GNU-radio/USRP-based software-defined radio testbed for distributed beamforming

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Credits

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Outline

• Distributed beamforming
  -> Introduction
  -> Synchronization problem
  -> Recent work

• Implementation on GNU-radio/USRP
  -> Why SDR, why GNU-radio/USRP?
  -> System model
  -> EKF
  -> Implementation challenges
  -> Results

• On-going work
  -> Time synchronization

• Conclusion
Distributed Beamforming (DBF)

### Experiment #1
- Tx 1, $P_{Tx1} = Q$
- $P_{Rx} = A^2 = P$

### Experiment #2
- Tx 1, $P_{Tx1} = 2Q$
- $P_{Rx} = 2A^2 = 2P$

### Experiment #3
- Tx 1, $P_{Tx1} = Q$
- Tx 2, $P_{Tx2} = Q$
- $P_{Rx} = (2A)^2 = 4P$
A motivating example

- $f = 3$ GHz, $BW = 10$ MHz
- $P_T = -10$ dBm, Altitude = 3000 m
- $P_R = -110$ dBm, $P_{rx\_noise} = -97$ dBm, $NF = 6$ dB,
- $SNR_R = -13$ dB (with single transmitter)
- $SNR_R = +13$ dB (with virtual array of 20 transmitters)
In a *virtual antenna array*:

- **frequency** and **phase offsets** are present between transmitters

- **Clocks of individual transmitters** *drift* over time
In a **virtual antenna array**: 

- Due to **irregular** geometry, implicit/explicit **CSI** is required for beamsteering 
- To send data, cooperating nodes must be **aligned in time** 
- Cooperating nodes will need to employ a network protocol for **scheduling** and **data sharing**
DBF in recent past

- A menu of synchronization techniques have been developed – featuring different sets of tradeoffs between complexity, overheads and performance

Prerequisites
- Coarse node locations
- Fine node locations
- Clock sync
DBF implementations in recent past

1-bit feedback algorithm

Really neat: no calibration, channel-estimation

If GOOD keep. Repeat. If BAD discard. And try again.
DBF implementations in recent past

• Previous work has established basic feasibility of distributed beamforming

• **Limitations of previous work:**
  – previous experimental demos of distributed beamforming all used **wired side-channels**
  – **common reference oscillator** for all nodes, so no frequency offsets!
  – based on **custom-built hardware** not compatible with any standard platform
At GHz frequencies, offsets between the nodes are ~ few kHz, so, can be tracked and compensated in software.
Why SDR?

- Easy to reconfigure, modify functionality
- Pushing more and more processing to baseband
- No more custom implementations
- Provide building blocks for next gen packet wireless networks
Why GNU-radio/USRP?

• GNU-radio
  - Open source software
  - efficient C++ libraries for DSP
  - adding custom functionality is convenient

• USRP
  - High-speed ADC’s/DAC’s
  - Powerful FPGA
  - High RF bandwidth

Together, the two make the most popular and most widely adopted SDR
Mailing lists are active and friendly
System model
Zoomed-in view of a transmitter

System model

Why SDR, GNU-radio/USRP?

Implementation on GNU-radio/USRP

Implementation challenges

Results

Frequency synchronization

Low-pass estimation → EKF → Freq. offset correction

Analyze feedback → 1-bit feedback algorithm

Phase synchronization

Rx antenna

Tx antenna

Low-pass filter
Zoomed-in view of receiver

[Diagram showing the process from Rx antenna to Tx antenna: Low-pass filter, Measure RSS, Generate feedback bit, Create GMSK packet]
Beamforming – timing diagram

Why SDR, GNU-radio/USRP?
System model
EKF
Implementation challenges
Results
EKF for frequency locking

- Transmitters use Extended Kalman filter (EKF) for frequency-offset estimation and prediction

\[
\begin{bmatrix}
\phi_{k+1} \\
\omega_{k+1}
\end{bmatrix} = \begin{bmatrix} 1 & T_{\text{slot}} \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \phi_k \\ \omega_k \end{bmatrix} + \mathbf{W}_k
\]

State evolution

\[
\mathbf{z}_k = \begin{bmatrix} \cos(\phi_k) \\ \sin(\phi_k) \\ \omega_k \end{bmatrix} + \mathbf{v}_k
\]

Measurement model
Performance of EKF

Phase of the received sum signal as a function of feedback rate

Standard deviation of the maximum phase error as a function of $1/T_{\text{slot}}$

Results shown above have been submitted to IEEE TWC (in review).
• The blue/red area represents the \{Tslot; Test\}-pairs for which the EKF converges/diverges with simulations
• The circles/crosses represents the \{Tslot; Test\}-pairs for which the EKF converges/diverges with the experimental setup
• The black line show the CRLB.

Results shown above have been submitted to IEEE TWC (in review).
@ Transmitter(s)

Async message passing between blocks
@ Receiver

Async packet transmissions
Results

• Feedback is CW
• costas loops for freq lock

Beamforming with three tx nodes

Data transmission using beamforming (Note the lack of time synchronization)

Results shown above were initially reported at IPSN’12.
Results shown above were initially reported at IPSN’12.
Beamforming with two tx nodes

Results shown above were initially reported at IPSN’12.
Results

• Feedback is packetized
• EKF for freq lock

Results shown above are to be presented at Globecom’12.
Ongoing work
Time synchronization

Time sync using Time of Packet Arrival (ToPA)
Ongoing work

Time synchronization

Tx node(s)
Ongoing work

Time synchronization

Tx node(s) – in GRC

• Sending timed packets
Initial Results

Ongoing work

Time synchronization
Short-term objectives

- Every node broadcasts packets to its neighbors sporadically.
- Node $i$ uses Extended Kalman filter to filter the noisy estimate of its frequency offset and predict and correct for the future offset.

Packets broadcast by its neighbors being received at node $i$
Long-term objectives

• Virtual MIMO
• Nullforming
• Interference cancellation
• Source localization
• Basic building blocks for beamforming
• Big aim is to bring this technique to WiFi, Zigbee and other practical packet wireless networks
• We welcome collaborators from industry and open-source and hobbyist communities. Please contact us if interested.
• Project description and source code are available at:
  http://research.engineering.uiowa.edu/wrl/content/ongoing-projects
  http://www.ece.ucsb.edu/~fquitin/
GNU-radio feature requests? (unresolved challenges)

• Blocks without fixed input-to-output-rate-ratio to enable wireless packet networks
• Efficient message passing between blocks
Thanks for your patience 😊

Questions ???