Software Defined Radio Implementation of Carrier and Timing Synchronization for Distributed Arrays
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**Antenna arrays can be used to improve communication**
- Extending the range of communication
- Improving energy efficiency
- Reducing interference to other users

Distributed Antenna Arrays
- Enables a group of radios to act as a directional antenna

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**Introduction**
For independent radios to work as a distributed array
- Symbol timing needs to be synchronized

\[
\begin{align*}
S1 & \quad S2 & \quad S3 \quad S4 \\
S1 & \quad S2 & \quad S3 \quad S4 \\
\end{align*}
\]
- Carrier frequency needs to be the same

Easy to implement using antenna arrays. Challenging using independent radios.

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**System Model**
Assuming \( N_T \) transmitters and \( N_R \) receivers.
Without cooperation at receiver \( m \), we get
\[
\tau_m(t) = \sum_{i=1}^{N_T} e^{j2\pi(c_i-c_m)t} h_{i,m}(t - \tau_i) + n_m(t)
\]
where
- \( c_i \) is the carrier frequency offset of radio \( i \)
- \( h_{i,m} \) channel coefficient between transmitter \( i \) and receiver \( m \)
- \( n_m \) a Gaussian random variable

\[
f_c + \epsilon_i \quad T_i \quad h_{i,m} \quad f_c + \epsilon_m \quad R_m \quad T_m
\]

**Requirements**
Using simulations, we study the performance degradation of beamforming resulting from both timing and frequency errors

Symbol Timing Errors
- Result in unsynchronized symbol transmissions, which leads to erroneous detection when beamforming

**Protocol**
We are focusing on intergroup synchronization using a master slave architecture
Master sends a packet consisting of
- Preamble made of multiple repetition of ZC sequences of duration \( T_0 \)
- A guard time
- Data

Slave uses the preamble to
- Estimate frequency error
- Synchronize Time
- ZC sequence
- zero auto correlation
- Used 10 repetition with length 63

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**Algorithm**
Slave correlates with ZC sequence
- Once the first preamble is detected data transmission is scheduled after the guard band
- The delay due to processing is less than the guard time

One shot frequency estimation is performed
- By Comparing the phase of consecutive ZC seq. using
  \[
  \hat{\delta} = \frac{x(t + T_0)x^*(t)}{2\pi}
  \]
  - Kalman filter is applied to track frequency.

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**Setup**
5 USRPs are used
- 1 Master: Sends Beacon
- 2 Slaves: Synch to master
- 2 Receivers: Evaluate Performance
- Oscilloscope: Tektronix DSG154

Evaluate timing accuracy
- Clocks
  - Master and Receivers share clock
  - Receivers are synchronized in time and frequency using a MIMO cable

**Parameters**
- \( f_c = 2.4 \text{ GHz} \)
- \( BW = 1\text{MHz} \)
- 10 samples per symbol

All processing is done in real-time using GNU Radio

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**Results**
Histogram of frequency difference between slaves as measured by receivers

**Conclusion & Future Work**
We developed and implemented a timing and frequency synchronization protocol using SDR. It provides
- Carrier Frequency Error < 10 Hz
- Symbol Timing Error < 0.05 \( T_d \)

Future Work
- Develop fractional delay compensation
- Implement a distributed beamforming algorithm
- Test with more slaves