Software Defined Radio Implementation of Carrier and Timing Synchronization for Distributed Arrays

Han Yan¹, Samer Hanna¹, Kevin Balke², Riten Gupta³, and Prof. Danijela Cabric¹
¹University of California, Los Angeles, ²Google Inc., ³UtopiaCompression Corp.

Mar. 8th 2019
Intro: Distributed Virtual Array System

- **Distributed virtual arrays**
  - Widely adopted in early-5G cellular systems

**Advantage**
- Excellent interference control among multiple cells

**Limitation**
- Fiber control/fronthaul; Not suitable for on-demand deployment

*Figure.* Current distributed virtual array system, aka cloud radio access network (C-RAN) and coordinated multi-points (CoMP)
Our Vision: Dist’d Virtual Arrays w/ Mobility

- Coordinated radios as mobile virtual arrays
  - Distributed beamforming (DBF) and link distance reduction
  - Provide well-conditioned MIMO channel in low scattering areas¹

* EE: Energy Efficiency; SE: Spectral Efficiency

- Other application
  - Infrastructure-free squad radio array in the battlefield

1. S. Hanna, H. Yan, and D. Cabric, “Distributed UAV Placement Optimization for Cooperative line-of-sight MIMO Communications,” accepted to IEEE ICASSP’19, Apr. 2019.
Challenge of Distributed Arrays

- **Tight synchronization among non-collocated radios**
  - GPS clock
  - DPS based synch. protocol (this work)

- Distributed array processing in the radio edge
- Energy management
Outline

• Introduction
• System model
• Proposed protocol & synch. requirement
• DSP based synchronization
  • Frame detection & integer sample timing acquisition
  • Frequency offset estimation & adjustment
  • Fractional sample timing acquisition
• SDR implementation
• Simulation and experiment results
• Discussion & conclusions
System Model and Objective in Synch.

- **Model btw. master and one slave**
  - “Broadcast” synch. manner
  - Straightforward to extend to more radios

- **Received signal model w. synch. error**
  \[
  r[n] = h_0 e^{j\epsilon_F n} \sum_{k=\infty}^{+\infty} s[k] p_{ps} \left( (n - k) T_s - \Delta \tau \right) + w[n].
  \]

- **Objectives**
  - Slave estimate STO and CFO of RF components
  - Adjust its digital baseband signal to synch.

| Item                              | Notation          |
|-----------------------------------|-------------------|
| Transmit signal                   | \( s[n] \)       |
| Channel btw. Master & Slave       | \( h_0 \)        |
| Sample duration\(^1\)             | \( T_s \)        |
| Sample timing offset (STO)        | \( \Delta \tau \) in [sec] |
| Carrier frequency offset (CFO)    | \( \Delta f \) in [Hz] |
| Normalized CFO                    | \( \epsilon_F = 2\pi T_s \Delta f \) in [rad] |
| RF pulse shaping function\(^2\)   | \( p_{ps} (t) \) |

1. Actual radio has sample clock skew offset. However, this is valid assumption as long as timing offset adjustment occur often enough. Therefore we assume it is identical for all radio
2. Due to low-pass filtering after DAC and band-pass filter after PA. Modeled as baseband low-pass filter center at \( t = 0 \) and width \( T_s \)
Proposed Frame Structure & Protocol

• Periodic sync. Preamble
  • Emphasis of paper
  • Constant frequency and timing resync.
  • Facilitates filtering among estimator in each preamble
  • Slave actively search, and sync. with it

• Idle period
  • For baseband processing latency in slave

• Cooperative communication
  • Master & slaves reaches good freq. and timing sync.
  • Requires less often phase adjustment than non-sync. freq.

Fig. Frame structure
Preamble Seq. & Notations

• Zadoff-Chu (ZC) sequence in preamble
  • Zero cyclic-autocorrelation: ideal for frame detection
  • Widely used in cellular network

• Received signal notational change
  \[ r[n] = h_0 e^{j\varphi n} \sum_{k=-\infty}^{+\infty} s[k]p_{ps}((n-k)T_s - \Delta \tau) + w[n]. \]
  
• Transmit signal
  \[ s[n] = \sum_{m=0}^{M-1} s_{zc}[n - mN_{zc}]. \]

• STO \( \Delta \tau \) rewritten as \( \Delta \tau = (d^{*} + \zeta^{*})T_s \)
  \( d^{*} \) is integer sample offset;
  \( \zeta^{*} \in [0,1) \) is fractional sample offset
Sim. Required Sync. Accuracy

- Simulation in range extension (DBF) application
  - Study the performance degradation due to Gaussian residual sync. error among groups
  - Conclusion: freq. & timing error within 20 Hz & $T_s/8$ is tolerable

| Parameter                | Value                          |
|--------------------------|-------------------------------|
| Distance (inter/intra)   | 20km/50m                      |
| Tx Power (per radio)     | 23 dBm                        |
| Channel Model            | LOS/Free-Space (no shadow/fading) |
| Carrier Freq.            | 2.4 GHz                       |
| AWGN BW                  | 10 MHz                        |
| Rx Noise Figure          | 4 dB                          |
| Data Frame Length        | 5 ms                          |

Impact of Residual Freq. Error

Impact of Residual Timing Error
Achievable Accuracy Analysis

• **Error variance: Cramer-Rao Lower Bound (CRLB)**
  • Theoretical limitation in estimator variance due to AWGN
  • CFO estimation CRLB
    \[
    \text{var}(\hat{f}) \geq \text{CRLB}(\hat{f}) = \frac{3}{2\pi^2 T_{\text{est}}^2 \text{SNR}_{\text{sync}}}
    \]
    CRLB predicts in 20 dB \(\text{SNR}_{\text{sync}}\) CFO estimation std. var. is at least 60 Hz Requires EKF averaging!

• STO estimation CRLB
    \[
    \text{var}(\hat{\tau}) \geq \text{CRLB}(\hat{\tau}) = \frac{12\pi T_s^3}{T_{\text{est}} \text{SNR}_{\text{sync}}}
    \]
    CRLB predicts in 20 dB \(\text{SNR}_{\text{sync}}\) STO estimation std. var. is at least 0.06\(T_s\) Would be accurate enough

• **Error mean: propagation delay in STO sync.**
  • Intra-group prop. delay is not incorporated
  • Level of 1–10ns static error in small group size (0.3–3m)
  • Can be incorporated via pair-wise sync.\(^{1,2}\); Overhead scales with \(N\)
DSP based Synchronziation

- Frame detection & integer sample timing acquisition
- Frequency offset estimation & adjustment
- Fractional sample timing acquisition
• **ZC correlation based preamble detection**
  - Threshold comparison
  - Accumulation over multiple ZC

\[
y_{\text{corr}}[n] \triangleq \sum_{m=0}^{M-1} \sum_{k=0}^{N_{zc}-1} s_{zc}[k] r^*[n + k + mN_{zc}] \left[ \begin{array}{c}
\frac{H_1}{\mathcal{H}_0} \\
\eta_{\text{TH}}
\end{array} \right]^2
\]

• **ZC-corr. based integer timing acquisition**
  - Finding the peak

\[
\hat{d}^* = \arg \max_n y_{\text{corr}}[n]
\]

• Note that \(d^*\) is sensitive to AWGN when fractional error is near \(\frac{1}{2}\)
  - Up to \(T_s\) error if no further fine estimation is used
Frequency Synchronization

• CFO estimation that utilize repetition of pilots

\[
\Delta \hat{\epsilon}_F = \angle \left( \sum_{n=0}^{(M-1)N_{zc}-1} r[\hat{d}^*] + N_{zc} + n r^*[\hat{d}^* + n] \right) / N_{zc}
\]

• Filtering over multiple estimator for better accuracy
  • Extended Kalman filter (EKF) with state update & observation model

\[
\begin{bmatrix}
\phi_k \\
\epsilon_{F,k}
\end{bmatrix} =
\begin{bmatrix}
1 & N_{CYC,k} \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
\phi_{k-1} \\
\epsilon_{F,k-1}
\end{bmatrix}
+ \begin{bmatrix}
\delta \phi_k \\
\delta \epsilon_{F,k}
\end{bmatrix}
+ \begin{bmatrix}
\cos(\hat{\phi}_k) \\
\sin(\hat{\phi}_k)
\end{bmatrix}
+ \begin{bmatrix}
\cos(\hat{\phi}_k) \\
\sin(\hat{\phi}_k)
\end{bmatrix}
+ w_k
\]

• Simple way for \( \cos(\hat{\phi}_k) \) and \( \sin(\hat{\phi}_k) \) is

\[
\cos(\hat{\phi}_k) = \Re(r[\hat{d}^*_k]) \text{ and } \sin(\hat{\phi}_k) = \Im(r[\hat{d}^*_k])
\]

• Freq. sync: use estimator to compensate Tx signal
Fractional Timing Sync.

- Correlation w. fractional delayed ZC seq.

\[ \hat{\zeta}^* = \arg \max_{\zeta \in D} \sum_{m=0}^{M-1} \sum_{n=0}^{N_{zc}-1} \hat{r}^*[n + \hat{d}^* + mN_{zc}] \tilde{s}_{zc}^{(\zeta)}[n] \]

- Each frac. delayed candidate is

\[ \tilde{s}_{zc}^{(\zeta)}[n] = \sum_{k=0}^{N_{zc}-1} s_{zc}[\text{mod}(n - k, N_{zc})]p_{pc}(t - \zeta - kT_s) \]

- Delay candidates depends on target accuracy

\[ Z = \left\{ \frac{-T_s}{2}, \frac{-T_s}{2} + \frac{T_s}{N_\zeta + 1}, \ldots, \frac{-T_s}{2} + \frac{N_\zeta T_s}{N_\zeta + 1} \right\} \]
SDR Implementation
Default solution:
USRP BB ref clock signal (10MHz & 1PPS)

Our solution: USRP RF Tx/RX for carrier & clock synch.
Via RF cabled & antenna
SDR Implementation Flow

- Processing algorithm flow in a slave radio

Input I/Q Stream
\( r[n] \)

CFO Estimation
Input:
I/Q stream \( r[n] \); Integer delay: \( \hat{d} \)
Output:
CFO est. (oneshot/EKF): \( \hat{\varepsilon}_F \)

Output I/Q Stream

Frame Detection & Int. Timing
Input:
I/Q stream \( r[n] \)
Output:
Frame decision: \( \{H_1, H_0\} \)
Integer delay: \( \hat{d} \)

\( \tilde{r}[n] \)

Frac. Timing Est. & Comp
Input:
I/Q stream \( r[n] \)
CFO est. \( \hat{\varepsilon}_F \)
Output:
Post-comp sig. \( s[n] \)
Gnuradio Processing Blocks (Slave)
Experiment Results

• Residual synchronization error measurement
• Distributed transmit beamforming w/ QPSK waveform
## Experiment Setup

| Carrier Freq. | Bandwidth | Preamble | Sync. Channel & Radios | Freq. Measurement | Timing Measurement |
|---------------|-----------|----------|------------------------|-------------------|--------------------|
| 2.4 GHz       | 1 MHz (w/o oversample) | • ZC sequence  
• $N_{zc} = 63$  
• $M = 10$ repetitions | • RF/ SMA-cable  
• >30dB SNR  
• 1 master  
• 2 slaves | • 2 perfect sync. receiver USRP  
• 0.25MS/s w. 1000x decimation  
• 256-FFT | • Tektronix DLS6154 w. 500ps resolution  
• ~650 measurements with $\geq$20s spacing |

### BB Process.  
PC (Intel i7, 8GB RAM)  
Test Sig.  
Tone/Sinc.
Synch. Accuracy Measurement in SDR

Table 1: Measured RCFO Analysis and Benchmarks Comparison

| Item               | Expression | Value   |
|--------------------|------------|---------|
| This work          |            |         |
| Mean [Hz]          | \( \mu(\Delta_{R,F}) \) | -0.322  |
| Std. Dev. [Hz]     | \( \sigma(\Delta_{R,F}) \) | 5.253   |
| Tail prob. at 5 Hz | \( \text{prob}(|\Delta_{R,F}| > 5) \) | 0.247   |
| Tail prob. at 10 Hz| \( \text{prob}(|\Delta_{R,F}| > 10) \) | 0.072   |
| Tail prob. at 15 Hz| \( \text{prob}(|\Delta_{R,F}| > 15) \) | 0.000   |

Globecom'12

| Item               | Expression | Value   |
|--------------------|------------|---------|
| Mean [Hz]          | \( \mu(\Delta_{R,F}) \) | <0.600  |
Distributed Beamforming

• **After time and freq. synch**
  - Each slave sends time multiplexed pulse
  - Receiver estimates phase difference
  - Feeds it back to slave 1
  - Slave 1 adjusts phase
Distributed Beamforming Results

- 2 Radio Transmit Beamforming
  - 2 slaves USRP synchronized by beacon of master
  - Common QPSK message w/ 1MHz symbol rate at USRPs
  - Signal coherently added over-the-air for tens of milliseconds
Conclusions & Future Research

- **Proposed & implemented SDR sync. algorithm**
  - Local radio group sync. w. low overhead
  - Reaches $\leq 5$ Hz in 70% time and always $\leq T_s/16$ (62.5 ns)
  - GPSDO comparable accuracy ($\pm 60$ Hz & $\pm 50$ ns)
  - Implemented distributed beamforming over the air

- **Future plan**
  - USRP FPGA implementation for lower delays
  - UAV on-board DBF/DMIMO (USRP B200 + Odroid + Intel Aero)
Engineer Change.

Acknowledgment
This work was supported in part by the Defense Advanced Research Projects Agency (DARPA) under contract D17PC00006. This work was supported in part by the CONIX Research Center, one of six centers in JUMP, a Semiconductor Research Corporation (SRC) program sponsored by DARPA.