Wireless Local Positioning System (WLPS)

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Supported by NSF ITR for National Priorities
National Instruments, ARL, CERDEC
Positioning System Categories

Positioning System

Global Positioning System
- Self Positioning System
  - Active Remote Positioning System
- Remote Positioning System
  - Passive Remote Positioning System

Local Positioning System
- Remote Positioning System
Motivation for WLPS

To develop an active remote positioning system:

Suitable:

• Urban and indoor areas;
• Any weather conditions;
• Variety of applications (defense, Security, Law enforcement, Road Safety).
• High $P_d$ and low $P_{fa}$ (Possible via Active Target Systems)

It Means:

• Not limited to the static base station.
• Flexible coverage area.
• Identify and Discriminate Mobiles;
• Need limited Power
WLPS?

ID Request (IDR) Signal transmitted by DBS

ID transmitted by the TRX

Time of Arrival

Duty Cycle = \( \tau / \text{IRT} \)

ID Request Repetition Time (IRT)

Interference at the DBS receiver: Inter-TRX-Interference (IXI)

Each DBS communicates with a number of TRXs in its coverage area.

- IXI can be resolved via CDMA + SDMA (beamforming)
Interference at the TRX receiver: Inter-DBS-Interference (IBI)

Each TRX communicates with a large number of DBSs in its coverage area.

IBI can be resolved via:
(a) CDMA techniques
(b) Taking IRT large enough
(c) Master node (Each TRX talk just to one DBS)
The Main Interference Source in WLPS

Overlap of the transmitted signals from TRX (DBS) at the receiver of DBS (TRX).

\[ P_{\text{over}} = 1 - (1 - d_c)^{K-1} \]

\[ d_c = \frac{\tau}{T} = \text{duty cycle} \]

\[ d_{c_{\text{TRXRCVR}}} = \frac{\tau_{\text{DBS}} (\text{DBS Pulse Duration})}{\text{Selected IRT}} \]

\[ d_{c_{\text{DBSRCVR}}} = \frac{\tau_{\text{TRX}} (\text{TRX Pulse Duration})}{\text{IRT}_{\text{min}} (\text{Range})} \]

Interference effects at the DBS receiver can be reduced via directional Antennas and Multiple-Access Schemes.
WLPS Structure

- **TRX**: CDMA transceiver with omni-directional antenna.

- **DBS**:

  - Hence, DBS transmits ID request signal whenever it is required (Not at all time).
  - The whole system: FDD/TDD/CDMA communication system.
Design Obstacles

1. High Probability of Detection;
2. High Performance DOA/TOA Estimation;
3. NLOS Identification;
High Probability of Detection

- Transmission Scheme: DS-CDMA
- Selection of IRT: As large as possible
- Beamforming: Exploiting Cyclostationary


TRX Receiver Simulation Results

![Experiment setup image]

![Graph showing probability of detection versus number of DBS]

- **DS-CDMA**
- **Standard**

The graph shows the probability of detection for various numbers of DBS. The DS-CDMA method (solid line) and the standard RCVR method (dashed line) are compared. The graph indicates that DS-CDMA performs better in terms of probability of detection as the number of DBS increases.
DBS Receiver: Beamforming Combined with DS-CDMA

\[ r_1(t) \rightarrow \text{RAKE for TRX}_j \]
\[ r_2(t) \rightarrow \text{RAKE for TRX}_j \]
\[ r_{M-1}(t) \rightarrow \text{RAKE for TRX}_j \]
\[ r_M(t) \rightarrow \text{RAKE for TRX}_j \]

Beamformer for the 1\textsuperscript{st} path of TRX\_j
Beamformer for the 2\textsuperscript{nd} path of TRX\_j
Beamformer for the \(L\textsuperscript{th}\) path of TRX\_j

Decision Rule
ID Detector

\[ z_j^1(i) \]
\[ z_j^2(i) \]
\[ z_j^L(i) \]
DBS Receiver with Beam Forming

The top two curves Simulation Results

DBS with Standard Receivers and Beam-forming leads to more than two fold capacity improvement at the $P_d = 0.99$. 
DBS Receiver with Optimal Antennas

Demodulation From antenna elements

\[ y_q^j[n] \]

Beamformer Path 1

\[ z_q^j[n] = w^H(\theta_q^j) \cdot y_q^j[n] \]

Beamformer Path \( L \)

Despreading and Path Diversity Combining

-- For conventional beamforming: \( w(\theta_q^j) = V(\theta_q^j) \)

-- For Linear Constrained Minimum Variance (LCMV) beamforming…
Linear Constrained Minimum Variance (LCMV) Beamforming

- **Design criteria:**

  \[
  \min \ w^H(\theta_q^j)R_q^jw(\theta_q^j) \quad s.t. \ w^H(\theta_q^j)v(\theta_q^j) = 1
  \]

  \[
  R_q^j = E[y_q^j \cdot y_q^{jH}]
  \]

- **Solution:**

  \[
  w_{opt}(\theta_q^j) = \frac{R_q^{-1}V(\theta_q^j)}{V^H(\theta_q^j)R_q^{-1}V(\theta_q^j)}
  \]

In general, LCMV leads to a better removal of interference effects compared to the Conventional Beamforming.
Covariance Matrix Estimation for LCMV BF

- Definition:
  \[ R^j_q = E[y^j_q \cdot y^{jH}_q] \]

- Standard estimation method:
  \[ \hat{R}^j_q = \frac{1}{\Gamma} \sum_{n=0}^{\Gamma-1} y^j_q[n] \cdot y^{jH}_q[n] \]

- Valid if:
  \[ E[y^j_q[n] \cdot y^{jH}_q[n]] = E[y^j_q[n+1] \cdot y^{jH}_q[n+1]] \]

- However......
Non-Stationarity in WLPS

- For WLPS:

\[ E[y_q[n] \cdot y_q^H[n]] \neq E[y_q[n + 1] \cdot y_q^H[n + 1]] \]

Different bits experience different interference
The Mean Square Error of Covariance Matrix Estimation

\[ \text{MSE} = \sum_{m=1}^{M} \sum_{u=1}^{M} (R_q^j(m,u) - \hat{R}_q^j(m,u))^2 \]
Solution: Cyclostationarity

Received signal in IRT period $T$

Interference Signal: TRX 3

Desired Signal: TRX 1

Interference Signal: TRX 2

Same Interference

Received signal in IRT period $T+1$

Same Interference

Estimated covariance matrix
For $n^{th}$ chip of desired user

$$\hat{R}_q^j[n] = \frac{1}{\Omega} \sum_{\omega=0}^{\Omega-1} y_q^j[\omega, n] \cdot y_q^H[j][\omega, n]$$

Number of Static User Frames

Received signal at $n^{th}$ chip of $\omega^{th}$ frame

20
LCMV Beam-forming using cyclostationarity for observed signal covariance matrix highly increases the performance and the capacity.
DIRECTION-OF-ARRIVAL (DOA) ESTIMATION

• Antenna Element Mutual Coupling;
• Antenna – Receiver Calibration;
• Priori Knowledge of the number of available sources;
• Signal-to-Noise Ratio;
• Complexity


Two Stage Fusion

- **Delay-and-Sum**
  - Pros: Fast, low power consumption
  - Cons: Low accuracy

- **Modified Root-MUSIC**
  - Pros: High accuracy
  - Cons: Slow, high power consumption
FUSION

1. Delay-and-Sum Coarse Estimation
2. Seed Root from Coarse Estimation
3. Modified Root-MUSIC
   Find single root of polynomial with seed + Newton’s Method
4. Calculate Fine DOA estimation from phase of root
Assumptions: 1 signal source, 6 antennas, 50 snapshots, 15dB SNR

Conclusions: Error increases as DOA deviates from bore-sight. Fusion method has the same error characteristics as Root-MUSIC.
**Assumptions:** 1 signal source, 6 antennas, DOA=30°, 15dB SNR

**Conclusions:** Delay-and-Sum can provide the lowest complexity, Fusion method provides same accuracy as Root-MUSIC with much lower complexity.
## Comparison

<table>
<thead>
<tr>
<th>Method</th>
<th>Sensitivity to SNR</th>
<th>Sensitivity to Calibration</th>
<th>Sensitivity to Multipath</th>
<th>Resolution</th>
<th>Complexity</th>
</tr>
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<tbody>
<tr>
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<td>Low</td>
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<td>Max Entropy</td>
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<td>High</td>
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<tr>
<td>Root MUSIC</td>
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<td>Lower</td>
<td>Very High</td>
<td>High</td>
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<td>Very High</td>
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<tr>
<td>Fusion</td>
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<td>Moderate</td>
<td>Lowest</td>
<td>Very High</td>
<td>Moderate</td>
</tr>
</tbody>
</table>
TOA Implementation

- Priori Knowledge: Number of available sources;
- Available Bandwidth;
- Signal-to-Noise Ratio;
- Number-of-Reflections;
- Complexity;

M. Pourkhaatoun, and S. A. Zekavat, “A Novel High Resolution ICA-based TOA Estimation Technique for Multi-path Environments,” *IET Communications*, Accepted.

Major Sources of Error

For this signal Model:

\[ x(t) = \sum_{i=1}^{M} \alpha_i \cdot s(t - \tau_i) + n(t) \]

Two major sources of error:

1. Additive noise
2. Multipath → Delay Difference is Important
Simple Scenario: UWB

\[ \Delta \tau \gg T_s \]

**Simple Solution:** Correlator + ML
Complex Scenario: Wide Band

\[ \Delta \tau \approx T_s \]

Solution is not Simple: Our focus!!
Proposed Fine TOA Approach

- Extraction of time delays in frequency domain
- **Based on:** Blind Signal Separation (BSS)
- Two Stages
  - Signal separation in Frequency domain
  - Extraction of time delays from separated signals
- This Technique leads to:
  - High Resolution
  - Low sensitivity to SNR and Band Width
  - Easy implementation
Independent Component Analysis (ICA)

• Estimates independent components (Orthogonal Basis) of an observed matrix;

\[ x = A \cdot s + n = A \cdot (s + \tilde{n}) = A \cdot \tilde{s} \]

**Observed Matrix:** Consists of mixed data

**Noise-Free ICA:**

\[ x = A \cdot s \]
## Conclusions

<table>
<thead>
<tr>
<th>Method</th>
<th>Sensitivity to SNR</th>
<th>Sensitivity to BW</th>
<th>Resolution</th>
<th>Implementation Complexity</th>
</tr>
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<tr>
<td>DLL</td>
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<tr>
<td>ICA-Based</td>
<td>Low</td>
<td>Low</td>
<td>High</td>
<td>Moderate</td>
</tr>
</tbody>
</table>
Concatenated Spectrum TOA
NLOS Identification and Localization

- Multi-Antenna NLOS Identification;
- Multi-Node NLOS Identification;
- Multi-Node NLOS Localization;


APPLICATIONS
Road Safety

- Injuries (or die) of hundreds of thousands of people.
- Intelligent vehicle initiative was announced in 1998 by the U.S. DOT.
Multi-UAV Coordination
Airport Security

- **Congress:** Improvement of airport security is required [1].
- **Security requires:** Positioning, Monitoring, Communicating with individuals, e.g., passengers, employees, guards.
- **Desire:** Security guards to find the position of everybody with respect to themselves at all times and all positions, inside and outside of the airport, and Whenever it is required.
- **Hence, System Characterization:** Infrastructure-less
  
  High Probability of Detection
  
  High Coverage (Indoor, Outdoor)

Implementation of WLPS for Indoor Areas (e.g., Airports): A Futuristic View

Plastic Card Boarding Pass

- Name: ____________
- Flight No.: _______
- Gate No.: ________
- Date: ___________
- Boarding Pass No: __________

Wristband Boarding Pass

- Name: ____________
- Gate No: _______ Flight No. : __________

DBS antenna arrays installed on the belt

- **Communication**: The wristband can receive the updated gate, flight, etc, information.
- **Monitoring**: The wristband can be equipped with a heart beat sensor which is required: (a) for security guard safety, (b) to make sure the wristband is in its position.
Central Command and Control

- Specific clusters of ID codes can be assigned to each group of people (employees, passengers, security guards)
1. The position of the Soldier carrying WLPS (DBS and TRX) is computed by the vehicle WLPS.

2. This position, along with the GPS positioning leads to exact position of all soldiers.
Applications in Law Enforcement:
Multi-Agent Operation
System Design
System Development on Matlab Simulink

Simulated Channel Performance measure

Spread Spectrum Transmitter Design and Test

Antenna Design and Test

Real Data Collection

Real Data Performance measure

FPGA/DSP Programming

Real Data Performance measure

Prototyping

System Reconfiguration
Patch Antenna Design

(1) Beam pattern: Directional (for road safety);
(2) Beam width: As large as possible (85°);
(3) Light weight;
(4) Easy to make;
(5) Low cost (less than $5)
(6) Bandwidth: As large as possible (~50MHz),
Patch Antenna Array

- Bandwidth: 2.41~2.469GHz;
- Dimension: 14.45''×2.40''×0.12'';
- Interface: 50Ω SMA female;
- Elements phase center distance: 2.41'' (λ/2)
- Application center frequency: 2.45GHz
- 3dB beam width: 14°×85.5°;
- Max Gain: 15dBi.
DBS System Design

- Down Sampling/DDC
- Phase compensation
- Buffer
- BF
- Equalizer
- Detection
- Transmitter
- Position Estimation
- Frequency tracking
- Start up calibration
- LR DOA
- HR DOA
- TOA
- Channel Estimation
- Sensor

Flowchart indicating the system design components and their interconnections. The system involves down sampling/decimation, phase compensation, buffering, beamforming (BF), equalization, detection, and position estimation.
Sundance DSP System Development

SMT399
System clock generator

SMT374
Processor

SMT349
RF front end

SMT350
Dual ADC/DAC
DSP System Structure

- SMT399: System clock generator
- SMT350: Dual ADC/DAC
- SMT349: RF front end
- SMT363: Processor
User Interface
Acknowledgement

• Hui Tong (Ph.D., Graduated)
• Jafar Pourrostam (Ph.D., Graduated)
• Wenjie Xu (Ph.D., Graduated)
• Mohsen Pourkhaatoon (Ph.D., Graduated)
• Zhonghai Wang (Ph.D., Graduated)
• Xiaofeng Yang (Master Student, Graduated)
• Greg Price (Master Student)
• Shankar Giri (Master Student)
• Andrew Kolbus (Undergraduate Student)
References

Thank you!

Questions?