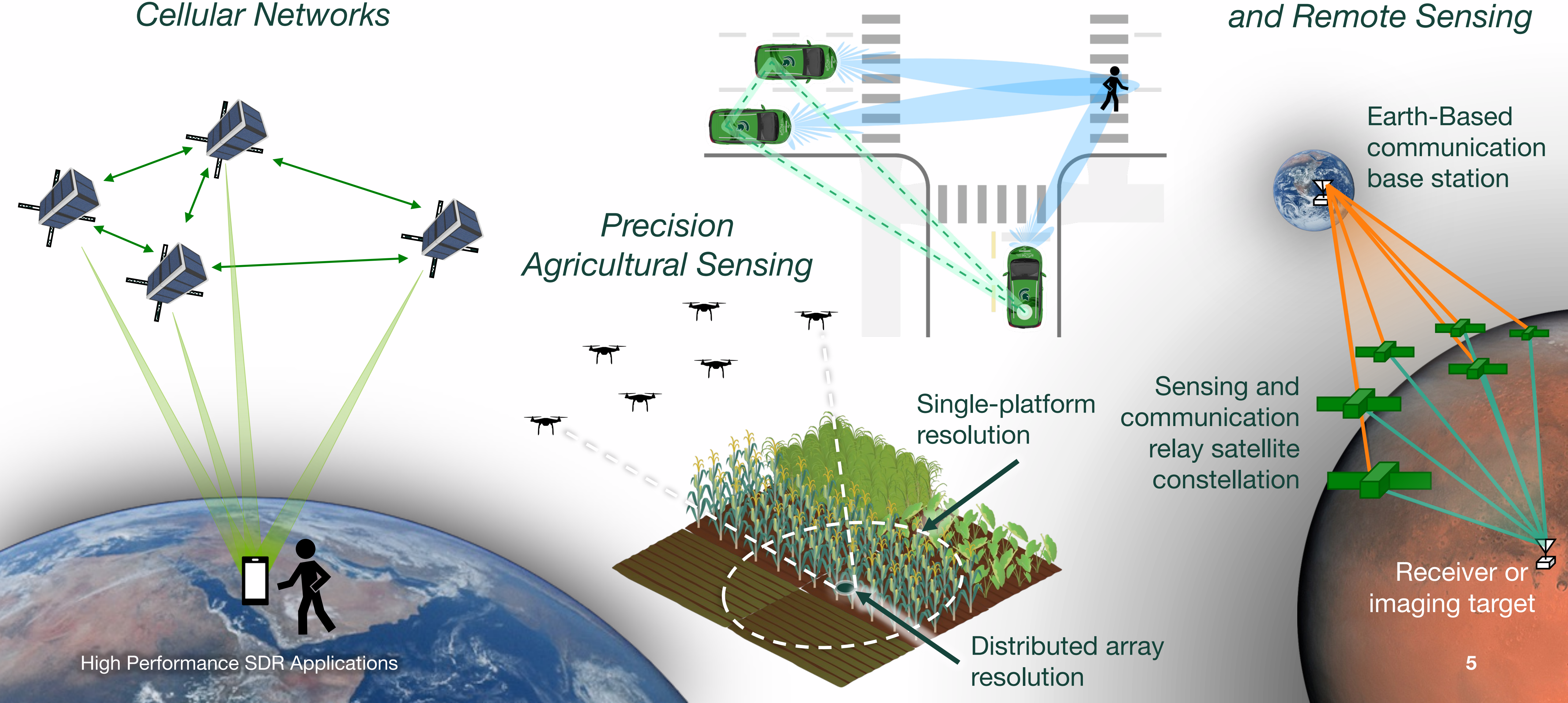
Applications of Coherent Distributed Arrays

Next Generation Satellite Cellular Networks

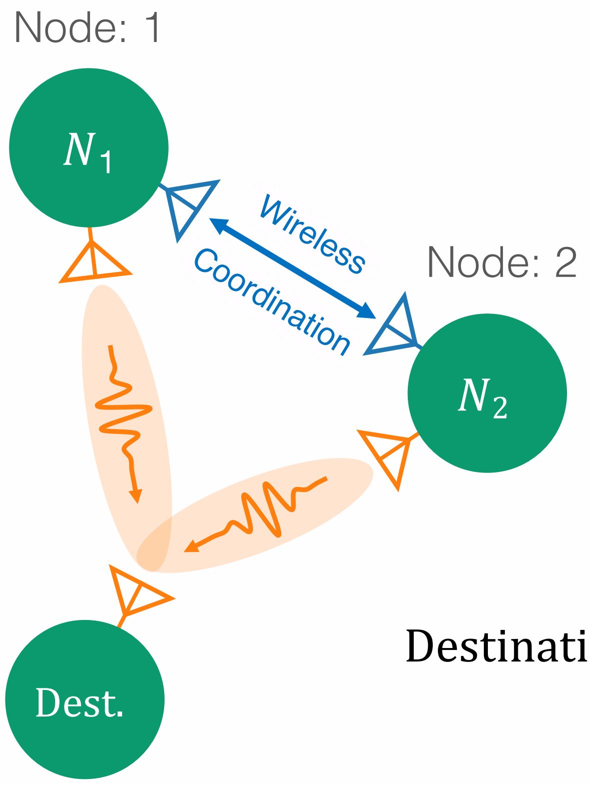
Distributed V2X Sensing

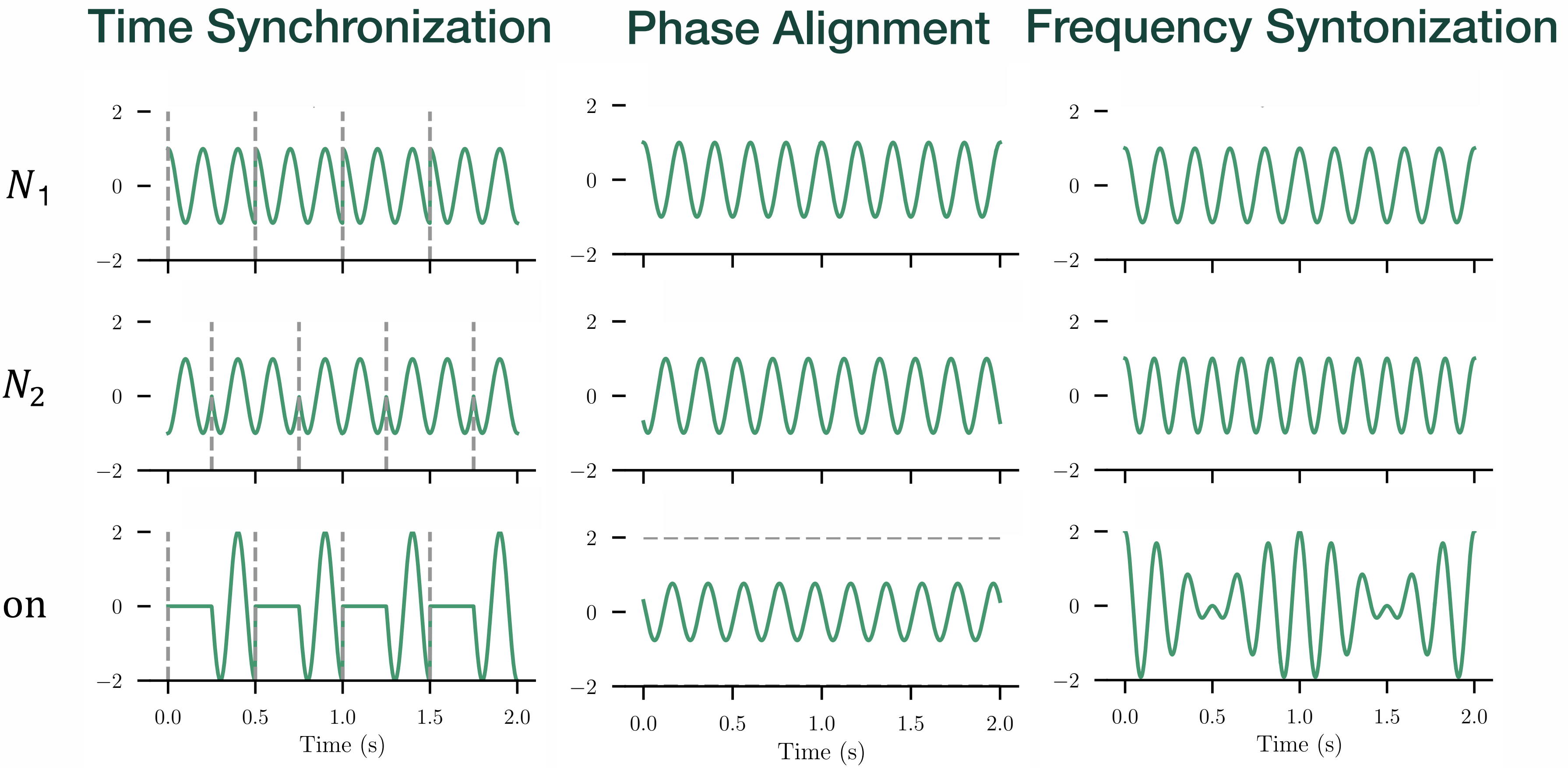
Space Communication and Remote Sensing

Precision Agricultural Sensing



Coherent Distributed Array Synchronization





$$s_1 + s_2 = \sum_{n=1}^{2} \alpha_n(t - \delta t_n) \exp\{j[2\pi(f + \delta f_n) + \phi_n]\}$$

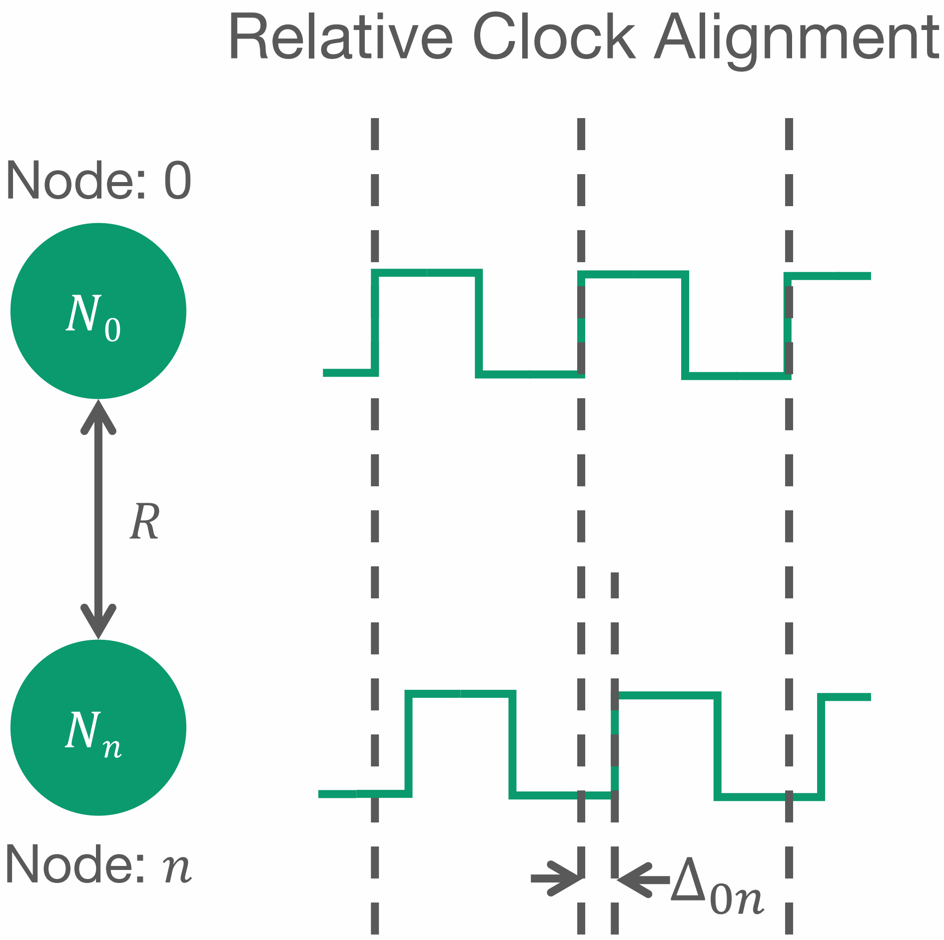
2 | **Synchronization Technique**

System Time Model

- Local time at node n:

$$T_n(t) = t + \delta_n(t) + \nu_n(t)$$

  - t : true time
  - $\delta_n(t)$: time-varying offset from global true time
  - $\nu_n(t)$: other zero-mean noise sources
  - $\Delta_{0n}(t) = T_0(t) - T_n(t)$
- Goal:
  - Estimate and compensate for Δ_{0n}



Time Synchronization Overview

Two-Way Time Synchronization

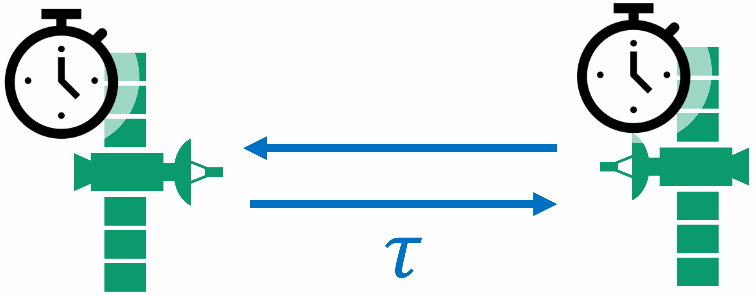
- *Assumptions:*
    - Link is <u>reciprocal</u> ⟹ <u>quasi-static</u> during the synchronization epoch
- Timing skew estimate:

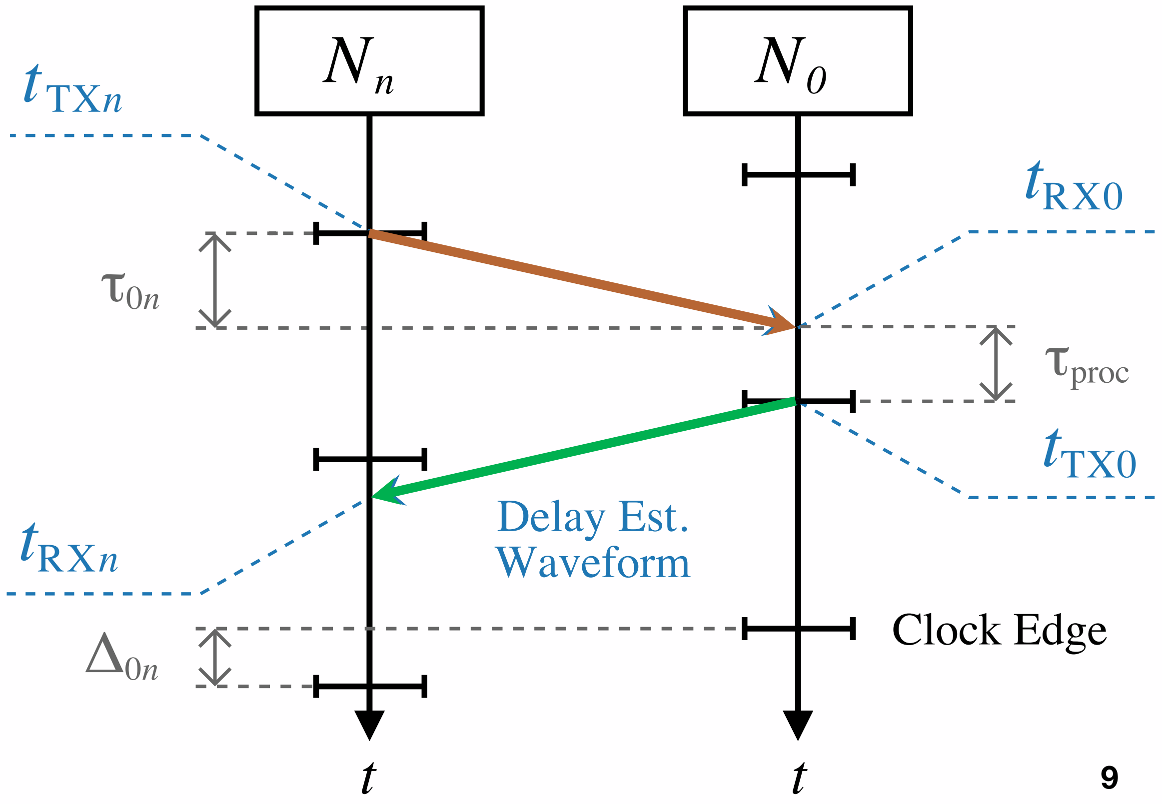
$$\Delta_{0n} = \frac{(T_{\mathrm{RX0}} - T_{\mathrm{TX}n}) - (T_{\mathrm{RX}n} - T_{\mathrm{TX0}})}{2}$$

- Inter-node range estimate:

$$D_{0n} = c \cdot \frac{(T_{\mathrm{RX0}} - T_{\mathrm{TX}n}) + (T_{\mathrm{RX}n} - T_{\mathrm{TX0}})}{2}$$

For compactness of notation: $T_m(t_{\mathrm{TX}n}) = T_{\mathrm{TX}n}$



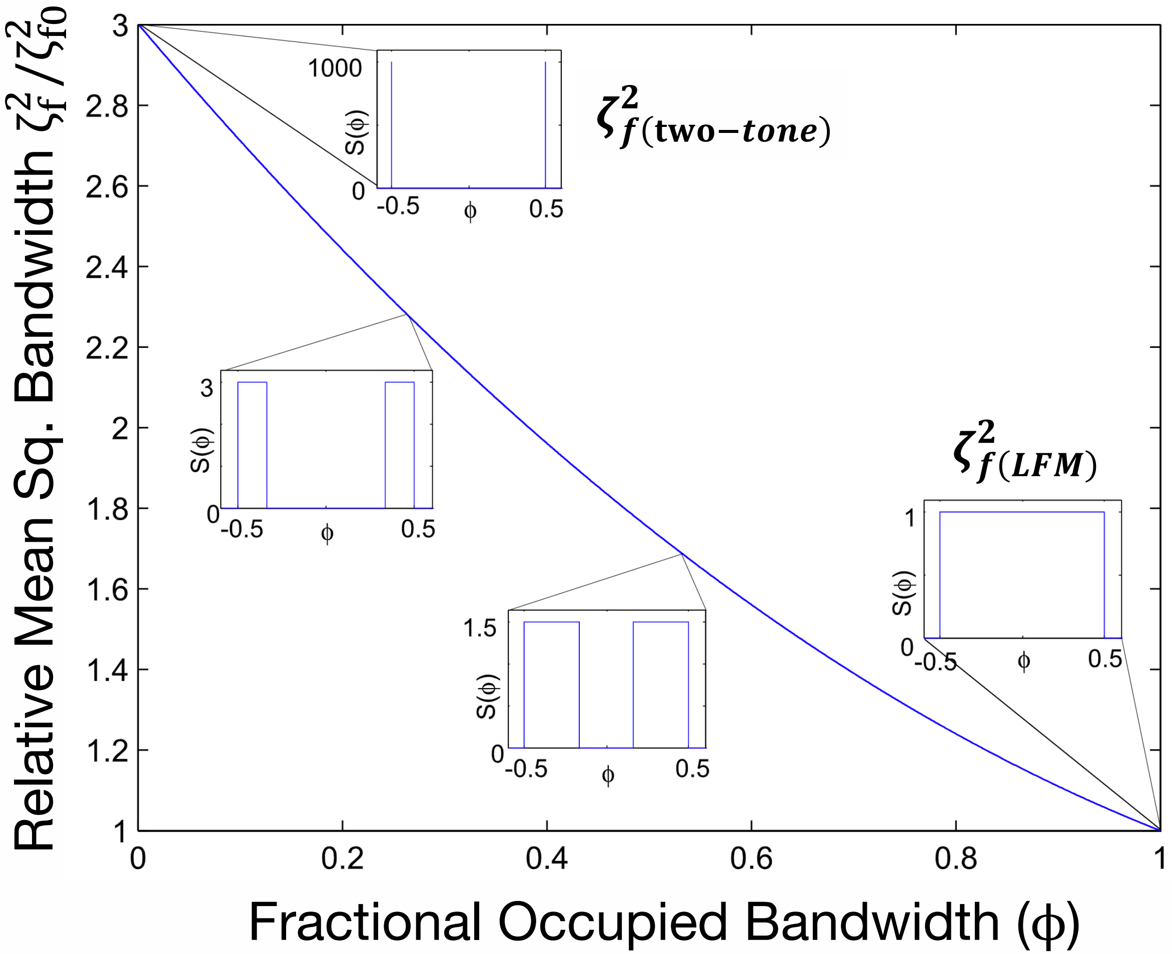


High Accuracy Delay Estimation

- The delay accuracy lower bound (CRLB) for time is given by

$$\mathrm{var}(\hat{\tau} - \tau) \geq \frac{1}{2\zeta_f^2} \cdot \frac{N_0}{E_s}$$

  - ζ_f^2: mean-squared bandwidth
  - N_0: noise power spectral density
  - E_s: signal energy
  - $\frac{E_s}{N_0}$: post-processed SNR



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[3] J. A. Nanzer and M. D. Sharp, “On the Estimation of Angle Rate in Radar,” *IEEE T Antenn Propag*, vol. 65, no. 3, pp. 1339–1348, 2017, doi: 10.1109/tap.2016.2645785.

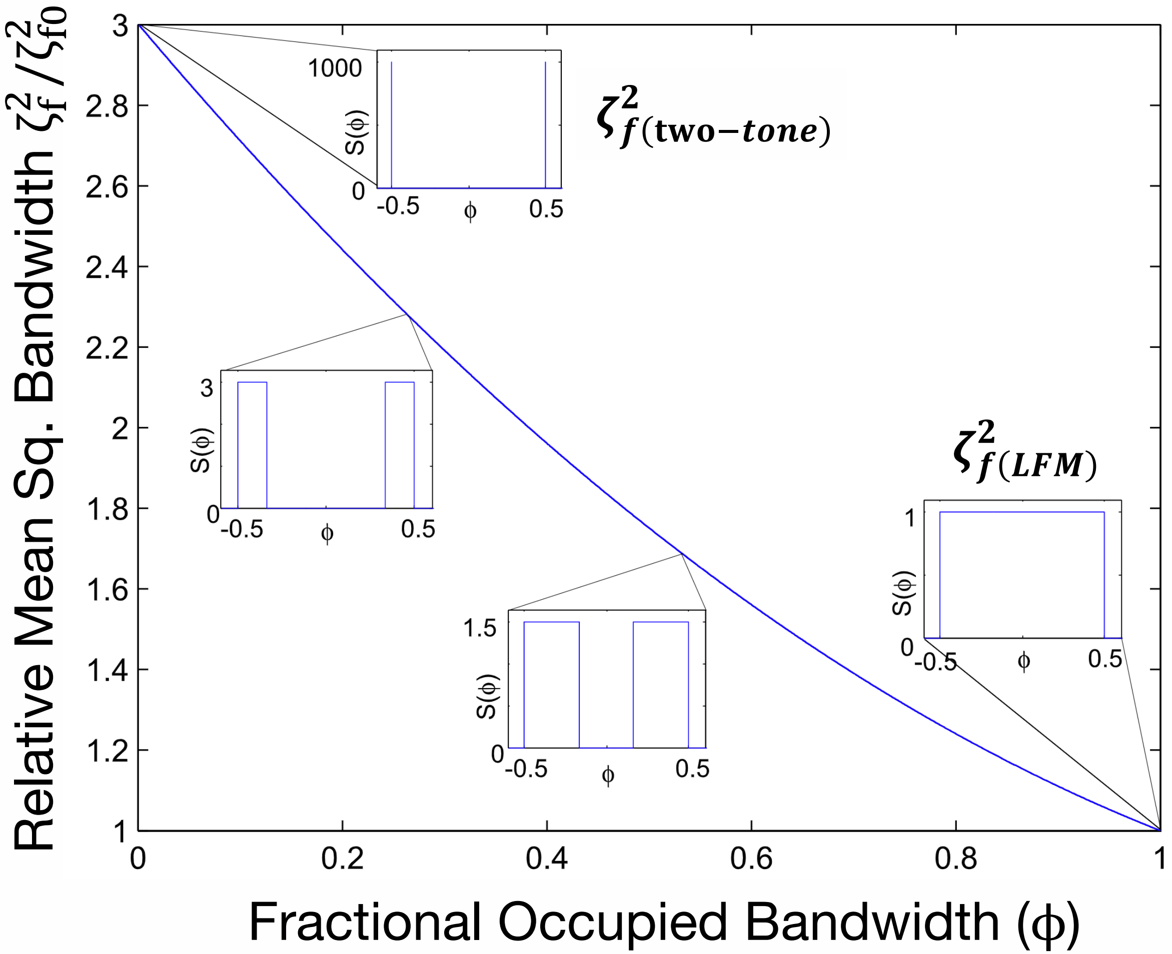
High Accuracy Delay Estimation

$$\text{var}(\hat{\tau} - \tau) \geq \frac{1}{2\zeta_f^2} \cdot \frac{N_0}{E_s}$$

- For constant-SNR, maximizing ζ_f^2 will yield improved delay estimation

$$\zeta_f^2 = \int_{-\infty}^{\infty} (2\pi f)^2 |G(f)|^2 df$$

- $\zeta_{f(LFM)}^2 = (\pi \cdot \mathrm{BW})^2 / 3$
- $\zeta_{f(\text{two-tone})}^2 = (\pi \cdot \mathrm{BW})^2$



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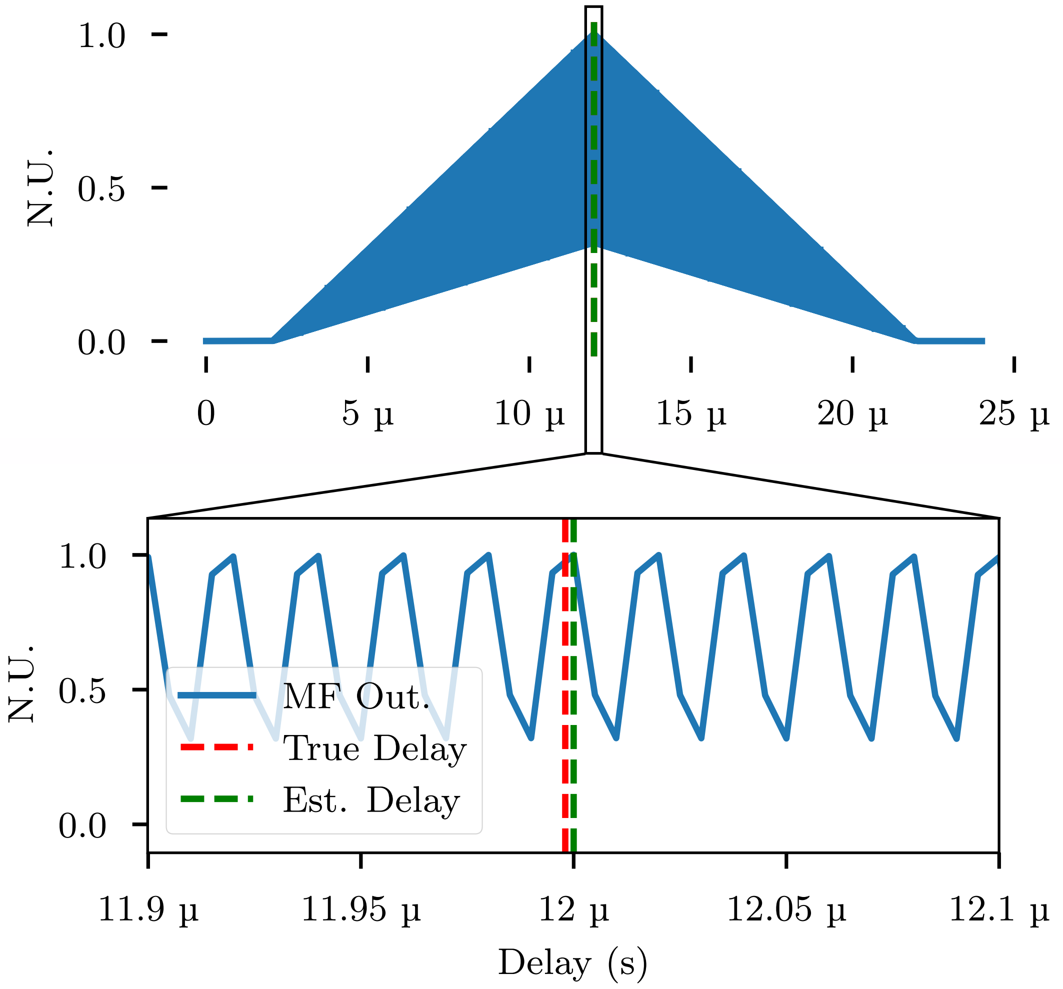
Delay Estimation

- Discrete matched filter (MF) used in initial time delay estimate

$$\begin{aligned} s_{\mathrm{MF}}[n] &= s_{\mathrm{RX}}[n] \circledast s_{\mathrm{TX}}^{*}[-n] \\ &= \mathcal{F}^{-1}\{S_{\mathrm{RX}} S_{\mathrm{TX}}^{*}\} \end{aligned}$$

- High SNR typically required to disambiguate correct peak

- Many other waveforms exist which balance accuracy and ambiguity



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[4] J. M. Merlo, S. R. Mghabghab and J. A. Nanzer, "Wireless Picosecond Time Synchronization for Distributed Antenna Arrays," in IEEE Transactions on Microwave Theory and Techniques, vol. 71, no. 4, pp. 1720-1731, April 2023, doi: 10.1109/TMTT.2022.3227878.

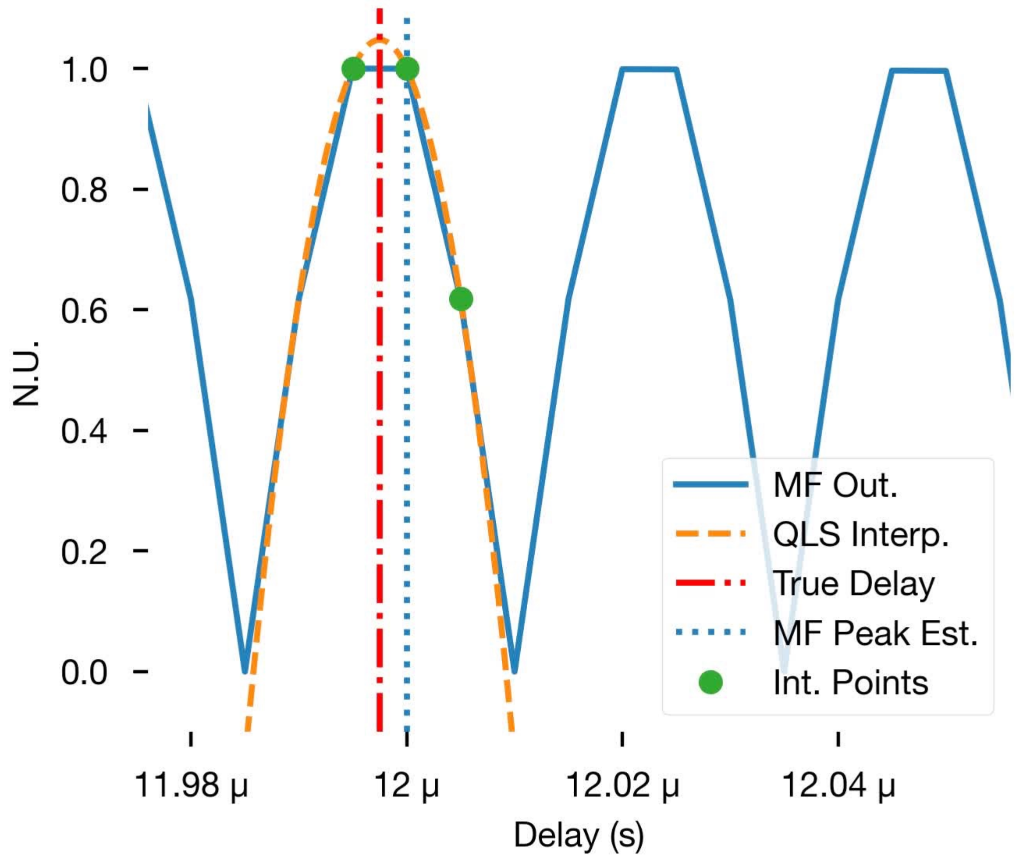
Delay Estimation Refinement

- MF causes estimator bias due to time discretization limited by sample rate
- Refinement of MF obtained using Quadratic Least Squares (QLS) fitting to find true delay based on three sample points

$$\hat{\tau} = \frac{T_s}{2} \frac{s_{\mathrm{MF}}[n_{\max} - 1] - s_{\mathrm{MF}}[n_{\max} + 1]}{s_{\mathrm{MF}}[n_{\max} - 1] - 2s_{\mathrm{MF}}[n_{\max}] + s_{\mathrm{MF}}[n_{\max} + 1]}$$

where

$$n_{\max} = \underset{n}{\operatorname{argmax}}\{s_{\mathrm{MF}}[n]\}$$



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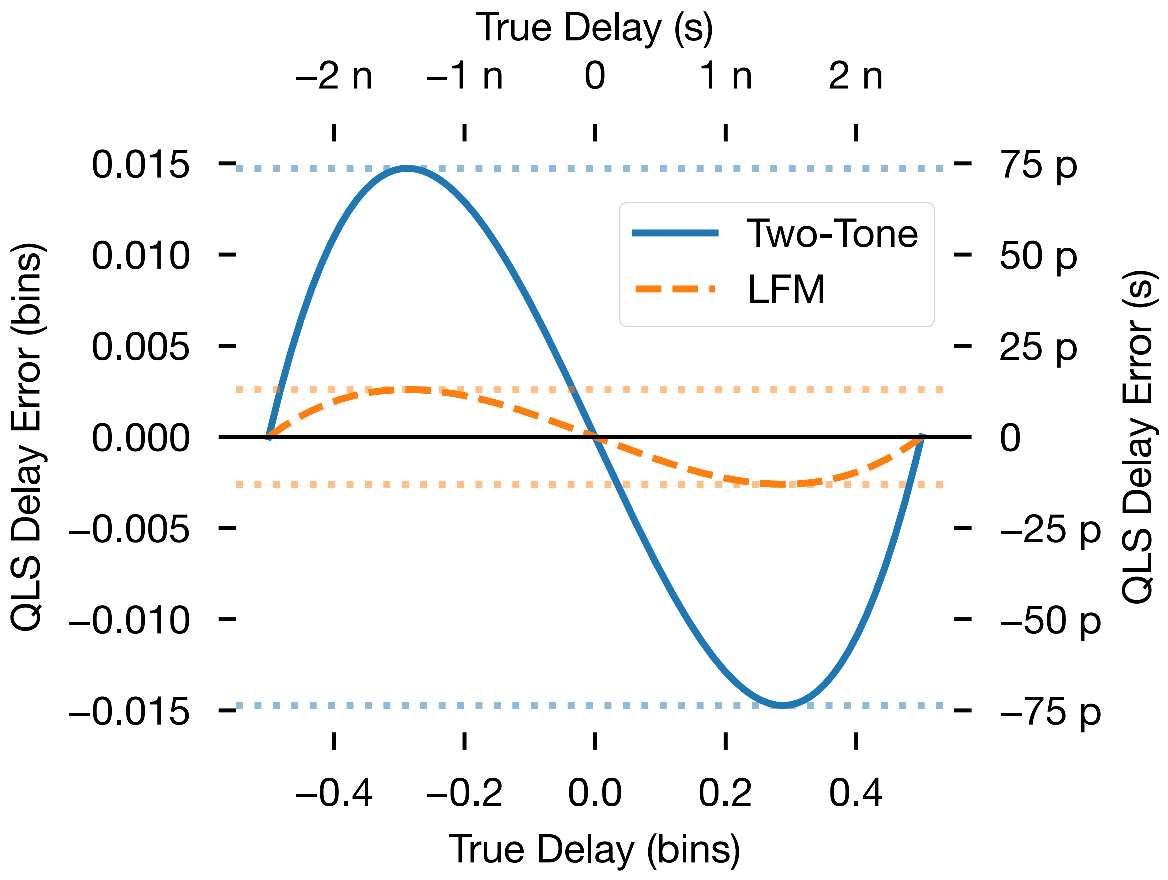
Delay Estimation Refinement

- QLS results in small residual bias due to an imperfect representation of the underlying MF output
- Residual bias is a function of waveform and sample rate
- Can be easily corrected via lookup table



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3 | Software Overview

Software Challenges

1. High/full sample rate with low CPU utilization
   → **Use “bursty” transmission scheme**

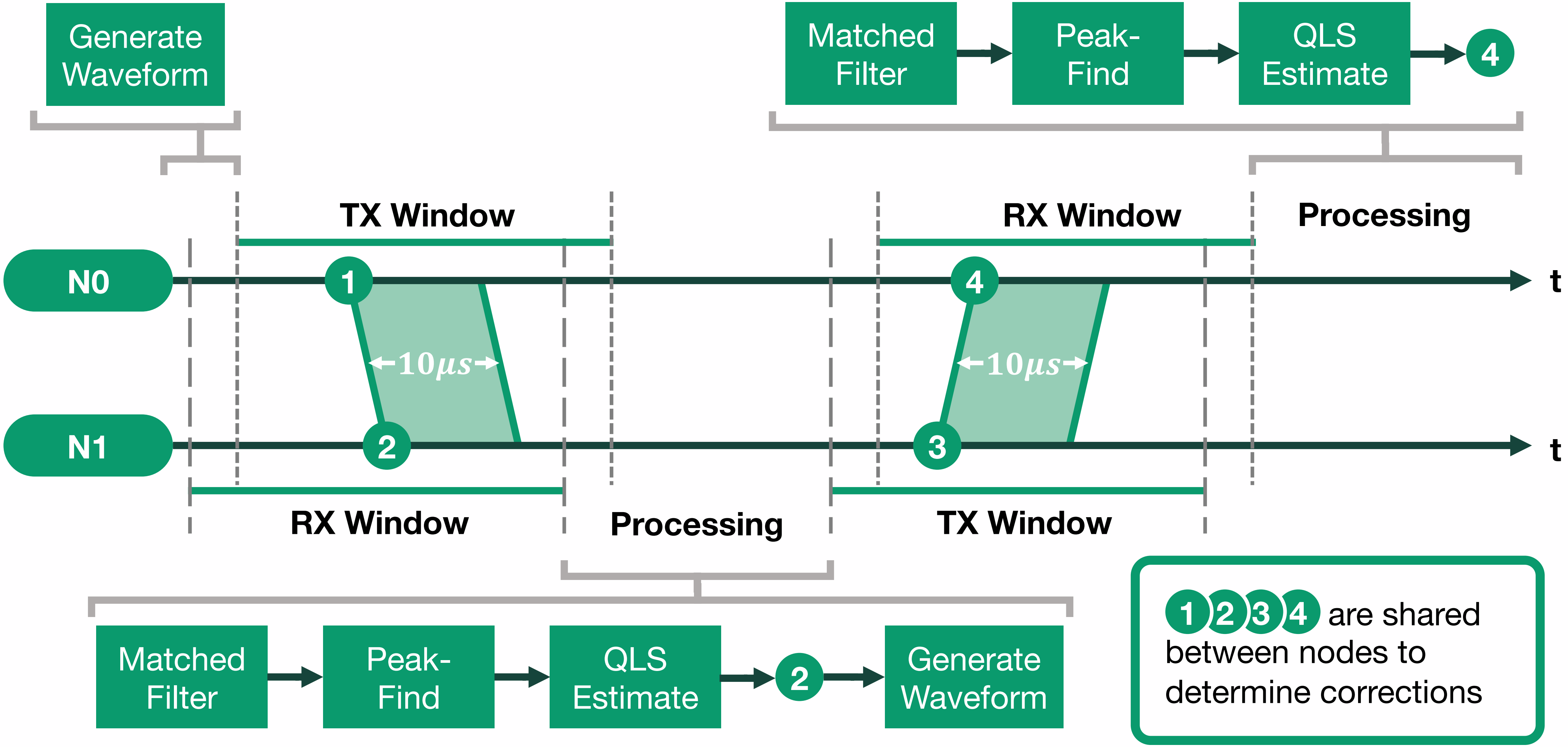
2. Reasonably low latency
   → **Use message/PDU-based flowgraph**

3. Maintain groupings of PDUs for each channel transmitted/received
   → **Use lists of PDUs**; initially created a “Wide PDU” type, but switched for compatibility with existing codebase

Software Guiding Principles

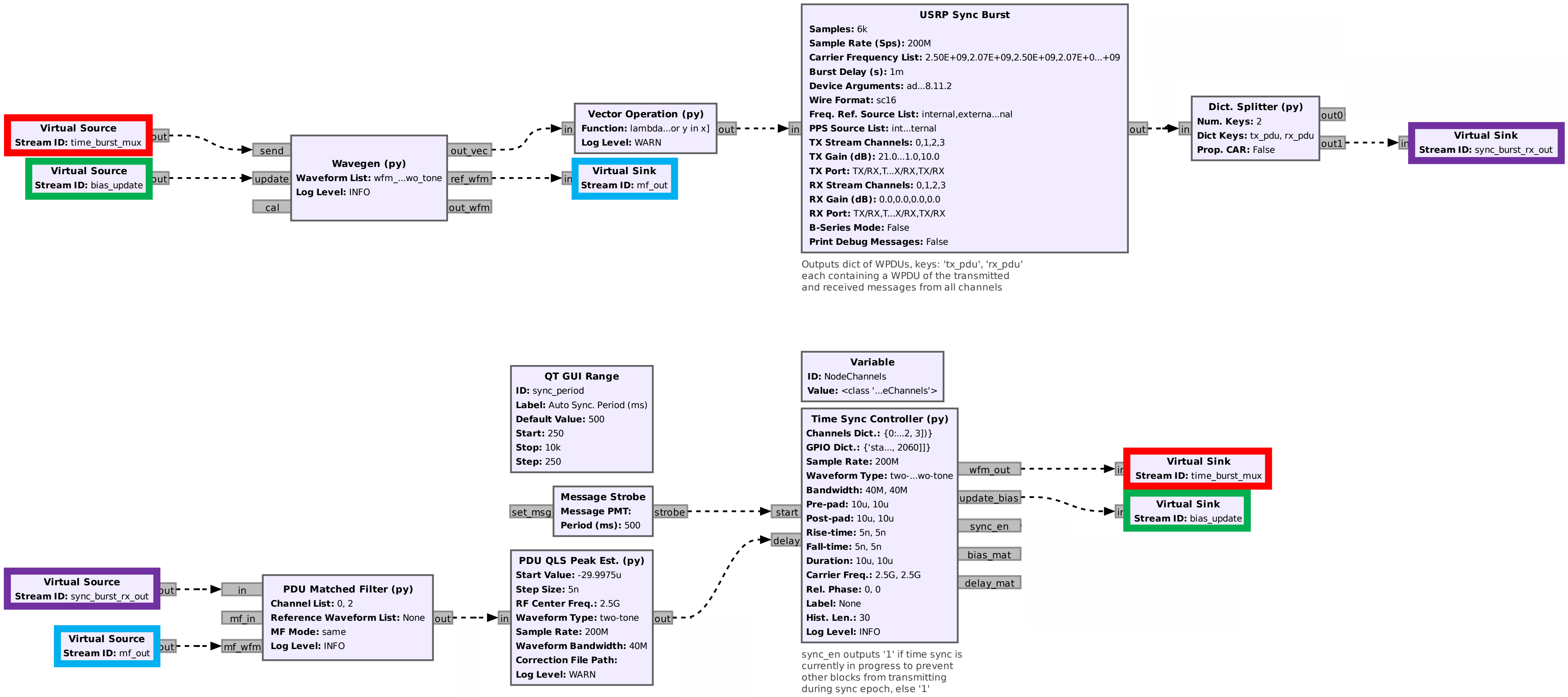
- **Code reusability**
  - → Implemented on top of **DELTA Python Package** for code reusability
- **Implementation/iteration speed**
  - → Scientific processing implemented in Python first, data manipulation in C++
  - → Benchmark, re-implement in C++ if necessary

Time Estimation Process



①②③④ are shared between nodes to determine corrections

Time Transfer Flow Graph



Virtual Source
Stream ID: time_burst_mux

Virtual Source
Stream ID: bias_update

Wavegen (py)
Waveform List: wfm_...wo_tone
Log Level: INFO

Vector Operation (py)
Function: lambda...or y in x]
Log Level: WARN

Virtual Sink
Stream ID: mf_out

USRP Sync Burst
Samples: 6k
Sample Rate (Sps): 200M
Carrier Frequency List: 2.50E+09,2.07E+09,2.50E+09,2.07E+0...+09
Burst Delay (s): 1m
Device Arguments: ad...8.11.2
Wire Format: sc16
Freq. Ref. Source List: internal,externa...nal
PPS Source List: int...ternal
TX Stream Channels: 0,1,2,3
TX Gain (dB): 21.0...1.0,10.0
TX Port: TX/RX,T...X/RX,TX/RX
RX Stream Channels: 0,1,2,3
RX Gain (dB): 0.0,0.0,0.0,0.0
RX Port: TX/RX,T...X/RX,TX/RX
B-Series Mode: False
Print Debug Messages: False

Outputs dict of WPDUs, keys: 'tx_pdu', 'rx_pdu'
each containing a WPDU of the transmitted
and received messages from all channels

Dict. Splitter (py)
Num. Keys: 2
Dict Keys: tx_pdu, rx_pdu
Prop. CAR: False

Virtual Sink
Stream ID: sync_burst_rx_out

QT GUI Range
ID: sync_period
Label: Auto Sync. Period (ms)
Default Value: 500
Start: 250
Stop: 10k
Step: 250

Variable
ID: NodeChannels
Value: <class '...eChannels'>

Message Strobe
Message PMT:
Period (ms): 500

Time Sync Controller (py)
Channels Dict.: {0:...2, 3])}
GPIO Dict.: {'sta..., 2060]]}
Sample Rate: 200M
Waveform Type: two-...wo-tone
Bandwidth: 40M, 40M
Pre-pad: 10u, 10u
Post-pad: 10u, 10u
Rise-time: 5n, 5n
Fall-time: 5n, 5n
Duration: 10u, 10u
Carrier Freq.: 2.5G, 2.5G
Rel. Phase: 0, 0
Label: None
Hist. Len.: 30
Log Level: INFO

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Stream ID: bias_update

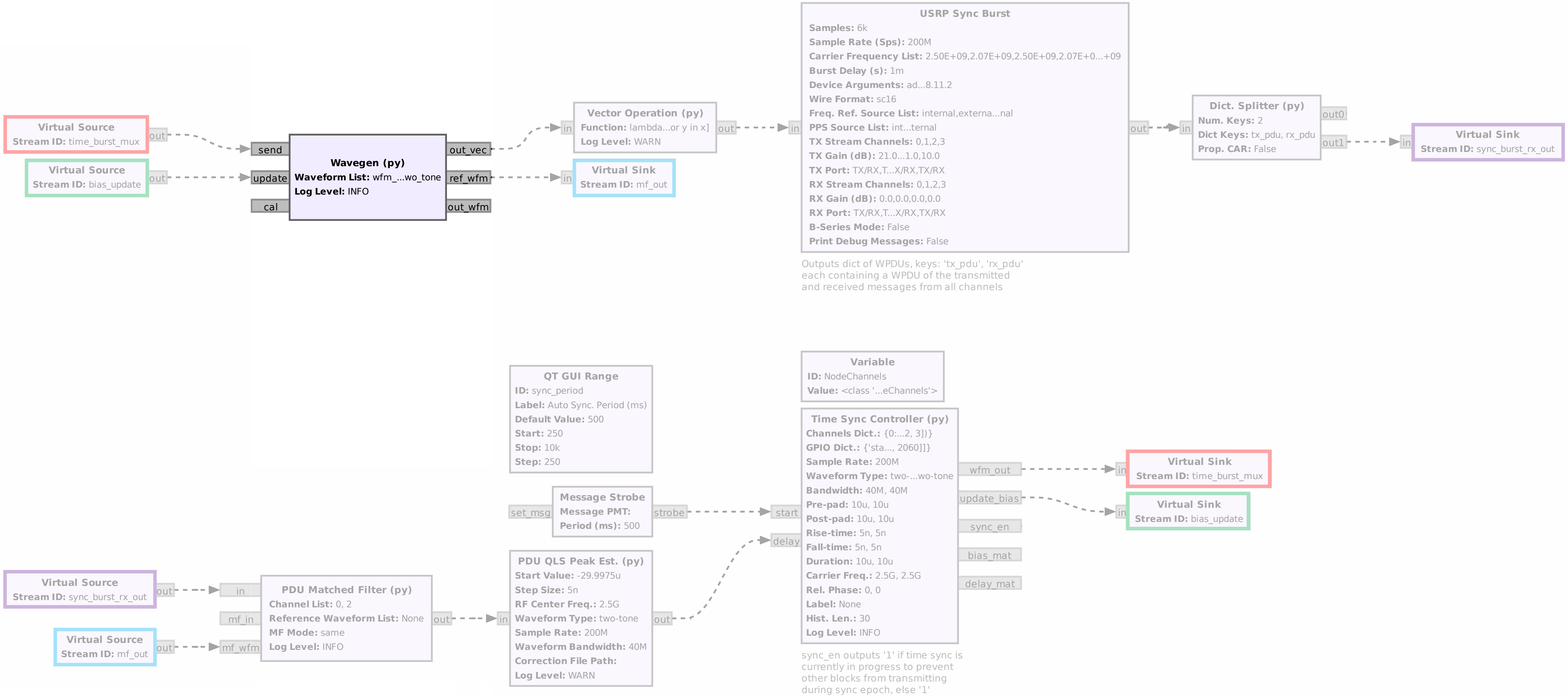
Virtual Source
Stream ID: sync_burst_rx_out

Virtual Source
Stream ID: mf_out

PDU Matched Filter (py)
Channel List: 0, 2
Reference Waveform List: None
MF Mode: same
Log Level: INFO

PDU QLS Peak Est. (py)
Start Value: -29.9975u
Step Size: 5n
RF Center Freq.: 2.5G
Waveform Type: two-tone
Sample Rate: 200M
Waveform Bandwidth: 40M
Correction File Path:
Log Level: WARN

Wavegen Block



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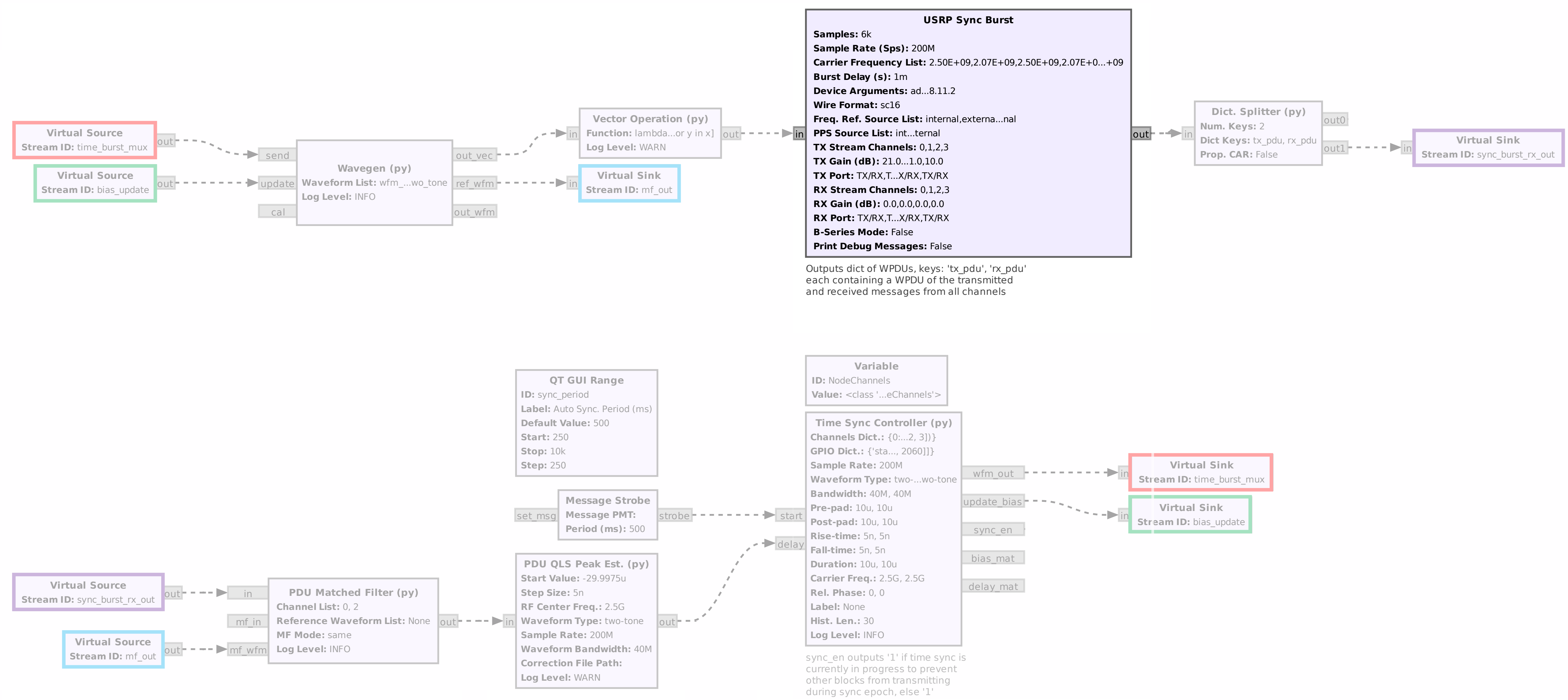
USRP Sync Burst Block



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Virtual Sink
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Burst Delay (s): 1m
Device Arguments: ad...8.11.2
Wire Format: sc16
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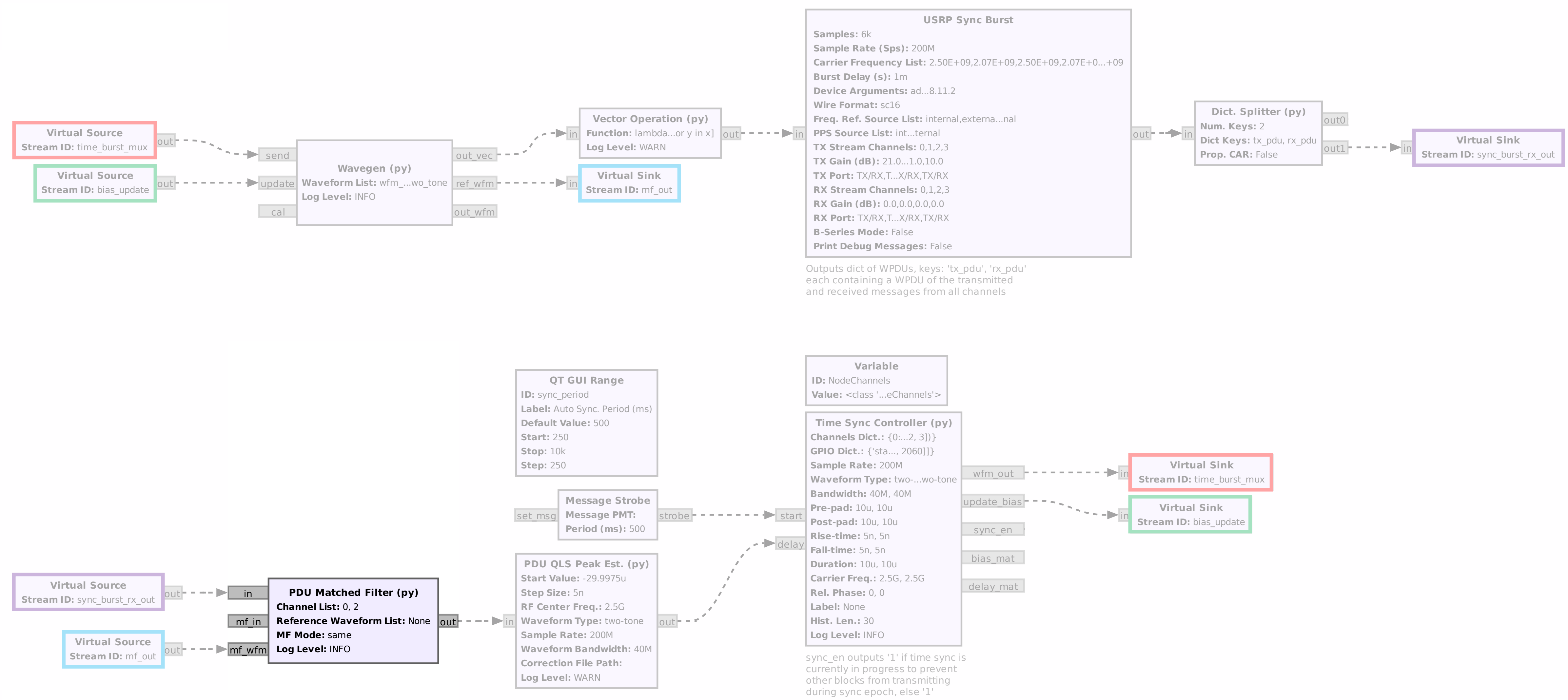
PDU Matched Filter Block



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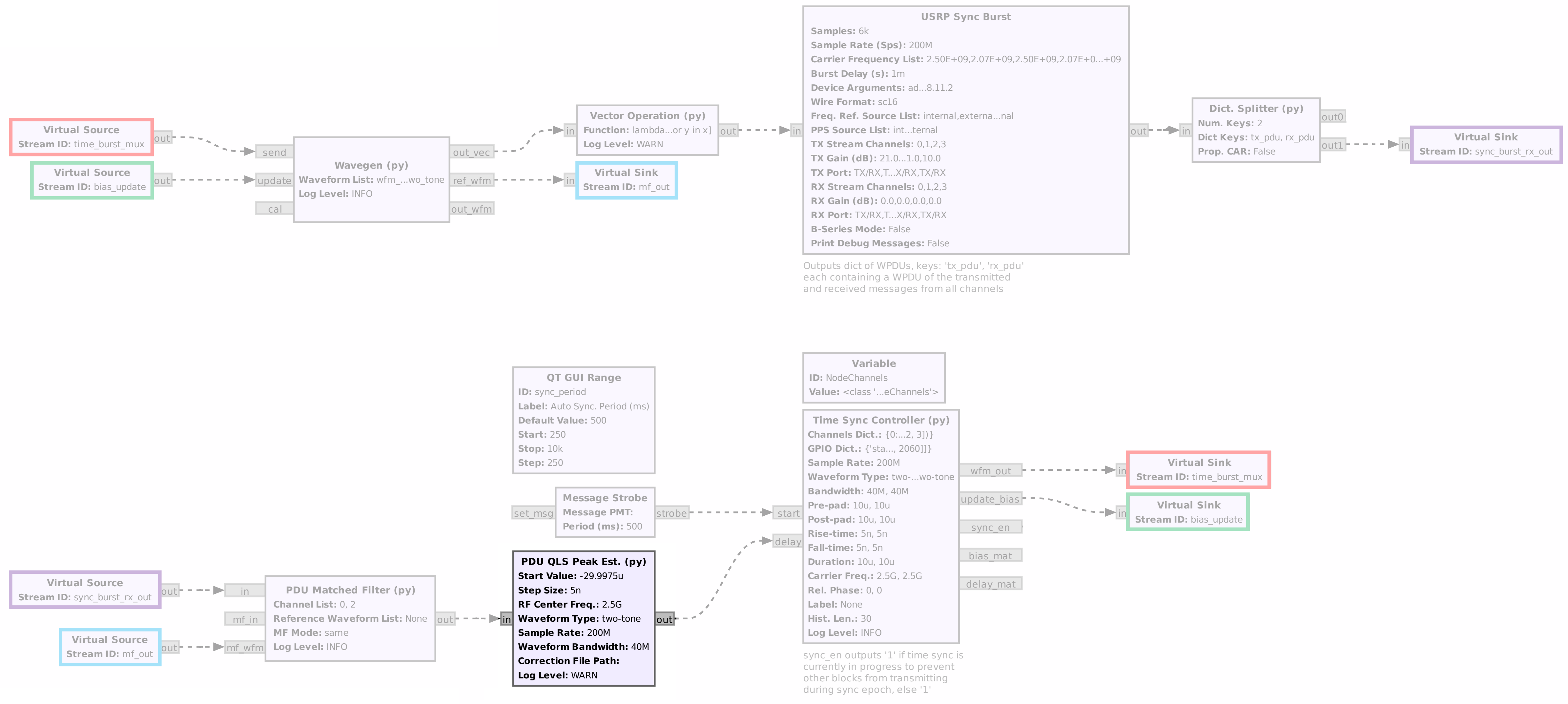

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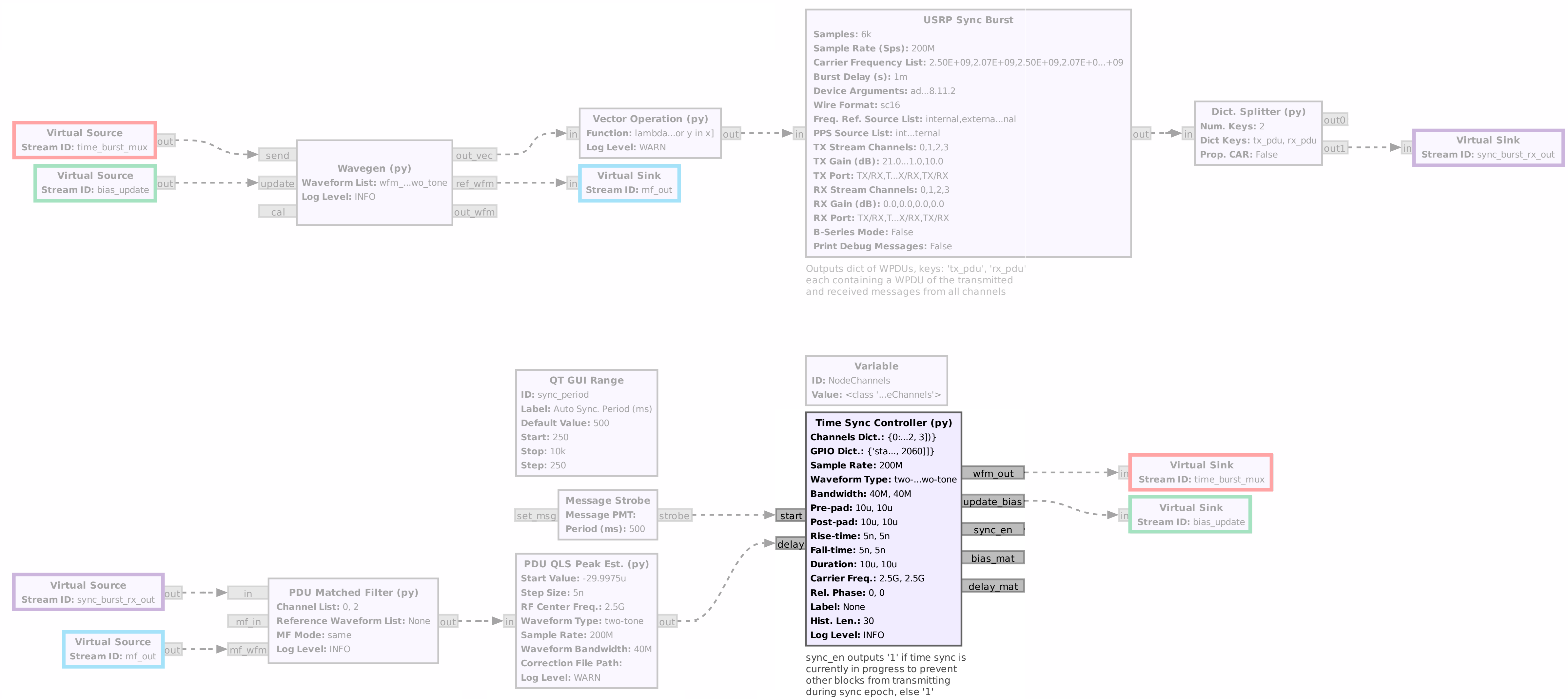
Virtual Source
Stream ID: sync_burst_rx_out

Virtual Source
Stream ID: mf_out

PDU Matched Filter (py)
Channel List: 0, 2
Reference Waveform List: None
MF Mode: same
Log Level: INFO

PDU QLS Peak Est. (py)
Start Value: -29.9975u
Step Size: 5n
RF Center Freq.: 2.5G
Waveform Type: two-tone
Sample Rate: 200M
Waveform Bandwidth: 40M
Correction File Path:
Log Level: WARN

Time Sync Controller Block



Virtual Source
Stream ID: time_burst_mux

Virtual Source
Stream ID: bias_update

Wavegen (py)
Waveform List: wfm_...wo_tone
Log Level: INFO

Vector Operation (py)
Function: lambda...or y in x]
Log Level: WARN

Virtual Sink
Stream ID: mf_out

USRP Sync Burst
Samples: 6k
Sample Rate (Sps): 200M
Carrier Frequency List: 2.50E+09,2.07E+09,2.50E+09,2.07E+0...+09
Burst Delay (s): 1m
Device Arguments: ad...8.11.2
Wire Format: sc16
Freq. Ref. Source List: internal,externa...nal
PPS Source List: int...ternal
TX Stream Channels: 0,1,2,3
TX Gain (dB): 21.0...1.0,10.0
TX Port: TX/RX,T...X/RX,TX/RX
RX Stream Channels: 0,1,2,3
RX Gain (dB): 0.0,0.0,0.0,0.0
RX Port: TX/RX,T...X/RX,TX/RX
B-Series Mode: False
Print Debug Messages: False

Outputs dict of WPDUs, keys: 'tx_pdu', 'rx_pdu'
each containing a WPDU of the transmitted
and received messages from all channels

Dict. Splitter (py)
Num. Keys: 2
Dict Keys: tx_pdu, rx_pdu
Prop. CAR: False

Virtual Sink
Stream ID: sync_burst_rx_out

QT GUI Range
ID: sync_period
Label: Auto Sync. Period (ms)
Default Value: 500
Start: 250
Stop: 10k
Step: 250

Variable
ID: NodeChannels
Value: <class '...eChannels'>

Message Strobe
Message PMT:
Period (ms): 500

Time Sync Controller (py)
Channels Dict.: {0:...2, 3])}
GPIO Dict.: {'sta..., 2060]]}
Sample Rate: 200M
Waveform Type: two-...wo-tone
Bandwidth: 40M, 40M
Pre-pad: 10u, 10u
Post-pad: 10u, 10u
Rise-time: 5n, 5n
Fall-time: 5n, 5n
Duration: 10u, 10u
Carrier Freq.: 2.5G, 2.5G
Rel. Phase: 0, 0
Label: None
Hist. Len.: 30
Log Level: INFO

sync_en outputs '1' if time sync is
currently in progress to prevent
other blocks from transmitting
during sync epoch, else '1'

Virtual Sink
Stream ID: time_burst_mux

Virtual Sink
Stream ID: bias_update

Virtual Source
Stream ID: sync_burst_rx_out

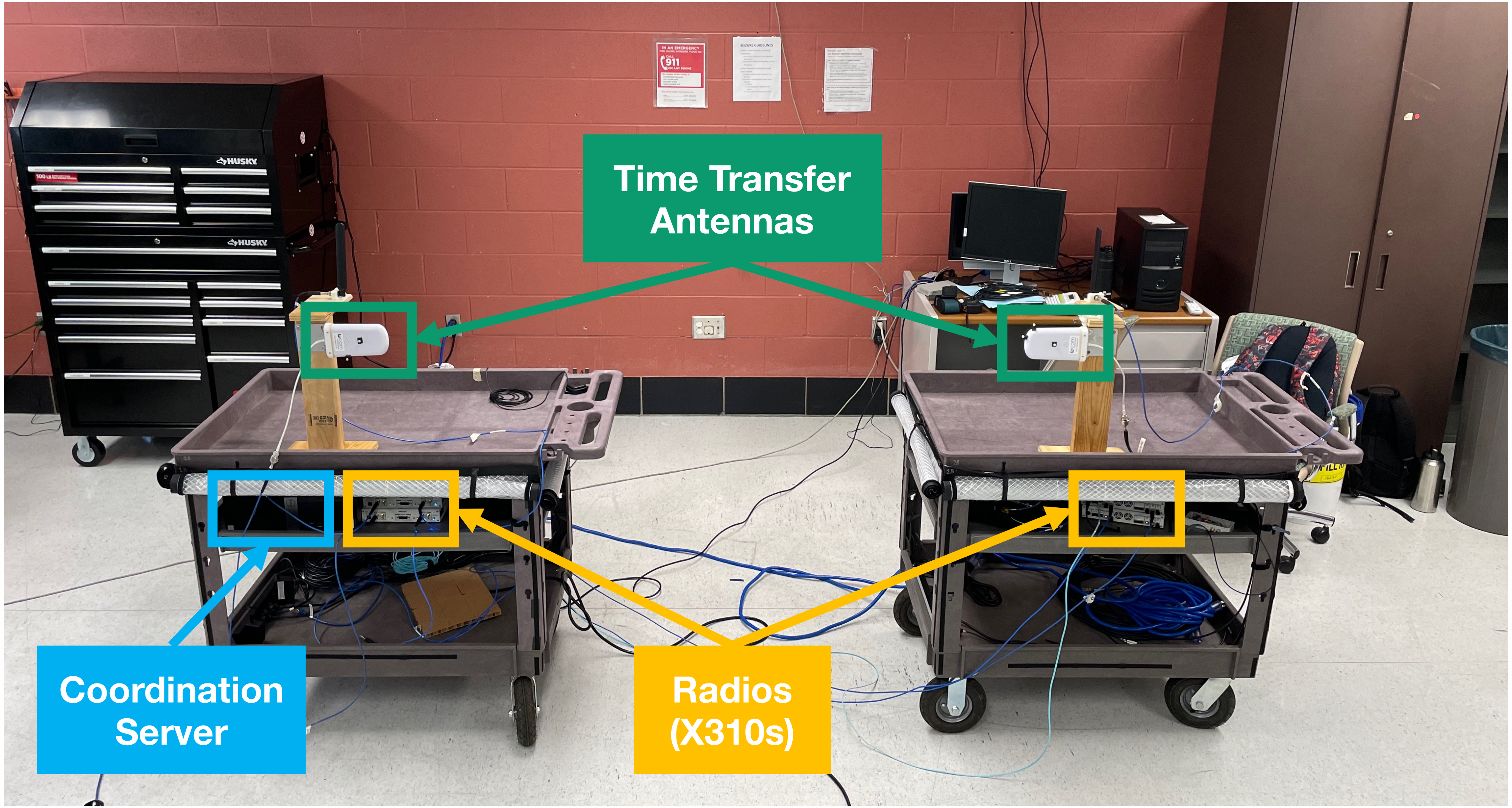
Virtual Source
Stream ID: mf_out

PDU Matched Filter (py)
Channel List: 0, 2
Reference Waveform List: None
MF Mode: same
Log Level: INFO

PDU QLS Peak Est. (py)
Start Value: -29.9975u
Step Size: 5n
RF Center Freq.: 2.5G
Waveform Type: two-tone
Sample Rate: 200M
Waveform Bandwidth: 40M
Correction File Path:
Log Level: WARN

Software Demo

Software Demo



Time Sync Trigger: Manual / Auto

Auto Sync. Period (ms) 500

Auto Re-Trigger: Off / On

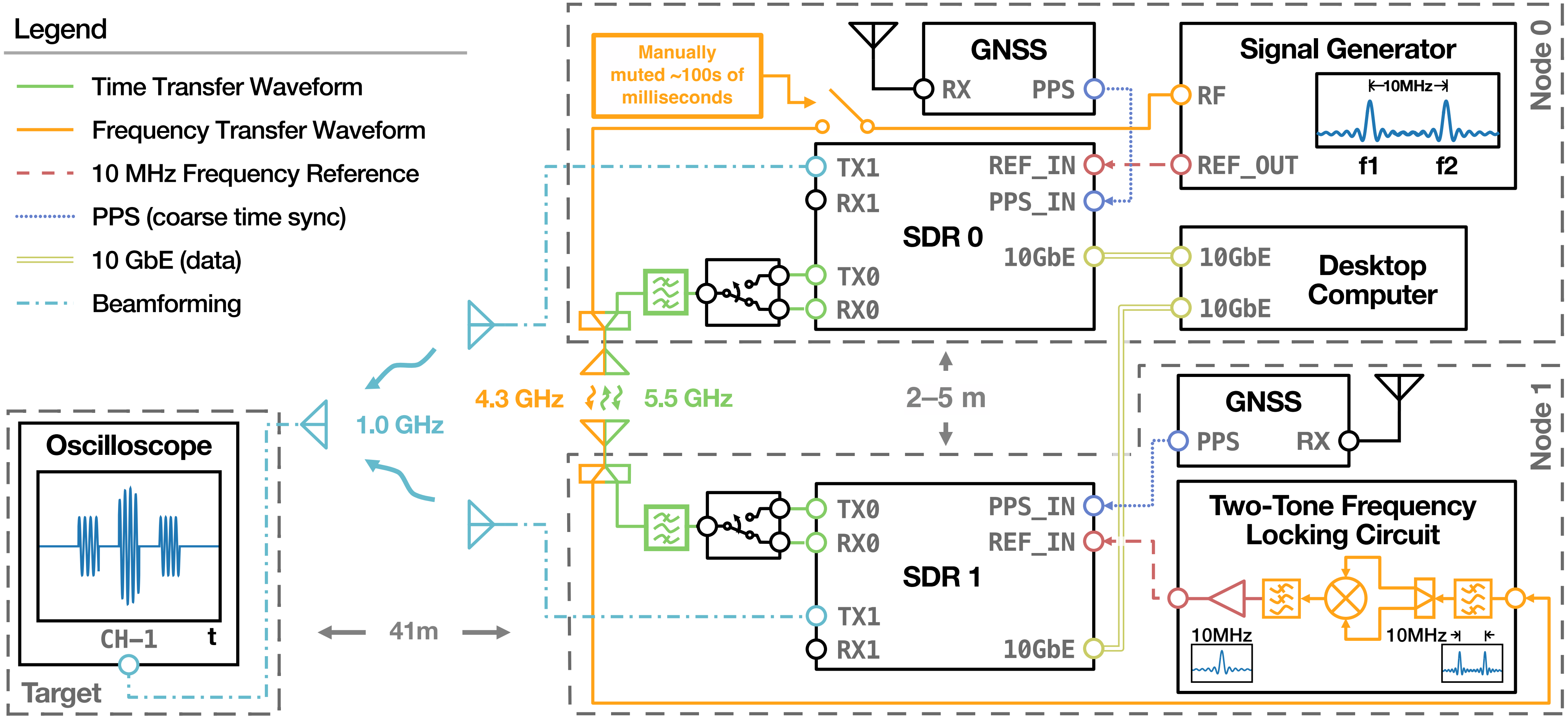
N0 SNR (Eig.): 0

N1 SNR (Eig.) 0

4 | **Experimental Results**

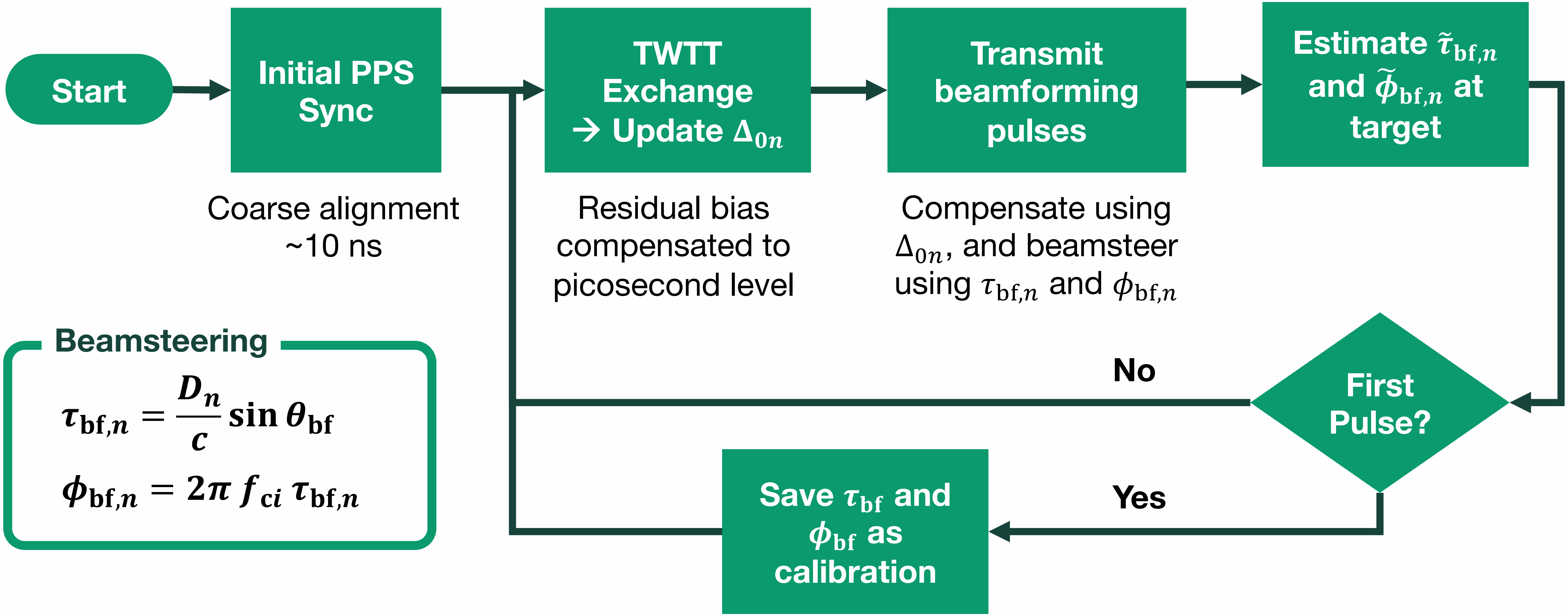
Beamforming

System Configuration



[5] J. M. Merlo, A. Schlegel and J. A. Nanzer, "High Accuracy Wireless Time-Frequency Transfer For Distributed Phased Array Beamforming," in *2023 IEEE/MTT-S International Microwave Symposium - IMS 2023*, San Diego, CA, USA, 2023.

System State Flow



Start

Initial PPS Sync

Coarse alignment ~10 ns

TWTT Exchange → Update Δ_{0n}

Residual bias compensated to picosecond level

Transmit beamforming pulses

Compensate using Δ_{0n}, and beamsteer using $\tau_{\mathrm{bf},n}$ and $\phi_{\mathrm{bf},n}$

Estimate $\tilde{\tau}_{\mathrm{bf},n}$ and $\widetilde{\phi}_{\mathrm{bf},n}$ at target

First Pulse?

No

Yes

Save τ_{bf} and ϕ_{bf} as calibration

Beamsteering

$$\boldsymbol{\tau_{\mathrm{bf},n} = \frac{D_n}{c} \sin \theta_{\mathrm{bf}}}$$

$$\boldsymbol{\phi_{\mathrm{bf},n} = 2\pi\, f_{ci}\, \tau_{\mathrm{bf},n}}$$

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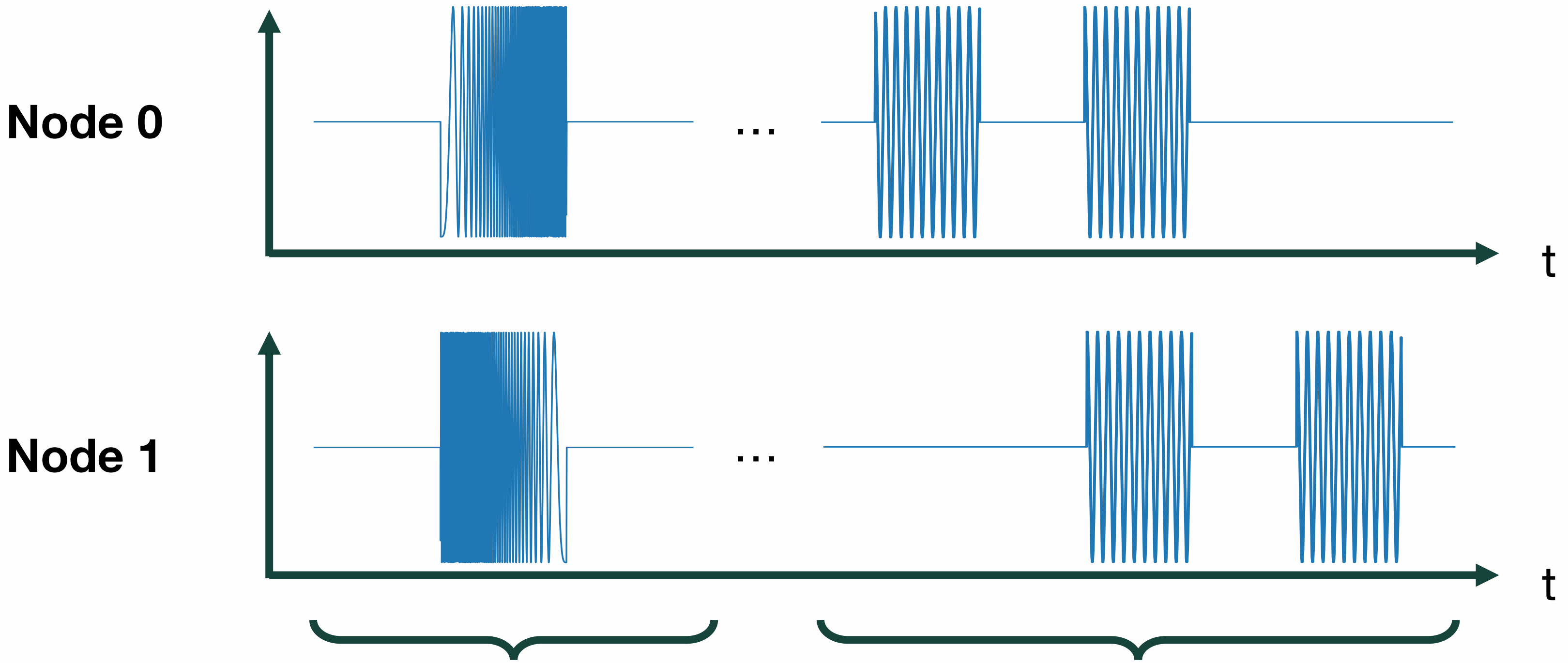
Performance Evaluation Waveforms

- Each node transmitted orthogonal LFMs followed by two CW pulses



LFM: Time/Phase Estimation CW Pulses: Coherent Gain Estimation

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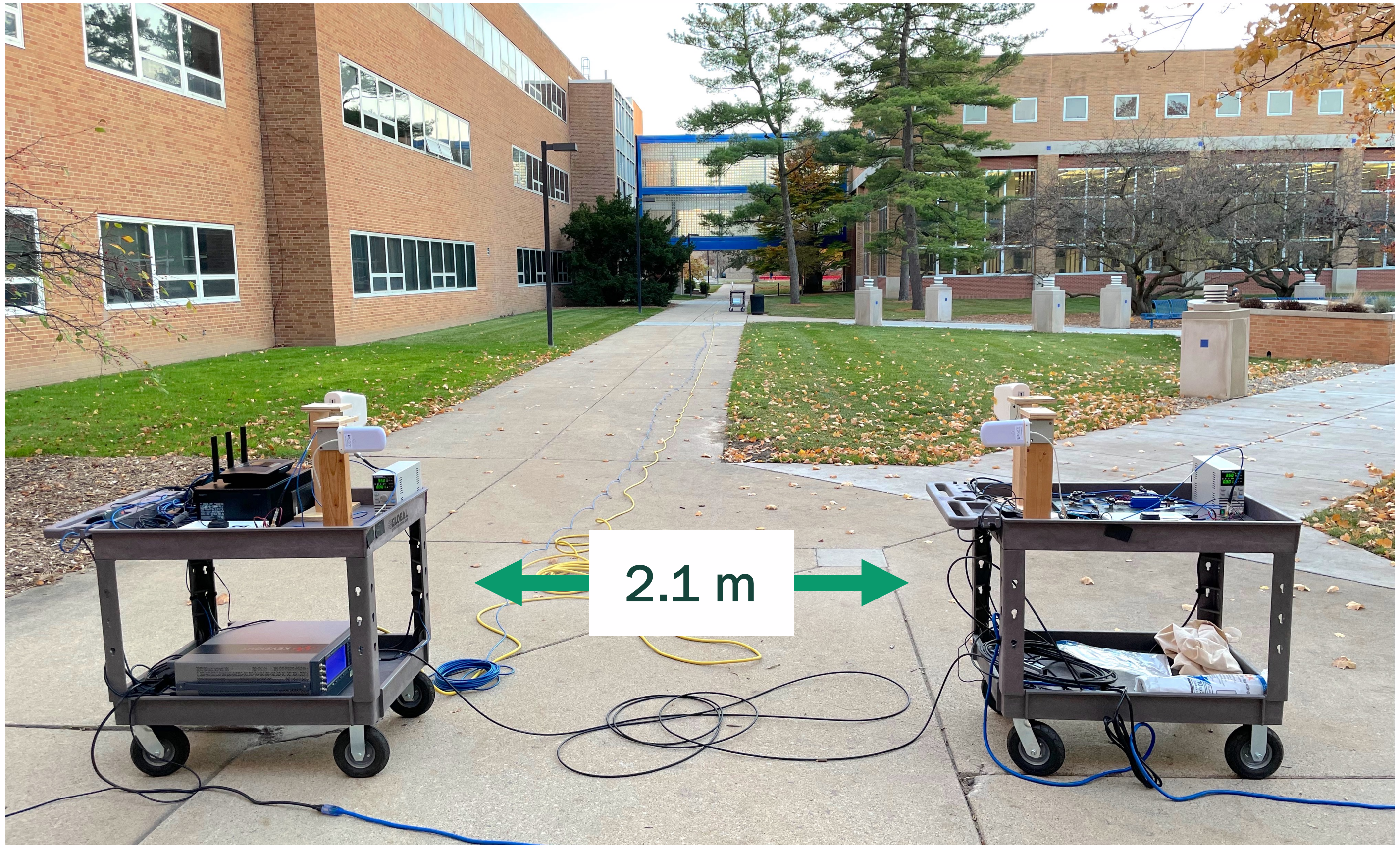
Experimental Configuration



Transmit Nodes Setup

Target Node Setup (41 m downrange)

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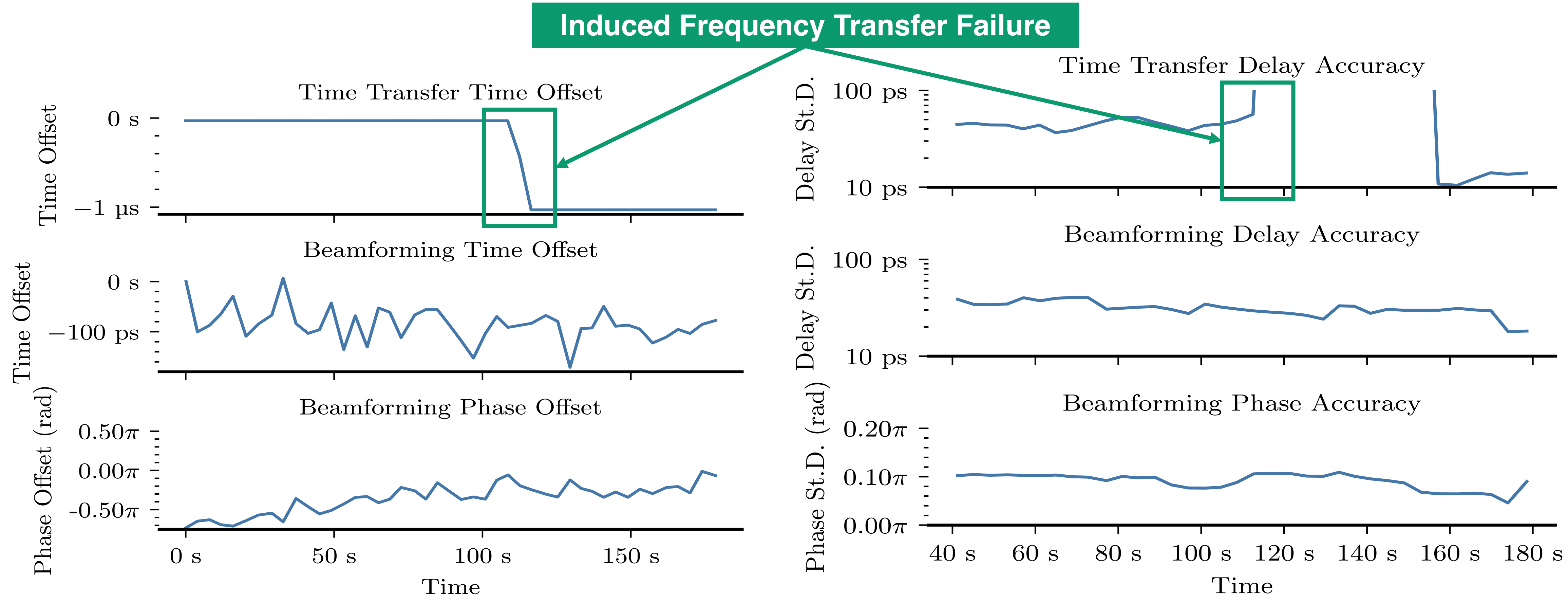
[5] J. M. Merlo, A. Schlegel and J. A. Nanzer, "High Accuracy Wireless Time-Frequency Transfer For Distributed Phased Array Beamforming," in *2023 IEEE/MTT-S International Microwave Symposium - IMS 2023*, San Diego, CA, USA, 2023.

Beamforming Results



Induced Frequency Transfer Failure

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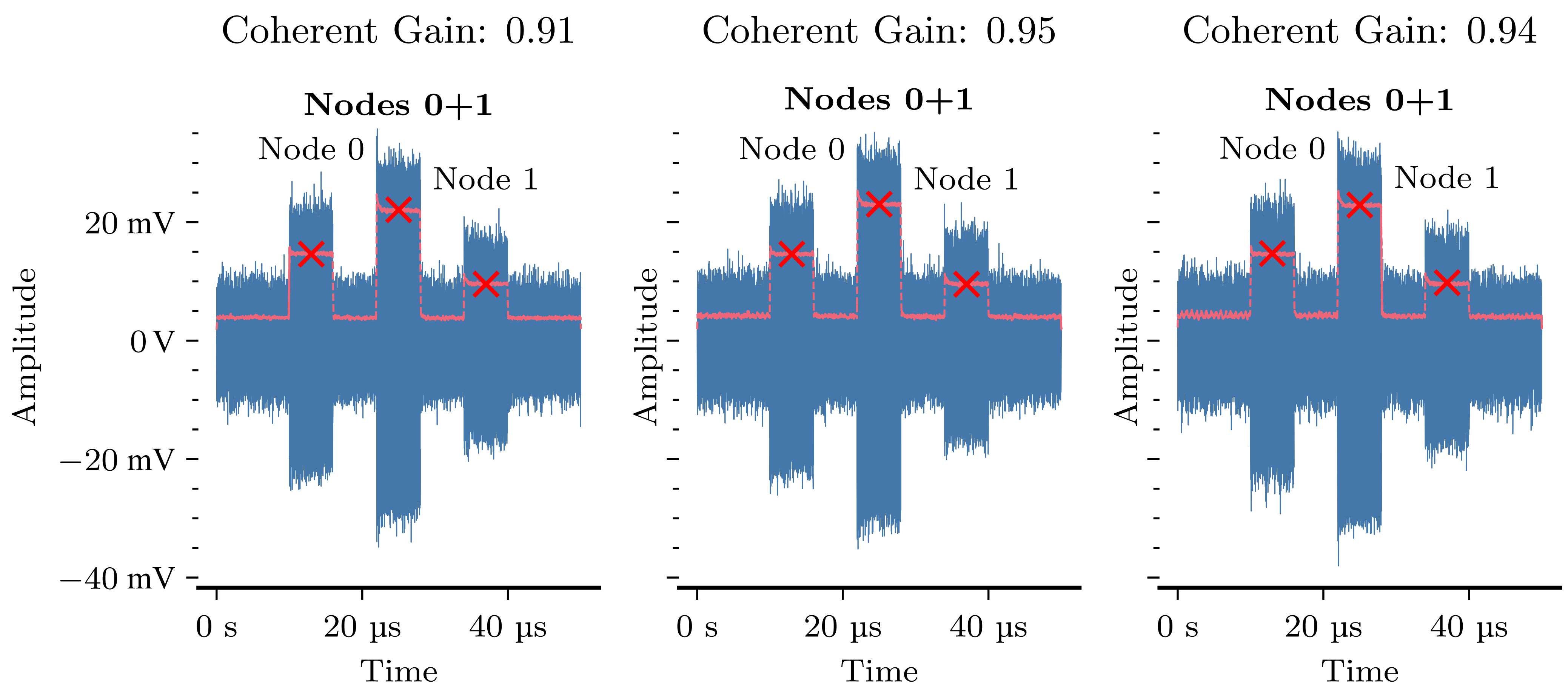
Beamforming Results



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Measurement Summary

Demonstrated fully wireless outdoor time-frequency synchronization and beamforming with $G_c > 0.9$ over a 41 m

Internode Distance	Min. Time Transfer Std.	Min. Beamforming Std.	Max. Throughput*	Max. Carrier Frequency†
2.1 m	10.47 ps	18.00 ps	5.56 Gbps	2.78 GHz
5.0 m	14.79 ps	24.02 ps	4.16 Gbps	2.08 GHz

* Maximum theoretical BPSK throughput; $\Pr(\boldsymbol{G_c} \geq \mathbf{0.9}) > \mathbf{0.9}$

† Maximum theoretical carrier frequency; $\Pr(\boldsymbol{G_c} \geq \mathbf{0.9}) > \mathbf{0.9}$

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Project Status and Conclusion

In Progress:

- Standardizing inter-block communications (use PDUs/list of PDUs)
- Complete fully distributed compute software implementation
  - Testing in progress
- Adding/improving documentation

Planned Work:

- Add test cases for CI/CD
- Open source releases
- Investigate use of streaming interface with managed latency to leverage existing streaming blocks

Questions?

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Office of Naval Research Science & Technology

National Science Foundation

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