DMIMO project: history, overview and a brief progress report

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Outline

- genesis of this project
  - a brief personal history
- other DMIMO-related work – a quick survey
- project goals
  - fundamentals, scalable algorithms
- experimental prototypes

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- genesis of this project
  - a brief personal history

Formal project details

Title: “Distributed coherence: fundamental building blocks, system concepts and experimental prototypes”

Sponsor: NSF

Dates: June 2013 – May 2016

Institutions: Iowa, WPI and UCSB

Personnel

PIs: Brown, Dasgupta, Madhow & Mudumbai

Students:

- Amy Kumar
- Ben Peiffer
- Faruk Gencel
- Radu David
- Rui Wang

Post-doc:

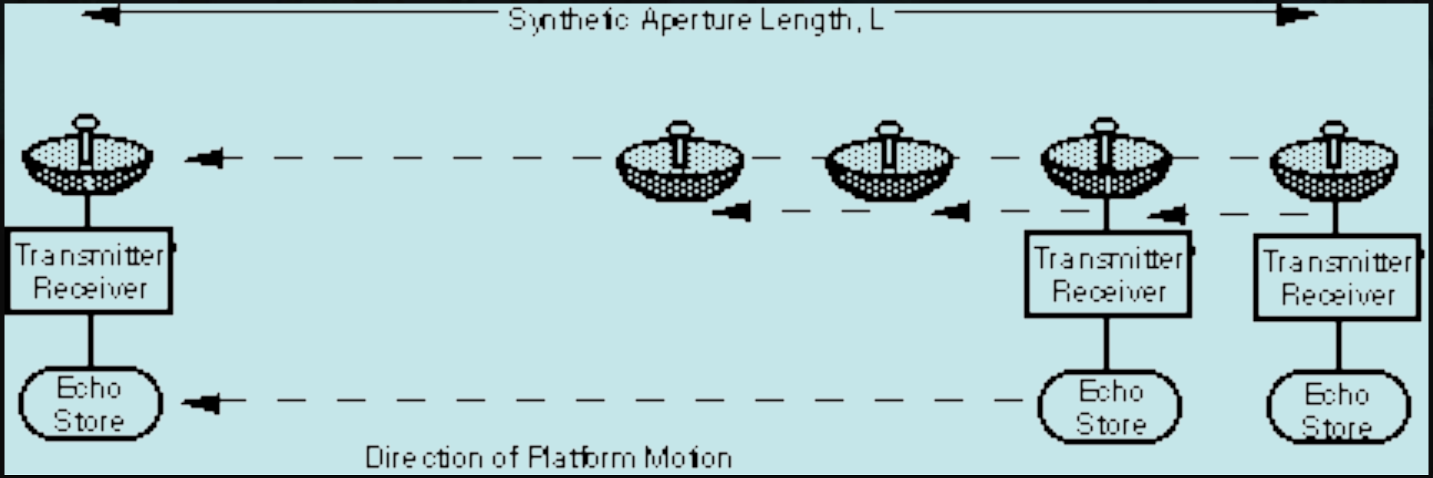
- Maryam Rasekh

A timeline

- precursors and prehistories
  - pre-2000
- distributed transmit beamforming
  - ~2002
  - CoMP, PrEW
- a surge of recent activity
  - ~2009
  - “Mega-MIMO”, “AirSync”, “pCell”

DMIMO in the olden days

- Radio-astronomy
  - VLA (New Mexico)
- Synthetic aperture radar



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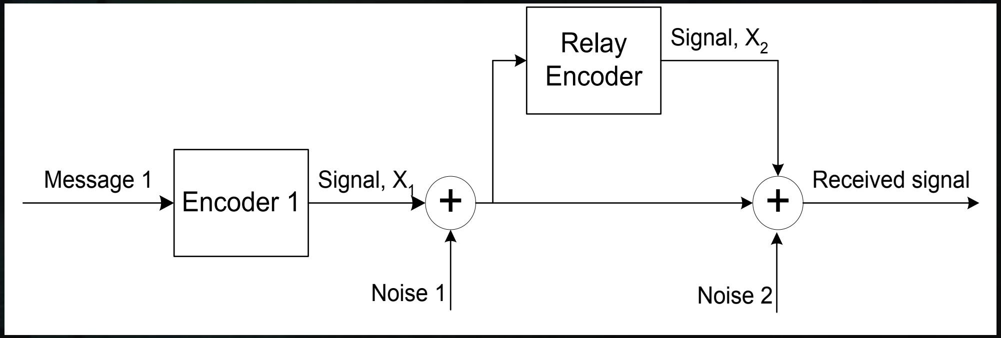
Distributed arrays in theory

- Cooperative diversity
  - [Erkip et al, 1998]
- Network coding
- Multi-user info theory
- …



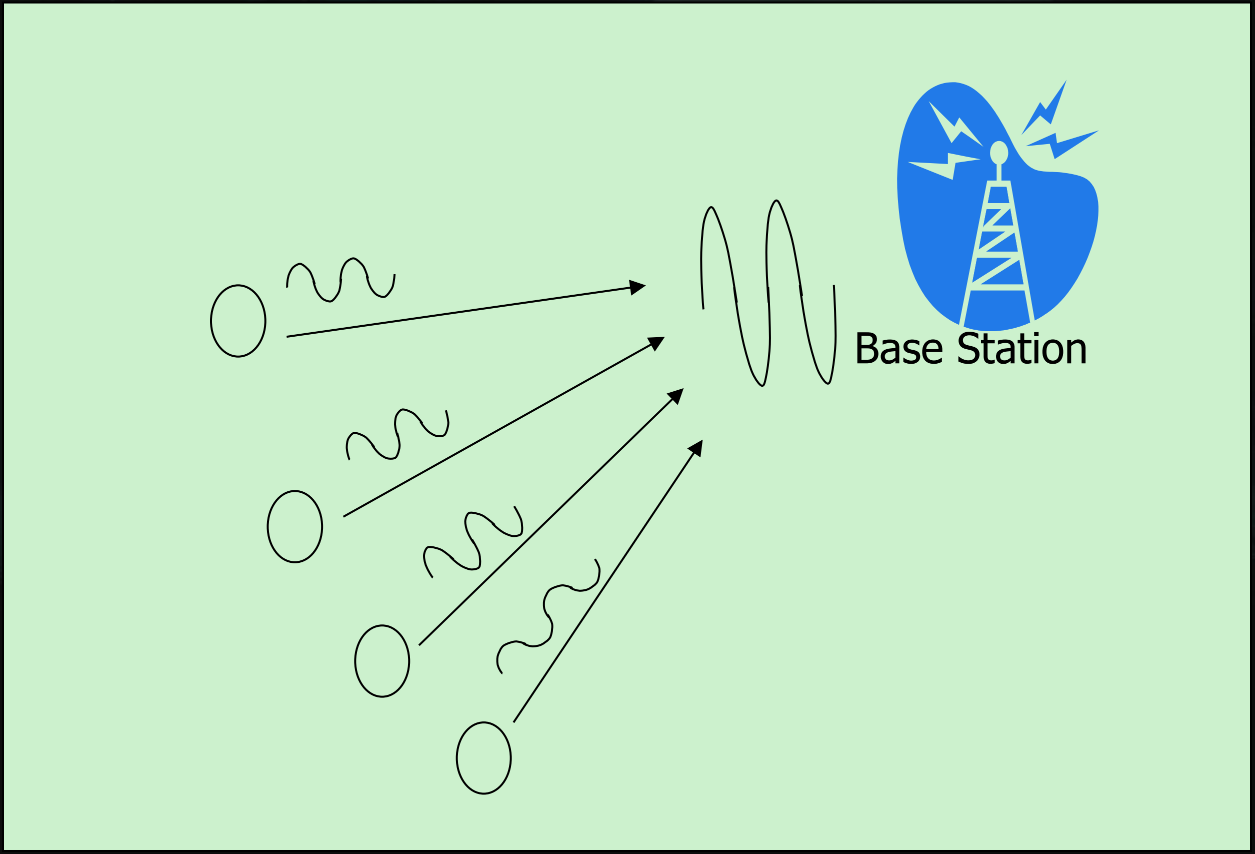
Baseband model ➔ implicit assumption of perfect synchronization

The synchronization challenge

Centralized	Distributed	Implication
All antennas driven by the same RF oscillator	Carrier signals from separate oscillators	Non-zero frequency offsets between nodes, and unknown phase drifts
Exploit array geometry for beamsteering	No regular array geometry for ad-hoc wireless networks	Need channel feedback for beamsteering

Distributed transmit beamforming

- simplest and easiest DMIMO scheme



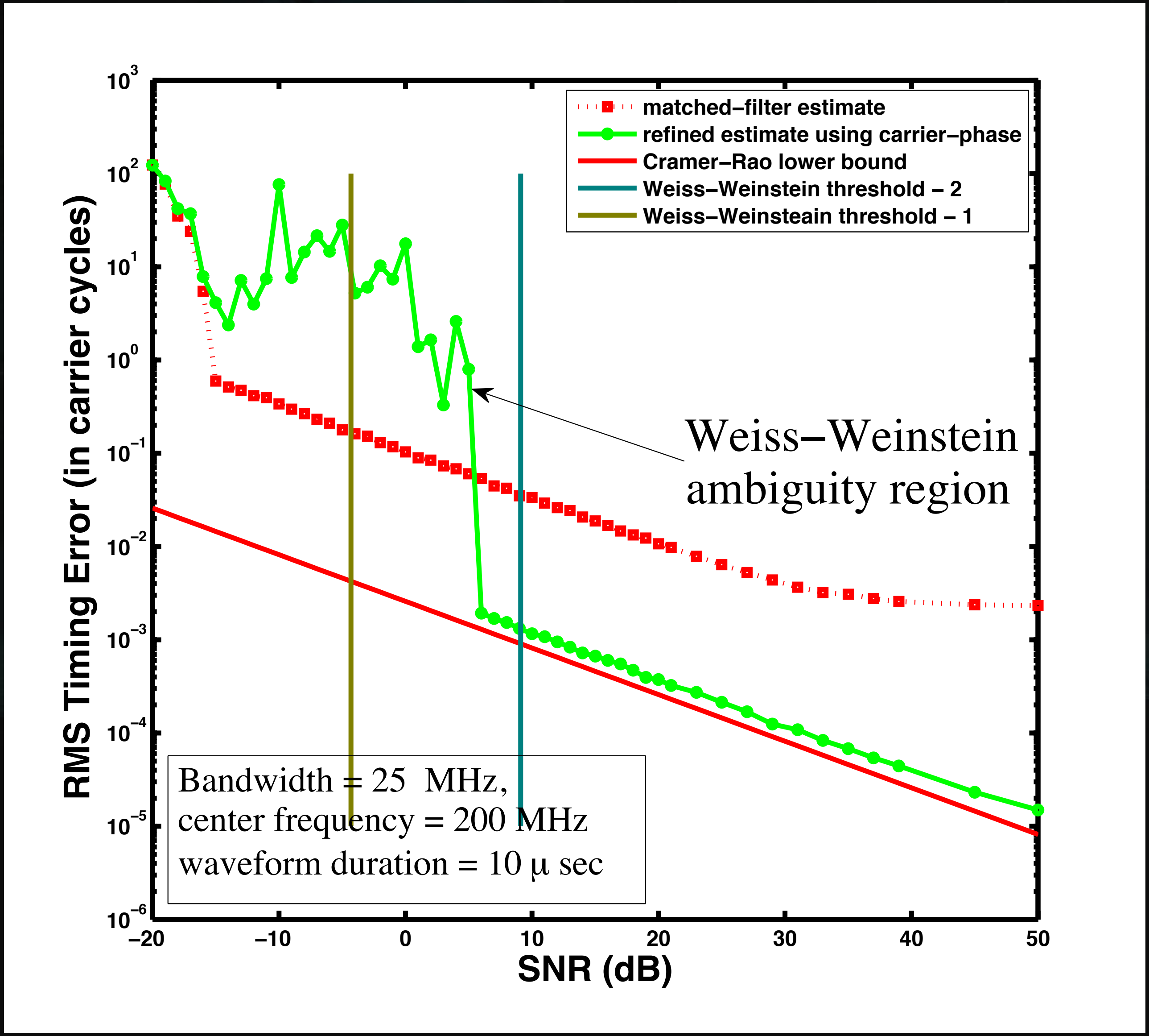
Lessons from PrEW

1. state-of-the-art in high-end oscillators is shockingly good
   – sufficient to sustain coherent tx for 10s of secs

2. oscillator drifts can be effectively predicted and tracked using Kalman filter-like tools
   – assuming we avoid phase-unwrapping issues

3. very high-precision time-of-flight estimation with reasonable complexity

achieving the Weiss-Weinstein bound



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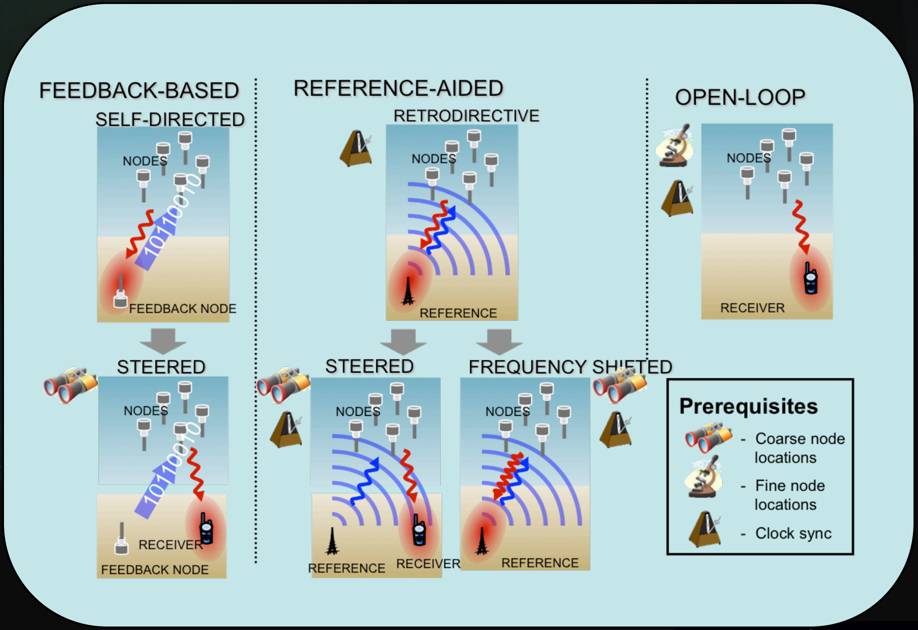
Key takeaway

Synchronization of RF signals for coherent transmission of eminently feasible

→ Dream bigger!



Concept of DMIMO

Null location

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- <u>other DMIMO-related work – a quick survey</u>

Cooperative Multipoint (CoMP)

"Coordinated multipoint: Concepts, performance, and field trial results" *Communications Magazine, IEEE* , vol.49, no.2, pp.102-111, February 2011

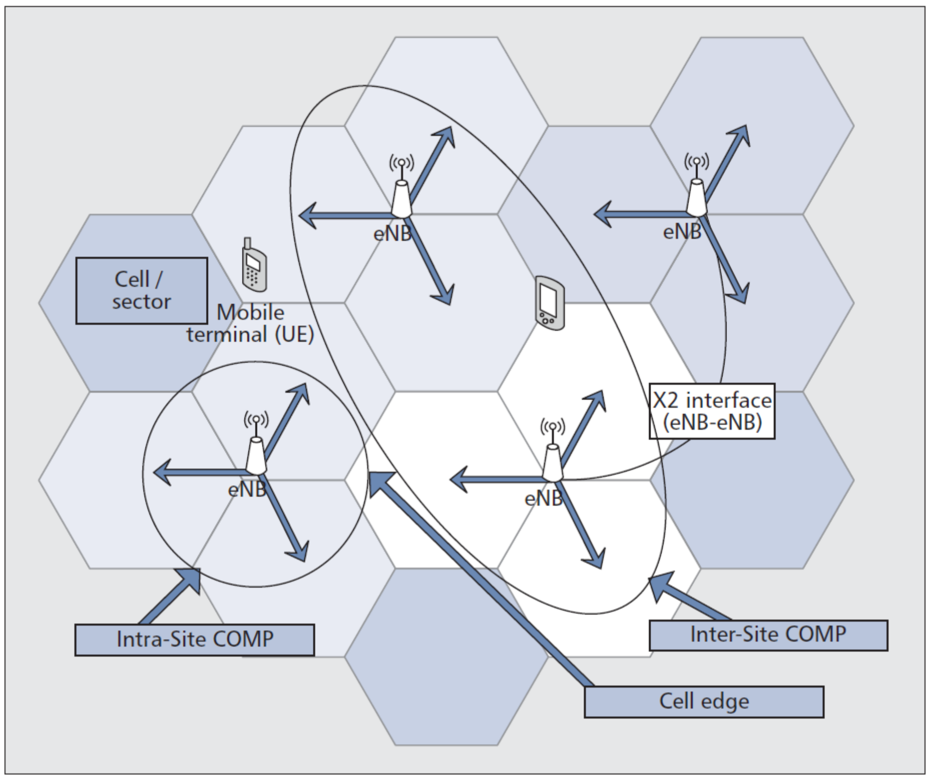
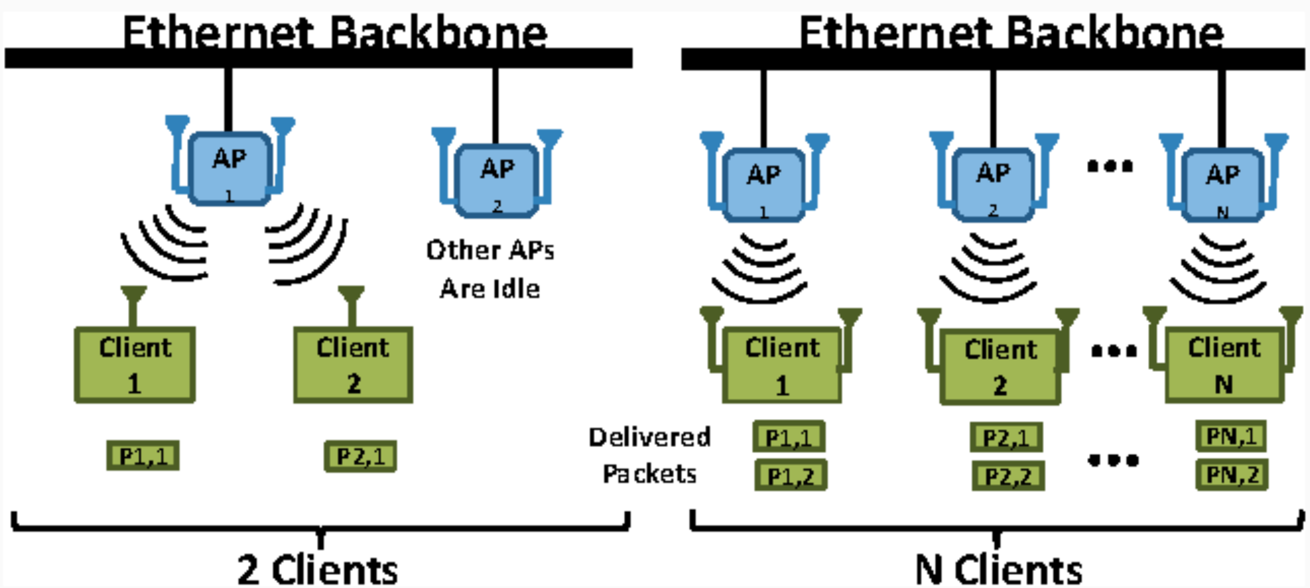


Figure 1. *Base station cooperation: intersite and intrasite COMP.*

"Joint Multiuser Beamforming" aka "MegaMMO"

Rahul, H., S. Kumar, and D. Katabi. "MegaMIMO: scaling wireless capacity with user demands." *ACM SIGCOMM*. 2012.

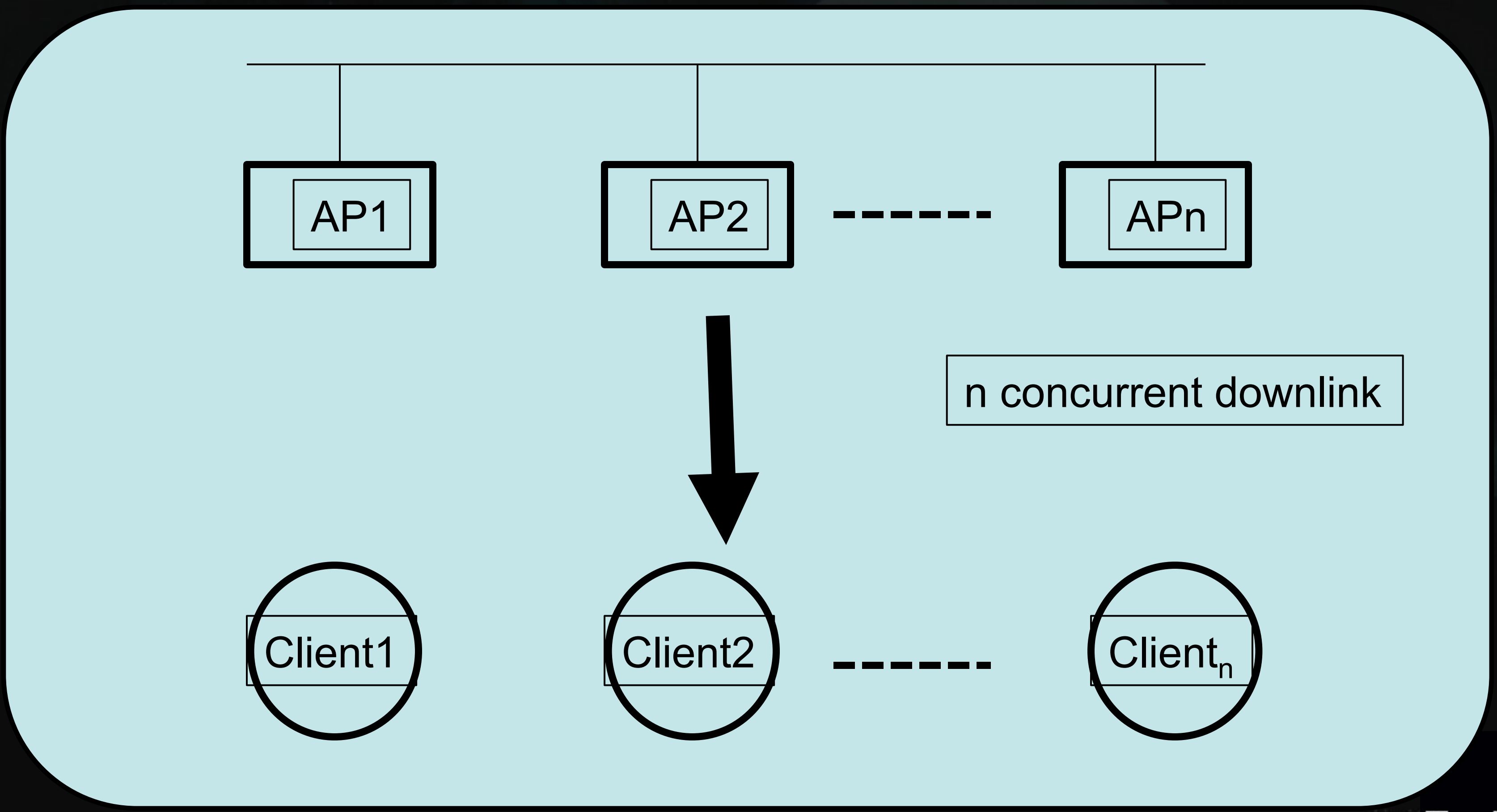


(a) 1 transmission for each antenna on a *single* AP

(b)1 transmission for each antenna on *all APs*

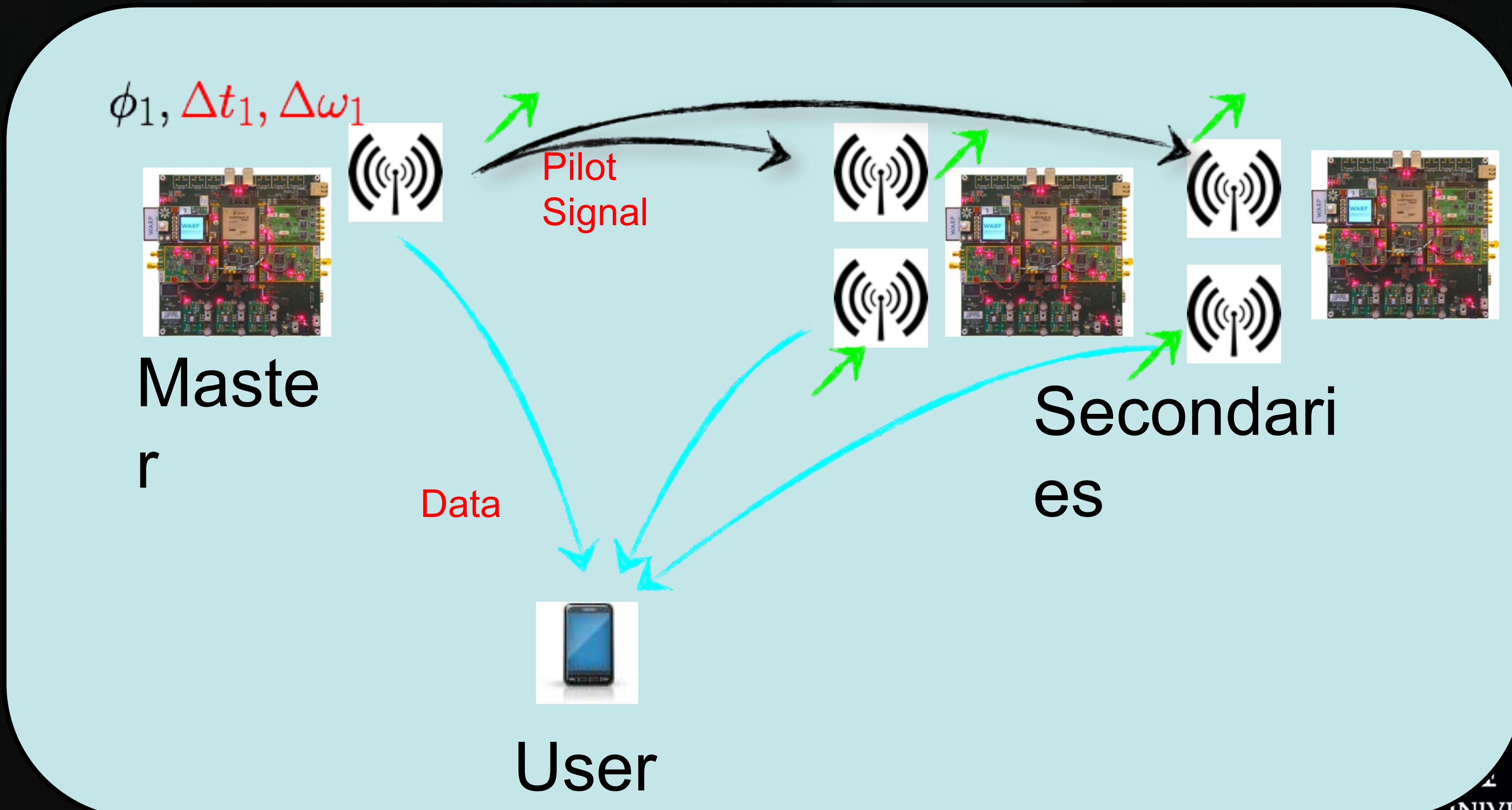
"Multi-point to Multi-point MIMO"

Yun, Sangki, Lili Qiu, and Apurv Bhartia. "Multi-point to Multi-point MIMO in Wireless LANs", INFOCOM 2013



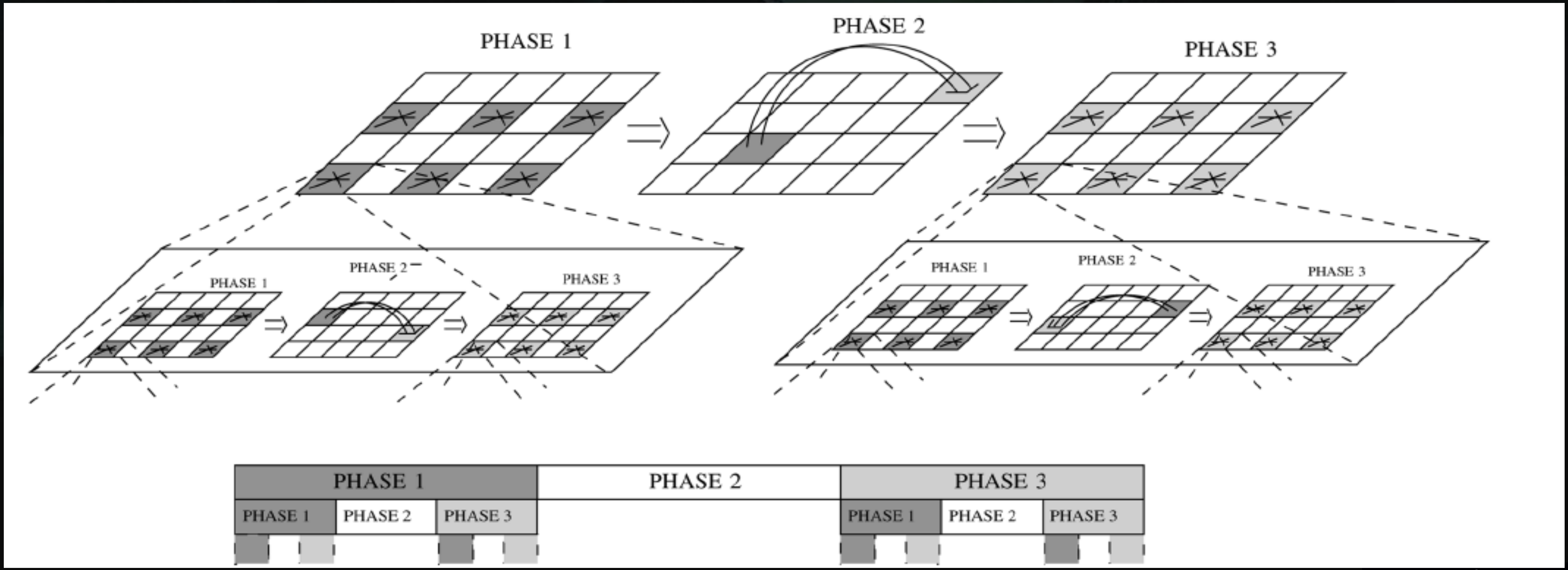
"AirSync"

Balan, H.V.; Rogalin, R.; Michaloliakos, A.; Psounis, K.; Caire, G., "AirSync: Enabling Distributed Multiuser MIMO With Full Spatial Multiplexing," *IEEE/ACM Transactions on Networking*



Hierarchical Cooperation

Ayfer Özgür, Olivier Lévêque and David N. C. Tse, ”Hierarchical Cooperation Achieves Optimal Capacity Scaling in Ad Hoc Networks”, IEEE Trans. Inf. Theory, vol. 53, no. 10, pp. 3549-3572, Oct. 2007



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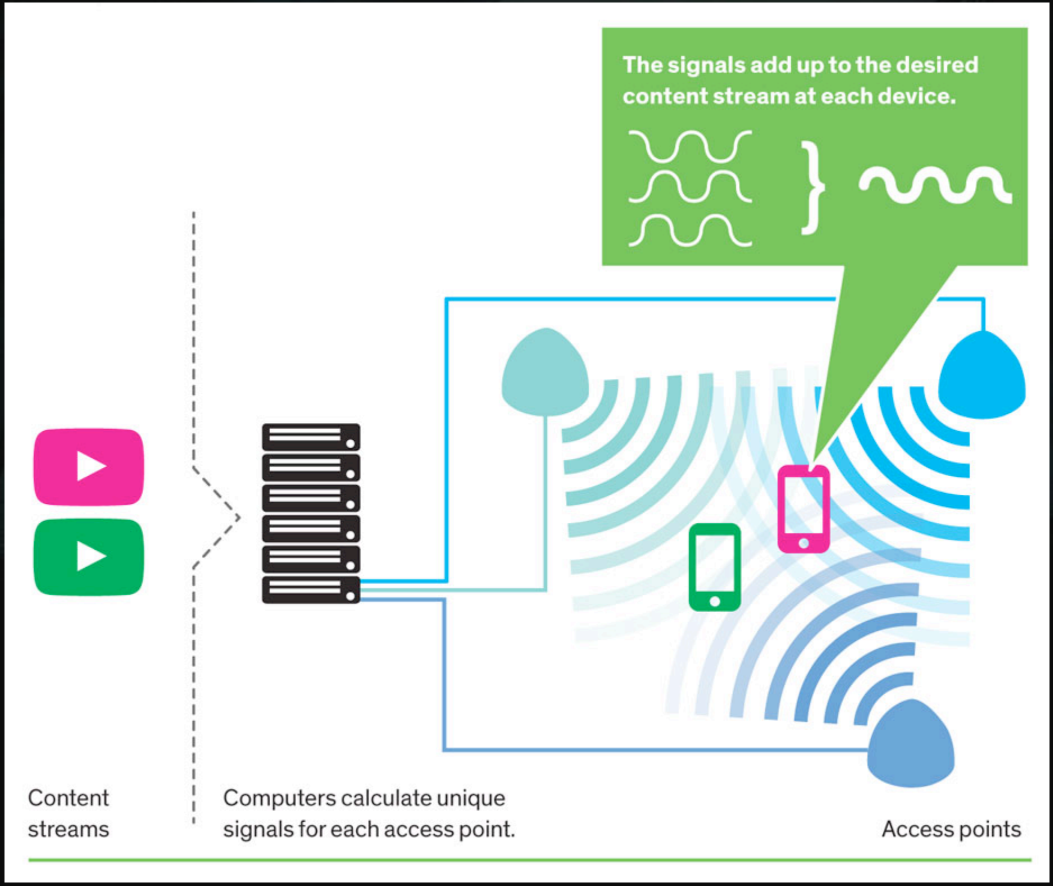
"Distributed input distributed output (DIDO)" aka "pCell"

http://spectrum.ieee.org/telecom/wireless/can-artemis-deliver-5g-service-on-your-4g-phone



pCell announcement

- Three major achievements
  - LTE-standard supporting Base-stations with small footprints on stock USRP hardware
  - Base-station cooperation without any client-side mods - and apparently with very little backhaul bandwidth
  - large-scale spatial mux (in “demos”, 8x scaling)

Skepticism ☹

"If you've done 6 impossible things this morning, why not round it off with breakfast at Milliways, the Restaurant at the End of the Universe?"

— Douglas Adams,
The Restaurant at the End of the Universe

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  - <u>fundamentals, scalable algorithms</u>

The big picture

Fundamentals	Scalable Techniques
Synchronization/overhead tradeoff State-space models Kalman tracking and prediction Phase/frequency/delay estimation Channel estimation	Summarized feedback Implicit feedback Receive beamforming Wideband extensions Kalman tracking for sync and CSI
Concept Systems	**Experiments**
Distributed base station Distributed 911	Open-source implementation on software defined radio platform Accoustic testbed for advanced virtual array techniques

Two key themes

- Fully wireless
  - we envision DMIMO arrays of “mobiles” rather than of “Base Stations”
  - no wired backhaul links
  - array coordination overhead cannot be too large
- Scalable
  - DMIMO gains are most compelling when the array size becomes large

Fundamentals: a fresh look at modeling clock drifts

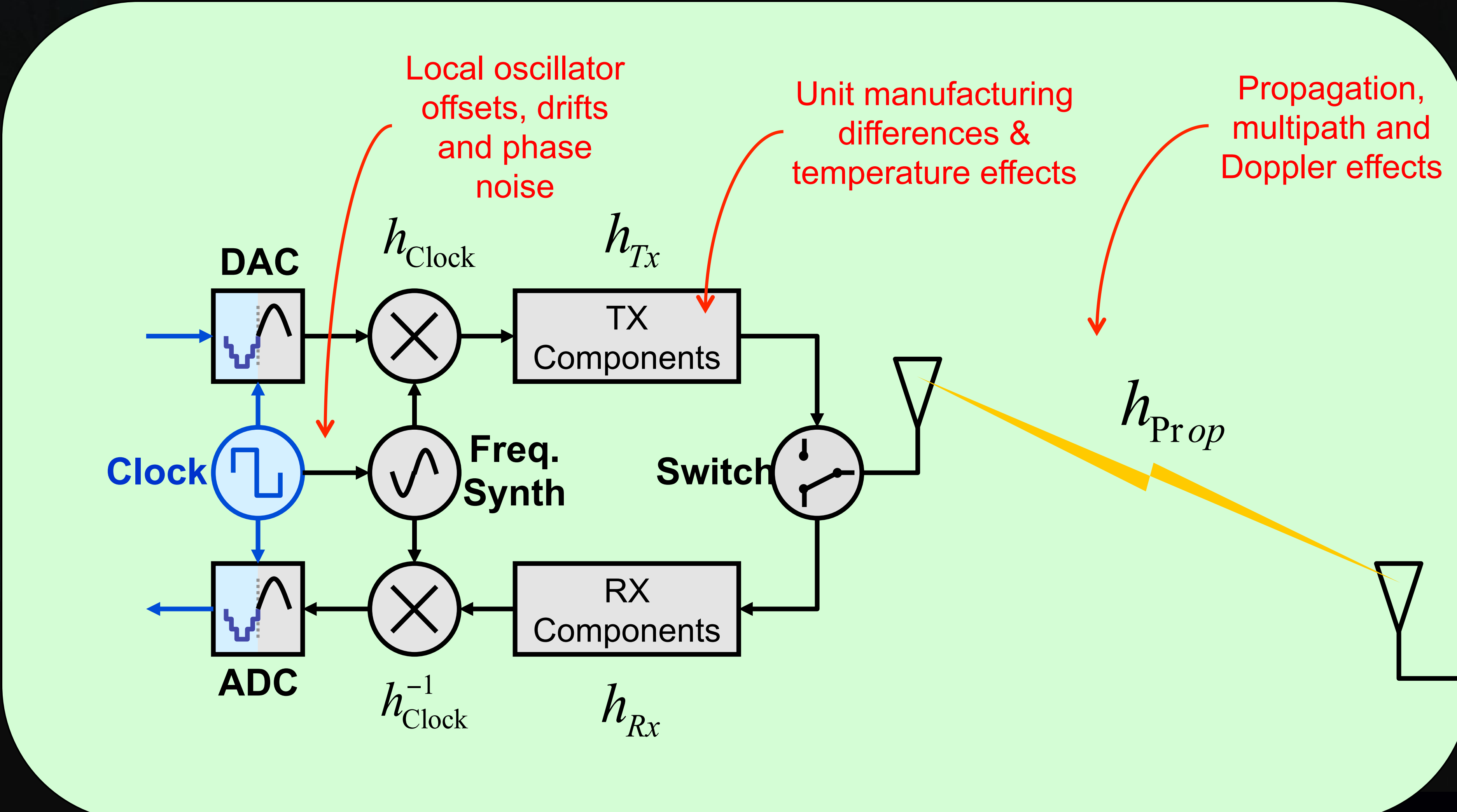
- we know KF-like methods "work"
  - assuming Brownian motion frequency and phase disturbances
  - using rough estimates of process noise covariances
    - obtained from Allan variances and other metrics that are designed to measure *long-term* stability
  - neglecting the possibility of "cycle slips" or unwrapping errors

Fundamentals: wideband signaling in multi-path channels

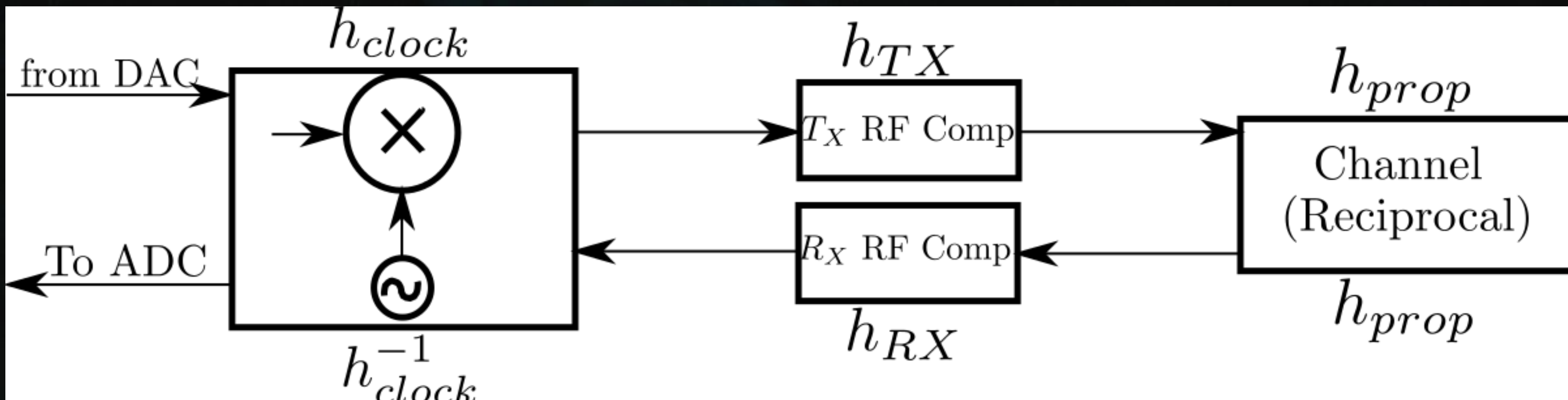
- Naïve method: use narrowband signaling independently on each subcarrier
  - highly suboptimal
  - neglects correlations of “effective channel” over subcarriers

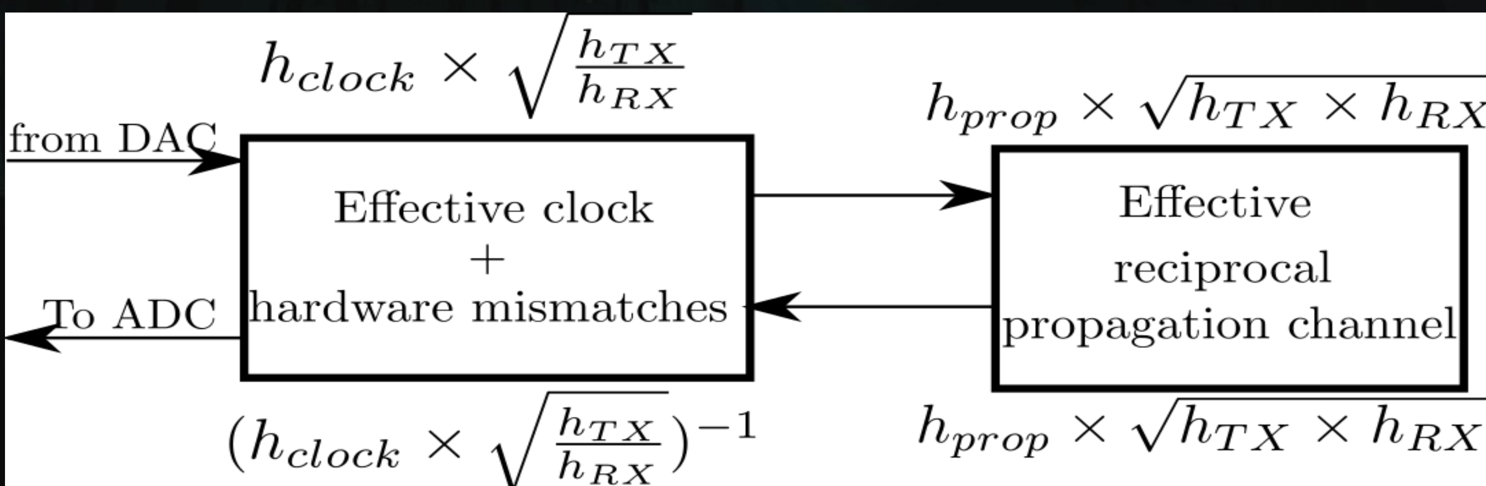
- Designing optimal OFDM receiver structures for DMIMO systems

Scalable algorithms: reciprocity



Scalable algorithms: reciprocity





Scalable algorithms: nullforming

- Nullforming using reciprocity?
  - nullforming ← global CSI
  - vs. beamforming

- How about local CSI + some small amount of additional feedback?

- Very powerful idea

Scalable algorithms: Rx beamforming

- brute-force method: all receive nodes exchange entire waveforms
  - optimal, but extremely high backhaul bandwidth requirements

- how much can we quantize?

- is there a clever way to aggregate waveforms with low overhead?

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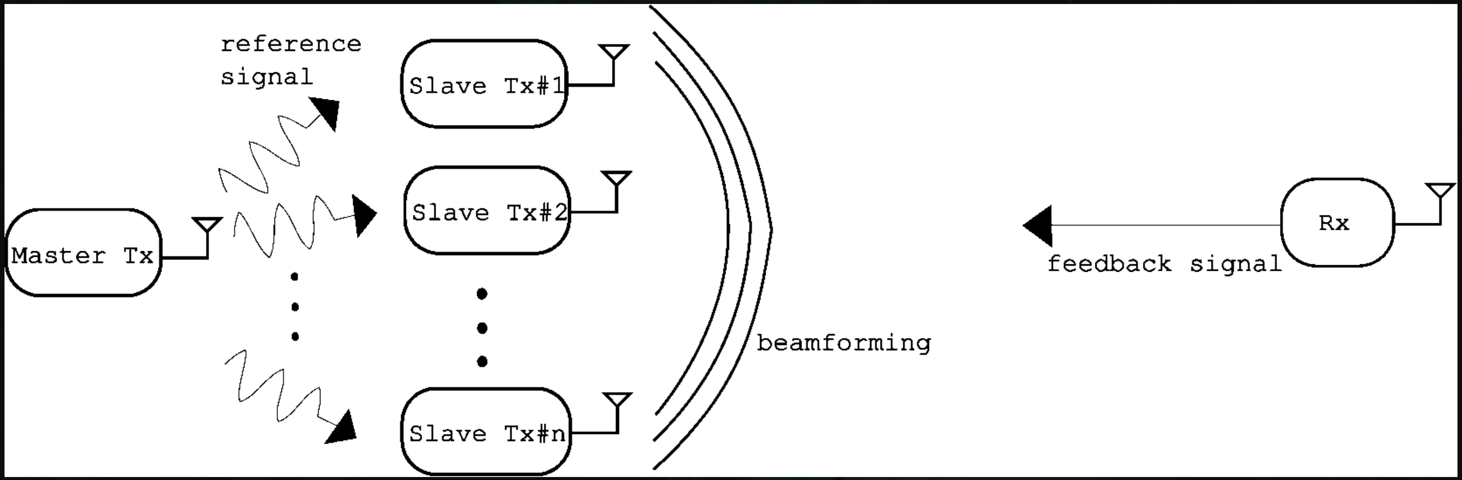
Open-source implementation: v1.0



- In our implementation, a dedicated “Master” node sends a pilot tone for “Slaves” to frequency-lock to
- Other arrangements possible
  - e.g. GPS satellite as Master node or Receiver itself as Master node
  - Different tradeoffs

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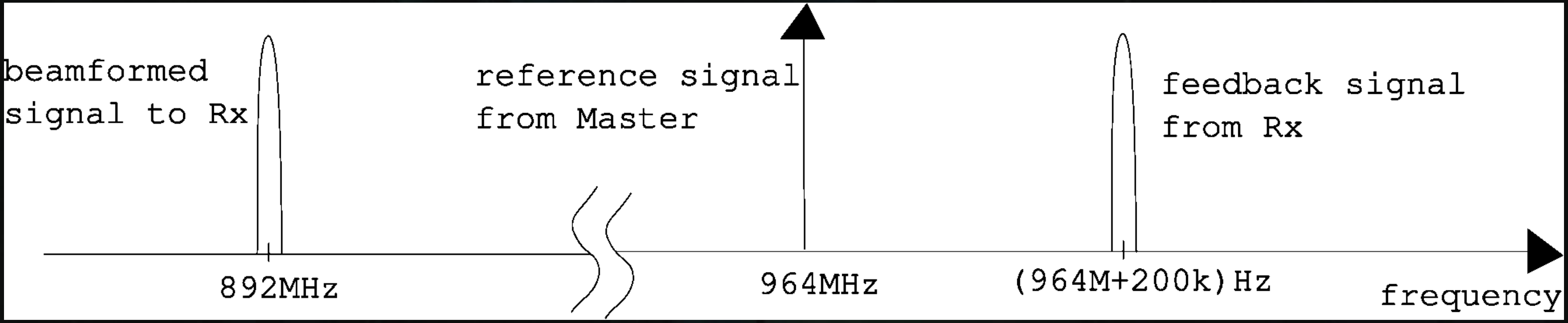
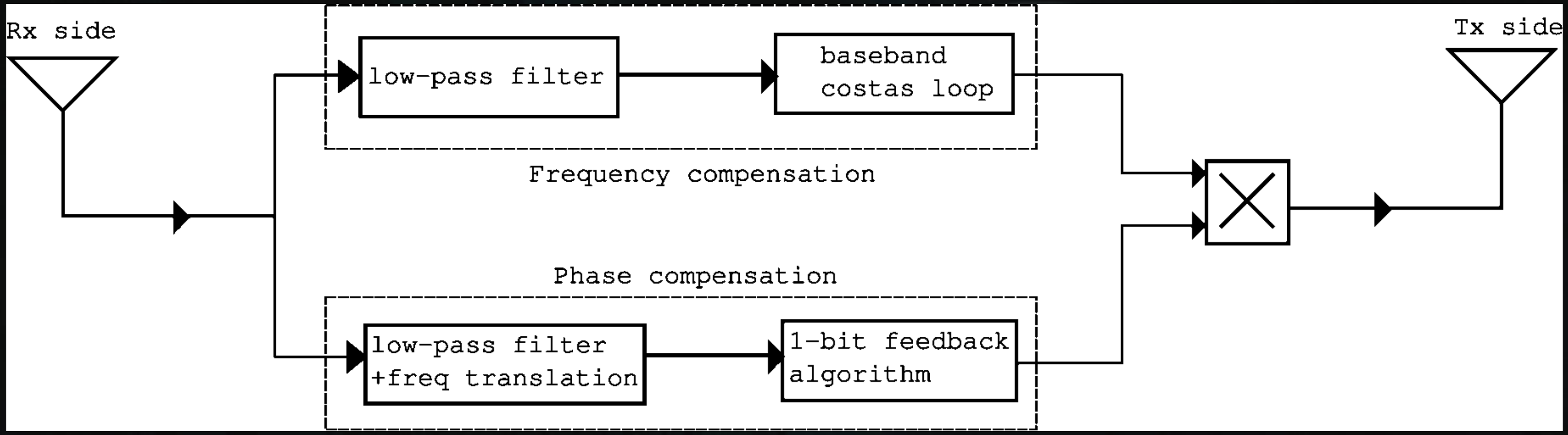
Multiplexing scheme

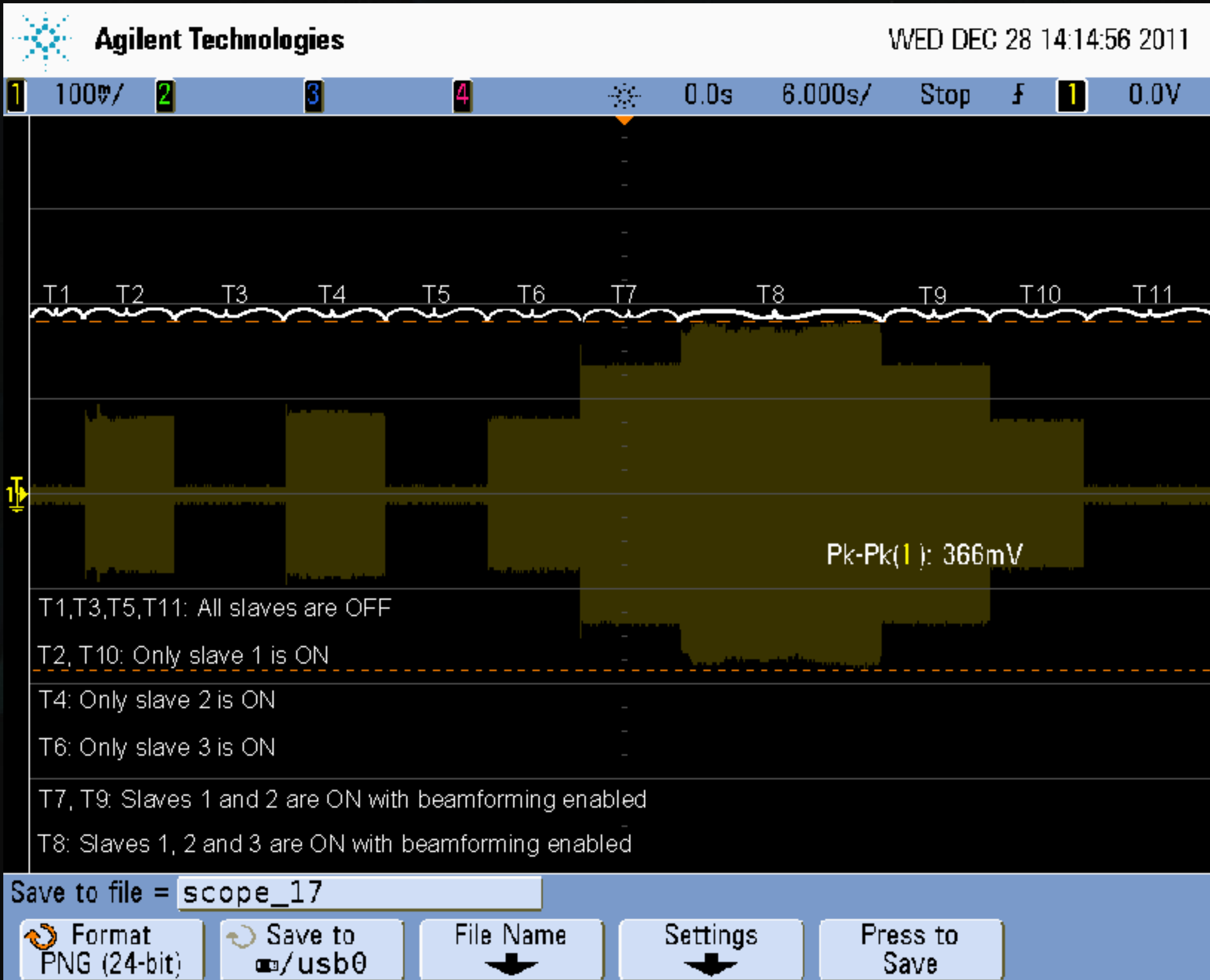


- Training signal from master at 964 MHz
- Feedback signal at 964 MHz + 200 kHz
  - Far enough apart to be separated by simple filtering
  - But close enough to be within slave nodes' receiving bandwidth

All the action is at the Slaves



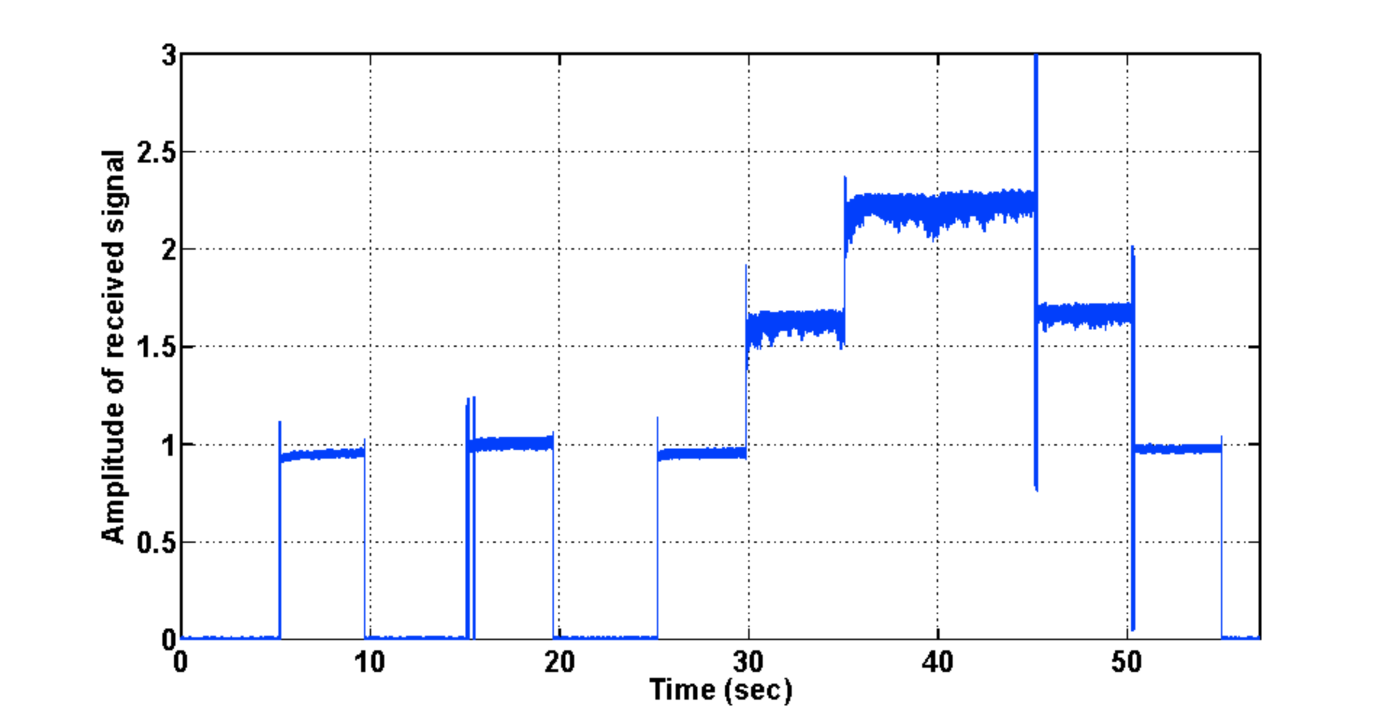
- Two parallel synchronization processes
  - frequency-locking using pilot tone from Master
  - beamsteering using 1-bit feedback from receiver



Agilent Technologies
WED DEC 28 14:14:56 2011
1 100mV/ 2 3 4 0.0s 6.000s/ Stop 1 0.0V
T1 T2 T3 T4 T5 T6 T7 T8 T9 T10 T11
Pk-Pk(1): 366mV
T1,T3,T5,T11: All slaves are OFF
T2, T10: Only slave 1 is ON
T4: Only slave 2 is ON
T6: Only slave 3 is ON
T7, T9: Slaves 1 and 2 are ON with beamforming enabled
T8: Slaves 1, 2 and 3 are ON with beamforming enabled
Save to file = scope_17
Format PNG (24-bit)
Save to /usb0
File Name
Settings
Press to Save

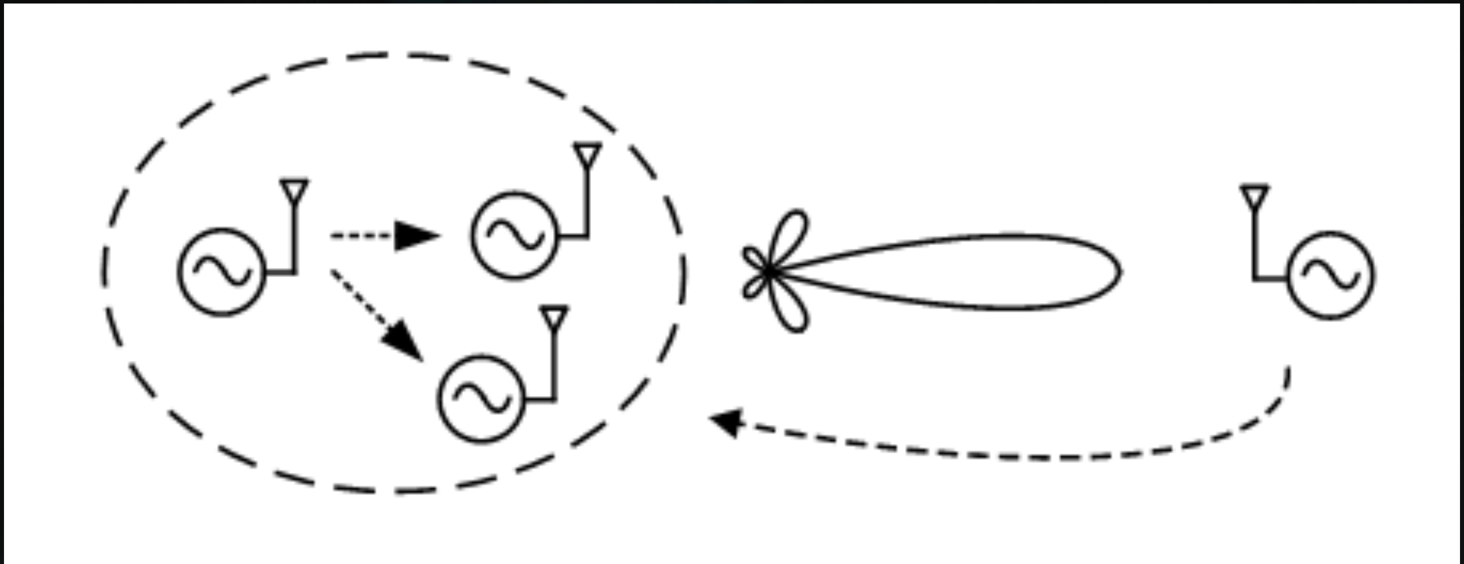
Same experimental data plotted in MATLAB

- 3 transmitters, individually and then together
- amplitude of received signal with beamforming ~ 3x greater ➔ SNR ~ 9x greater



v2.0: more refined and optimized for packet networks

Digital packetized feedback signal



– digital feedback in short packet bursts

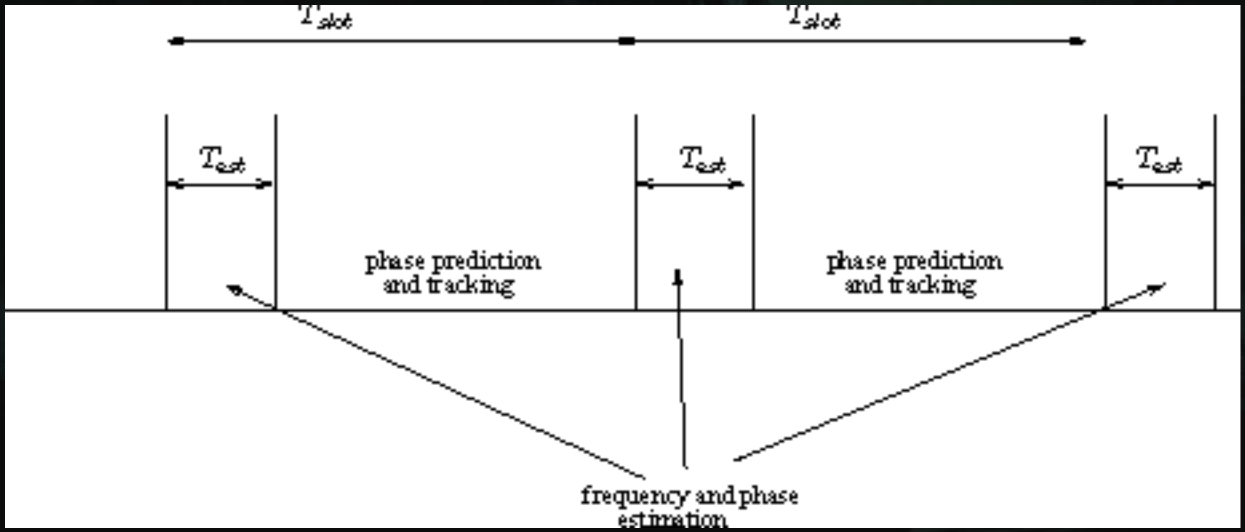
➔ minimize power consumption

– use same feedback signal for frequency locking as well as beamforming

➔ no need for separate Master node

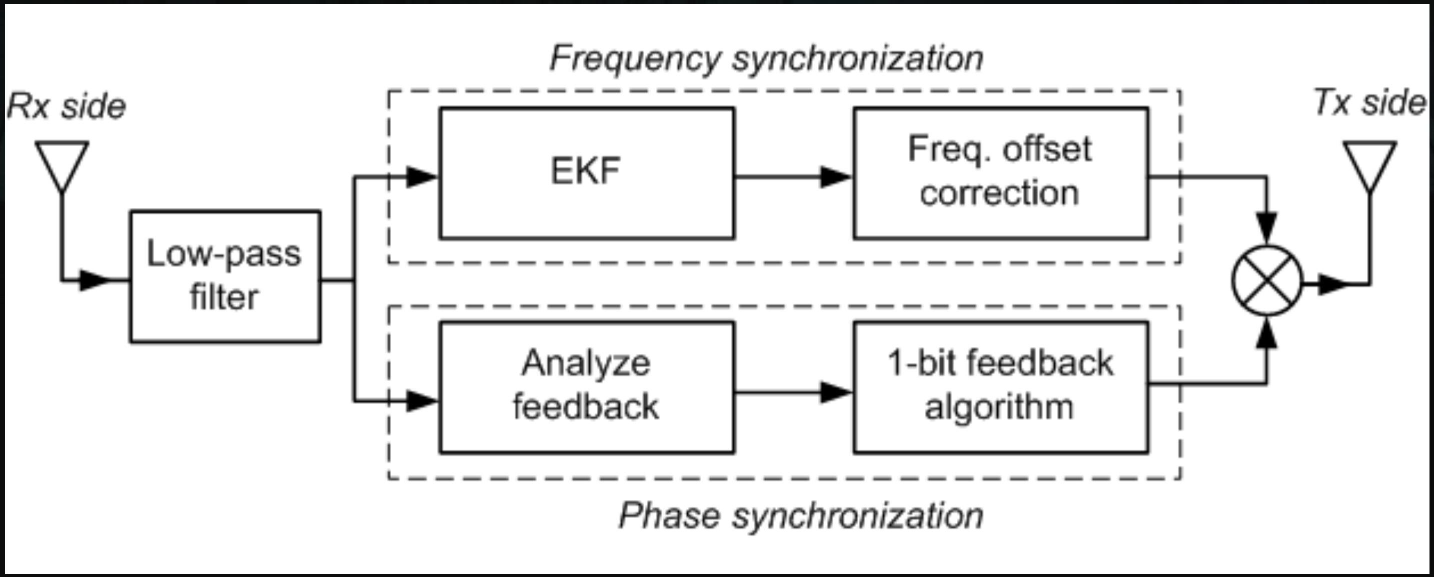
Very low sync overhead

- Training/feedback sent in short packet bursts

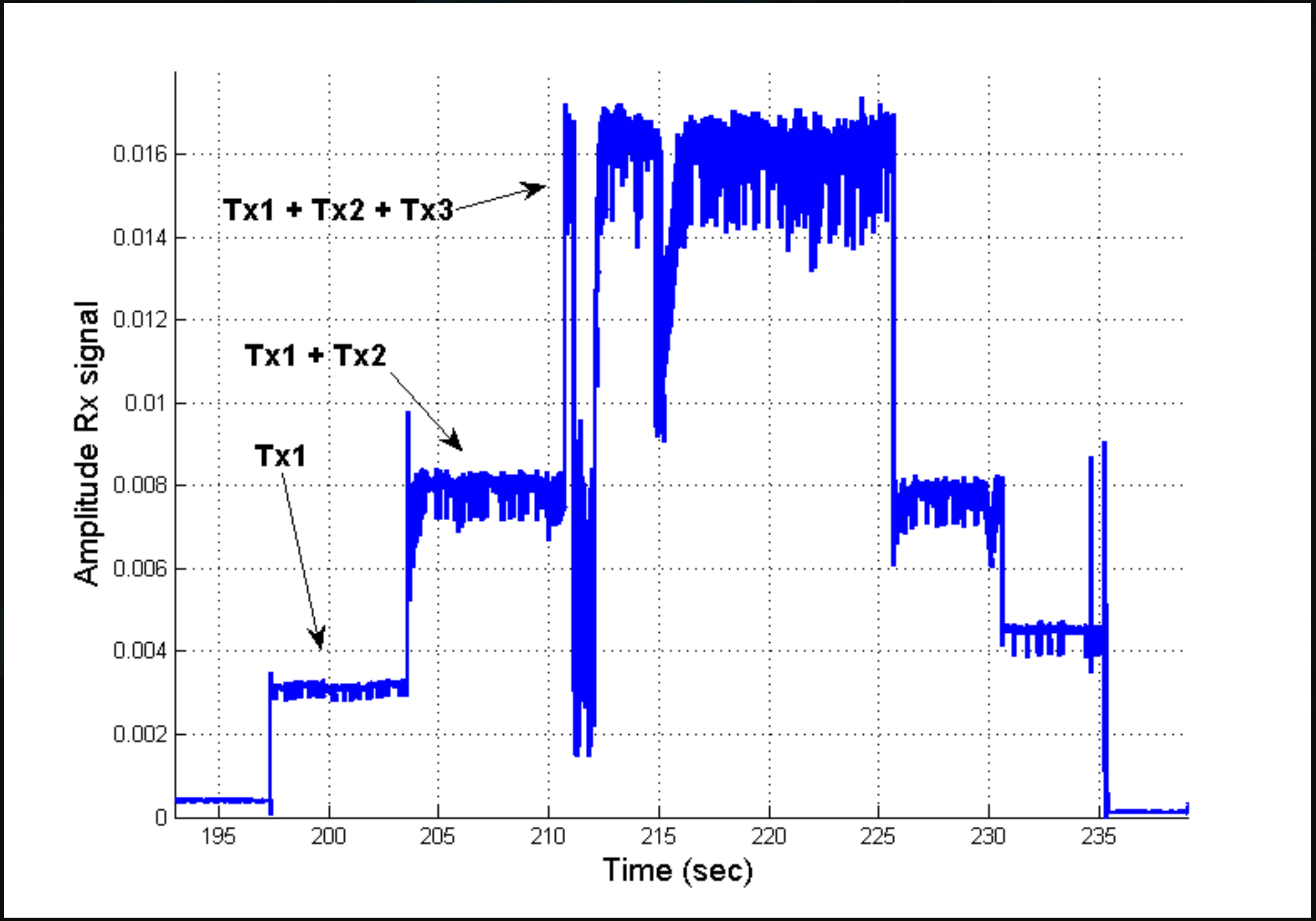


Extended Kalman filters

- EKF performs better than Costas loop
  - more robust, accurate frequency estimation
- EKF more flexible
  - works with digital feedback packet signal



Beamforming RSS with 3 Tx



Ongoing work

- a “pre-synchronized” DMIMO array using low-complexity signal processing
- a protocol for initializing and maintaining a pre-synced array with low overhead
- using EKFs on packet preambles