Reciprocity-based DMISO in dynamic multipath environments

P. Bidigare
18 August 2014
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.
  - Logistics enabled by proliferation of small-SWaP SDR radios

### MIMO Communications Taxonomy

- **Centralized MIMO**
- **Distributed (Virtual) MIMO**

#### Incoherent

#### Coherent Feedback-Based (FDD)

#### Coherent Reciprocity-Based (TDD)

**Talk Focus**
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:
  
  \[
  r(x,t) = \cos(\omega(t - \frac{|x_n|}{c}))
  \]

- Mixing by twice the carrier conjugates signal.

\[
\cos(\omega(t - |x_n|/c))\cos(2\omega t) = \frac{1}{2}\cos\left(\omega\left(t + \frac{|x_n|}{c}\right)\right) + \frac{1}{2}\cos\left(\omega\left(3t - \frac{|x_n|}{c}\right)\right)
\]

- Reflected signals add up coherently at reference

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

\[
v(0,t) = N_p \cos(\omega t)
\]
Pon array limitations

- Not fully distributed:
  - Arbitrary phase center locations but
  - 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

Programmable FIR filter allows pre-distortion of baseband waveform

Local oscillator offsets, drifts and phase noise

Unit manufacturing differences & temperature effects

Propagation, multipath and Doppler effects

Propagator: Antennas & Propagation

Programmable FIR filter: allows pre-distortion of baseband waveform

Local oscillator offsets, drifts and phase noise

Unit manufacturing differences & temperature effects

Propagation, multipath and Doppler effects

Propagator: Antennas & Propagation

Linear time-invariant device and propagation modeling
Retrodirective Beamforming Cycle

Alice digitally transmits SYNC filter coefficients to Bob and Charlie.

Alice computes C→A SYNC filter for signal received from Charlie.

Charlie transmits ranging waveform.

Alice Coordination

Alice rebroadcasts signal received from Tanya to Bob and Charlie.

Bob & Charlie compute TDOA equalizers for Alice’s retransmitted signal.

Bob & Charlie apply both SYNC & TDOA Equalizers to align to Alice’s transmitted waveform.

Tayna N² growth of power

Retro-directive BF

Tayna Intercepted

Alice, Bob, and Charlie receive Tanya’s emitted signal.

Tayna emits unknown signal

Rebroadcast of Interception

Unknown Transmission

Synchronized Receive

Key:
- Transmit
- Receive

Retro-directive 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

   \[
   H_{BA}^{\text{sync}} = H_{BA}^{\text{Ch}} \quad H_{CA}^{\text{sync}} = 1/H_{CA}^{\text{Ch}}
   \]

3. **Alice** broadcasts the equalizers to **Bob and Charlie**

4. **Tanya** transmits unknown waveform to **Alice, Bob and Charlie**

5. **Alice** rebroadcasts **Tanya’s** waveform to **Bob and Charlie**

6. **Bob and Charlie** compute the “TDOA” filter which, when applied to the signal received directly from **Tanya**, produces the rebroadcast signal seen from **Alice**

   \[
   H_{\text{TDOA}}^{\text{BF}} = H_{\text{Ch}}^{\text{TA}} H_{\text{Ch}}^{\text{AB}} / H_{\text{Ch}}^{\text{TB}} H_{\text{Ch}}^{\text{CA}} / H_{\text{Ch}}^{\text{TC}}
   \]

7. **Bob and Charlie** compute “BF” filters as the products of their SYNC and TDOA filters.

   \[
   H_{\text{BF}}^{\text{BF}} = H_{\text{Ch}}^{\text{TA}} H_{\text{Ch}}^{\text{AB}} / H_{\text{Ch}}^{\text{TB}} H_{\text{Ch}}^{\text{BA}} / H_{\text{Ch}}^{\text{TC}} H_{\text{Ch}}^{\text{CA}}
   \]

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

   \[
   H_{\text{BF}}^{\text{BF}} H_{\text{BF}}^{\text{BF}} = H_{\text{Ch}}^{\text{TA}} H_{\text{Ch}}^{\text{AB}} / H_{\text{Ch}}^{\text{TB}} H_{\text{Ch}}^{\text{BA}} / H_{\text{Ch}}^{\text{TC}} H_{\text{Ch}}^{\text{CA}} = H_{\text{Ch}}^{\text{TA}}
   \]
Similarity with other techniques


Our retrodirective beamforming technique:

$$H_{\text{BF}}^T(f) = \frac{H_{\text{TA}}^T(f) H_{\text{Ch}}^A(f) H_{\text{Ch}}^A(f) H_{\text{TB}}^T(f) H_{\text{Ch}}^B(f) H_{\text{Ch}}^B(f)}{H_{\text{TA}}^T(f) H_{\text{TB}}^T(f) H_{\text{Ch}}^A(f) H_{\text{Ch}}^B(f)}$$
Time reversal cannot achieve 90% of ideal beamforming when multipath energy exceeds ~12% of direct path energy.

Pre-equalization technique achieves coherency requirement even for severe multipath.
Retrodirective Beamforming Block Diagram

Coordinating Node Processing

Subordinate Node Processing

Coop-BF and Retro-BF Processing

Retro-BF Only Processing
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
- 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?