Reciprocity-based DMISO in dynamic multipath environments

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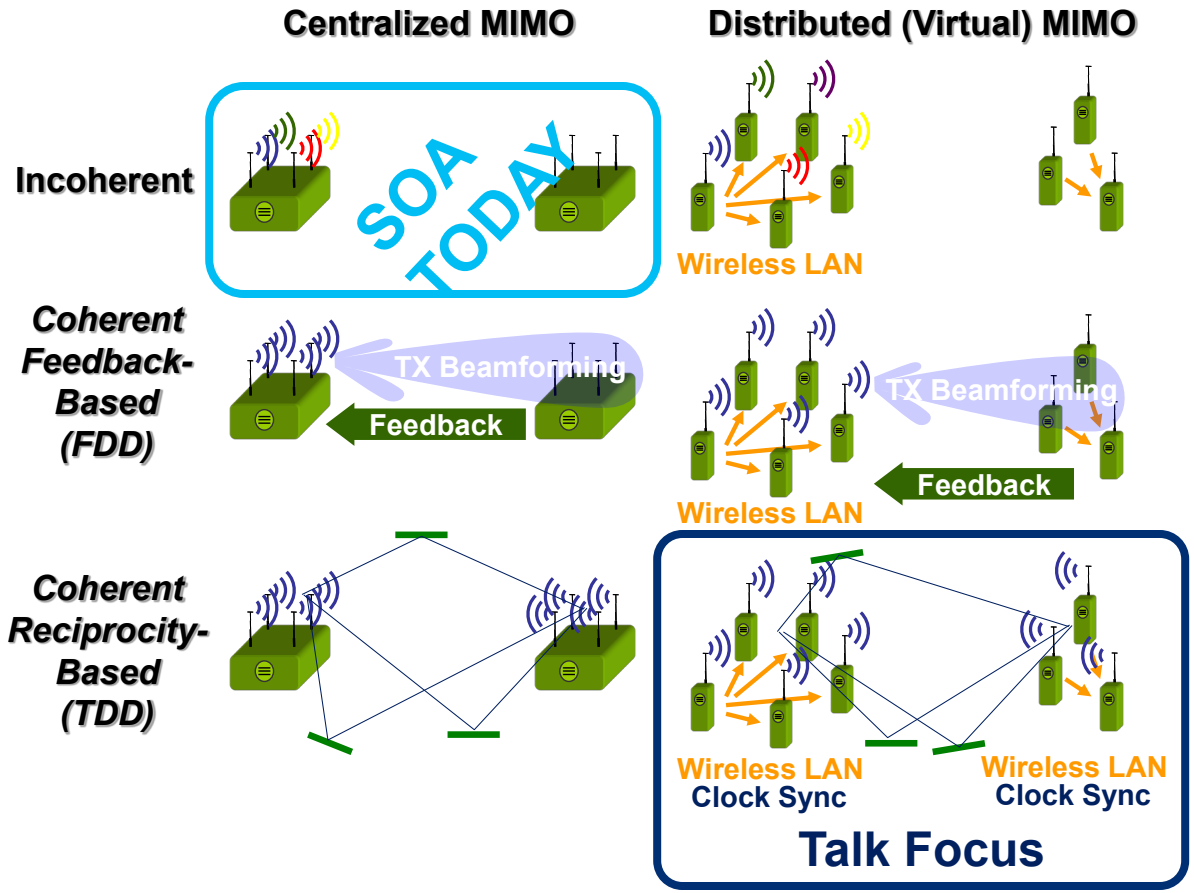
Introduction

Motivation for Coherent Distributed Communications

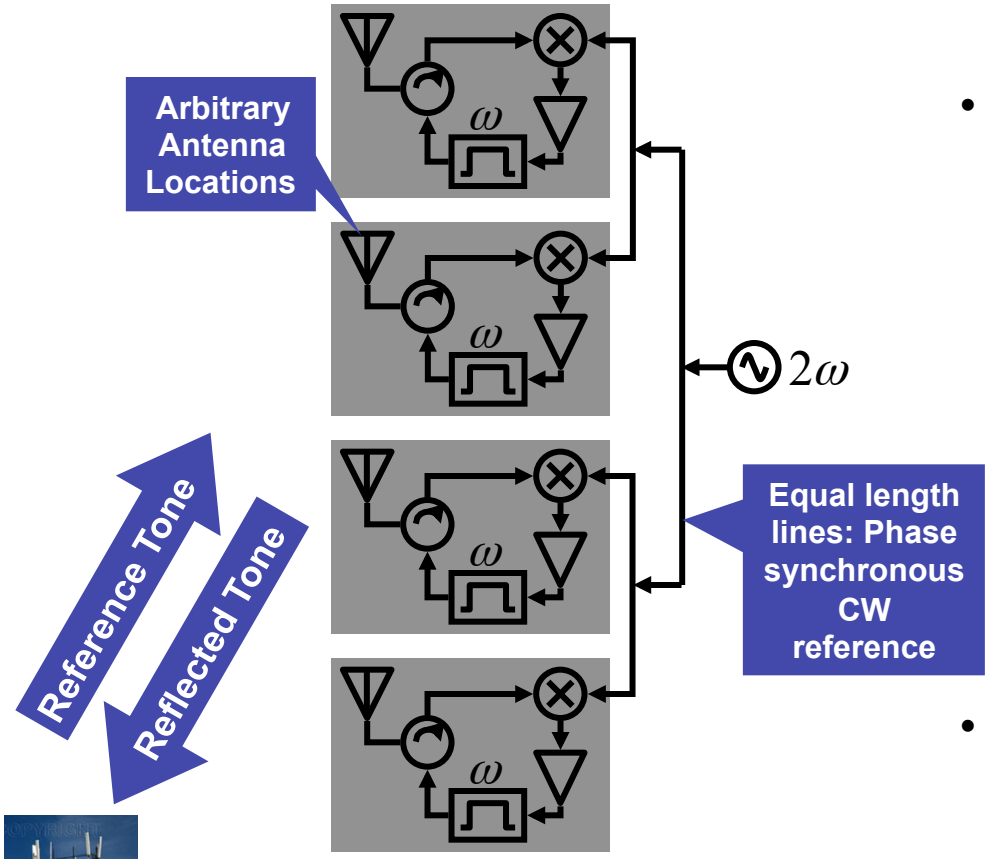
- **Why Coherent Distributed MIMO?**
  - Longer ranges and/or higher data rates
  - Simple augmentation by adding more nodes, graceful degradation with node loss
  - Smaller size, weight and power and cost radios
  - Interference resistant
- **Why Now?**
  - $1.2T/year cellular market has developed cheap, highly capable radio ICs.
  - Logisitcs enabled by proliferation of small-SWaP SDR radios

MIMO Communications Taxonomy



Pon Arrays 101

Retrodirective array with arbitrary antenna element locations.

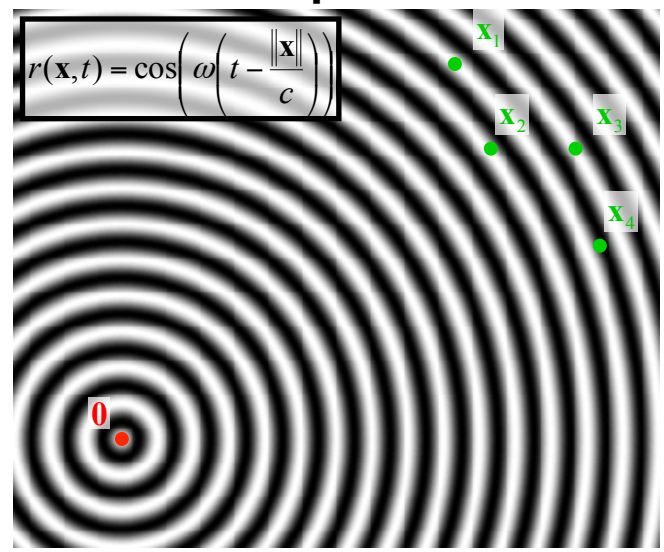


Classic Pon Array

- Mixing by twice the carrier frequency does signal conjugation.
- Signal conjugation is the narrow-band equivalent of time reversal.

Classic (1964) Pon Array

- CW reference produces:



- Mixing by twice the carrier conjugates signal.

$$\cos\left(\omega\left(t - \frac{\|\mathbf{x}_n\|}{c}\right)\right)\cos(2\omega t) = \frac{1}{2}\cos\left(\omega\left(t + \frac{\|\mathbf{x}_n\|}{c}\right)\right) + \overbrace{\frac{1}{2}\cos\left(\omega\left(3t - \frac{\|\mathbf{x}_n\|}{c}\right)\right)}^{\text{filtered out}}$$

- Reflected signals add up coherently at reference

$$v(\mathbf{x},t) = \sum_{n=1}^{N_p}\cos\left(\omega\left(t + \frac{\|\mathbf{x}_n\|}{c} - \frac{\|\mathbf{x}-\mathbf{x}_n\|}{c}\right)\right)$$

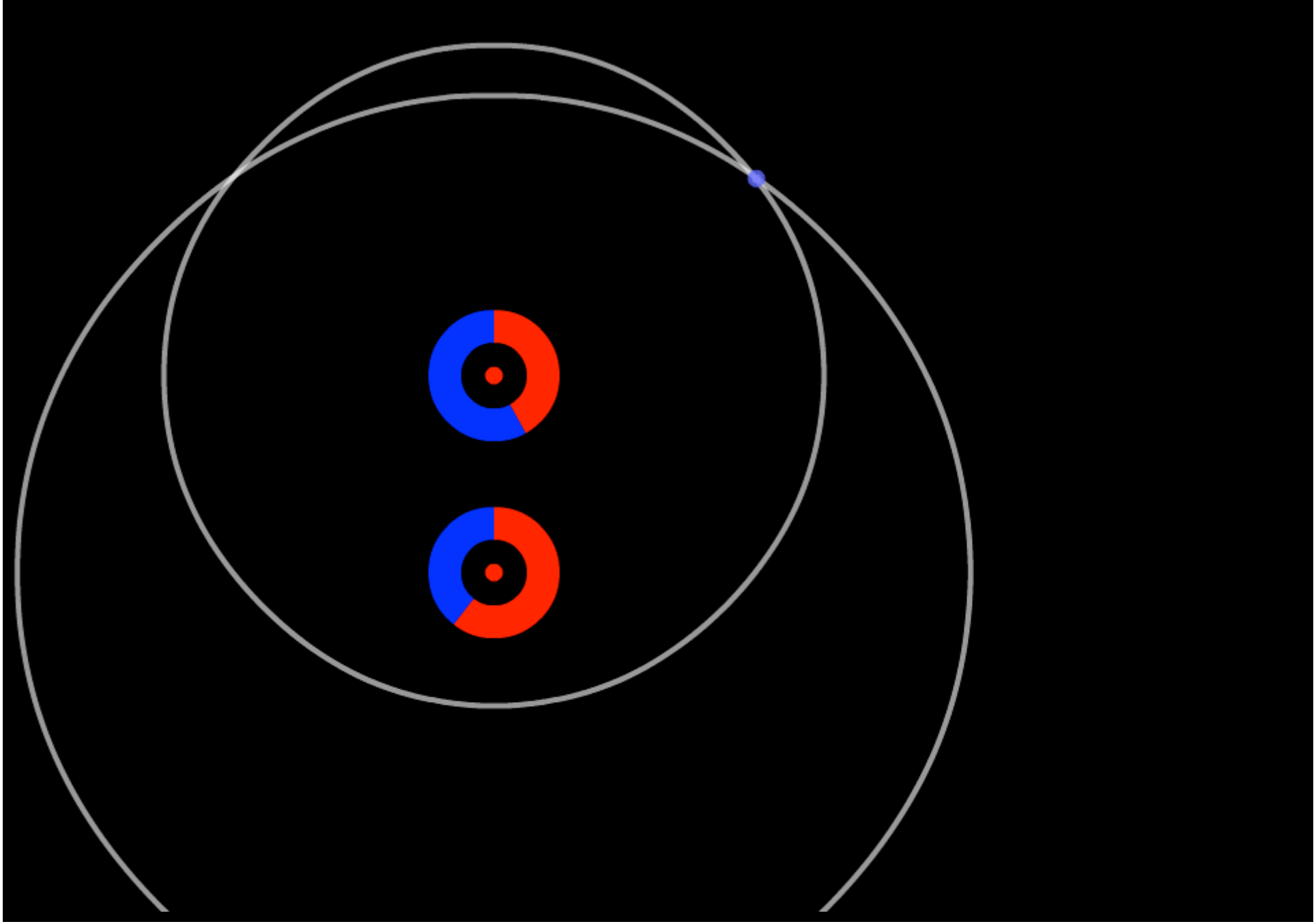
$$\boxed{v(\mathbf{0},t) = N_p\cos(\omega t)}$$

Pon array limitations

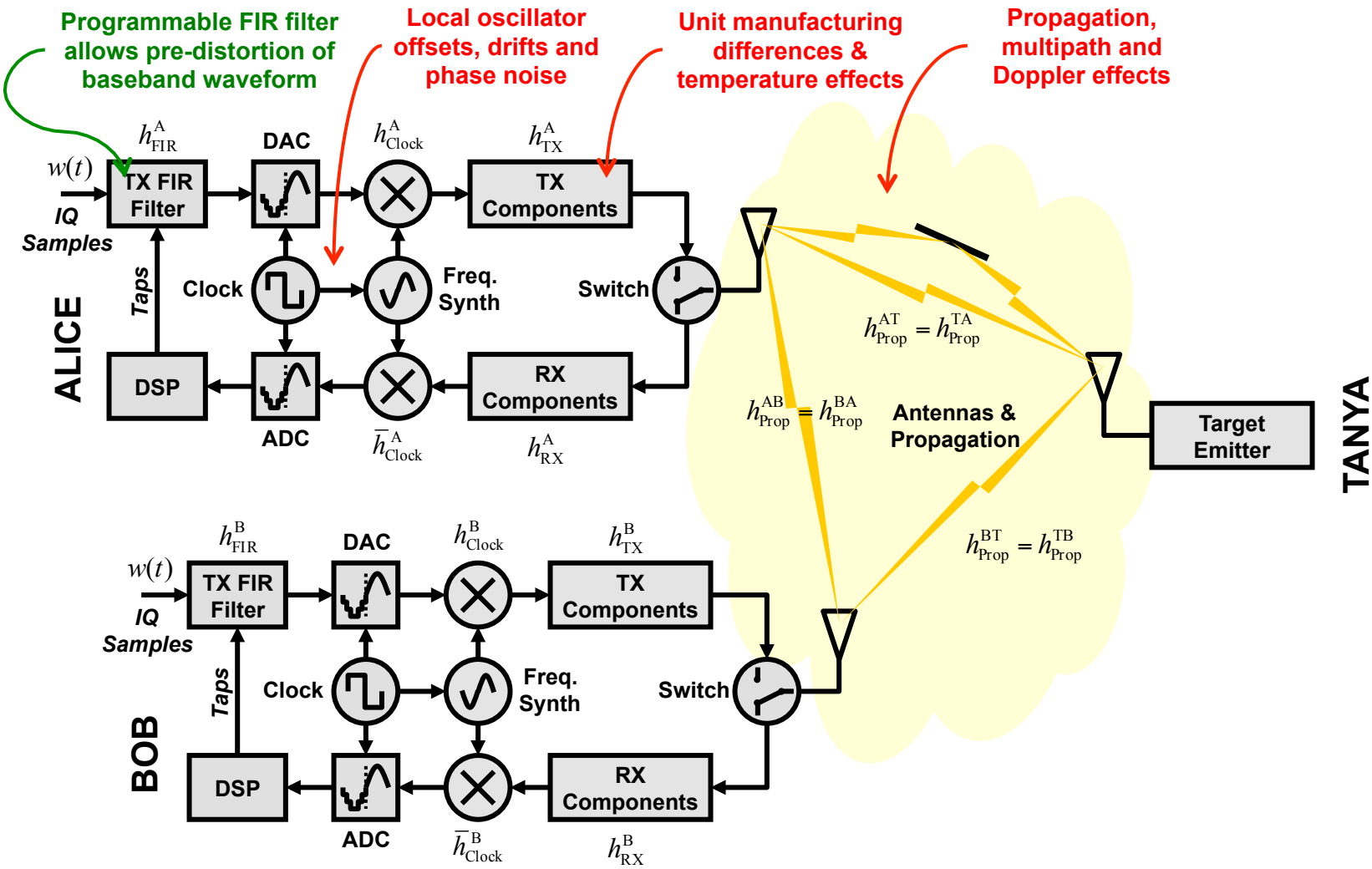
- **Not fully distributed:**
  - **Arbitrary phase center locations <u>but</u>**
  - **Common local oscillator required**
- **Retrodirectively beamformed signal is not arbitrary: it's the spectral inverse of what was received**
- **Beamforming is degraded by multipath**
- **Requires identical unit-to-unit hardware component delays**

Distributed Retrodirective Beamforming

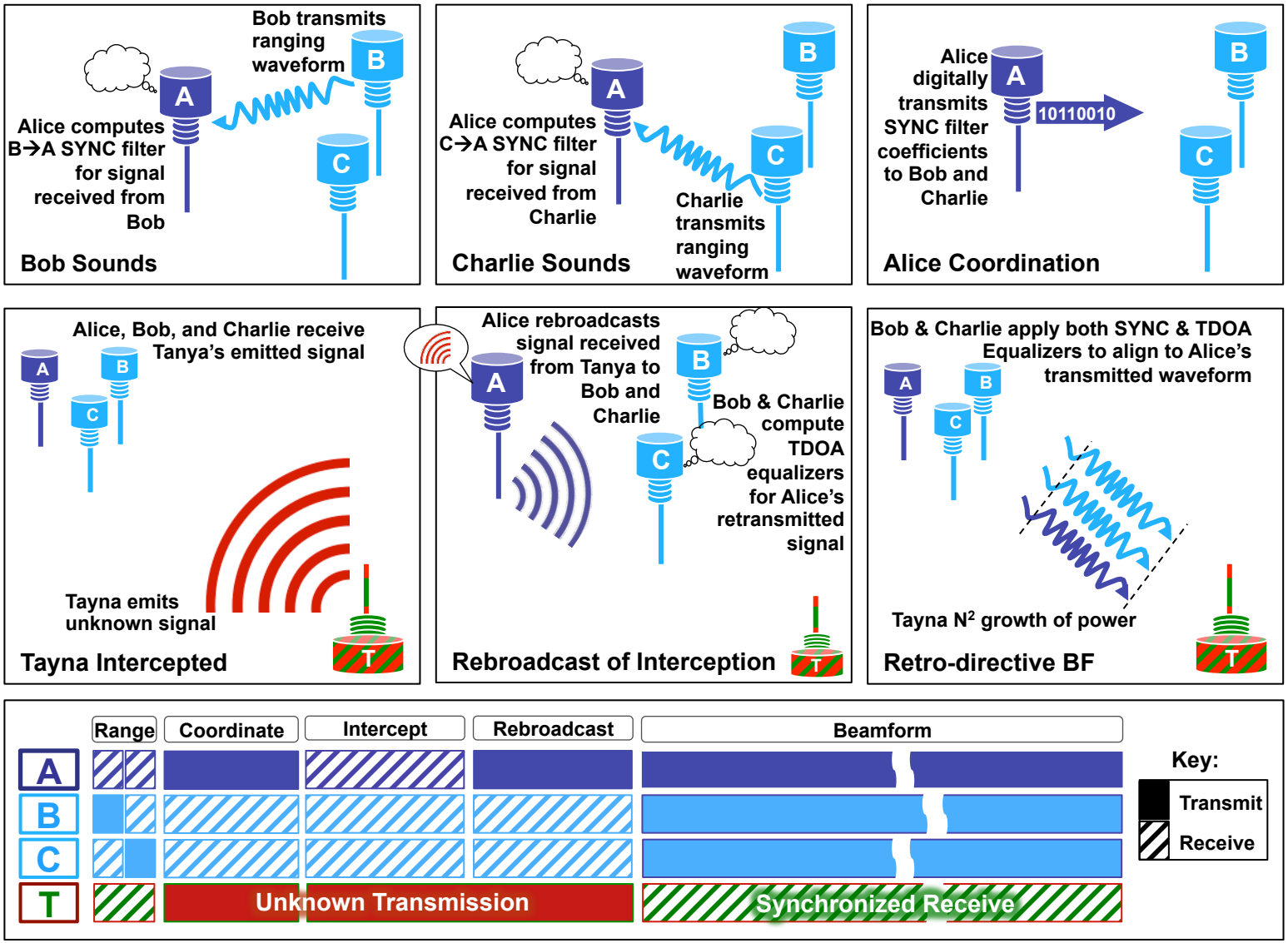
Retrodirection with stationary, single-path propagation



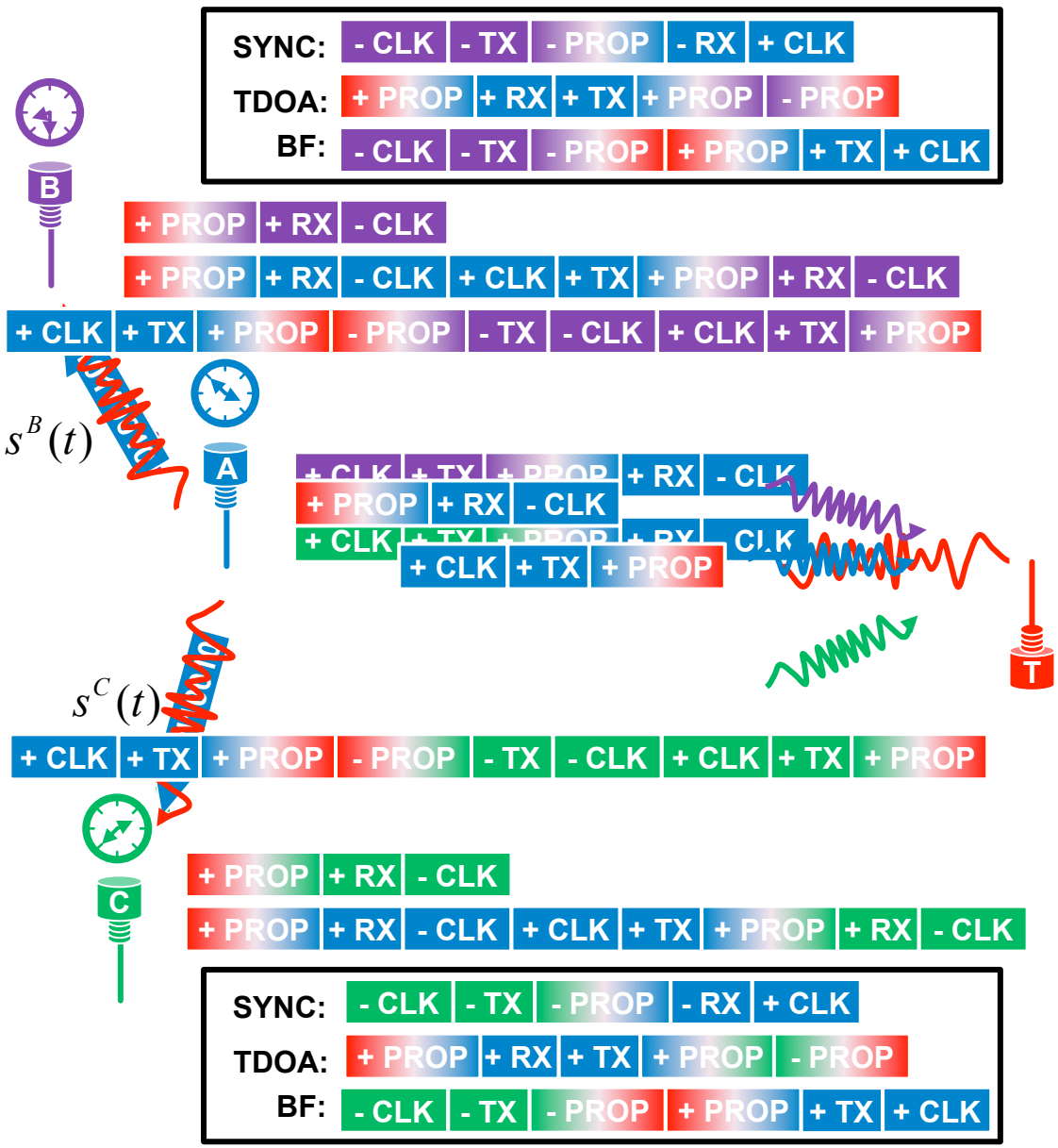
Linear time-invariant device and propagation modeling



Retrodirective Beamforming Cycle



Retrodirective Beamforming: Stationary Case



1. Bob and Charlie transmit known ranging waveforms to Alice
2. Alice estimates the channels and computes "SYNC" equalizers for these

$$H^{BA}_{Chan} = H^{B}_{Clock} H^{B}_{TX} H^{BA}_{Prop} H^{A}_{RX} \overline{H}^{A}_{Clock}$$
$$H^{CA}_{Chan} = H^{C}_{Clock} H^{C}_{TX} H^{CA}_{Prop} H^{A}_{RX} \overline{H}^{A}_{Clock}$$
$$H^{BA}_{SYNC} = 1/H^{BA}_{Chan} \qquad H^{CA}_{SYNC} = 1/H^{CA}_{Chan}$$

3. Alice broadcasts the equalizers to Bob and Charlie
4. Tanya transmits unknown waveform to Alice, Bob and Charlie
5. Alice rebroadcasts Tayna's waveform to Bob and Charlie
6. Bob and Charlie compute the "TDOA" filter which, when applied to the signal received directly from Tayna, produces the rebroadcast signal seen from Alice

$$H^{TB}_{TDOA} = H^{TA}_{Chan} H^{AB}_{Chan} / H^{TB}_{Chan} \qquad H^{TC}_{TDOA} = H^{TA}_{Chan} H^{AC}_{Chan} / H^{TC}_{Chan}$$

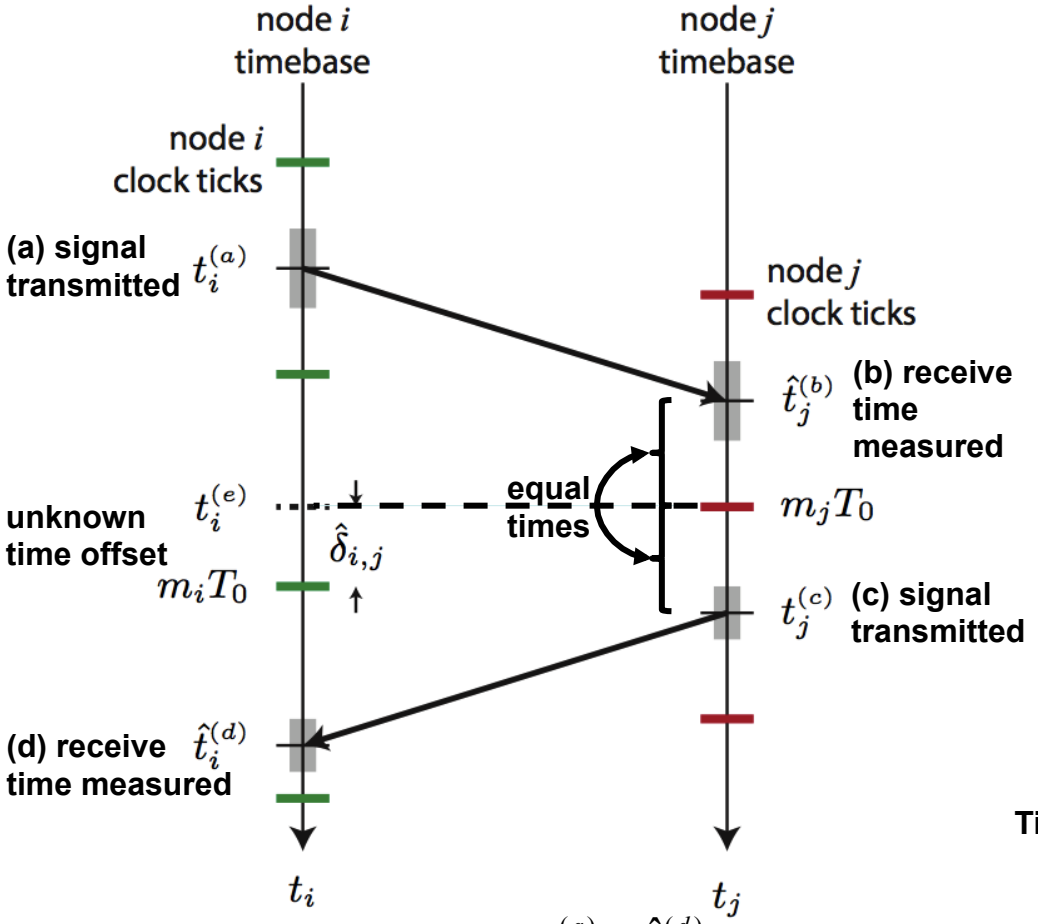
7. Bob and Charlie compute "BF" filters as the products of their SYNC and TDOA filters.

$$H^{TB}_{BF} = H^{TA}_{Chan} H^{AB}_{Chan} / H^{TB}_{Chan} H^{BA}_{Chan} \qquad H^{TC}_{BF} = H^{TA}_{Chan} H^{AC}_{Chan} / H^{TC}_{Chan} H^{CA}_{Chan}$$

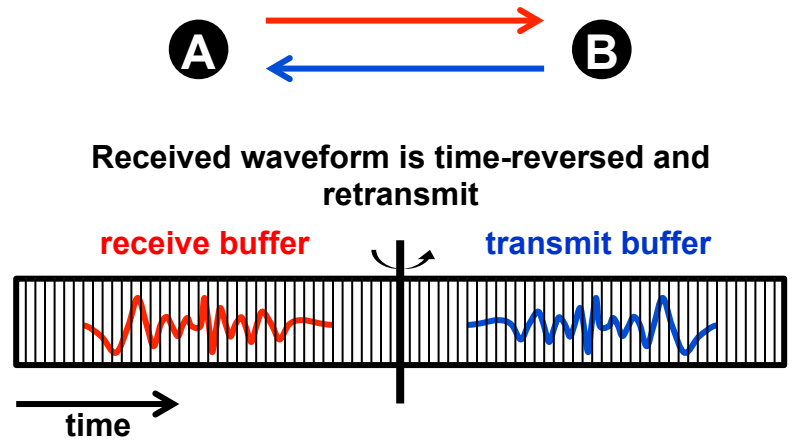
8. Alice, Bob and Charlie transmit a common signal to Tayna. Bob and Charlie precompensate using their BF filters. After propagation, the signals add constructively

$$H^{TB}_{BF} H^{BT}_{Chan} = H^{TA}_{Chan} H^{AB}_{Chan} H^{BT}_{Chan} / H^{TB}_{Chan} H^{BA}_{Chan} = H^{TA}_{Chan}$$
$$H^{TC}_{BF} H^{CT}_{Chan} = H^{TA}_{Chan} H^{AC}_{Chan} H^{CT}_{Chan} / H^{TC}_{Chan} H^{CA}_{Chan} = H^{TA}_{Chan}$$

Similarity with other techniques



(e) offset estimated $\hat{\delta}_{i,j} = m_i T_0 - \dfrac{t_i^{(a)} + \hat{t}_i^{(d)}}{2}$



$$H_{\text{Chan}}^{\text{AB}} = H_{\text{Clock}}^{\text{A}} H_{\text{TX}}^{\text{A}} H_{\text{Prop}}^{\text{AB}} H_{\text{RX}}^{\text{B}} \overline{H}_{\text{Clock}}^{\text{B}} \qquad H_{\text{Chan}}^{\text{BA}} = H_{\text{Clock}}^{\text{B}} H_{\text{TX}}^{\text{B}} H_{\text{Prop}}^{\text{BA}} H_{\text{RX}}^{\text{A}} \overline{H}_{\text{Clock}}^{\text{A}}$$

Aggregate frequency response:

$$H_{\text{TR-SYNC}}^{\text{BA}} = H_{\text{Chan}}^{\text{AB}}(-f) H_{\text{Chan}}^{\text{BA}}(f) = \left(H_{\text{Clock}}^{\text{B}}(f) \overline{H}_{\text{Clock}}^{\text{A}}(f)\right)^2 \underbrace{H_{\text{Other}}(f)}_{\text{symmetric for identical electronics}}$$

Offset estimate: $\hat{\delta}_{A,B} = \dfrac{1}{2} \arg\max_t \left(h_{TR-SYNC}^{AB}(t)\right)$

Time-reversal based retrodirective beamforming:

$$H_{\text{TR-BF}}^{\text{TB}}(f) = H_{\text{Chan}}^{\text{TA}}(f) H_{\text{Chan}}^{\text{AB}}(f) H_{\text{Chan}}^{\text{TB}}(-f) H_{\text{Chan}}^{\text{BA}}(-f)$$

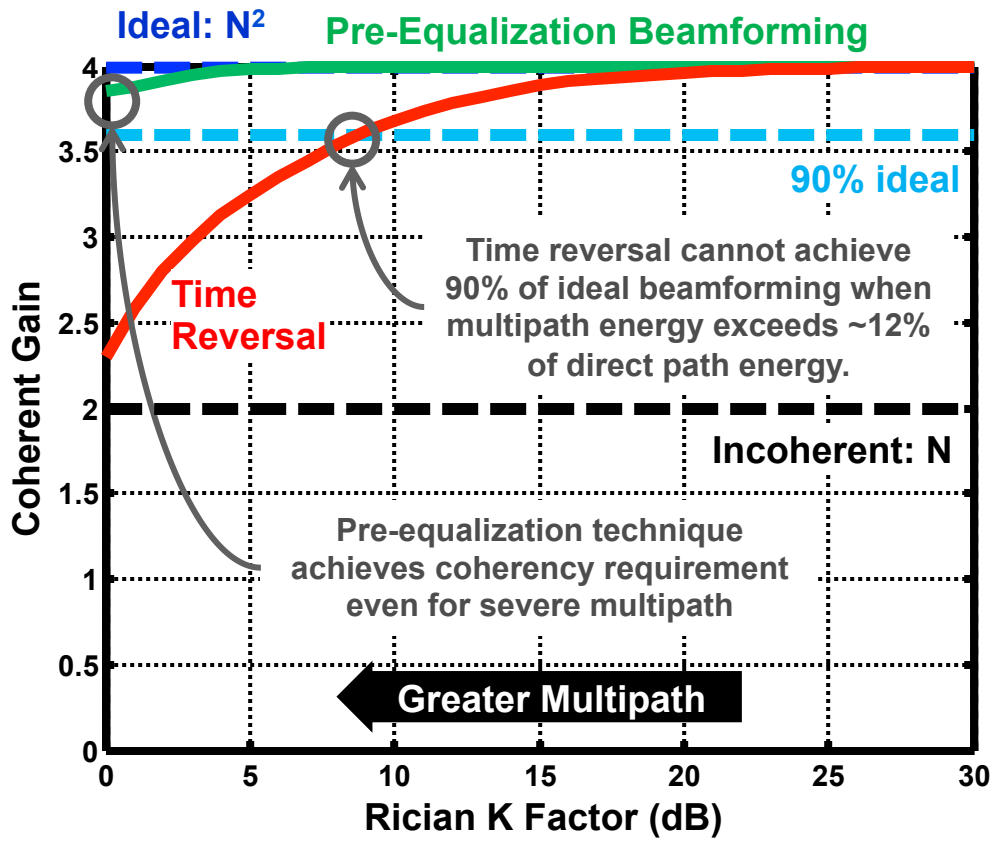
Our retrodirective beamforming technique:

$$H_{\text{BF}}^{\text{TB}}(f) = \frac{H_{\text{Chan}}^{\text{TA}}(f) H_{\text{Chan}}^{\text{AB}}(f)}{H_{\text{Chan}}^{\text{TB}}(f) H_{\text{Chan}}^{\text{BA}}(f)}$$

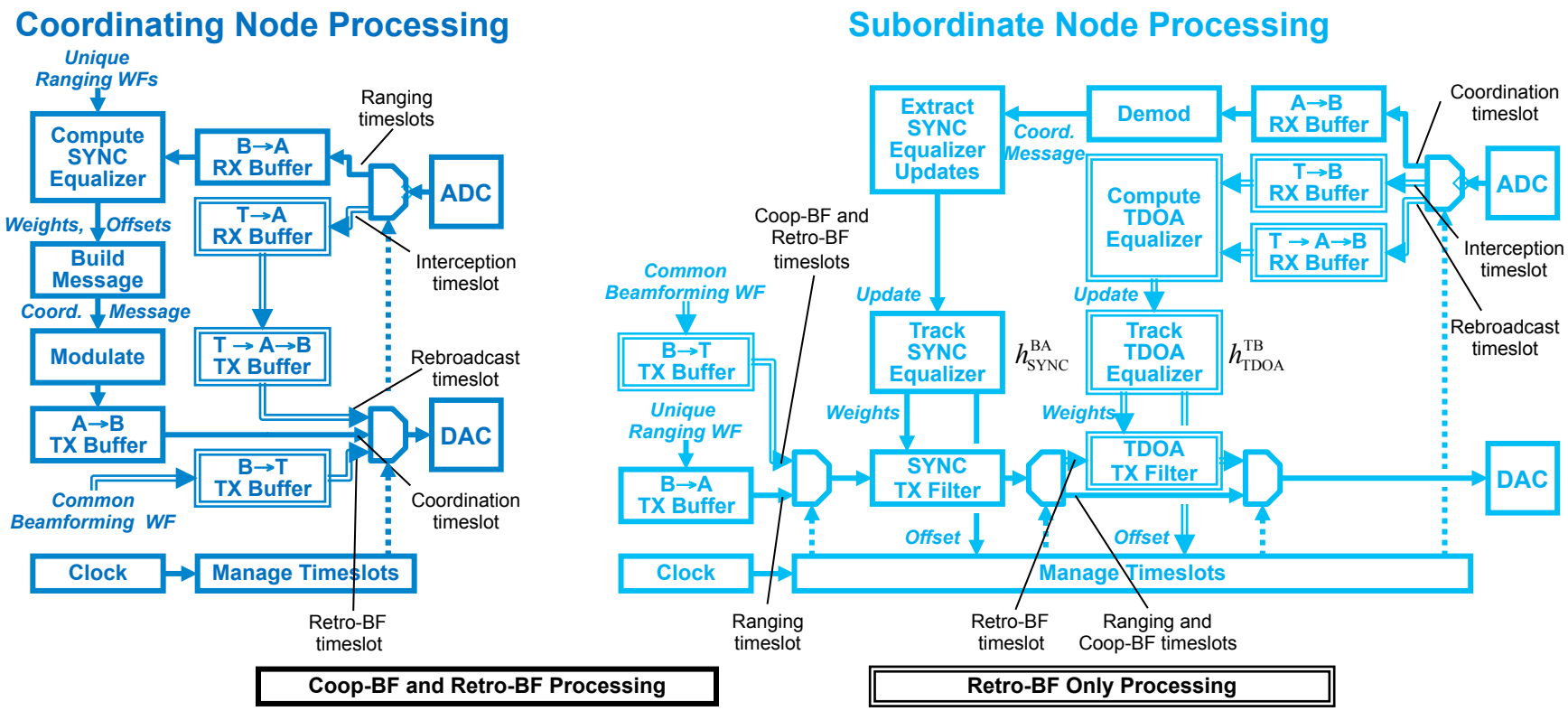
[1] D.R. Brown III and A.G. Klein. Timestamp-Free Network Synchronization with Random Pairwise Message Exchanges. Proceedings of the 39th International Conference on Acoustics, Speech, and Signal Processing (ICASSP2014). Florence, Italy, May 4-9, 2014.

[2] David F. Smith, Anis Husain U.S. Patent 8743976 Techniques and systems for communications based on time reversal pre-coding. Filed: September 3, 2010 Issued: June 3, 2014

Simulation results with Rician fading channels



Retrodirective Beamforming Block Diagram



Open Questions

- What approximations to the zero-forcing equalizer filters are suitable for
  - Channel estimation errors
  - Finite impulse response filters with constrained numbers of taps
  - Low peak-to-average power ratio (PAPR) waveforms
- Can we generalize this technique beyond the star topology presented here?
- How can we make use of measurements between subordinate nodes (Bob ⇔ Charlie)?
- Is there a generalization to the MIMO case?
- How can feedback-based nullforming be integrated with retrodirective beamforming?
- How can dynamic channels be parsimoniously modeled?
- what filters are suitable for predicting these?
- Are there a theoretical advantages of retrodirective beamforming over feedback-based beamforming?
- What are the fundamental limits of retrodirective beamforming performance as a function of wavelength, clock and motion and update rate?