Wireless Local Positioning System (WLPS)

Reza Zekavat,

Wireless Positioning Lab; Michigan Tech

VIEWComm

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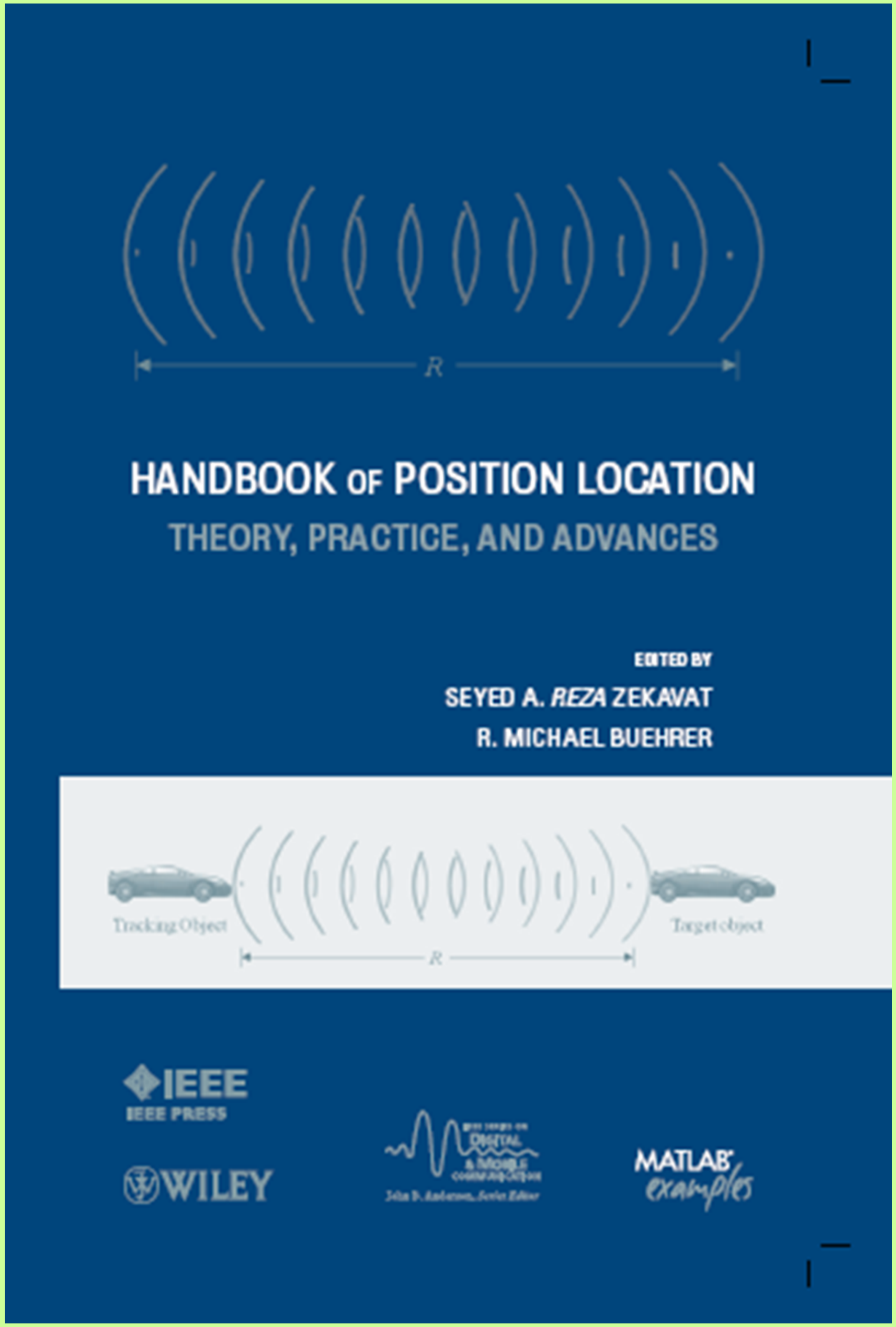
National Instruments, ARL, CERDEC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HANDBOOK OF POSITION LOCATION
THEORY, PRACTICE, AND ADVANCES
EDITED BY
SEYED A. REZA ZEKAVAT
R. MICHAEL BUEHRER
Tracking Object
Target object
R
IEEE
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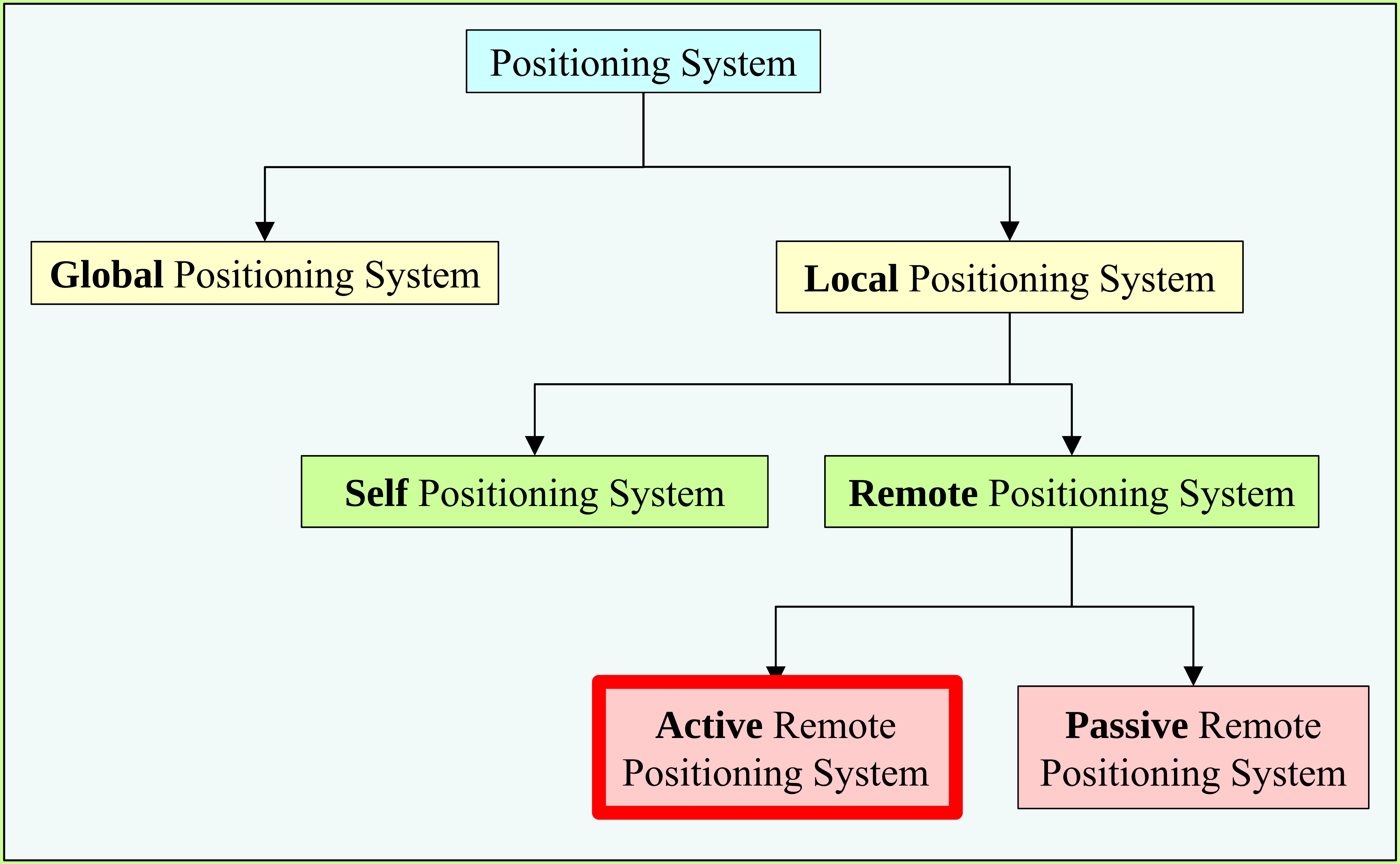
WILEY
MATLAB
examples

Positioning System Categories



Motivation for WLPS

To develop an active remote positioning system:

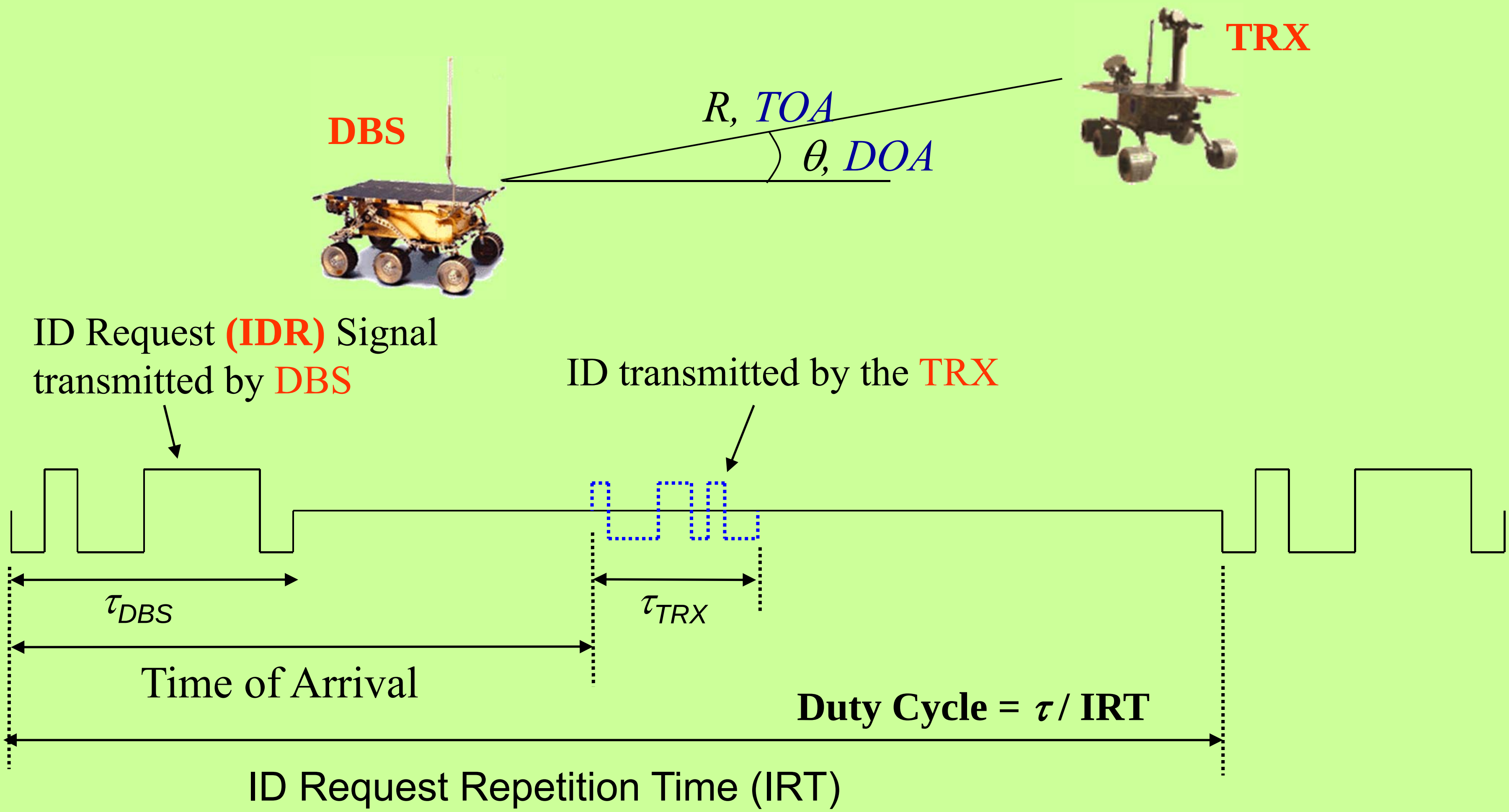
Suitable:

- 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

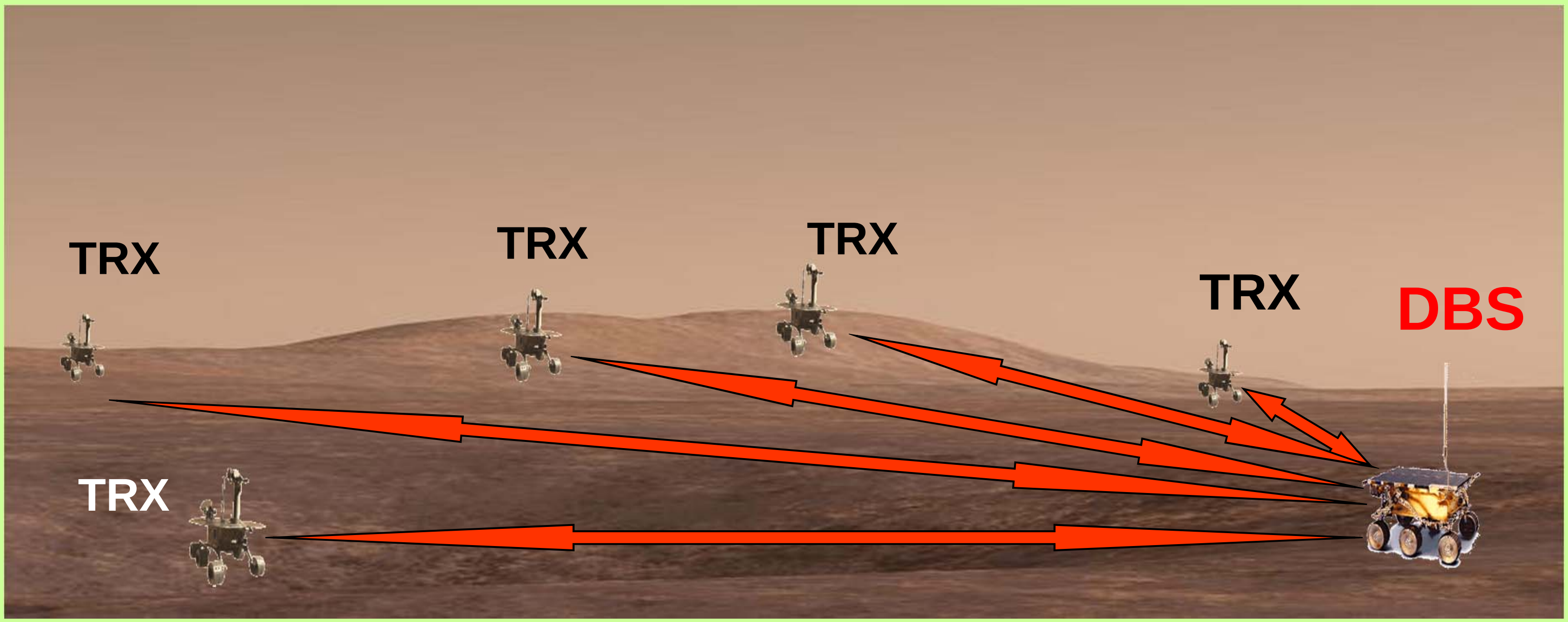
WLPS?



Seyed A. (Reza) Zekavat, Wireless Local Positioning System (WLPS), US Patent 7,489,935;

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

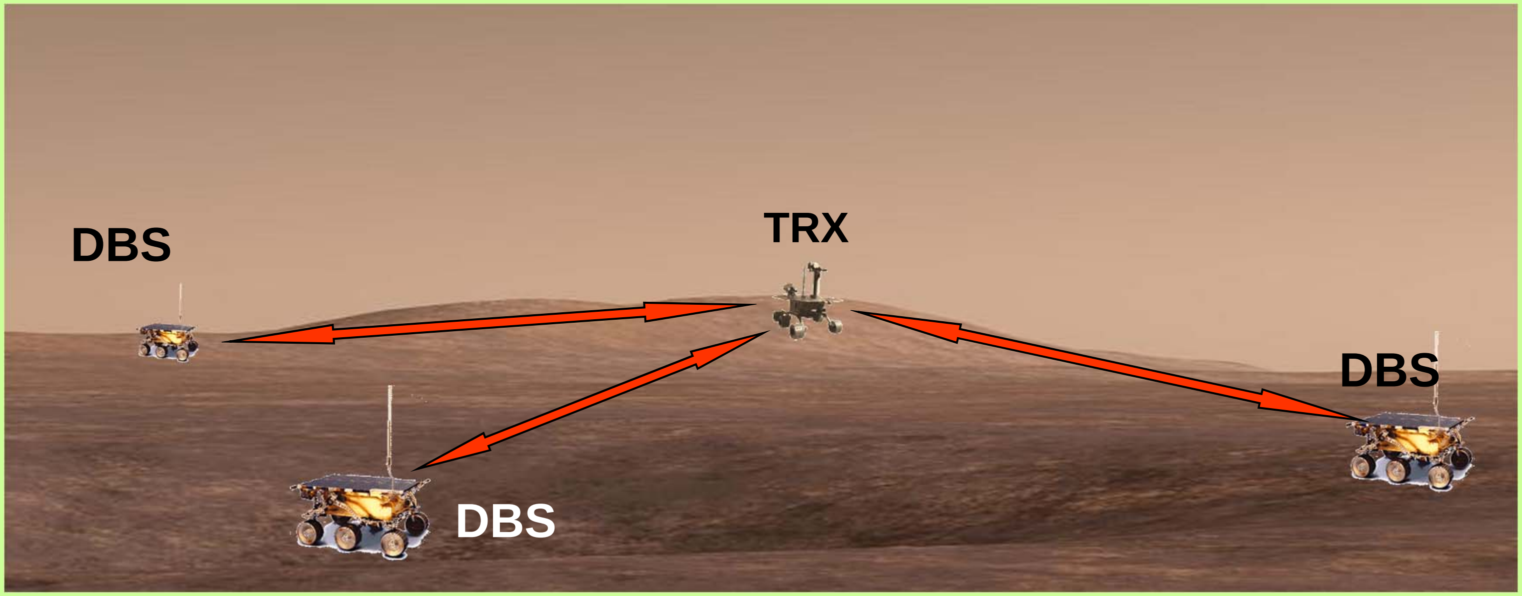
Each DBS communicates with a number of TRXs in its coverage area.



- 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:

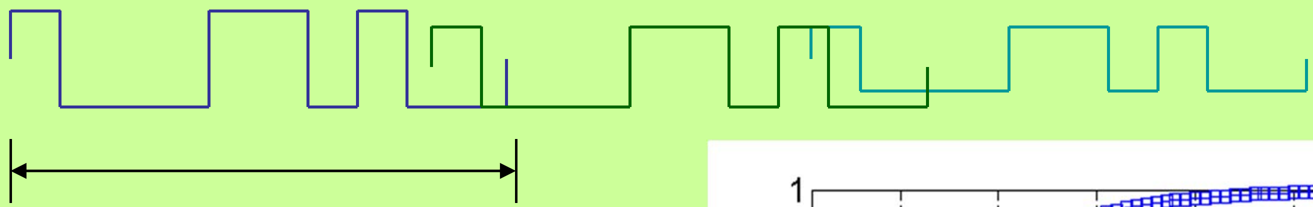
(a) CDMA techniques

(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).



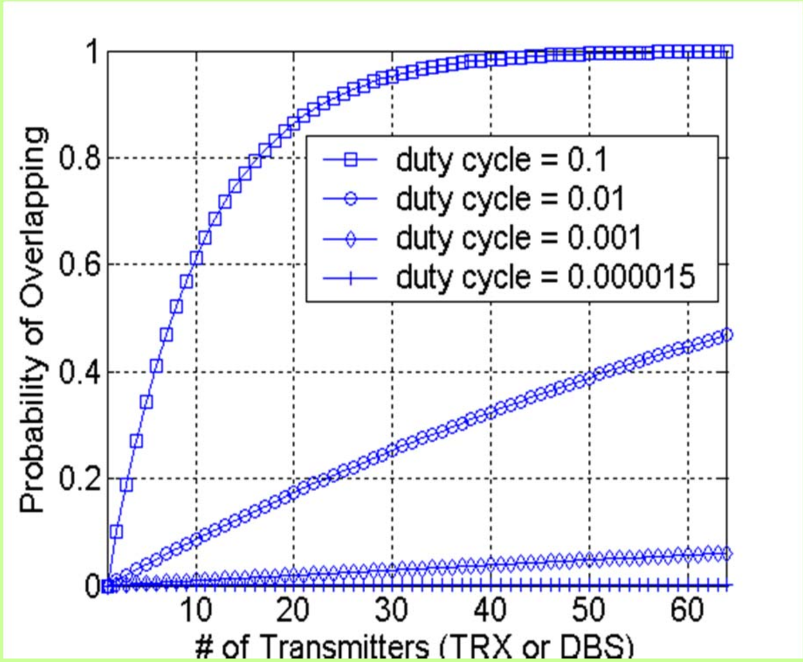
$\tau_{DBS}(\tau_{TRX})$ *in TRX (DBS) receiver*

$$P_{over} = 1 - (1 - d_c)^{K-1}$$

$$d_c = \tau / T = \text{duty cycle}$$

$$d_{c\_TRXRCVR} = \frac{\tau_{DBS}(DBS\ Pulse\ Duration)}{Selected\ IRT}$$

$$d_{c\_DBSRCVR} = \frac{\tau_{TRX}(TRX\ Pulse\ Duration)}{IRT_{\min}(Range)}$$

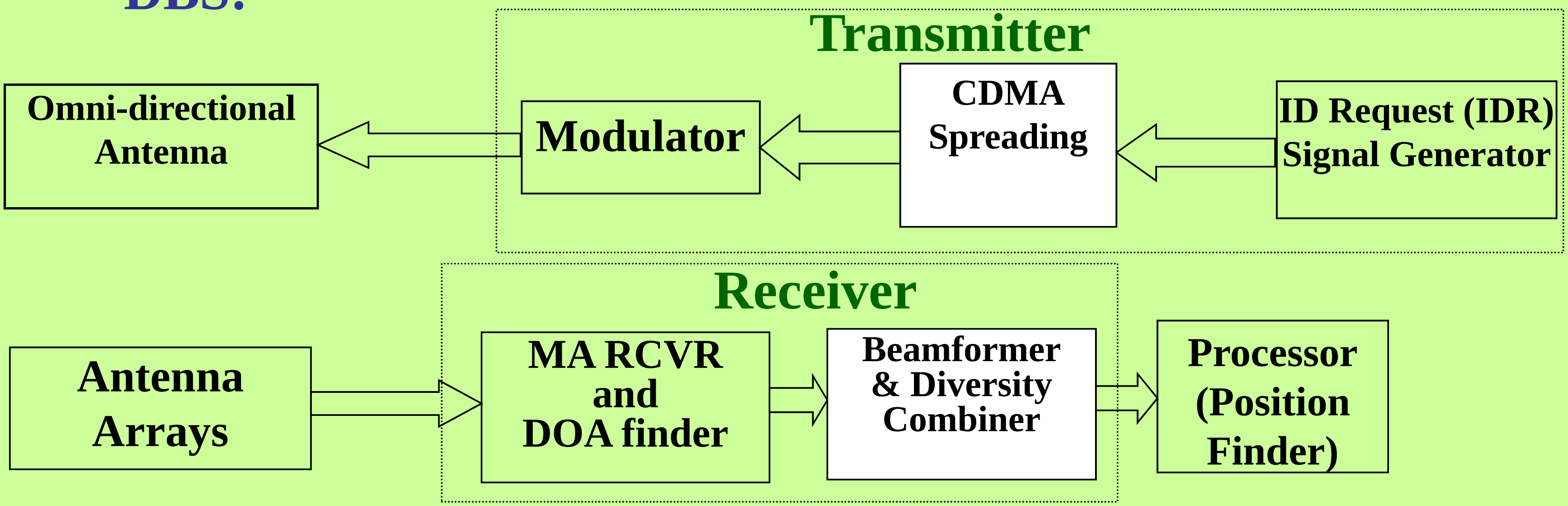


Interference effects at the DBS receiver can be reduced via directional Antennas and Multiple-Access Schemes

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;

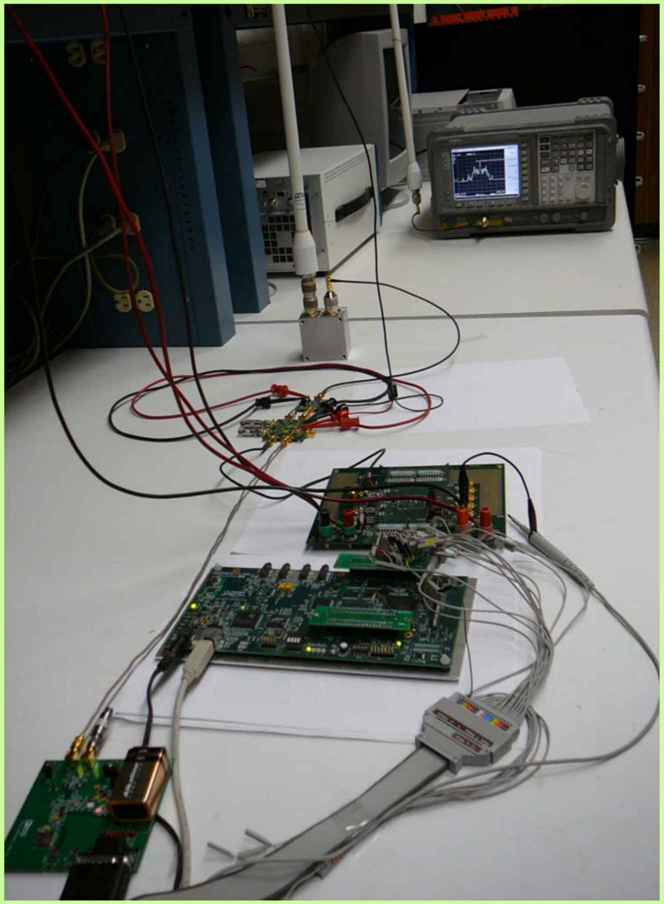
High Probability of Detection

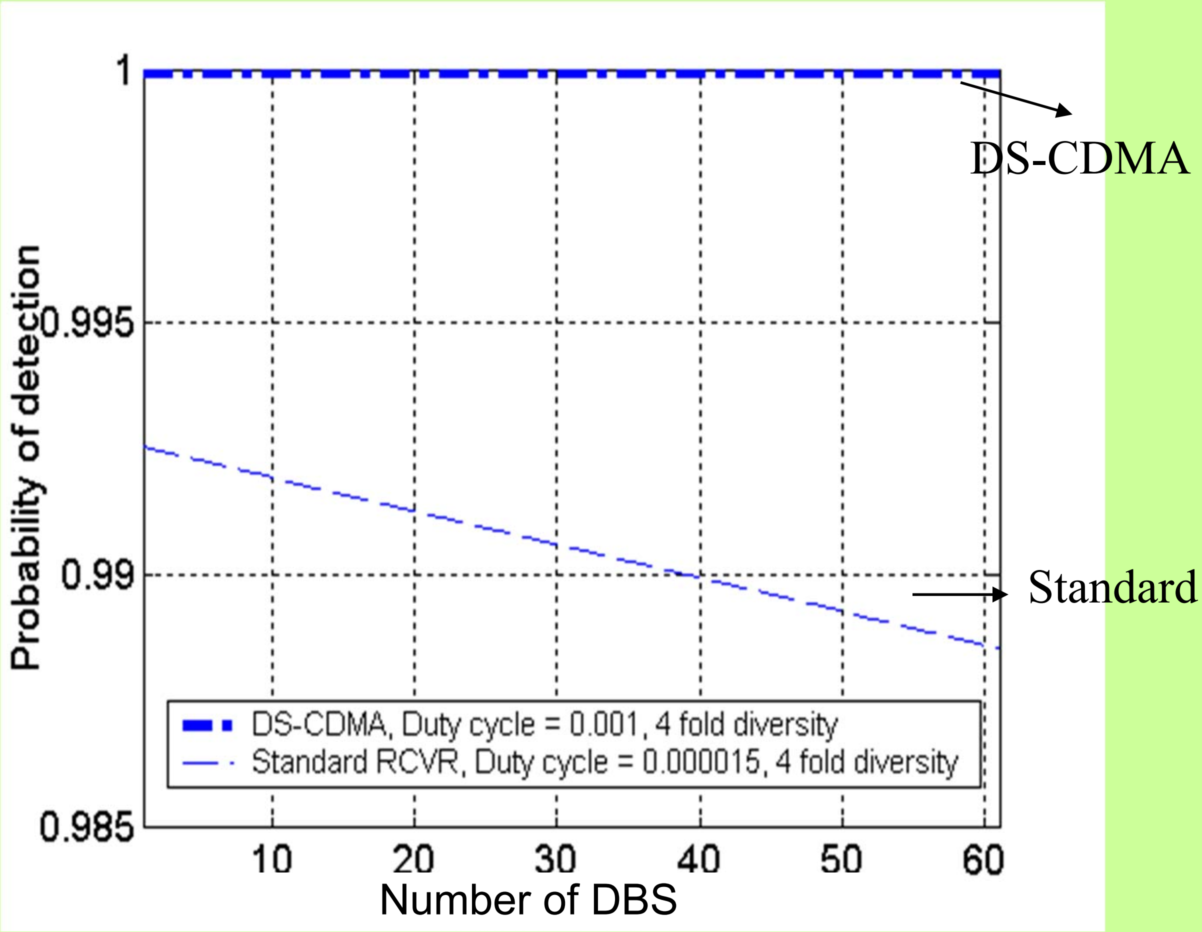
- Transmission Scheme: DS-CDMA
- Selection of IRT: As large as possible
- Beamforming: Exploiting Cyclostationary

H. Tong, J. Pourrostam, and S. A. Zekavat, "Optimum Beam-forming for a Novel Wireless Local Positioning System: A Stationarity Analysis and Solution," *EURASIP Journal on Advances in Signal Processing,* vol. 2007, Article ID 98243, 12 pages, 2007.

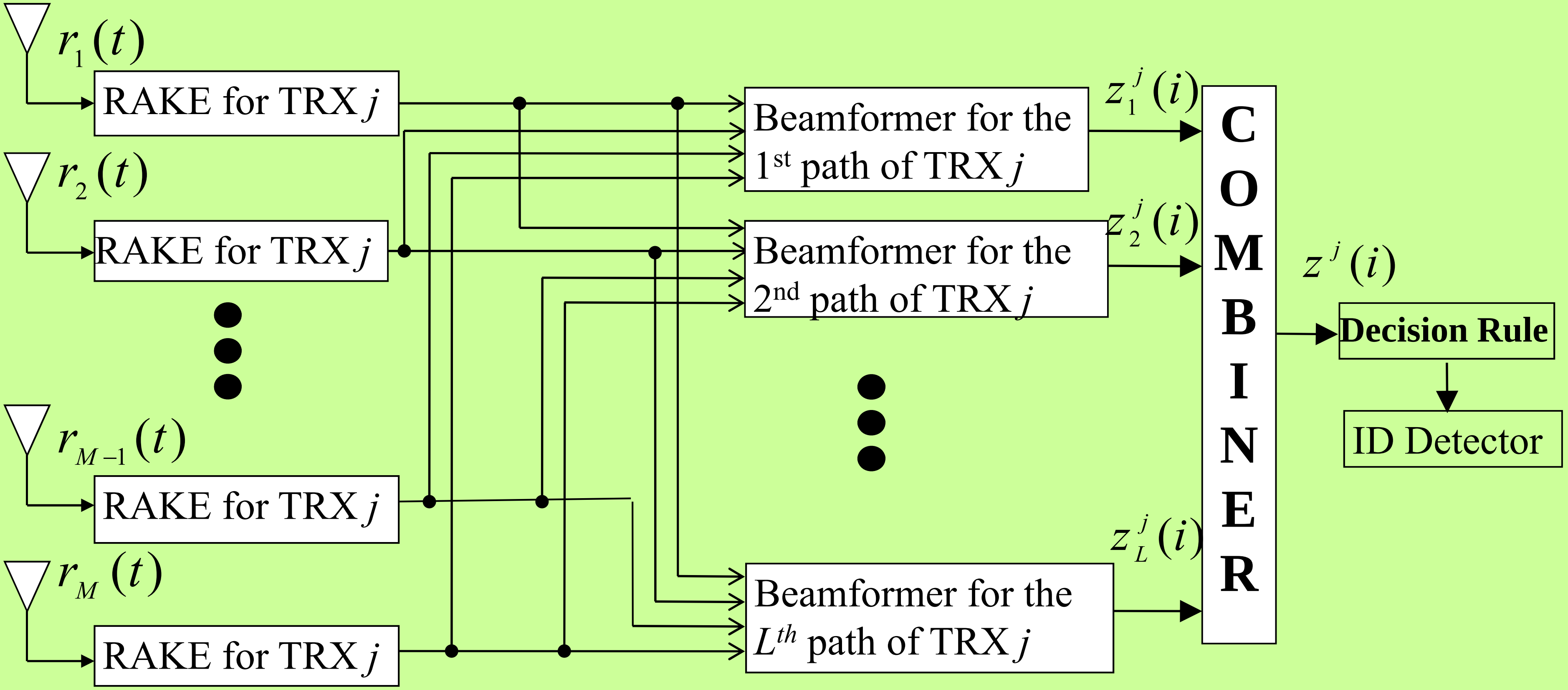
H. Tong and S. A. Zekavat, "A Novel Wireless Local Positioning System via Asynchronous DS-CDMA and Beam-forming: Implementation and Perturbation Analysis," *IEEE Transactions on Vehicular Technology,* vol. 56, no. 3, pp. 1307 – 1320, May 2007.

TRX Receiver Simulation Results



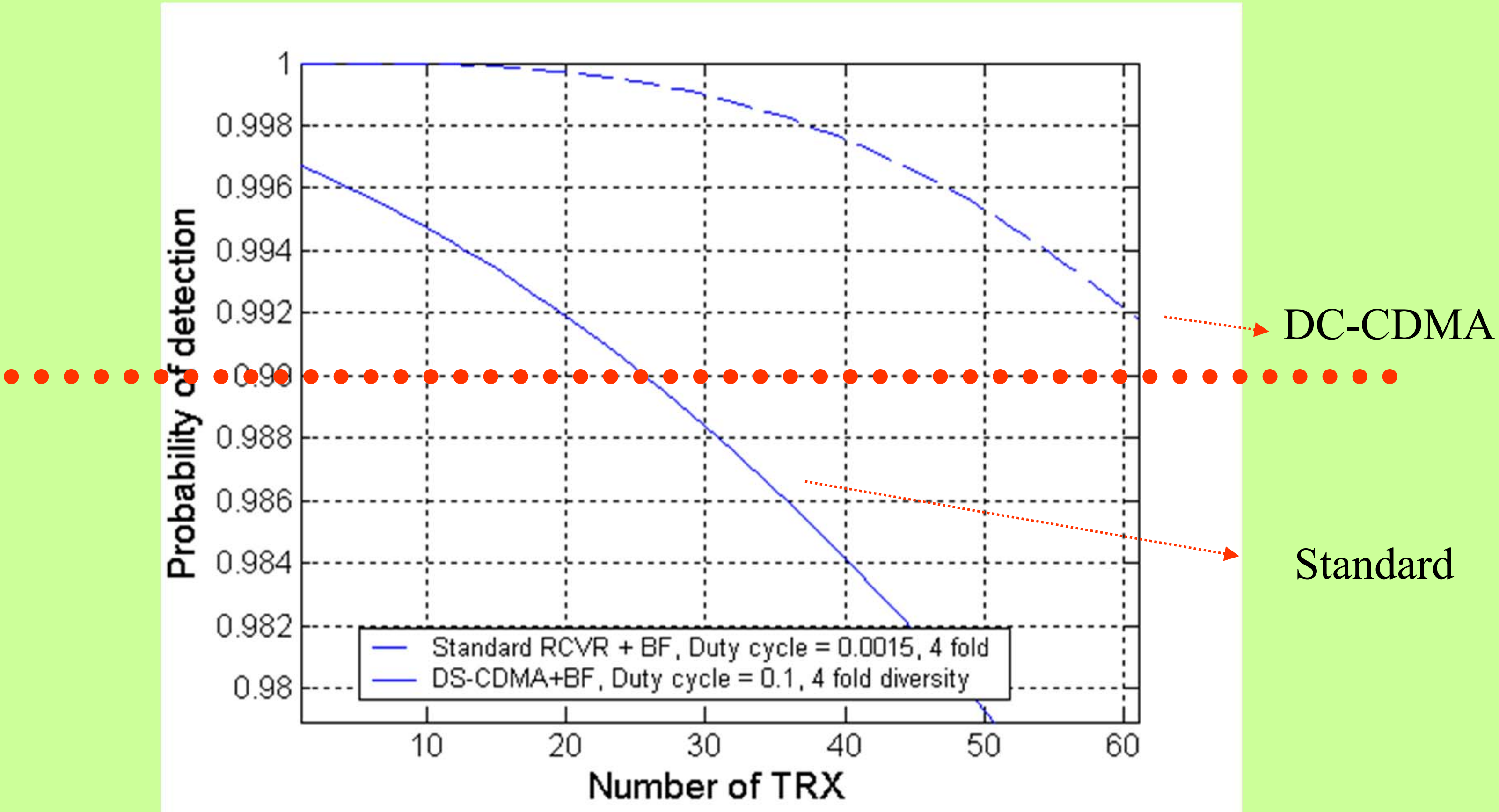


DBS Receiver: Beamforming Combined with DS-CDMA



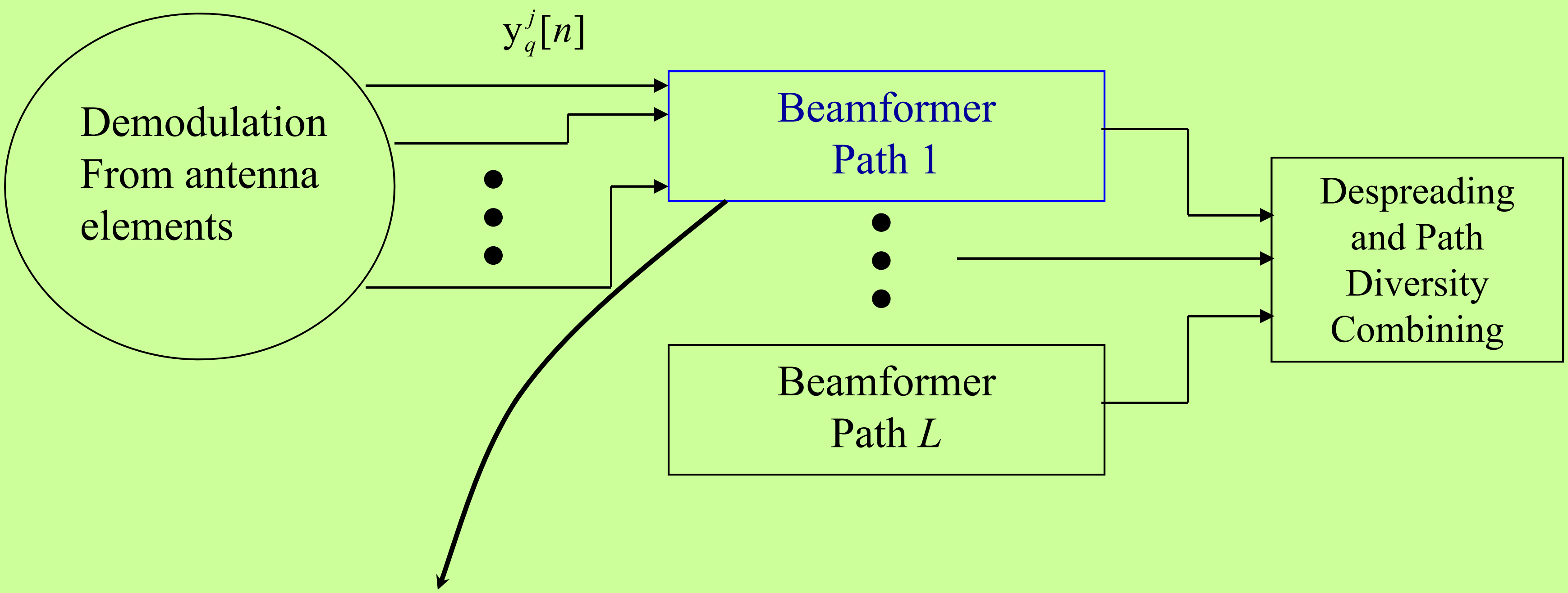
DBS Receiver with Beam Forming

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



$$z_q^j[n] = \mathbf{w}^H(\theta_q^j) \cdot \mathbf{y}_q^j[n]$$

-- For conventional beamforming: $\mathbf{w}(\theta_q^j) = \mathbf{V}(\theta_q^j)$

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

Linear Constrained Minimum Variance (LCMV) Beam Forming

- **Design criteria:**

$$\min \ \mathbf{w}^H(\theta_q^j)\mathbf{R}_q^j\mathbf{w}(\theta_q^j) \qquad s.t. \ \mathbf{w}^H(\theta_q^j)\mathbf{v}(\theta_q^j) = 1$$

$$\mathbf{R}_q^j = \mathrm{E}[\mathbf{y}_q^j \cdot \mathbf{y}_q^{jH}]$$

- **Solution:**

$$\mathbf{w}_{opt}(\theta_q^j) = \frac{\mathbf{R}_q^{j^{-1}}\mathbf{V}(\theta_q^j)}{\mathbf{V}^H(\theta_q^j)\mathbf{R}_q^{j^{-1}}\mathbf{V}(\theta_q^j)}$$

In general, LCMV leads to a better removal of interference effects compared to the Conventional Beamforming.

Covariance Matrix Estimation for LCMV BF

- Definition:

$$\mathbf{R}_q^j = \mathrm{E}[\mathbf{y}_q^j \cdot \mathbf{y}_q^{j^H}]$$

- Standard estimation method:

$$\hat{\mathbf{R}}_q^j = \frac{1}{\Gamma}\sum_{n=0}^{\Gamma-1}\mathbf{y}_q^j[n]\cdot\mathbf{y}_q^{j^H}[n]$$

- Valid if:

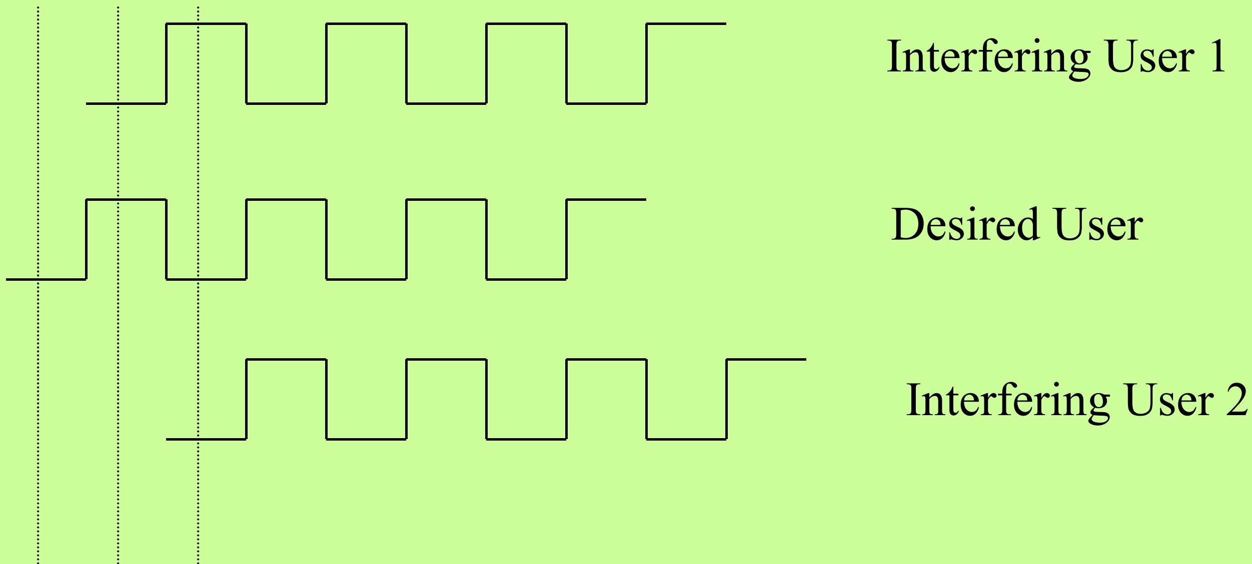
$$\mathrm{E}[\mathbf{y}_q^j[n]\cdot\mathbf{y}_q^{j^H}[n]] = \mathrm{E}[\mathbf{y}_q^j[n+1]\cdot\mathbf{y}_q^{j^H}[n+1]]$$

- However……

Non-Stationarity in WLPS

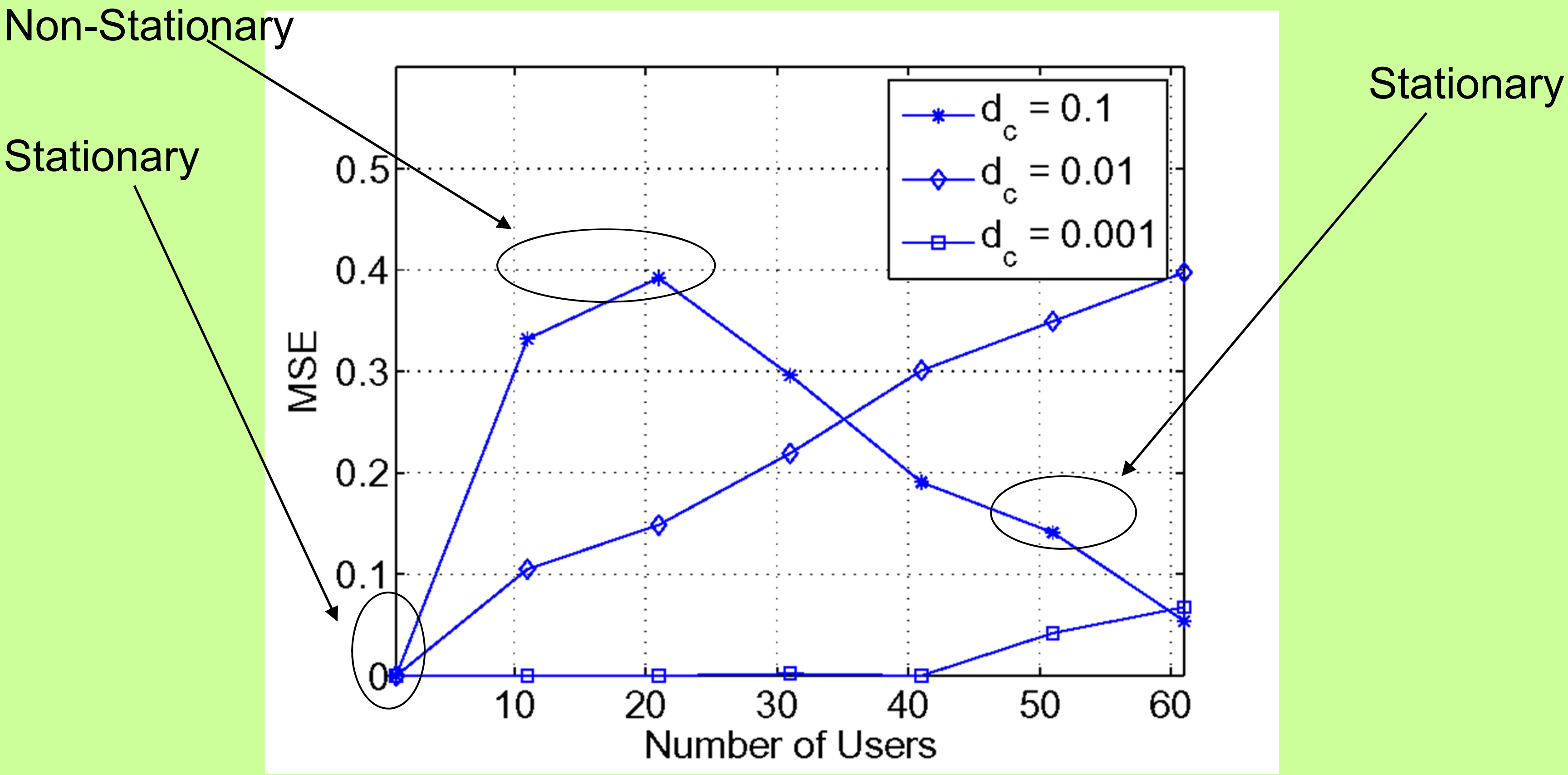
- For WLPS:

$$\mathrm{E}[\mathbf{y}_q^j[n]\cdot\mathbf{y}_q^{j^H}[n]] \neq \mathrm{E}[\mathbf{y}_q^j[n+1]\cdot\mathbf{y}_q^{j^H}[n+1]]$$



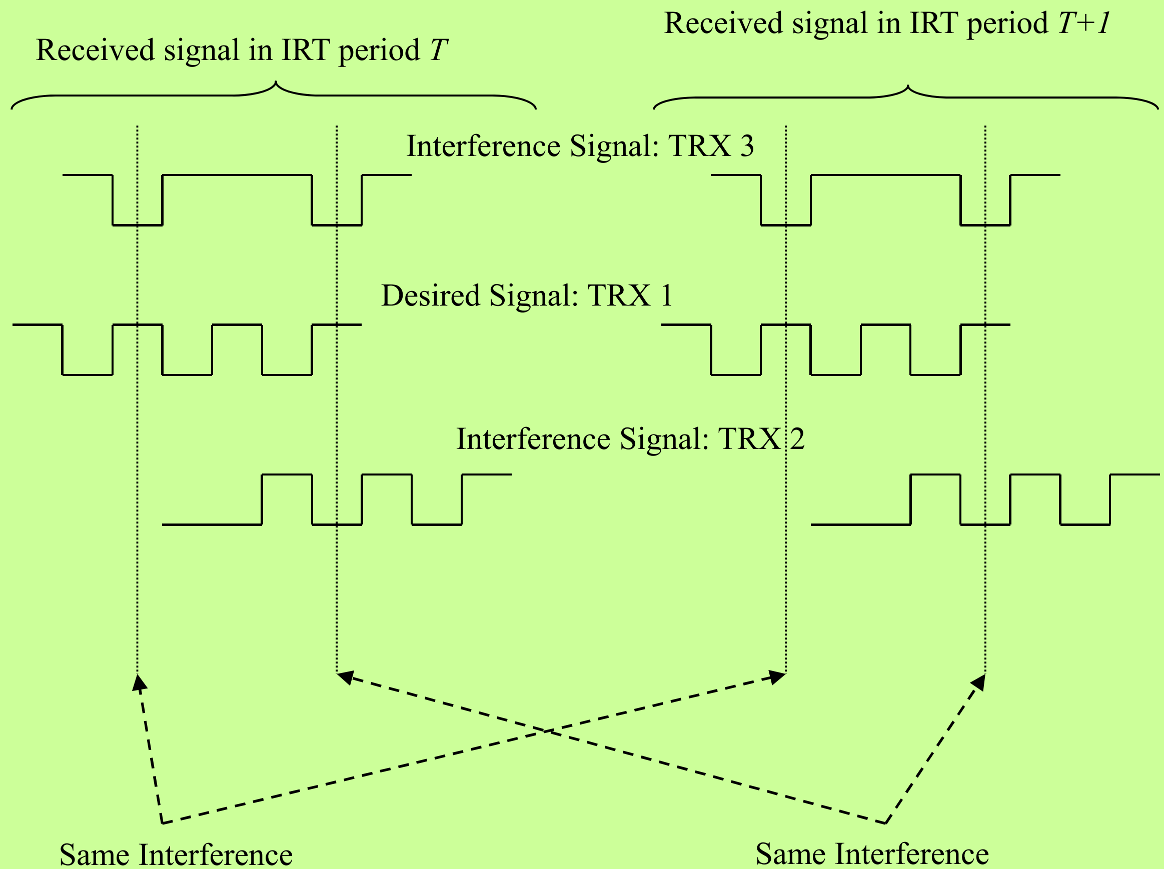
Different bits experience different interference

The Mean Square Error of Covariance Matrix Estimation



$$MSE = \sum_{m=1}^{M}\sum_{u=1}^{M}(\mathbf{R}_q^j(m,u) - \hat{\mathbf{R}}_q^j(m,u))^2$$

Solution: Cyclostationarity



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

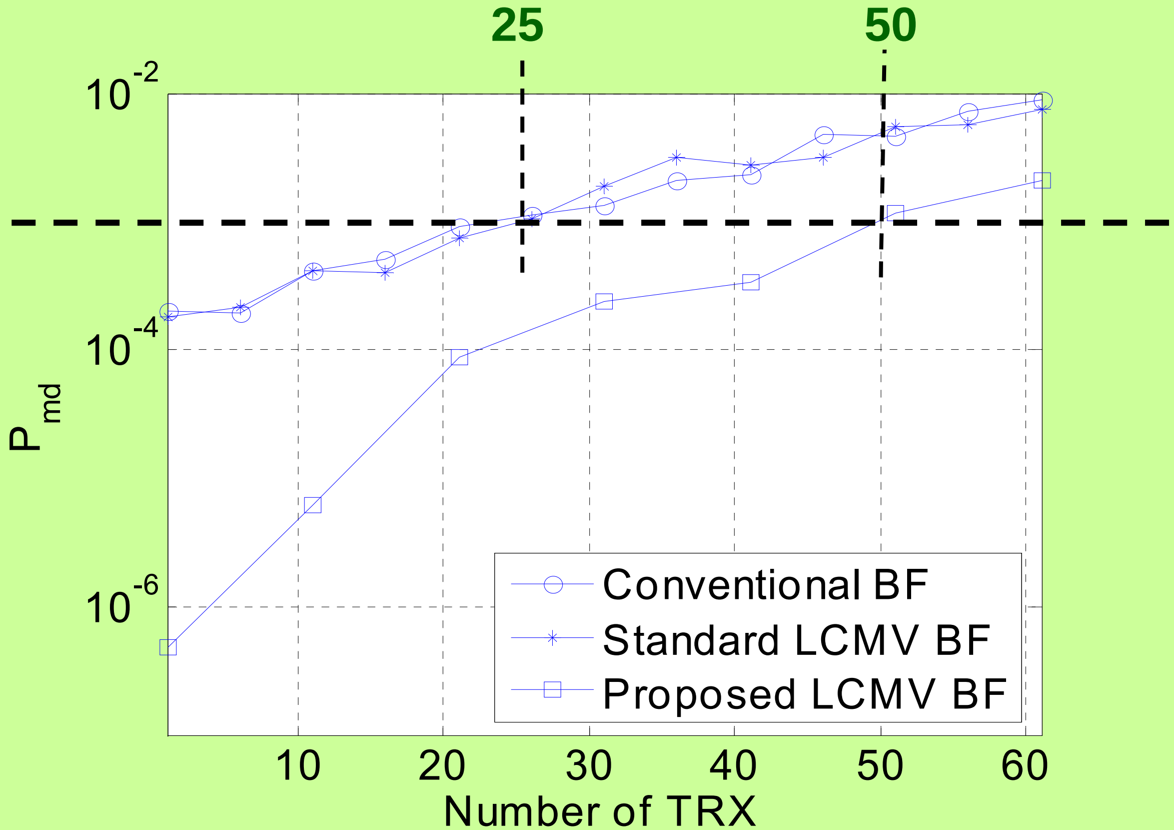
$$\hat{\mathbf{R}}_q^j[n] = \frac{1}{\Omega} \sum_{\omega=0}^{\Omega-1} \mathbf{y}_q^j[\omega, n] \cdot \mathbf{y}_q^{j^H}[\omega, n]$$

Number of Static User Frames

Received signal at n^{th} chip of ω^{th} frame

Probability of Miss-Detection Performance

Cyclostationarity remains for 8 frames (IRT)



LCMV Beam-forming using cyclostationarity for observed signal covariance matrix highly increases the performance and the capacity.

DIRECTION-OF-ARRIVAL (DOA) ESTIMATION

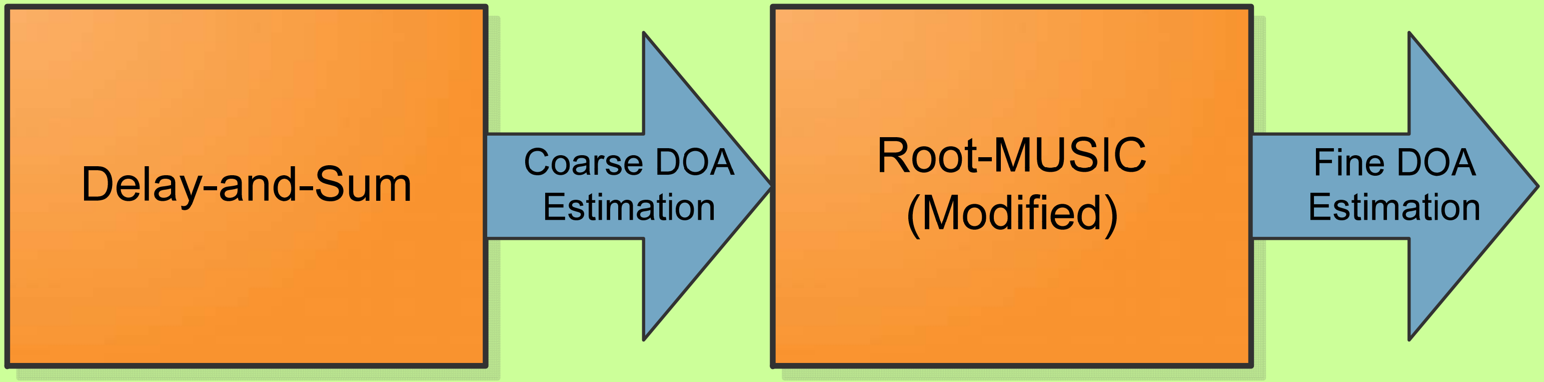
- Antenna Element Mutual Coupling;
- Antenna – Receiver Calibration;
- Priori Knowledge of the number of available sources;
- Signal-to-Noise Ratio;
- Complexity

W. Wang, and S. A. Zekavat, "A Novel Semi-distributed Localization via Multi-node TOA-DOA Fusion," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 7, pp. 3426 – 3435, Sept. 2009.

W. Wang, and S. A. Zekavat, "Comparison of Semi-Distributed Multi-Node TOA-DOA Fusion Localization and GPS-Aided TOA (DOA) Fusion Localization for MANETs," *EURASIP Journal on Advances in Signal Processing,* vol. 2008, Article ID 439523, 16 pages, 2008. doi:10.1155/2008/439523, 2008.

S. A. Zekavat, A. Kolbus, X. Yang, Z. Wang, J. Pourrostam, and M. Pourkhaatoon, "A Novel Implementation of DOA Estimation for Node Localization on Software Defined Radios: Achieving High Performance with Low Complexity," proceedings *IEEE ICSPC 2007*, Dubai, UAE, 26 – 27 Nov. 2007.

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

Delay-and-Sum

Coarse Estimation

Seed Root from Coarse Estimation

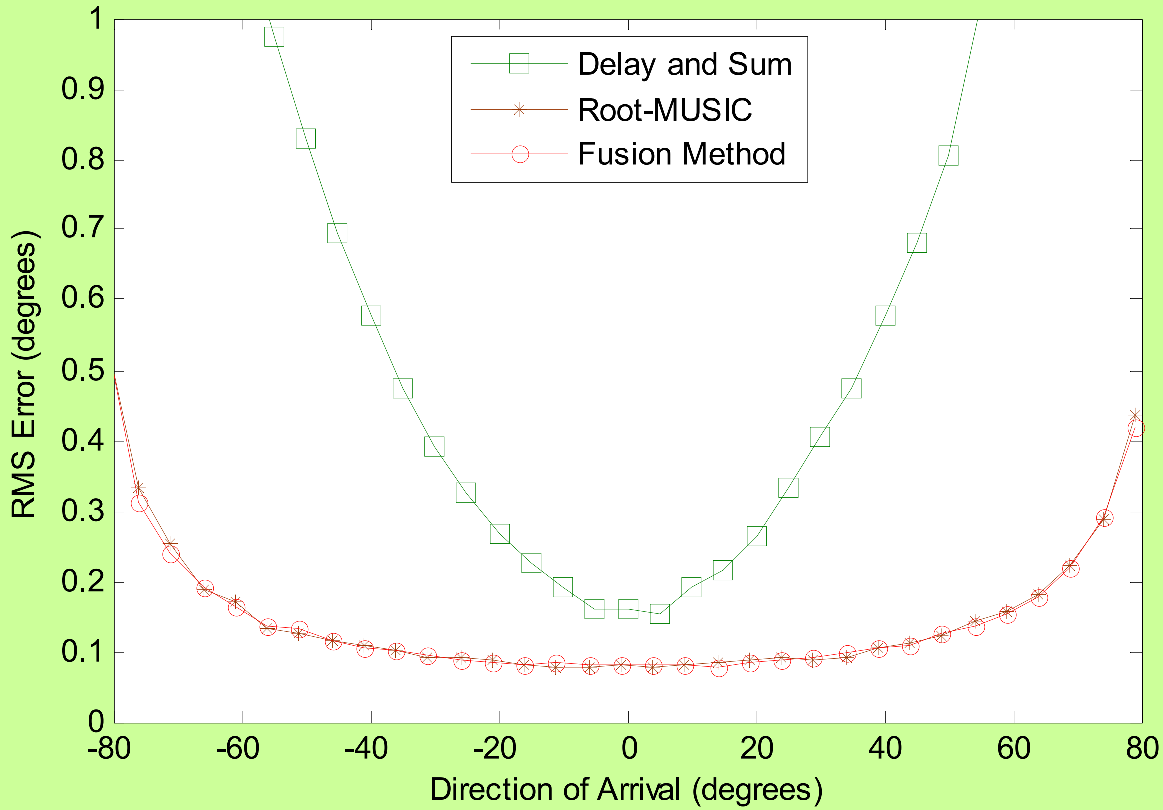
Modified Root-MUSIC

Find *single* root of polynomial with seed + Newton's Method

Calculate Fine DOA estimation from phase of root

Accuracy

Assumptions: 1 signal source, 6 antennas, 50 snapshots, 15dB SNR

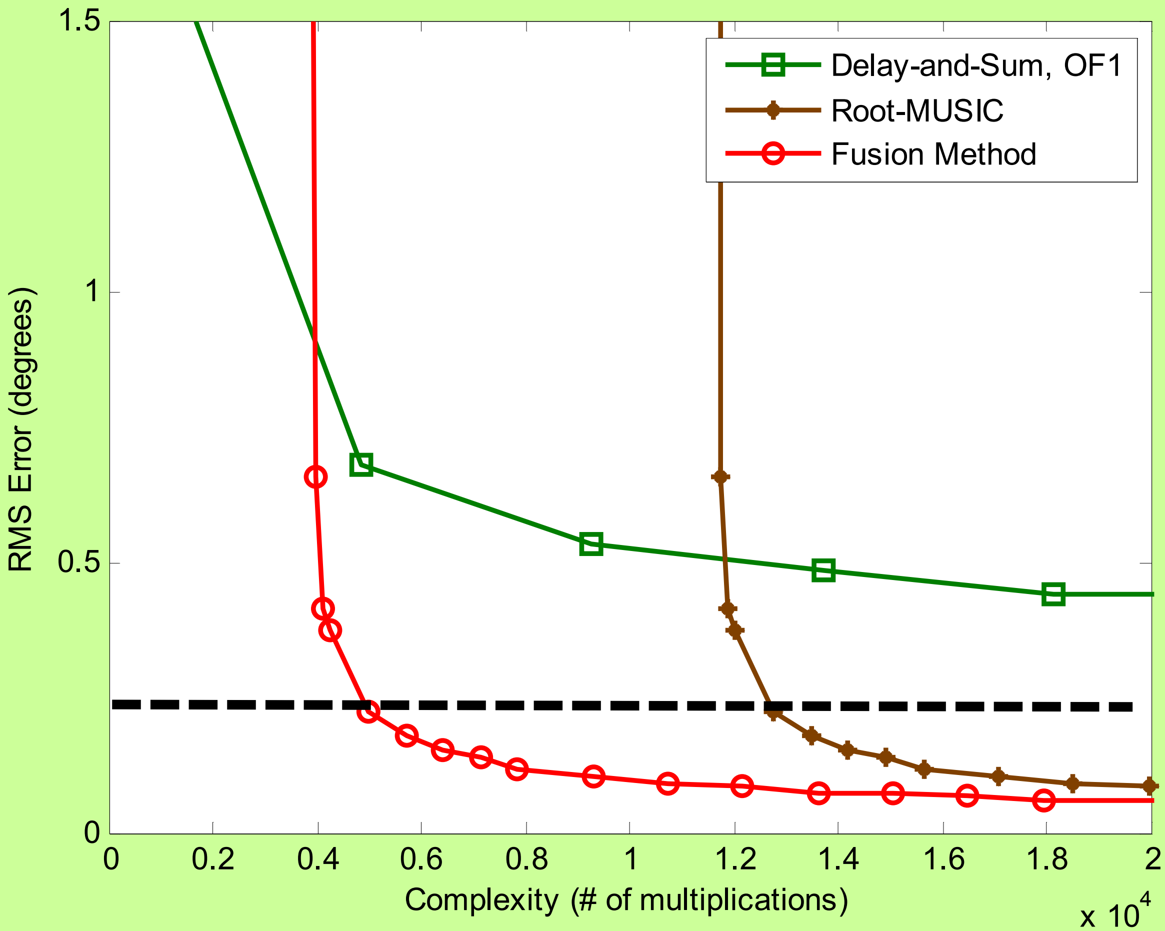


Conclusions: Error increases as DOA deviates from bore-sight.

Fusion method has the same error characteristics as Root-MUSIC .

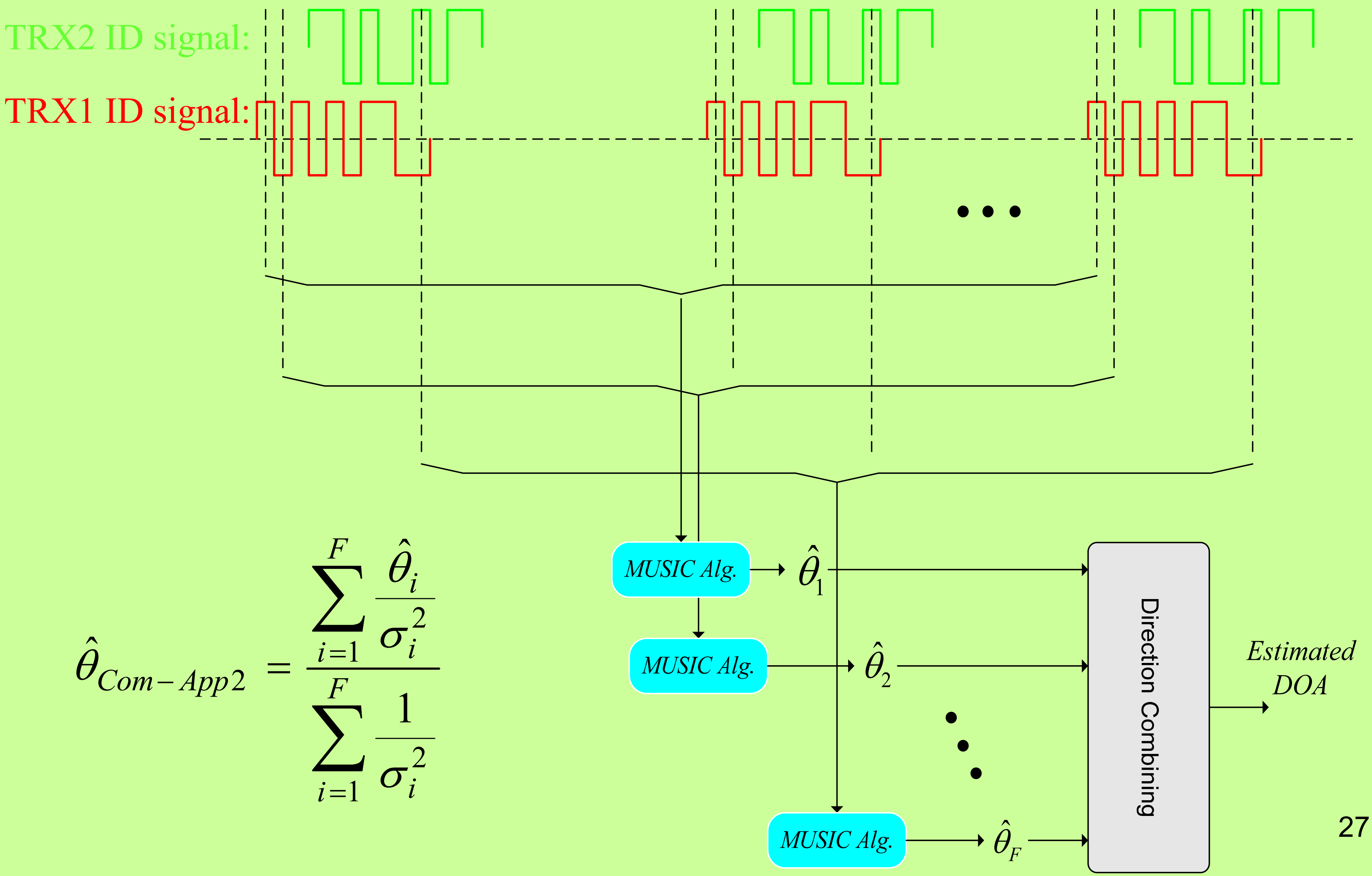
Complexity

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.

Cyclostationary: Direction Combining



$$\hat{\theta}_{Com-App2} = \frac{\sum_{i=1}^{F} \frac{\hat{\theta}_i}{\sigma_i^2}}{\sum_{i=1}^{F} \frac{1}{\sigma_i^2}}$$

Comparison

	Sensitivity to SNR	Sensitivity to Calibration	Sensitivity to Multipath	Resolution	Complexity
D-S	High	Moderate	High	Low	Low
Max Entropy	Moderate	Moderate	Moderate	Moderate	Moderate
MUSIC	Low	High	Low	High	High
Root MUSIC	Lower	High	Lower	Very High	High
ESPIRIT	Low	Low	Low	High	Very High
Fusion	Low	Moderate	Lowest	Very High	Moderate

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.

M. Pourkhaatoun, and S. A. Zekavat, “High Precision Concatenated Spectrum Cognitive Radio-Based Range Estimation,” proceedings *IEEE MILCOM’2010*, Nov. 03 – 06, 2010, San Jose, CA.

Major Sources of Error

For this signal Model:

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

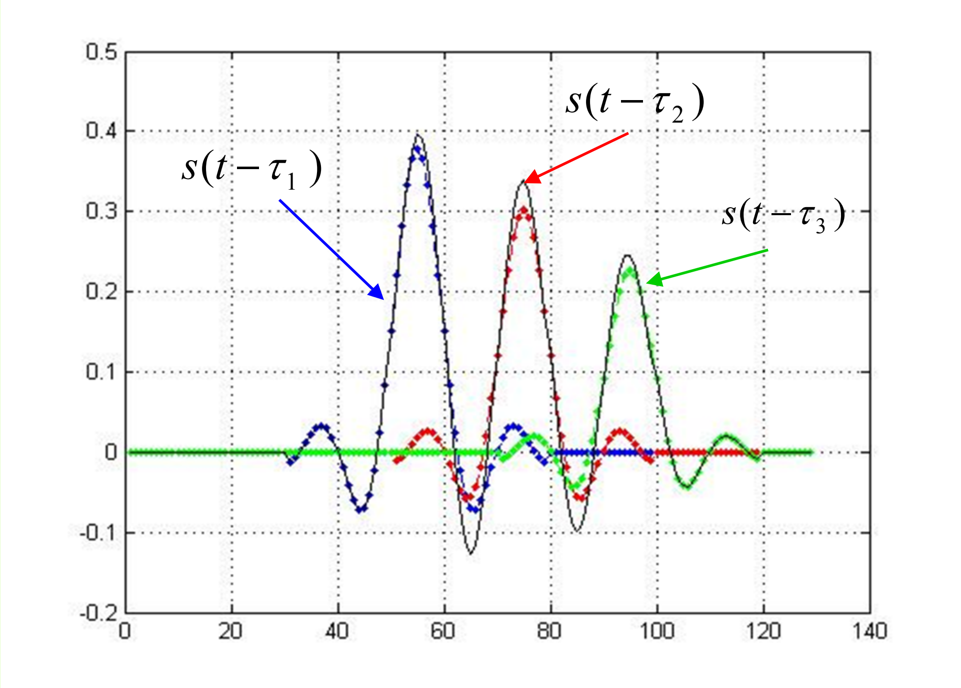
Multipath **Noise**

Two major sources of error:

1. Additive noise
2. Multipath $\longrightarrow$ Delay Difference is Important

Simple Scenario: UWB

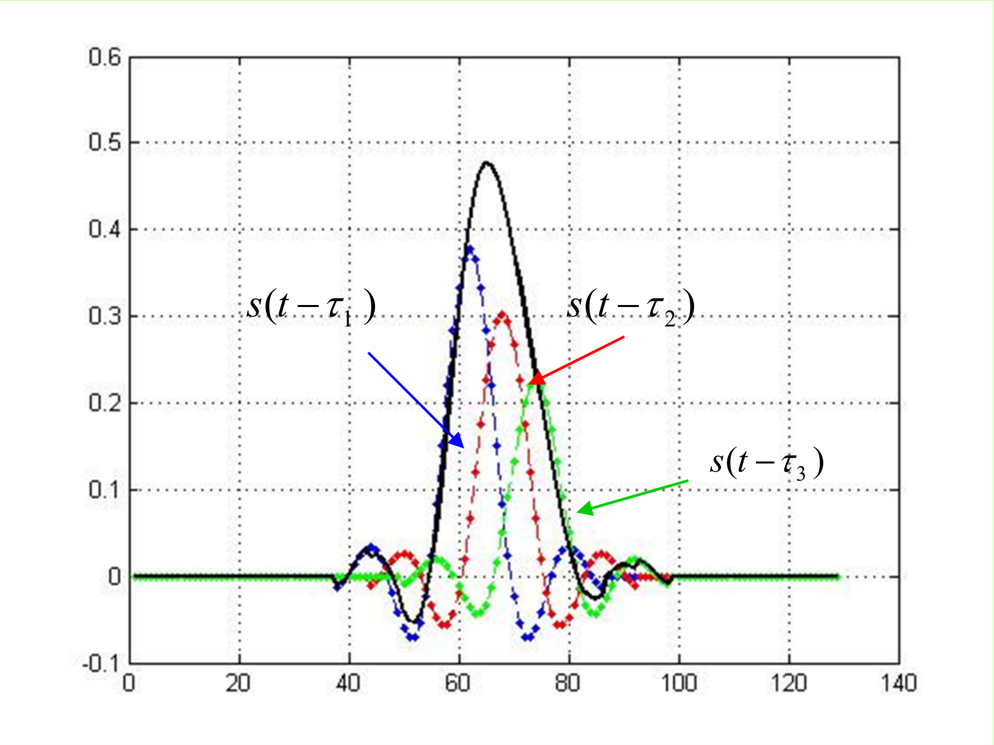
$$\Delta\tau >> T_s$$



Simple Solution: Correlator + ML

Complex Scenario: Wide Band

$$\Delta\tau \approx T_s$$



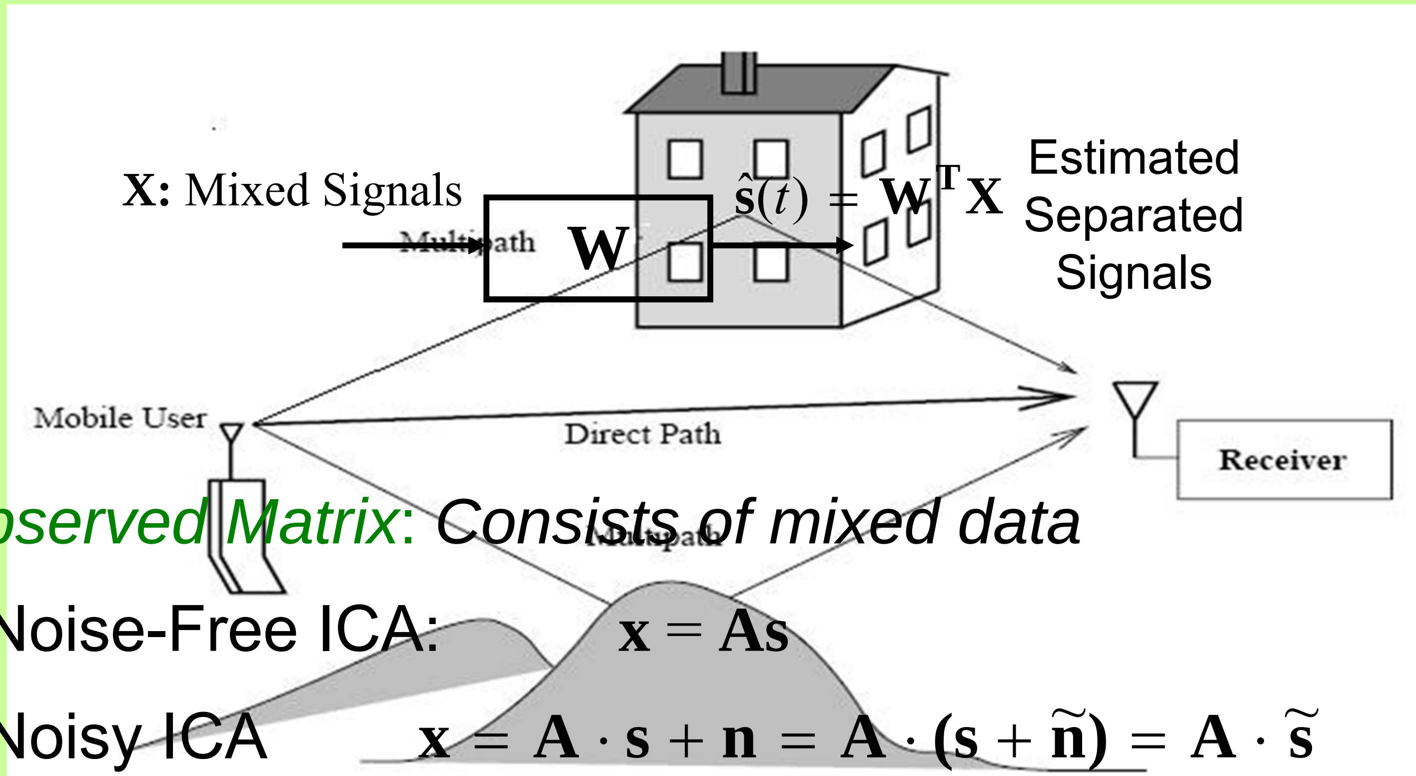
Solution is not Simple: Our focus!!

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;



Observed Matrix: *Consists of mixed data*

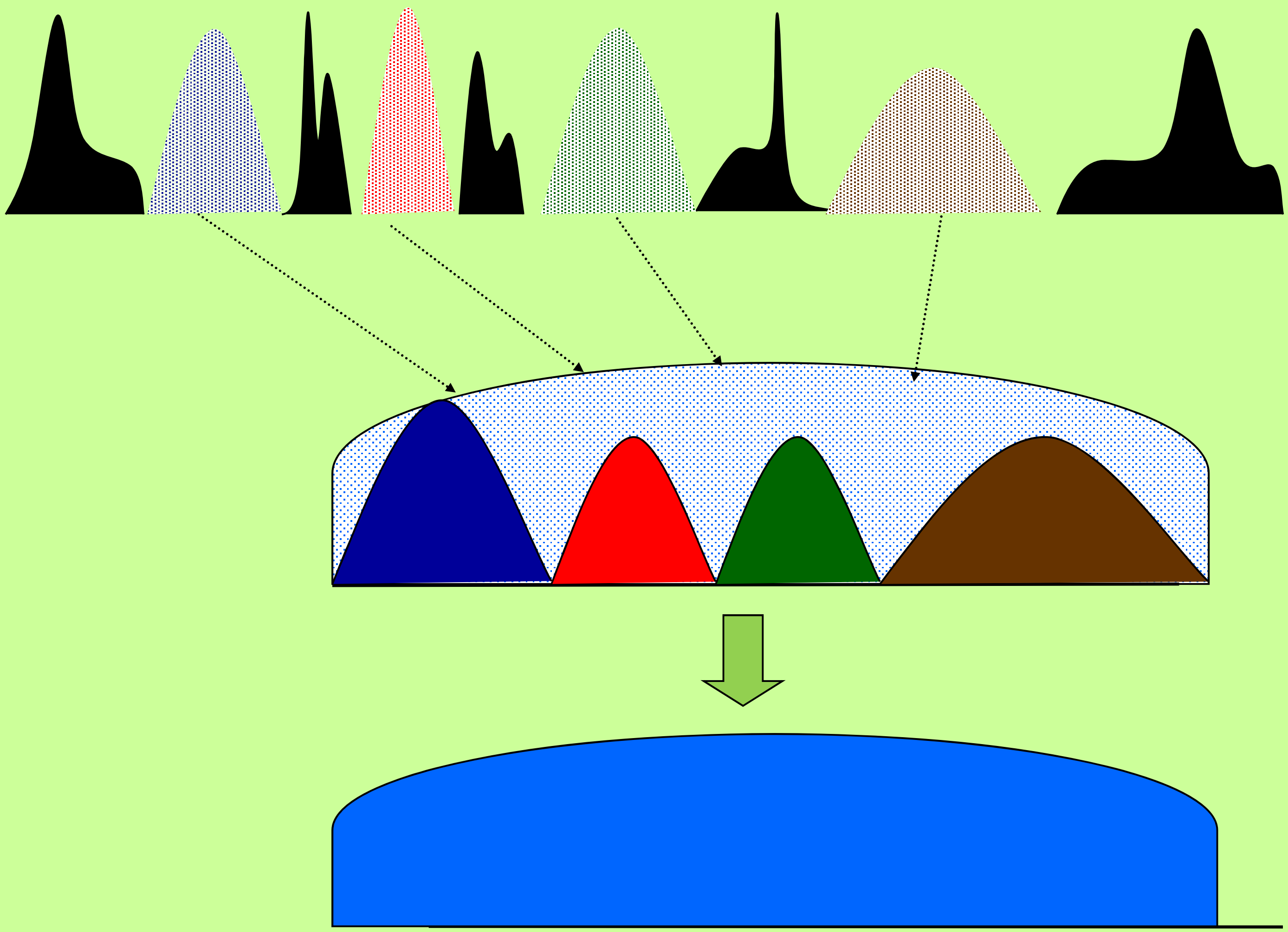
Noise-Free ICA: $\mathbf{x} = \mathbf{A}\mathbf{s}$

Noisy ICA $\mathbf{x} = \mathbf{A} \cdot \mathbf{s} + \mathbf{n} = \mathbf{A} \cdot (\mathbf{s} + \tilde{\mathbf{n}}) = \mathbf{A} \cdot \tilde{\mathbf{s}}$

Conclusions

	Sensitivity to SNR	Sensitivity to BW	Resolution	Implementation Complexity
DLL	High	High	Low	Low
MLE	Moderate	High	Moderate	Moderate to High
EKF	Low	Moderate	Moderate	Moderate
MUSIC	Low	Low	High	High
ICA-Based	Low	Low	High	Moderate

Concatenated Spectrum TOA



NLOS Identification and Localization

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

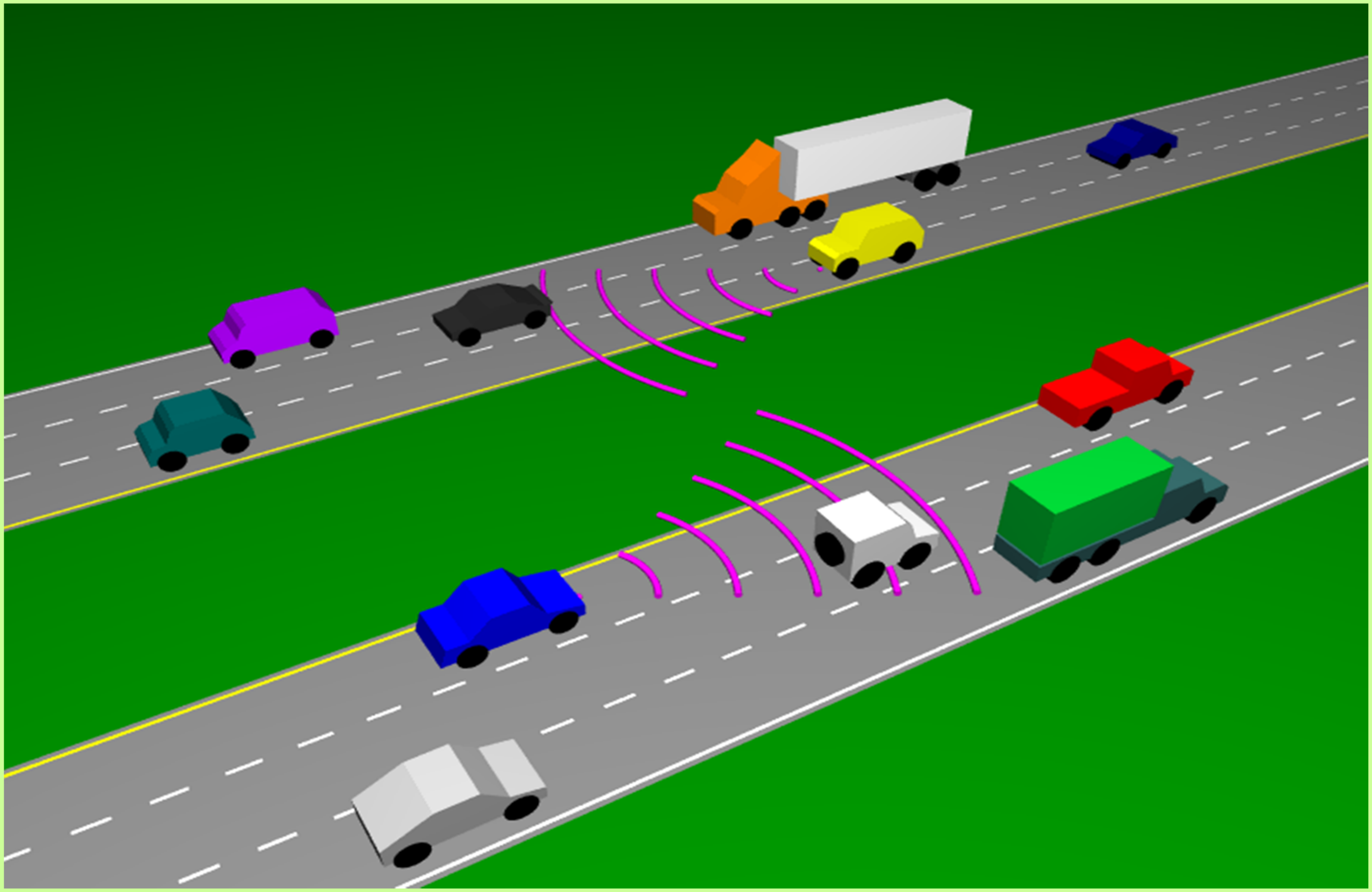
W. Xu, Z. Wang, and S. A. Zekavat, "Non-Line-of-Sight Identification in Wireless Localization via Phase Difference Statistics across Two Antenna Elements," *IET Communications*, Accepted.

Z. Wang, and S. A. Zekavat, "Omni Mobile Node Localization in NLOS Scenarios," *IEEE Transactions on Mobile Computing*, Accepted (with Minor Revisions).

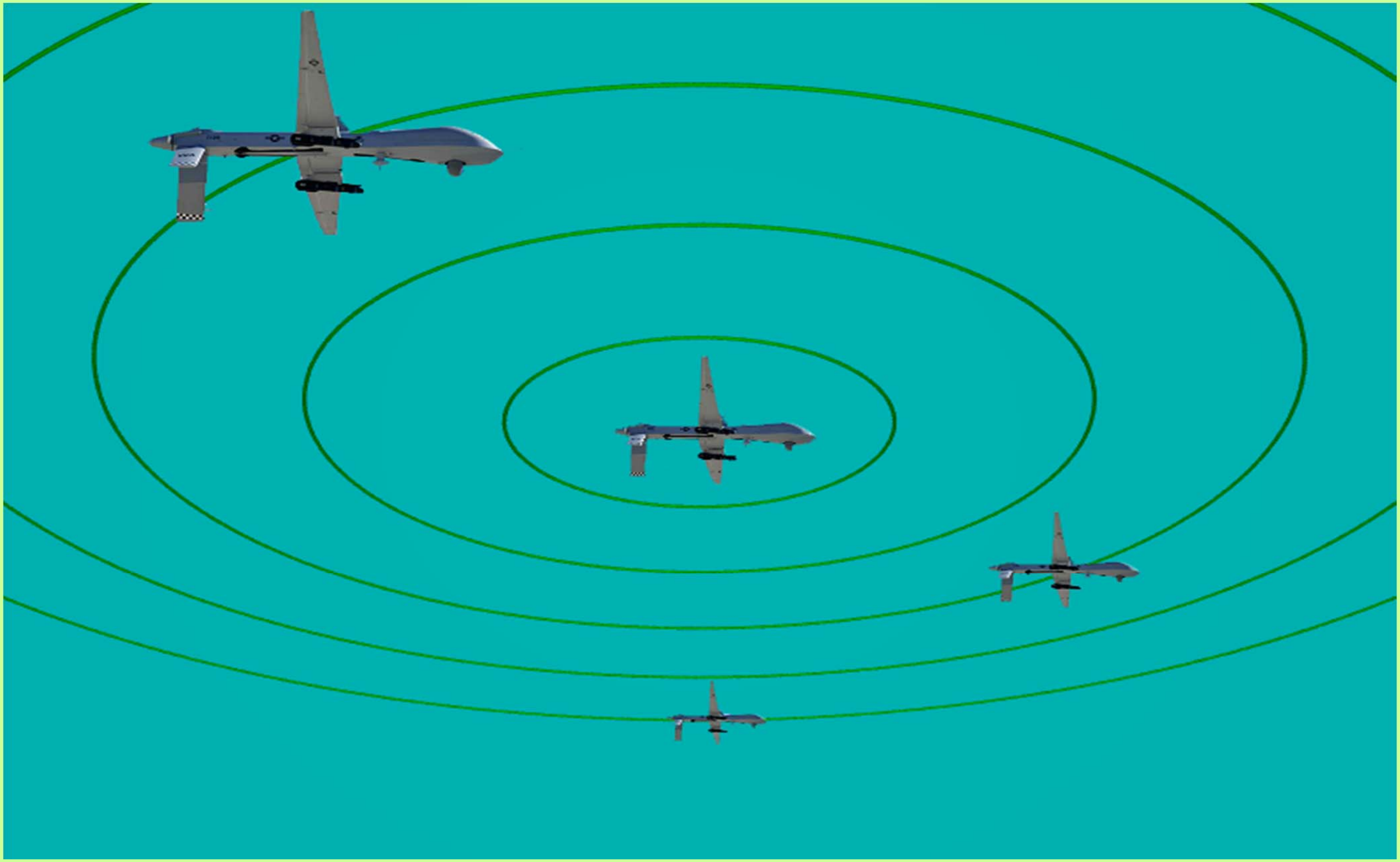
APPLICATIONS

Road Safety

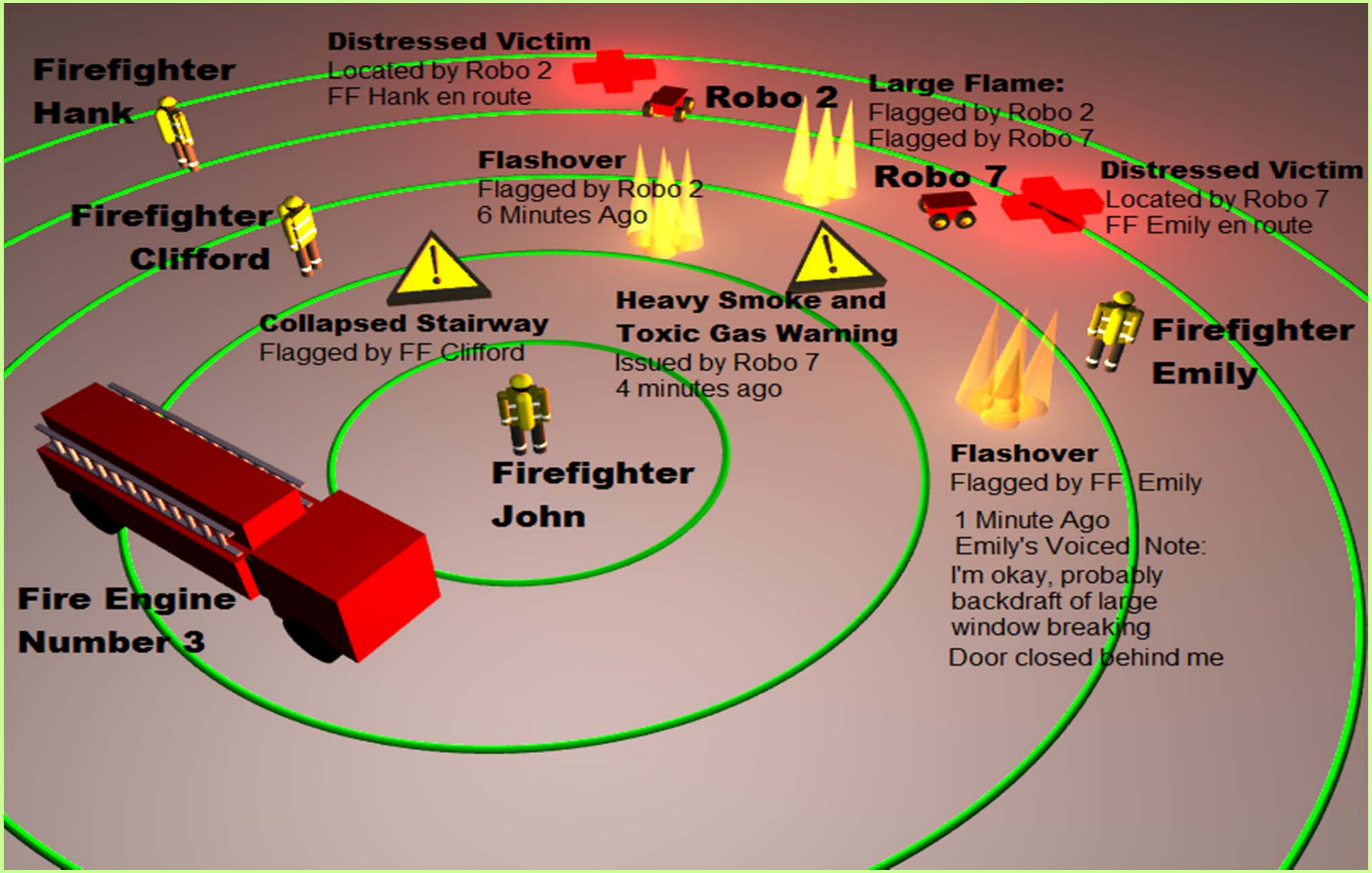
- Injuries (or die) of Hundreds of thousands of people.
- Intelligent vehicle initiative was announced in 1998 by the U.S. DOT.



Multi-UAV Coordination



Firefighters and Indoor Safety



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

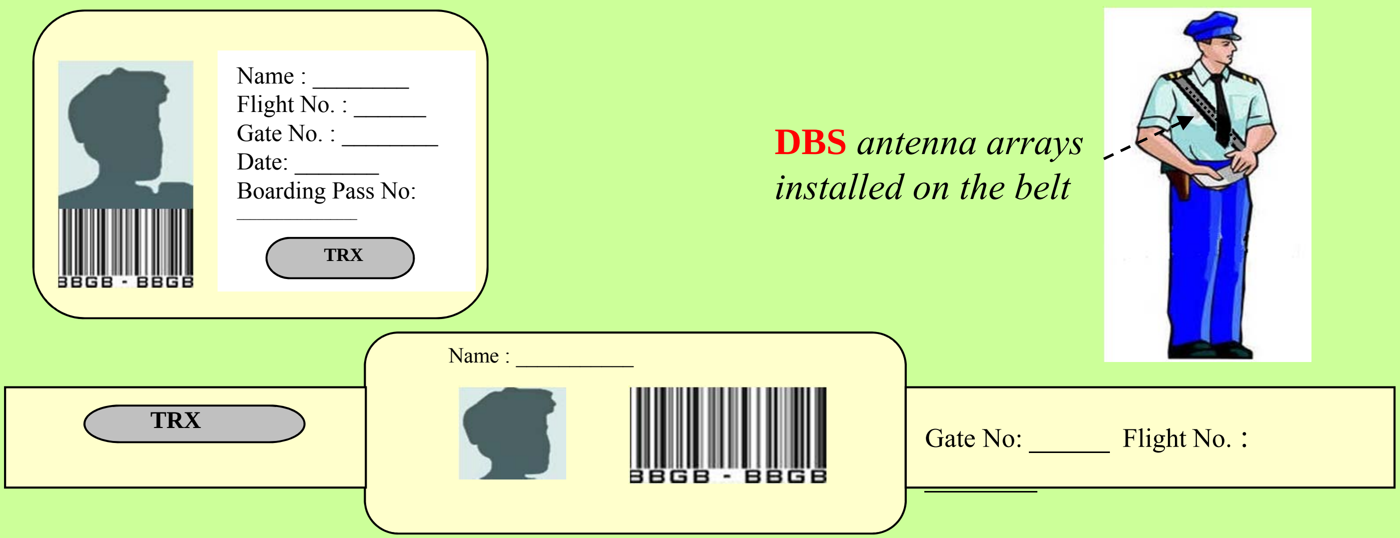
  High Probability of Detection

  High Coverage (Indoor, Outdoor)

[1] Transportation Security Administration, "Aviation Security: Improvement still Needed in Federal Aviation Security Efforts", GAO-04-0592T, March 30, 2004.

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

Plastic Card Boarding Pass

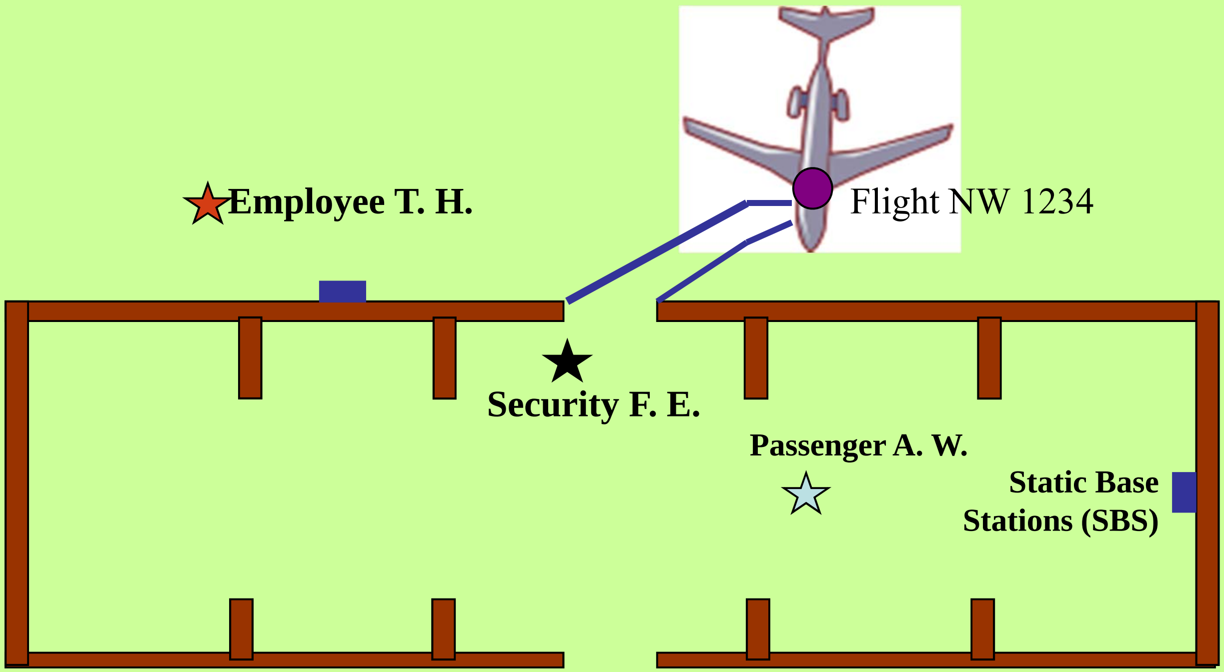


Wristband Boarding Pass

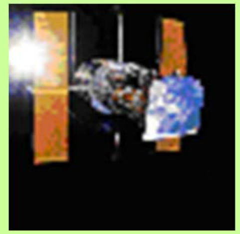
- Communication: The wristband can receive the updated gate, flight, etc, information.
- Monitoring: The wristband can be equipped with a heart beat sensor which is required: (a) for security guard safety, (b) to make sure the wristband is in its position.

Central Command and Control

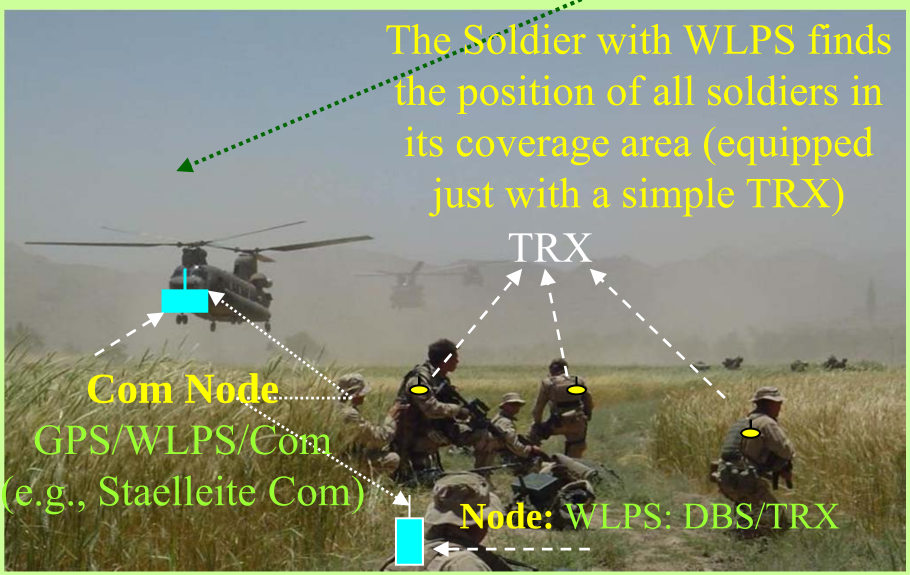
- Specific clusters of ID codes can be assigned to each group of people (employees, passengers, security guards)

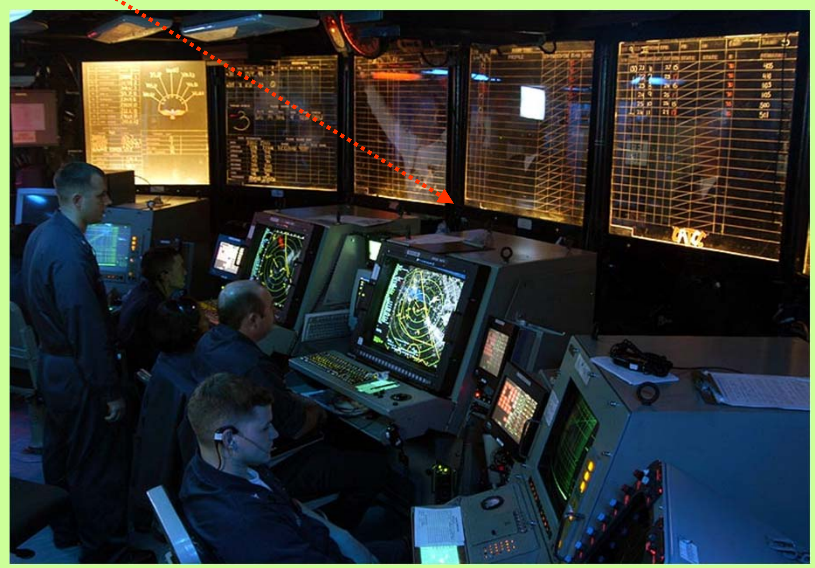


Application in Battlefield Command and Control



Precise Location Information of All Soldiers are Submitted to the Center via Satellite

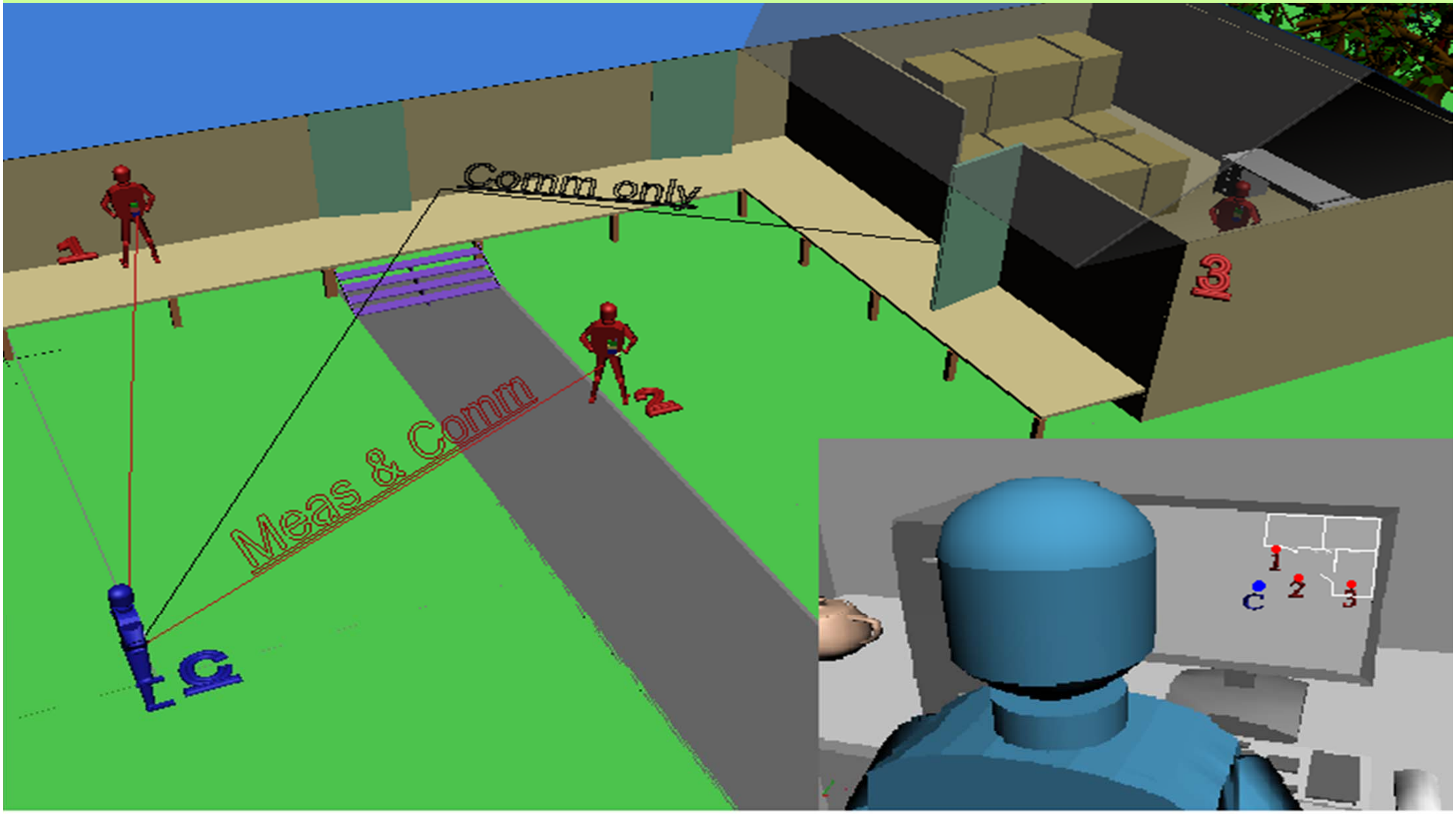




Central Command and Control

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



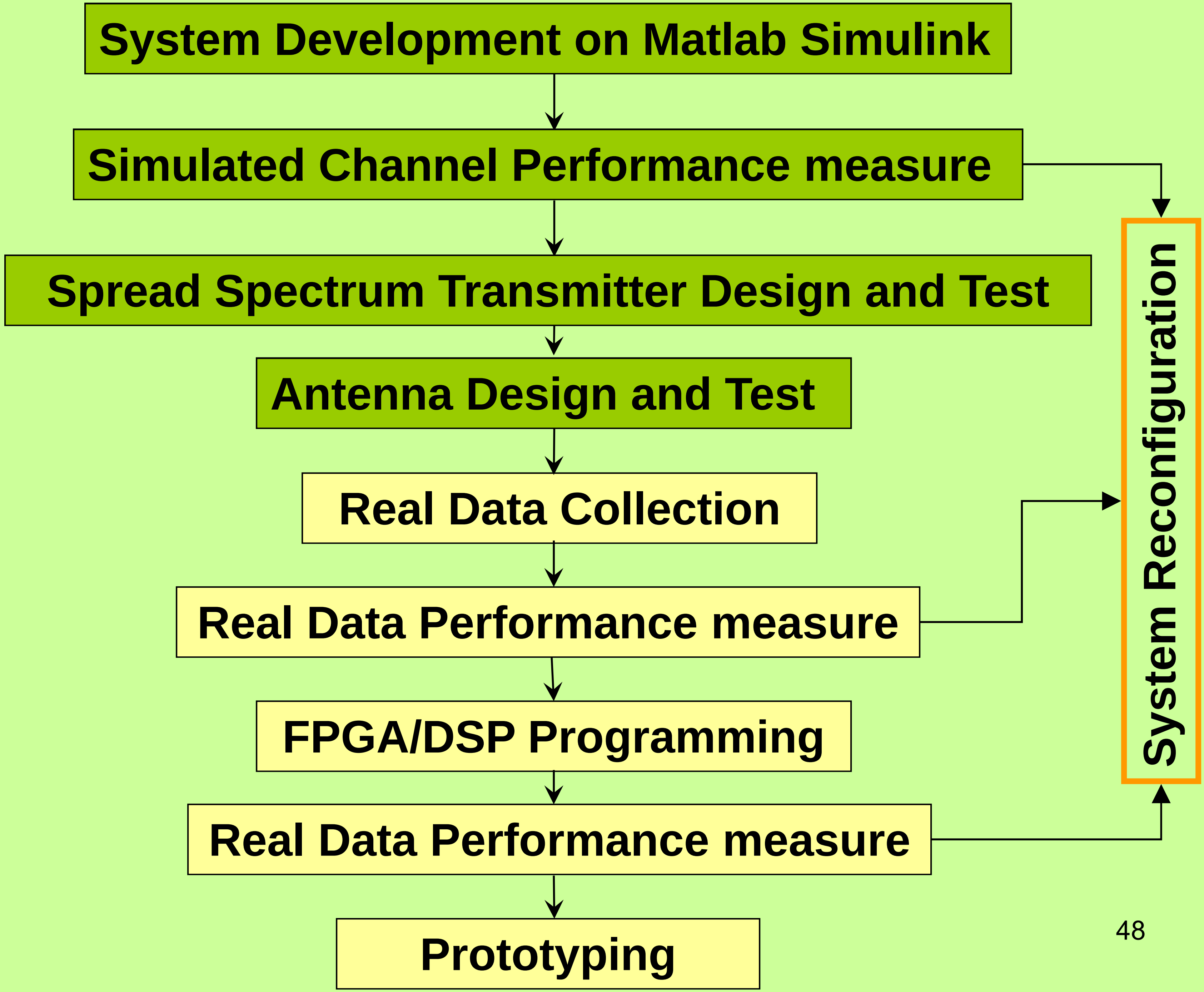
TRX package transmitted to DBS

IDS	INS data	Other sensor data

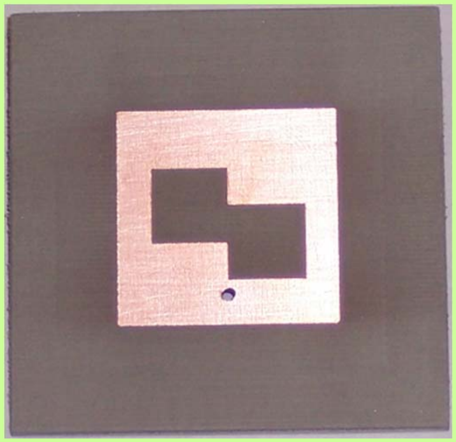
Comm--Communication Meas--Measurement
C--Commander: Equiped with DBS/INS/GPS/Comm
1,2,3--Officer: Equiped with TRX/INS/other sensor

System Design

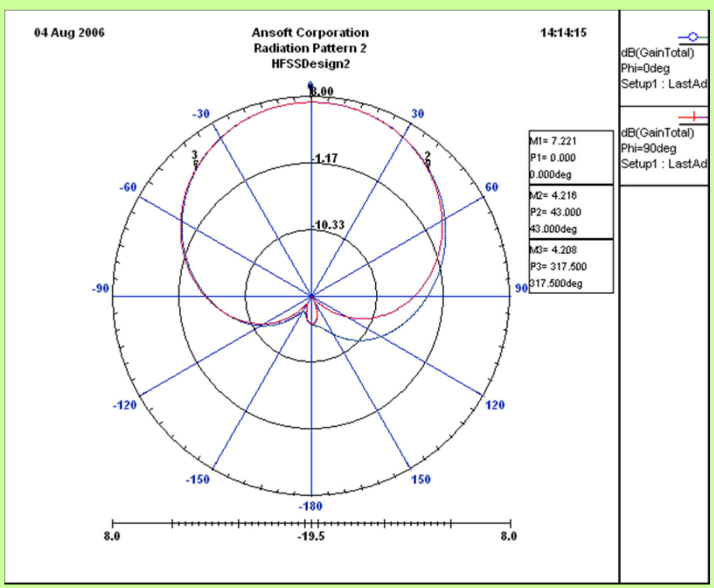
Design Flowchart

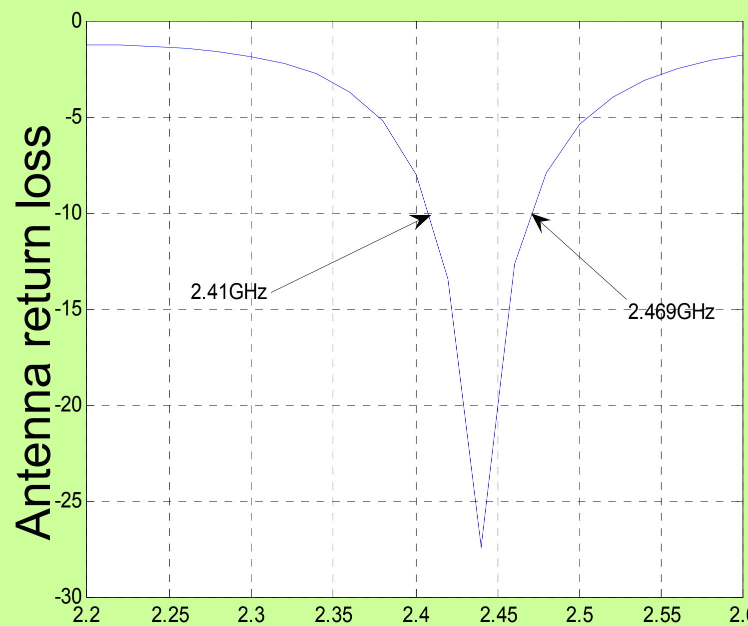


Patch Antenna Design



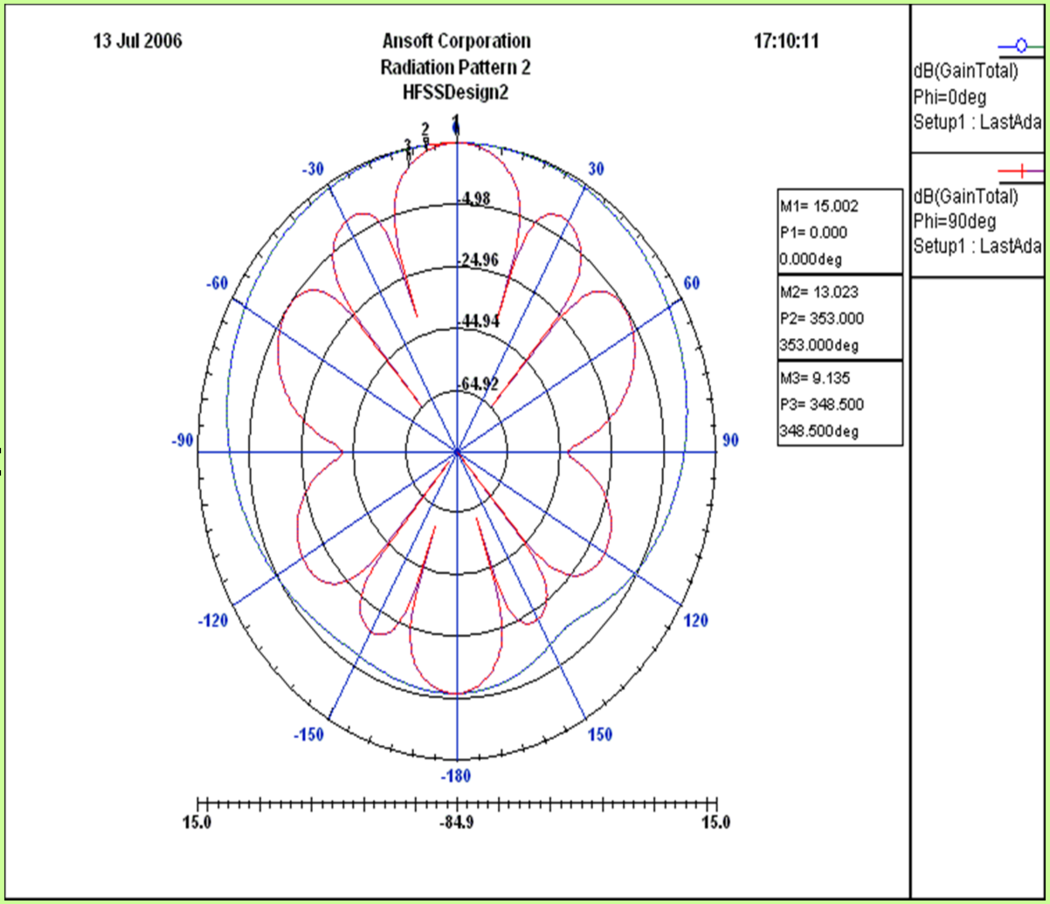
(1) Beam pattern: Directional (for road safety);
(2) Beam width: As large as possible (85^o);
(3) Light weight;
(4) Easy to make;
(5) Low cost (less than $5)
(6) Bandwidth: As large as possible (~50MHz),



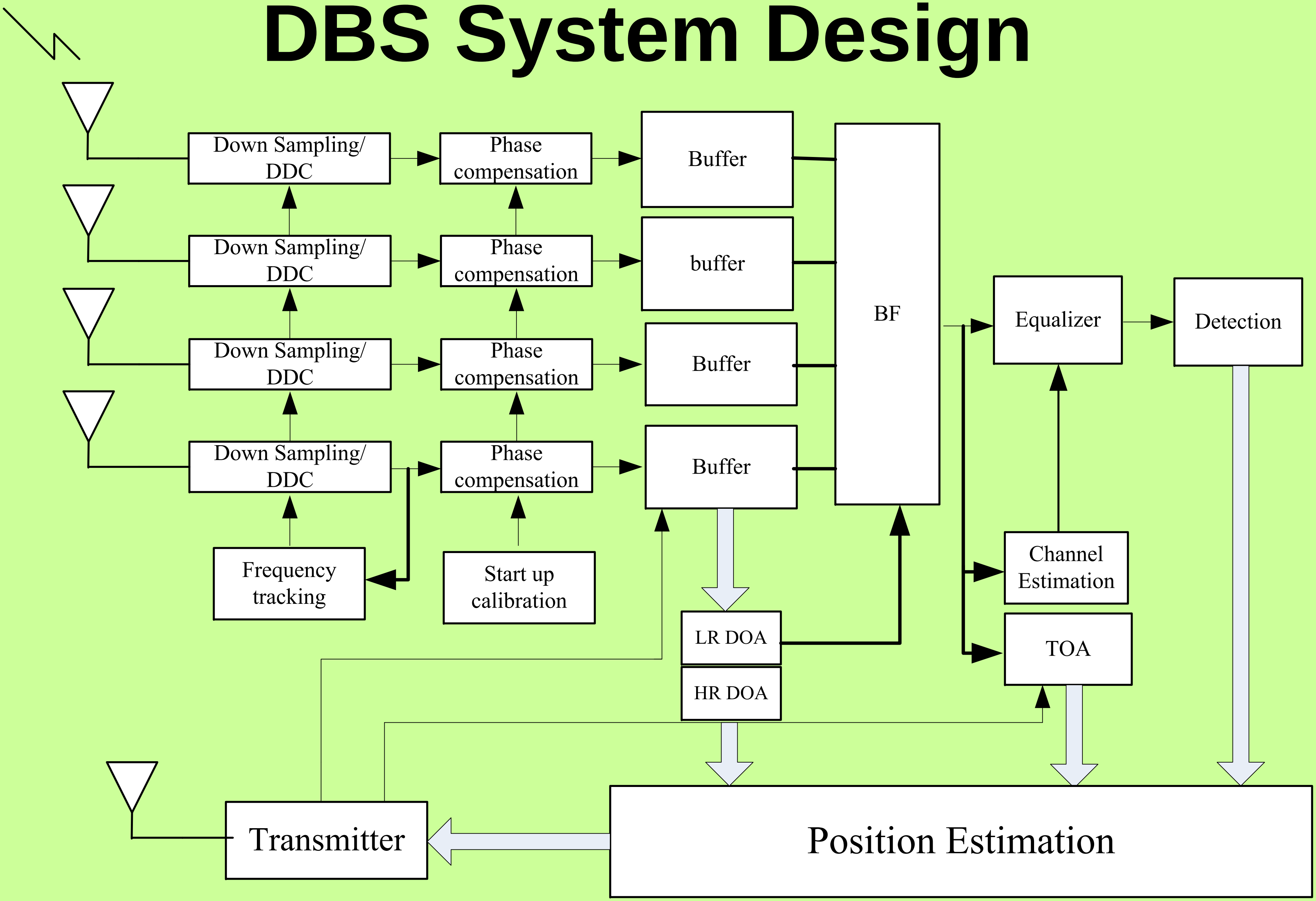


Patch Antenna Array

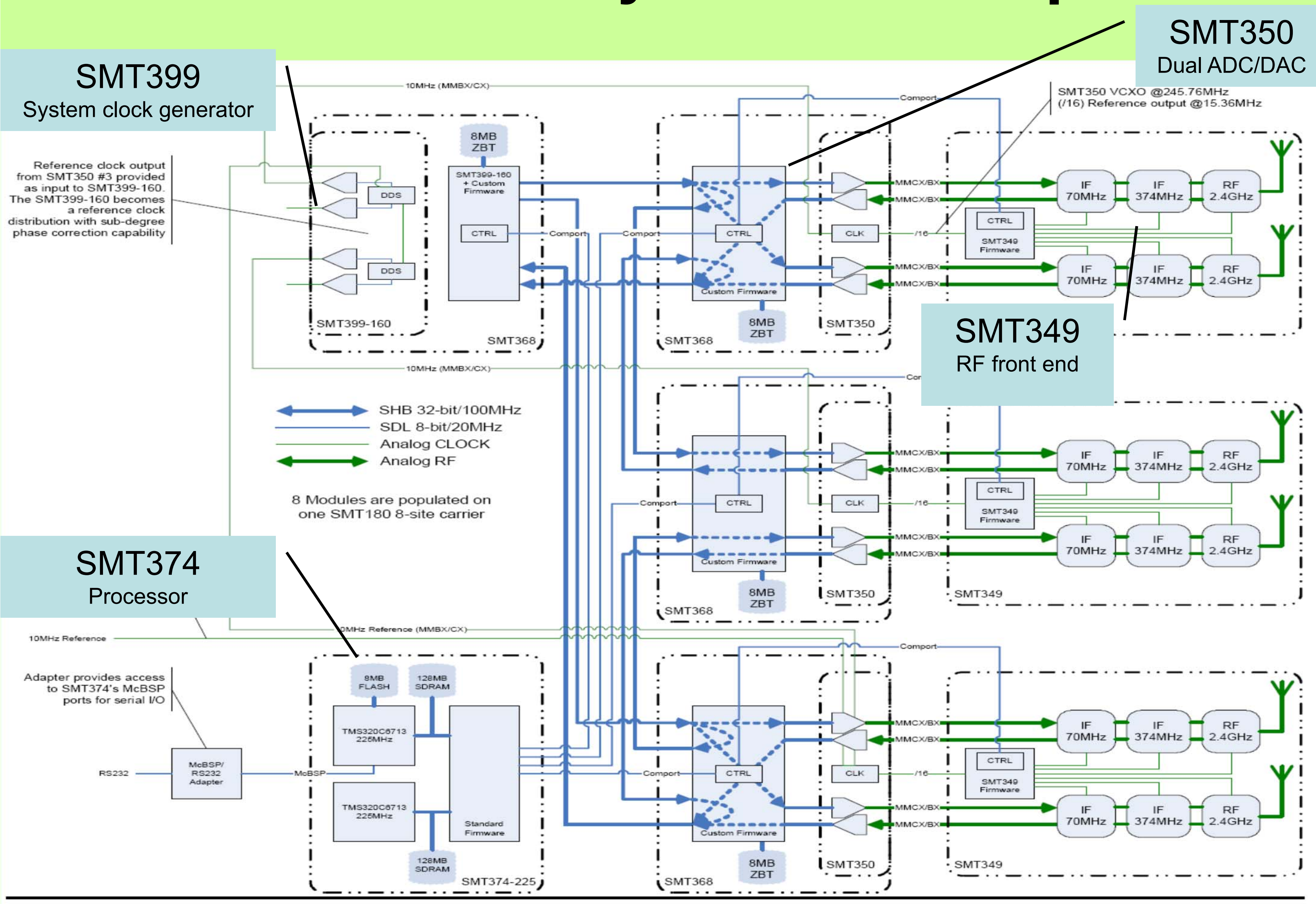
- Bandwidth: 2.41~2.469GHz;
- Dimension: 14.45´´×2.40´´×0.12´´;
- Interface: 50Ω SMA female;
- Elements phase center distance: 2.41'' (λ/2)
- Application center frequency: 2.45GHz
- 3dB beam width: 14º×85.5º;
- Max Gain: 15dBi.



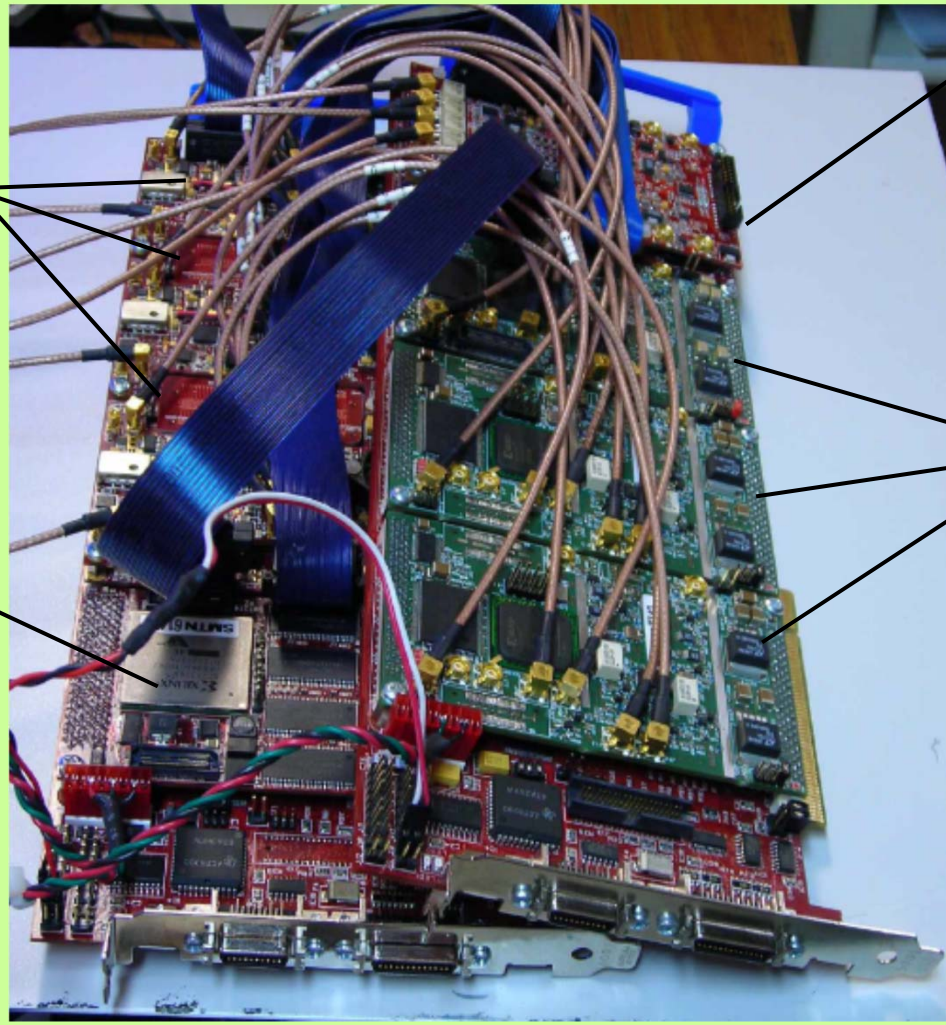
DBS System Design



Sundance DSP System Development



DSP System Structure



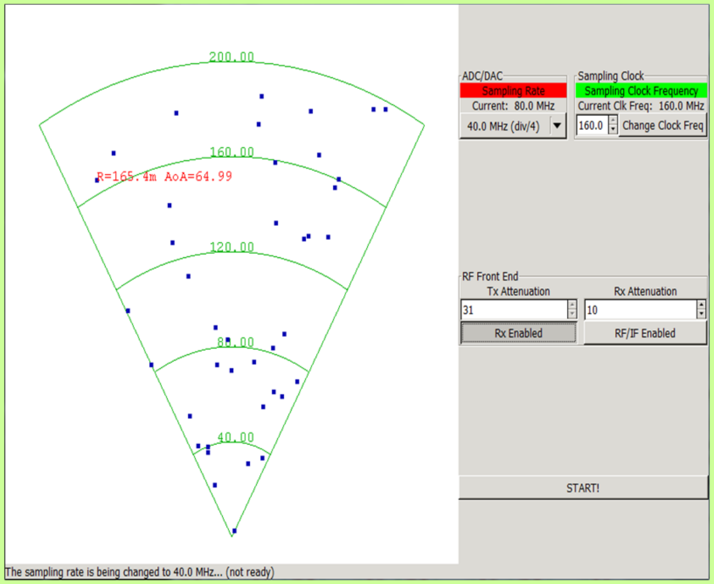
SMT399
System clock generator

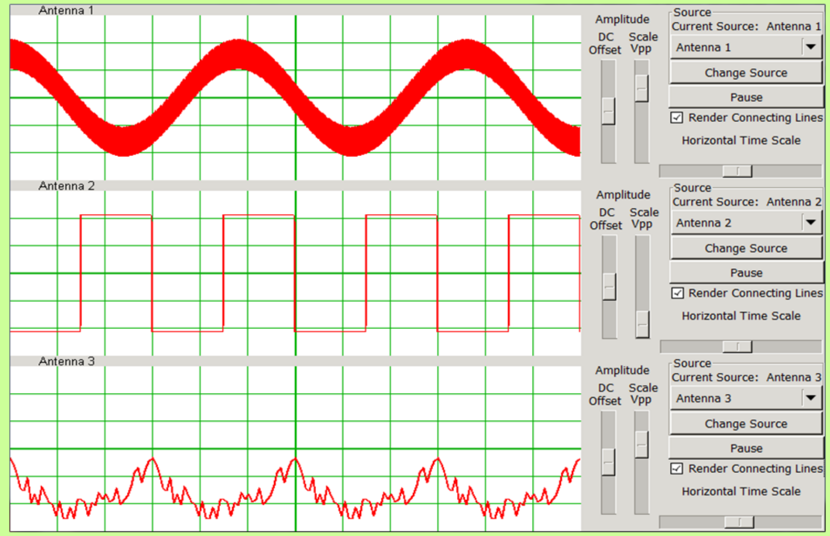
SMT349
RF front end

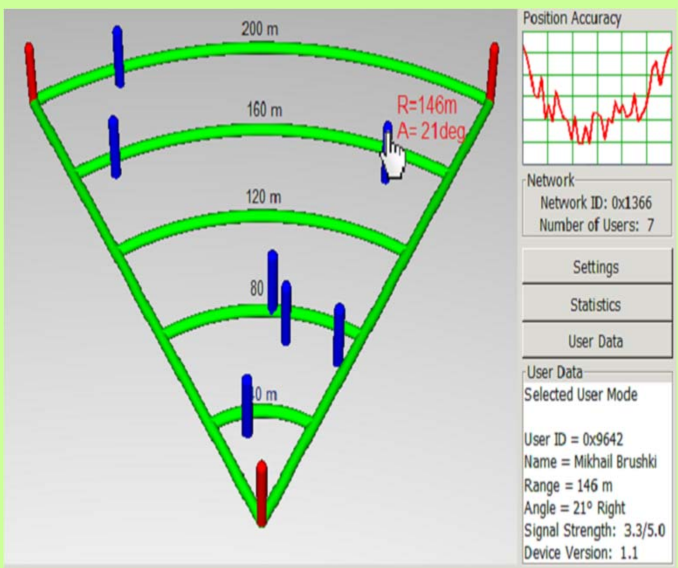
SMT350
Dual ADC/DAC

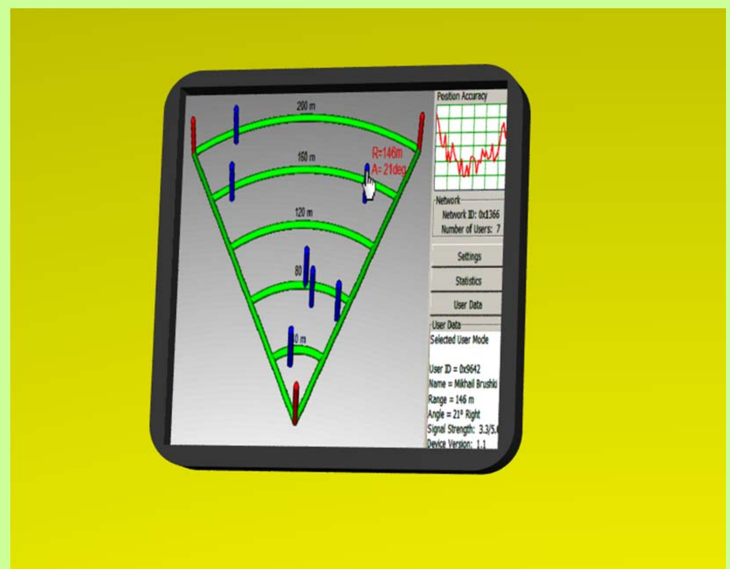
SMT363
Processor

User Interface









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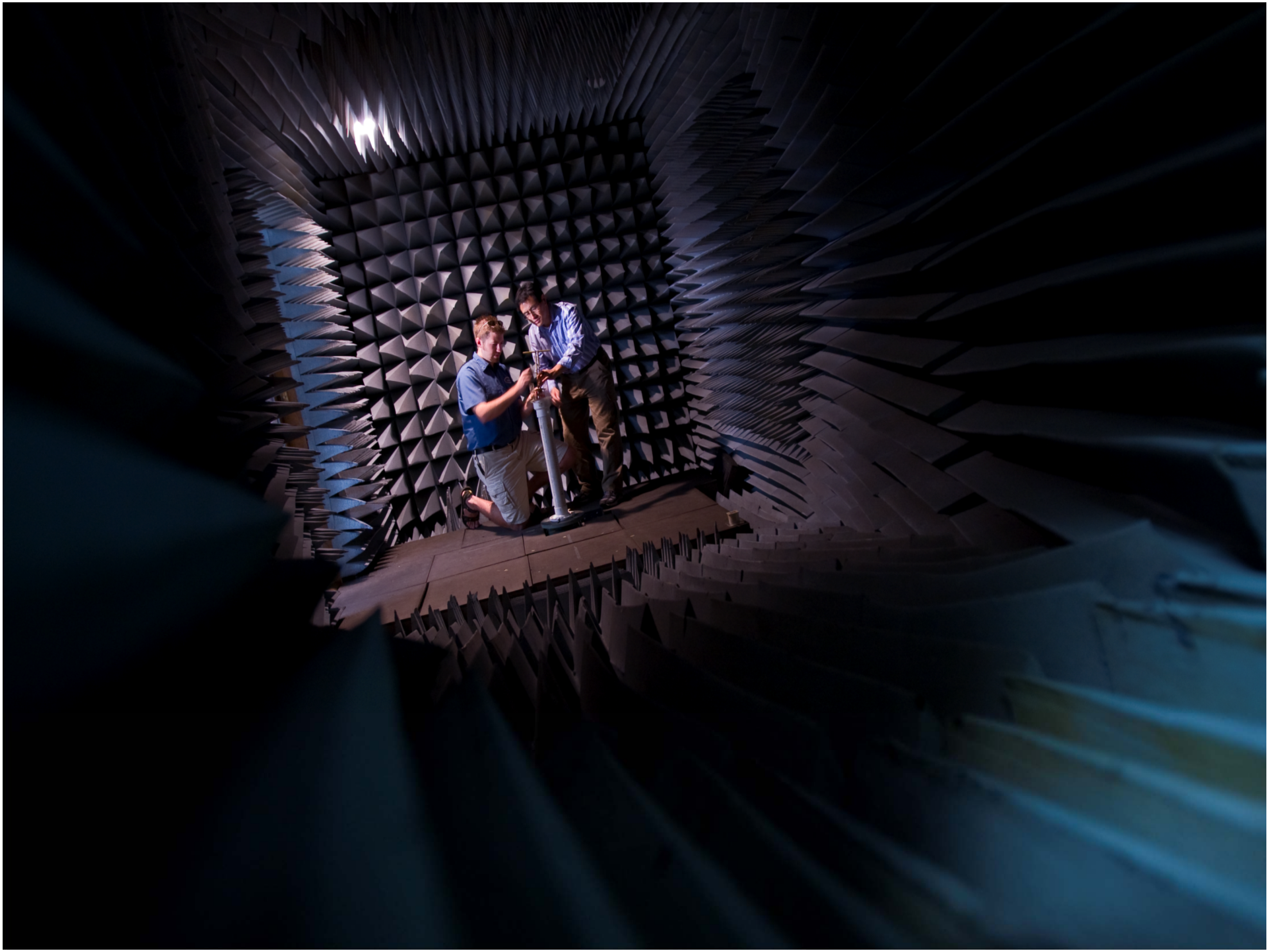


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Thank you!
Questions?