gr-harmonia:
A Synchronization Toolkit for Software-defined Radios in a Distributed Network

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Outline

- Introduction
- Synchronization Procedure
- gr-harmonia: Blocks and Features
- Experimental Validation
- Conclusions and Future Work

Outline

- **Introduction**
  - Motivation
  - Signal Model
- Synchronization Procedure
- gr-harmonia: Blocks and Features
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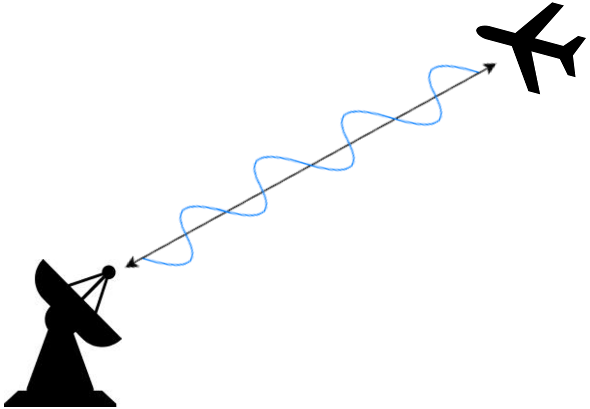
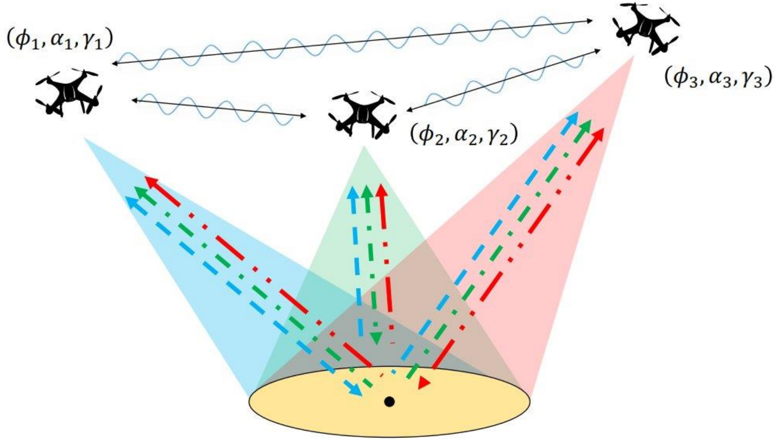
Introduction

Motivation

Traditional Monostatic Radar



Distributed Radar System



[1] R. H. Kenney and J. W. McDaniel, "Cooperative Navigation of Mobile Radar Sensors Using Time-of-Arrival Measurements and the Unscented Kalman Filter," in IEEE Transactions on Radar Systems, vol. 1, pp. 435-447, Aug. 2023.
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Introduction

Signal Model

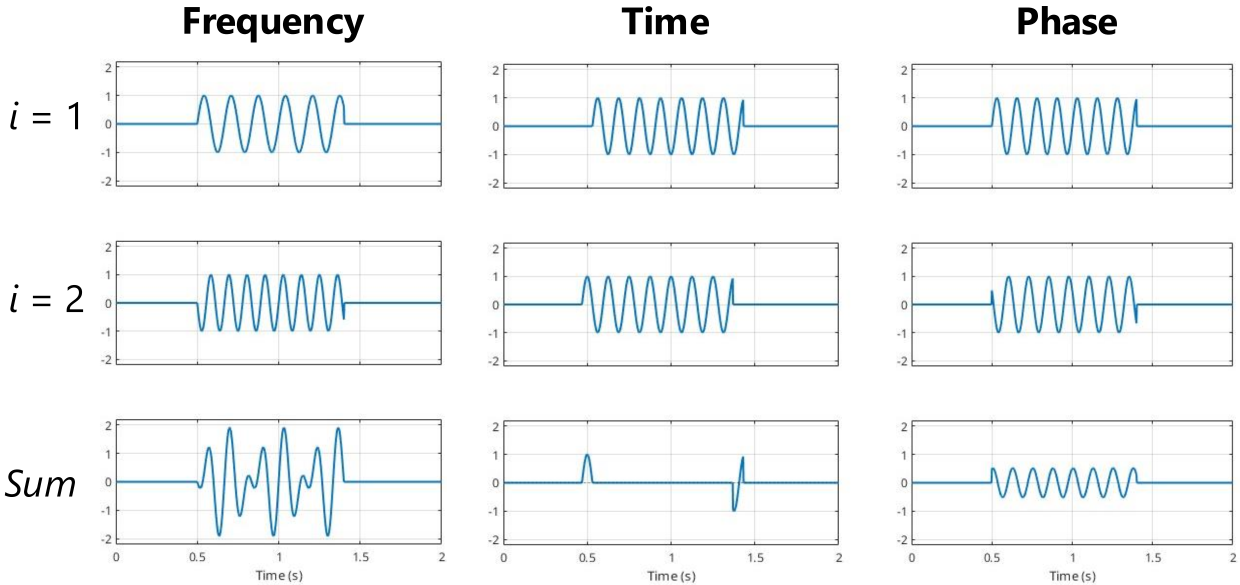
- Clock Drift (α)
- Clock Bias (ϕ)
- Carrier Phase (γ^{tx}, γ^{rx})

Clock drift definition

$$\alpha_i = f_i^{\text{MO}} / f^{\text{MO}}$$

Local time on platform *i*

$$\tau_i = \alpha_i t + \phi_i$$



- Received signal can be expressed in terms of the receiver's local clock

$$r_{i,j}(\tau_i) = \underbrace{s_j\left(\frac{\alpha_j}{\alpha_i}\tau_i - \left(\frac{\alpha_j}{\alpha_i}\phi_i - \phi_j + \alpha_j \frac{R_{i,j}}{c}\right)\right)}_{\text{Baseband Signal}} \underbrace{\exp\left(\mathrm{j}\, 2\pi f^c \left(\frac{\alpha_j}{\alpha_i} - 1\right)\tau_i\right)}_{\text{Residual Carrier Frequency Error}} \underbrace{\exp\left(-\mathrm{j}\, 2\pi f^c \left(\frac{\alpha_j}{\alpha_i}\phi_i - \phi_j + \alpha_j \frac{R_{i,j}}{c}\right)\right)}_{\text{Residual Clock Bias and Propagation Delay Phase}} \underbrace{\exp\left(\mathrm{j}\, \gamma_{i,j}^{\text{err}}\right)}_{\text{Carrier Phase Error}}$$

[1] R. H. Kenney and J. W. McDaniel, "Cooperative Navigation of Mobile Radar Sensors Using Time-of-Arrival Measurements and the Unscented Kalman Filter," in IEEE Transactions on Radar Systems, vol. 1, pp. 435-447, Aug. 2023.

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- Introduction
- **Synchronization Procedure**
  - Assumptions and Time-Division Multiple Access
  - Clock Drift Estimation and Compensation
  - Clock Bias and Carrier Phase Estimation and Compensation
- gr-harmonia: Blocks and Features
- Experimental Validation
- Conclusions and Future Work

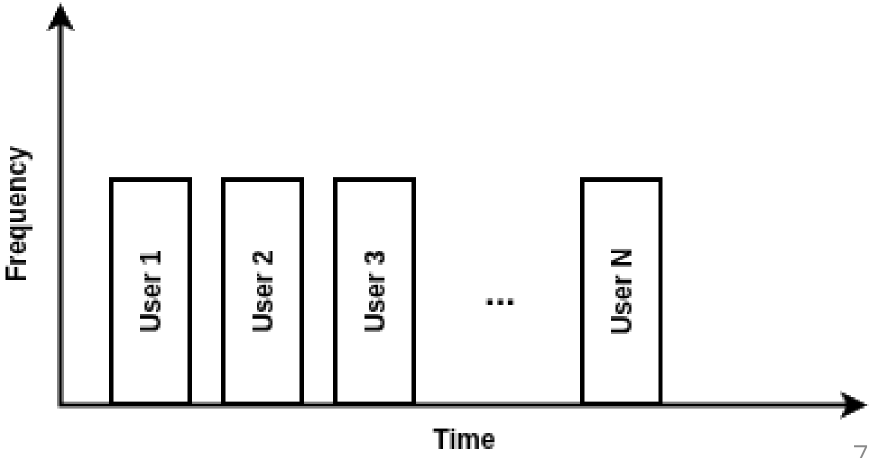
Synchronization Procedure

Assumptions

- Each distributed radar platform i has an independent main oscillator with a nominal frequency f^{MO} and a true frequency f_i^{MO}
- Each platform is stationary
- Coarse synchronization performed beforehand

Time-Division Multiple Access

$$\tau_j^{\mathrm{tx}} = (j-1)\Delta_{\mathrm{TDMA}}, \quad j = 1, 2, \ldots, N$$



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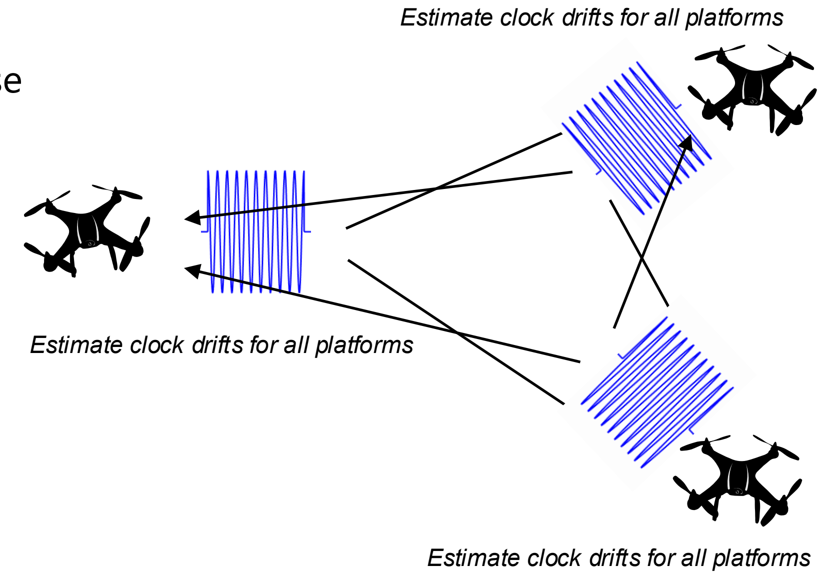
Synchronization Procedure

Clock Drift Estimation

1. Single-Tone Pulse Broadcasts
   a) Each platform **broadcasts** specific frequency pulse
   b) RX platforms **estimate** frequency from each TX
   c) Each platform **shares** estimated frequency
   d) Each platform **solves** equations for clock drifts
   e) Each platform **compensates** drift on TX and RX



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Synchronization Procedure

Clock Drift Estimation

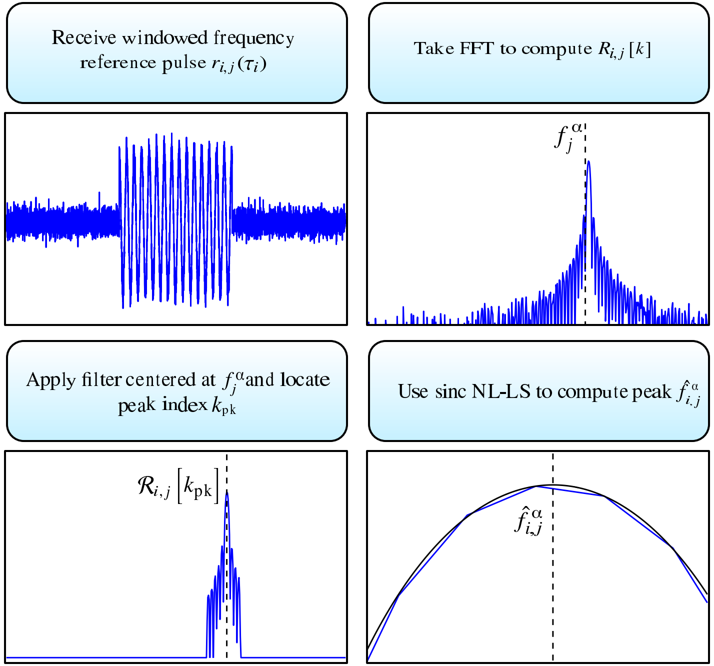
- Estimate frequency peak using sinc NL-LS [2]
  - Yields an estimate $\hat{f}_{i,j}^{\alpha}$
- All platforms exchange frequency estimates
- Estimates nominally related to clock drifts by

$$\hat{f}_{i,j}^{\alpha} = \left(\frac{\alpha_j}{\alpha_i} - 1\right) f^c + \frac{\alpha_j}{\alpha_i} f_j^{\alpha}$$

- Rearrange to give

$$\left(\hat{f}_{i,j}^{\alpha} + f^c\right)\alpha_i - \left(f_j^{\alpha} + f^c\right)\alpha_j = 0$$

- Relative drifts – set one drift to unity (e.g., $\alpha_1 = 1$)
- Each platform uses linear LS to solve above equations for drift estimates $\hat{\alpha}_i$



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Synchronization Procedure

Clock Drift Compensation

- On transmit: recompute baseband signal w/ new time axis and apply carrier correction

$$s'_j(\tau_j) = s_j\left(\frac{\tau_j}{\hat{\alpha}_j}\right)\exp\left(\mathrm{j}\,2\pi f^c\left(\frac{1}{\hat{\alpha}_j}-1\right)\tau_j\right)$$

- On receive: scale RX signal w/ new time axis $\tau'_i = \tau_i/\hat{\alpha}_i$ and apply carrier correction

$$r^b_{i,j}(\tau'_i) = r_{i,j}(\tau'_i)\exp\left(\mathrm{j}\,2\pi f^c(\hat{\alpha}_i-1)\,\tau'_i\right)$$

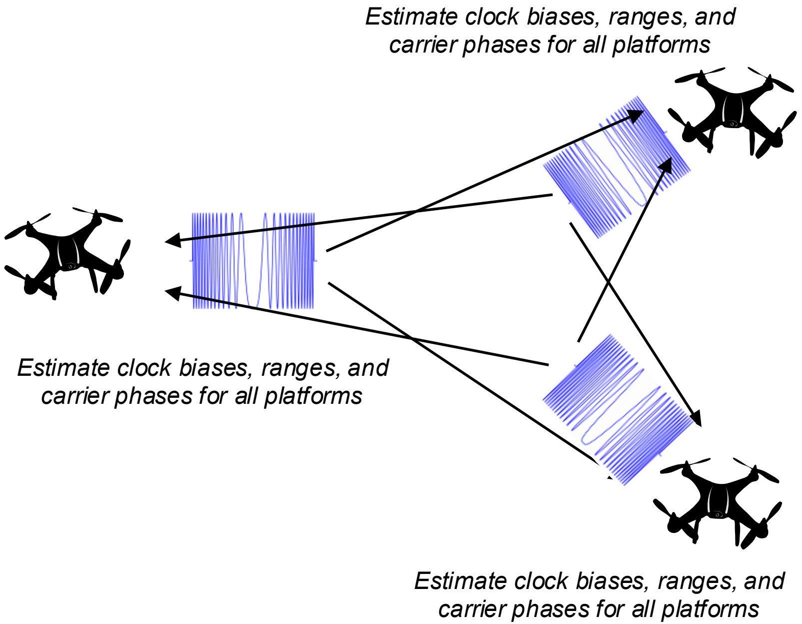
$$= s_j\left(\tau'_i-\left(\frac{1}{\hat{\alpha}_i}\phi_i-\frac{1}{\hat{\alpha}_j}\phi_j+\frac{\alpha_j}{\hat{\alpha}_j}\frac{R_{i,j}}{c}\right)\right)\exp\left(-\mathrm{j}\,2\pi f^c\left(\frac{1}{\hat{\alpha}_i}\phi_i-\frac{1}{\hat{\alpha}_j}\phi_j+\frac{\alpha_j}{\hat{\alpha}_j}\frac{R_{i,j}}{c}\right)\right)\exp\left(\mathrm{j}\,\gamma^{\mathrm{err}}_{i,j}\right)$$

[3] R. H. Kenney and J. W. McDaniel, "All-Digital Carrier Frequency Synchronization for Distributed Radar Sensor Networks," 2024 IEEE/MTT-S International Microwave Symposium – IMS 2024, Washington, DC, USA, Jul. 2024.

Synchronization Procedure

Clock Bias and Carrier Phase Estimation

1. Linear Frequency Modulated (LFM) Pulse Broadcasts
   a) Each platform **broadcasts** ranging waveform
   b) Each platform **estimates** time-delay and phase
   c) Platforms **share** time-delay and phase estimates
   d) Each platform **solves** for range, clock biases, and carrier phases
   e) Each platform **compensates** clock bias and carrier phase on TX and RX



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Synchronization Procedure

Clock Bias and Carrier Phase Estimation

- Assumes clock drifts now compensated – works identically to procedure in [2]
- Pulse-compression waveforms broadcast amongst platforms, and time-delays estimated

$$m_{i,j} = \frac{1}{\hat{\alpha}_i}\phi_i - \frac{1}{\hat{\alpha}_j}\phi_j + \frac{\alpha_j}{\hat{\alpha}_j}\frac{R_{i,j}}{c}$$

- Share time-delay estimates and phase at pulse-compression peak with all other platforms
- Exploit signal symmetry to compute range and bias differences

$$\hat{R}_{i,j} = \frac{\alpha_j}{\hat{\alpha}_j}R_{i,j} = \frac{c\left(m_{i,j} + m_{j,i}\right)}{2}$$

$$\hat{\phi}_{i,j} = \frac{1}{\hat{\alpha}_i}\phi_i - \frac{1}{\hat{\alpha}_j}\phi_j = \frac{m_{i,j} - m_{j,i}}{2}$$

- Compute network average of clock biases and estimates of carrier phase differences

$$\tilde{\phi}_i = \frac{1}{N}\sum_j \hat{\phi}_{i,j}$$

$$\hat{\gamma}^{\text{err}}_{i,j} = \angle d_{i,j}(m_{i,j}) + 2\pi f^c\left(\frac{\hat{R}_{i,j}}{c} + \hat{\phi}_{i,j}\right)$$

[2] S. Prager, M. S. Haynes, and M. Moghaddam, “Wireless Subnanosecond RF Synchronization for Distributed Ultrawideband Software-Defined Radar Networks,” IEEE Transactions on Microwave Theory and Techniques, vol. 68, no. 11, pp. 4787–4804, Nov. 2020.

Synchronization Procedure

Clock Bias and Carrier Phase Compensation

- For all future TX signals at platform *i*:
  - Apply fractional delay of $\tilde{\phi}_i$ to correct bias in delay
  - Apply phase correction of $\exp\left(-\mathrm{j}\,2\pi f^c \tilde{\phi}_i\right)$ to correct bias phase
  - Apply phase correction of $\exp\left(-\mathrm{j}\,\hat{\gamma}_i^{\mathrm{tx}}\right)$ to correct carrier phase
- For all future RX signals at platform *i*:
  - Apply fractional delay of $-\tilde{\phi}_i$ to correct bias in delay
  - Apply phase correction of $\exp\left(\mathrm{j}\,2\pi f^c \tilde{\phi}_i\right)$ to correct bias phase
  - Apply phase correction of $\exp\left(\mathrm{j}\,\hat{\gamma}_i^{\mathrm{rx}}\right)$ to correct carrier phase

[2] S. Prager, M. S. Haynes, and M. Moghaddam, "Wireless Subnanosecond RF Synchronization for Distributed Ultrawideband Software-Defined Radar Networks," IEEE Transactions on Microwave Theory and Techniques, vol. 68, no. 11, pp. 4787–4804, Nov. 2020.

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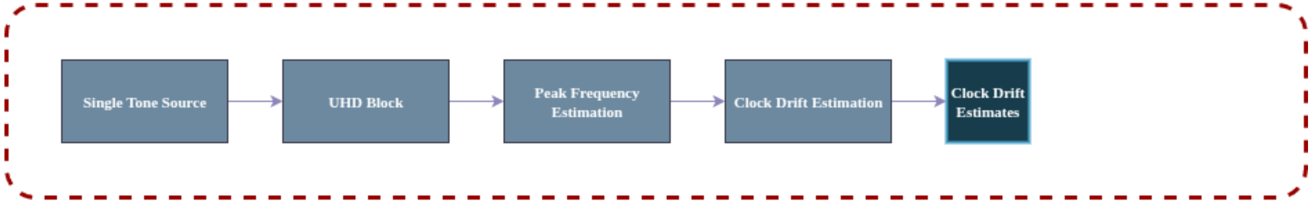
- Synchronization Procedure
- **gr-harmonia: Blocks and Features**
  - Waveform Generation
  - USRP Interfacing and TDMA
  - Clock Drift Estimation
  - Clock Bias and Carrier Phase Estimation
  - Waveform Compensation
- Experimental Validation
- Conclusions and Future Work

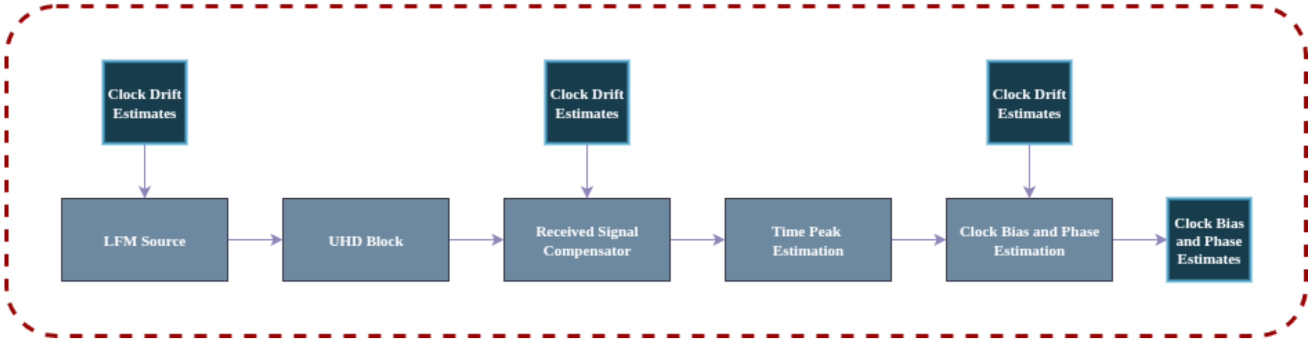
gr-harmonia: Blocks and Features

- All blocks operate in the message domain and exchange **protocol data units** (**PDUs)** via message ports.

Clock Drift Estimation



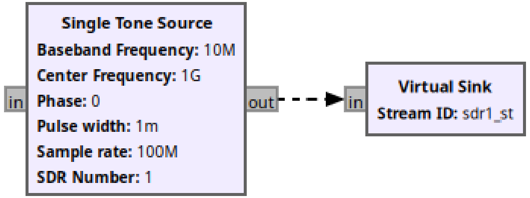
Clock Bias and Carrier Phase Estimation

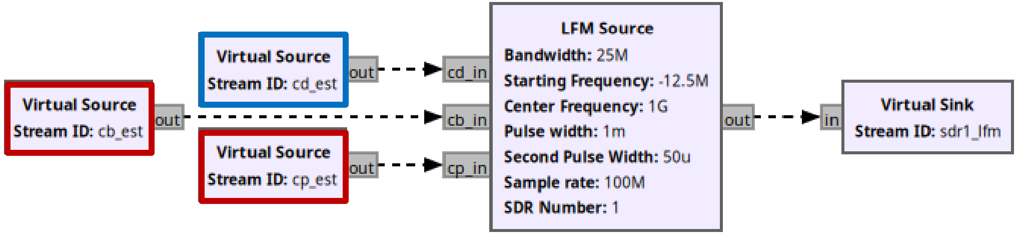


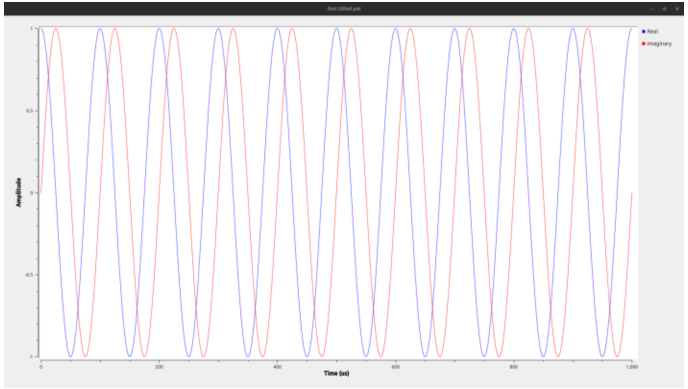
gr-harmonia: Blocks and Features

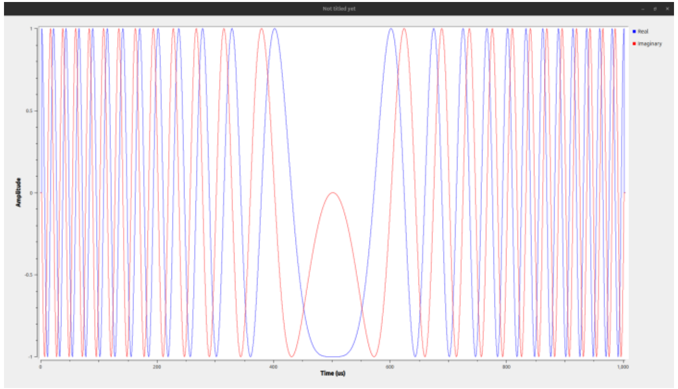
Waveform Generation

- **Single-Tone** and **LFM** Block





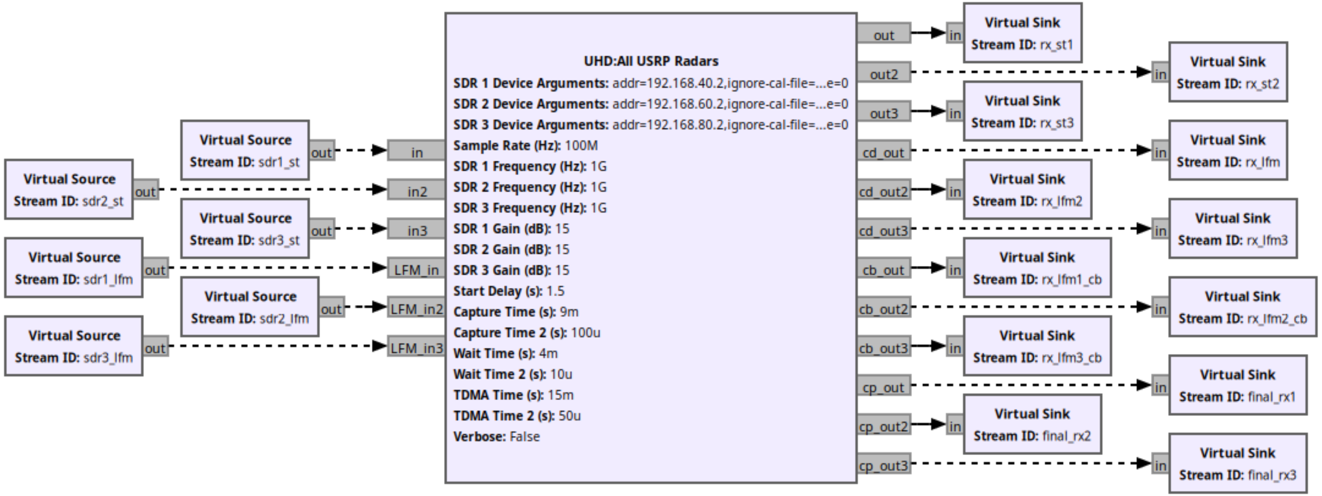




gr-harmonia: Blocks and Features

UHD Interfacing and TDMA

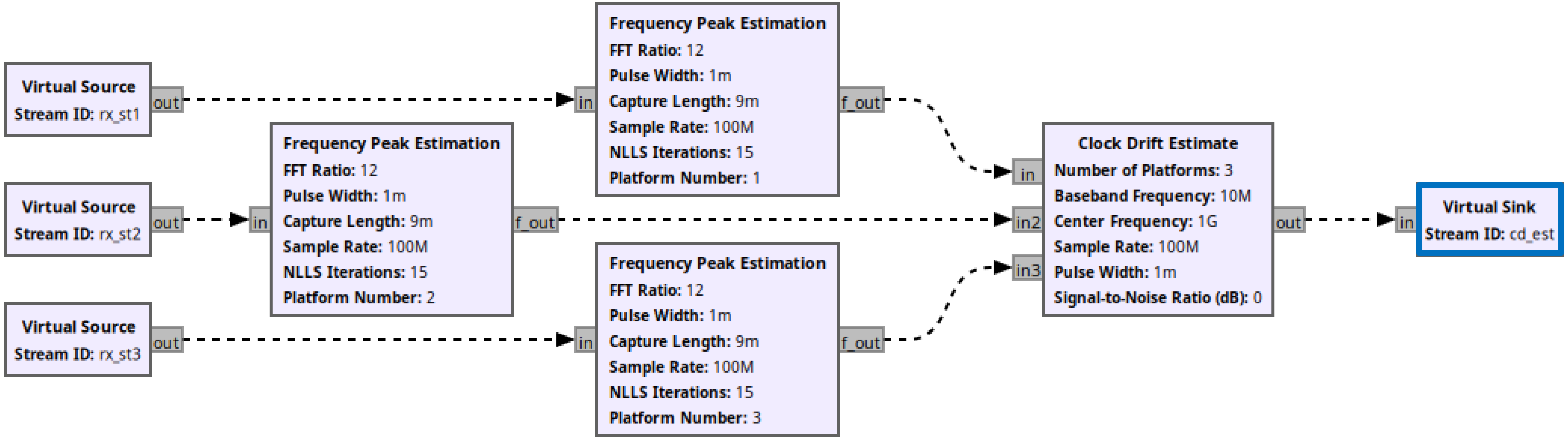
- **UHD: ALL USRP** Block



gr-harmonia: Blocks and Features

Clock Drift Estimation

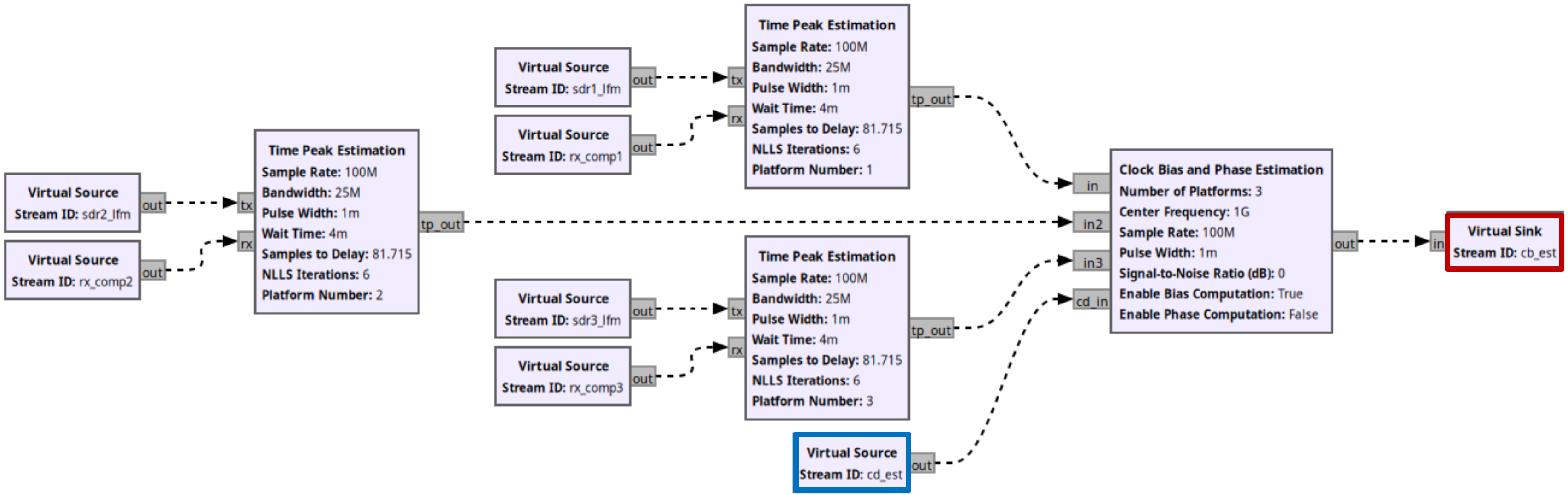
- **Frequency Peak Estimation** and **Clock Drift Estimation** Block



gr-harmonia: Blocks and Features

Clock Bias and Carrier Phase Estimation

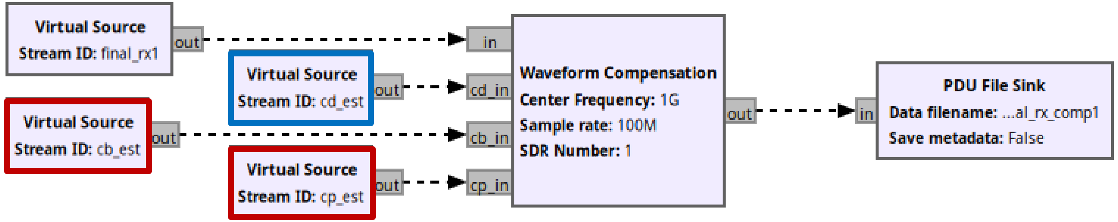
- **Time Peak Estimation** and **Clock Bias and Carrier Phase Estimation** Block



gr-harmonia: Blocks and Features

Waveform Compensation

- **Compensation** Block



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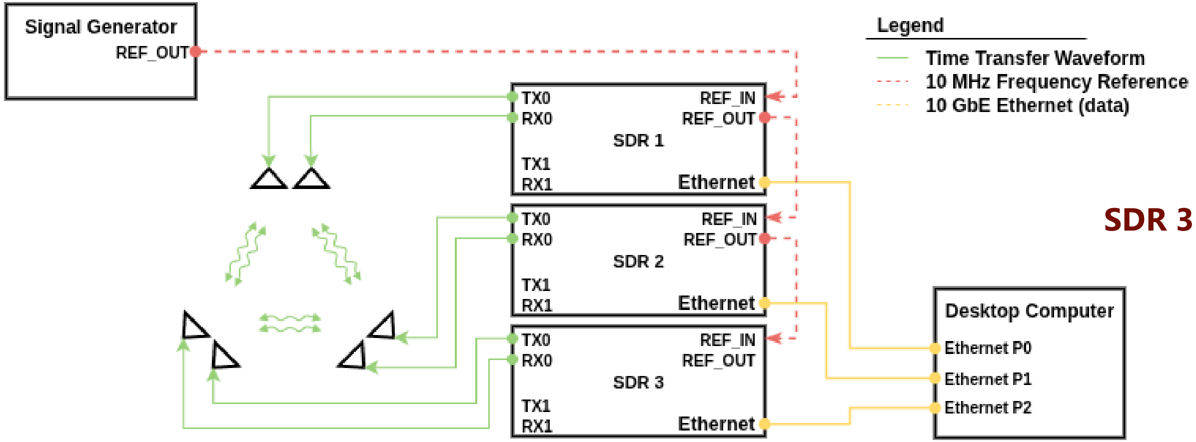
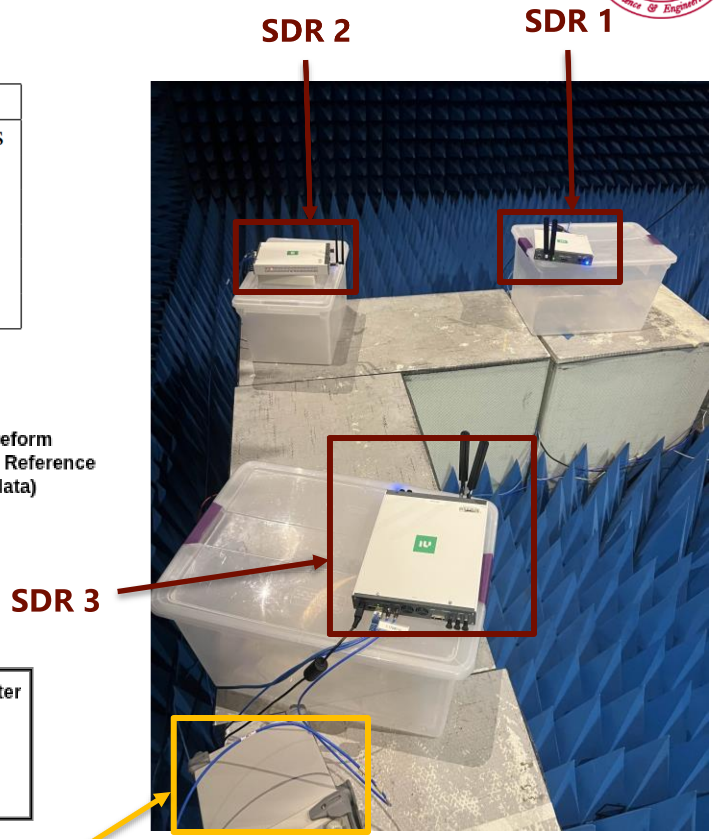
Experimental Validation

Configuration

- Over-the-air experiments
- Ettus X310s with UBX 160 daughterboards
- Monopole antennas

Parameters	Value
Sample rate	100 MS/s
Center frequency	1 GHz
Baseband frequency	10 MHz
Bandwidth	25 MHz
Pulse width	1 ms
Capture length	9 ms





Signal Generator

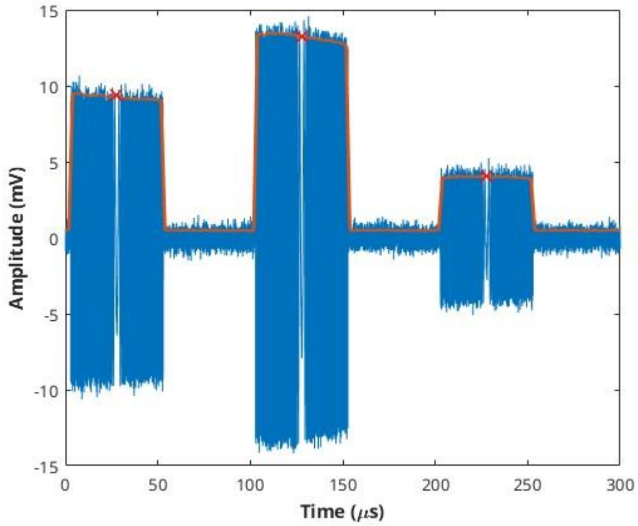
Experimental Validation

Experimental Results

- External 10 MHz reference clock
  - Measure the performance of clock drift

SDR	Standard Deviation
2	7.17 ppb
3	6.77 ppb

Coherent Gain: 98.62%



- Internal reference clock and external reference clock assuming ideal clock drift estimation
  - Measure the performance of clock bias and carrier phase

Test	Dev 1 → Dev 2	Dev 1 → Dev 3	Dev 2 → Dev 3
	Standard Deviation		
Internal Clock	26.18 cm (0.87 ns)	45.73 cm (1.52 ns)	61.57 cm (2.05 ns)
External Clock	3.22 cm (0.10 ns)	3.92 cm (0.13 ns)	4.48 cm (0.15 ns)

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Conclusion and Future Work

Conclusion

- Implemented a distributed SDR synchronization module
- Characterized clock drift, clock bias, and carrier phase estimation
- Reduce clock drift to ~7 ppb
- Achieved a maximum of 98.62% gain and reduced clock bias to 3-5 cm with an external 10 MHz reference

Future Work

- Improve documentation of module
- Add UHD block for multiple host implementations
- Incorporate SNR estimation, weighted least squares (WLS) estimation, and Kalman filtering to improve module performance

Thank you!

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