WE2F-01

Millimeterwave Imaging Sensor Nets: A Scalable 60-GHz Wireless Sensor Network

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Outline

- Motivation

  (1) A **scalable, simplistic approach** to the wireless sensor network

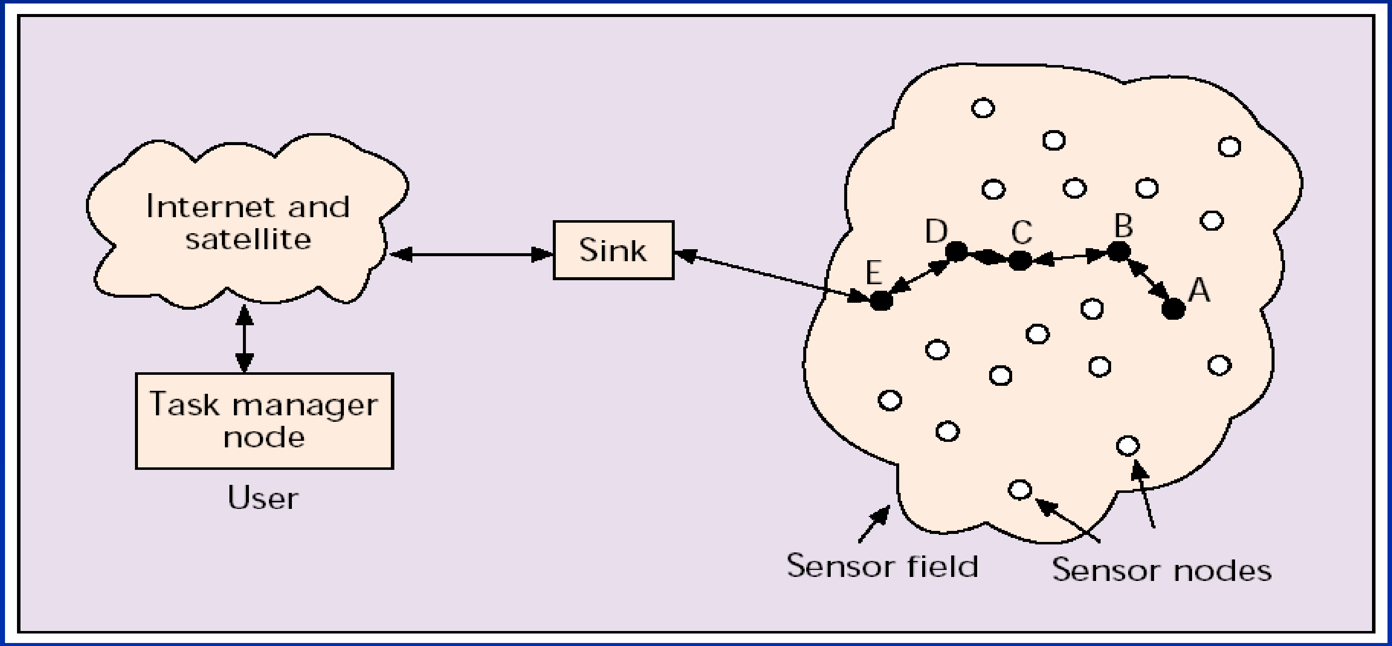
  (2) Exploit **millimeter-wave** frequencies
- Proposed Approach
- Collector System
- 60-GHz Passive sensors
- Indoor Radio Experiment

Wireless Sensor Networks (WSN)

- Goal: Distributed **data collection & localization** to obtain **an information map, D[x,y,z,t]**
- Many scientific, industrial and military applications
  - Environmental monitoring,
  - Wildlife research,
  - Seismic activity detection,
  - remote sensing,
  - battle field surveillance,
  - border policing,
  - planetary exploration,
  - Body-area network,
  - …

Current WSN Practice

- Data collection: Multi-hop based communication
  - Low-power communication ☺
  - Not very suitable for large-scale networks ☹
- Localization: Fixed ID code, GPS, acoustics, etc
  - Tends to make sensors costly, complex ☹

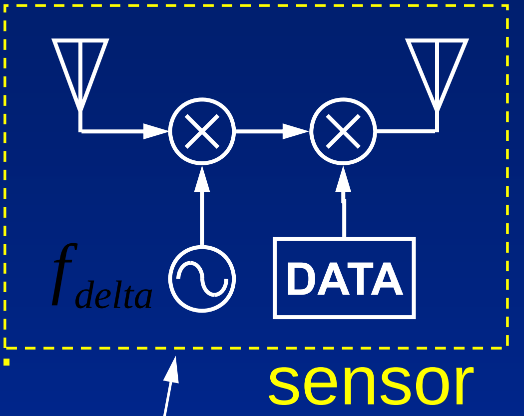


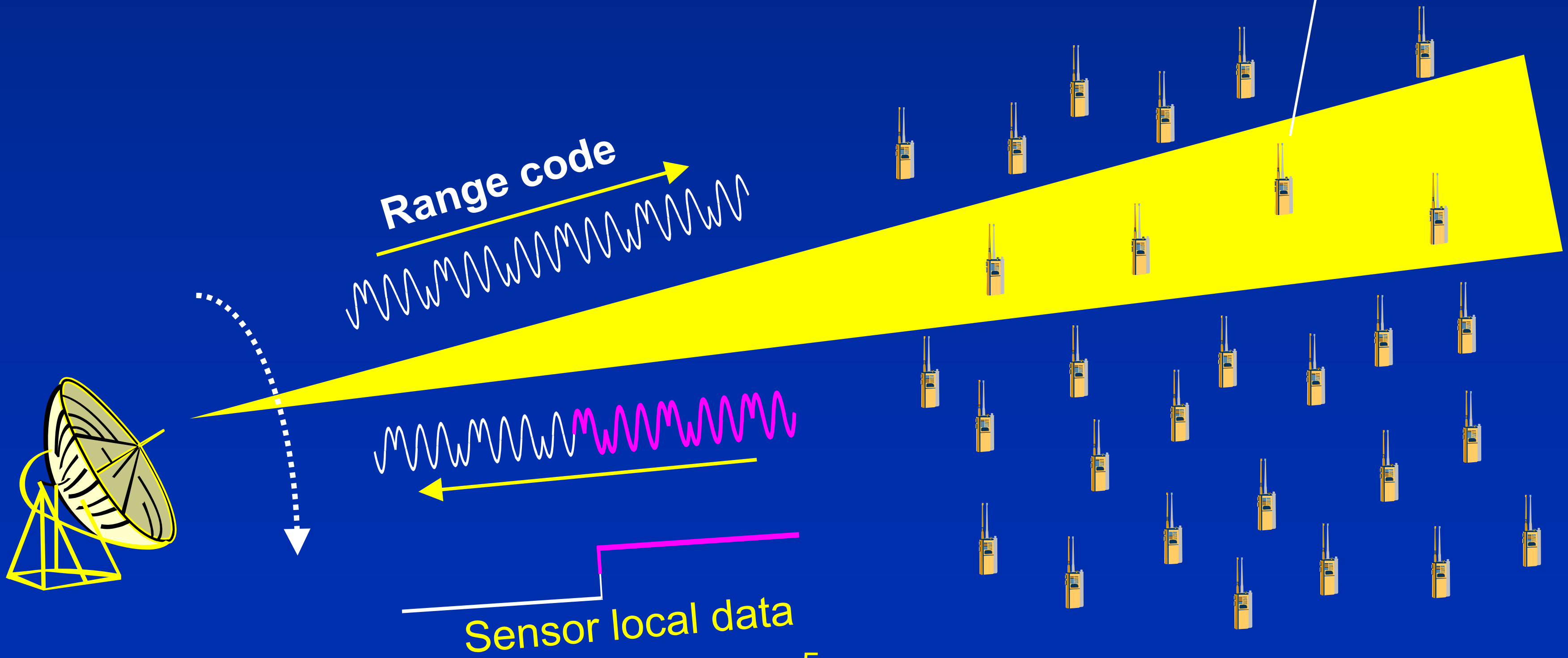
From Akyildiz et al, IEEE Comm. Mag., Aug. 2002

Simplistic Sensor Approach

Sensor with minimal functionality
Move all complexity to the collector

(1) Collector sweeps a beam
(2) Sensors receive, modulate and transmit it back.
(3) Collector jointly detects data & location





Simplistic Approach

- **Similarities with optical imaging & radar**
- **Scalability**
  - Communication grows linearly as # of sensors
- **Built-in Localization**
  - Range resolution by a wideband range-code
  - Angular resolution by a narrow beam
- **Simplistic sensors (= low-cost, low-power)**
  - No communication among sensors
  - No localization capability required.
- **Concerns**
  - Need line-of-sight, complex collector signal processing

Exploit Millimeter-waves

$$D = 4\pi \frac{A_e}{\lambda^2} = \frac{41{,}000}{\theta^{\circ}_{HPBW}\phi^{\circ}_{HPBW}}$$

- Motivations:
  - Higher angular resolution @ same antenna aperture
  - Higher range resolution @ same fractional BW
  - High data rate
  - Unlicensed band @60GHz (BW>5GHz)

Signal Processing Principle

- **Localization**
  - Goal: Find the most likely sensor location.
  - How? 3-D matched filtering (M/F)

    (1) Range correlation (Tx Range code)

    (2) Azimuth correlation (w/ AGF)

    (3) Elevation correlation (w/ AGF)

    (4) Find a peak!

    } Maximum-likelihood detection

    Accuracy eventually limited by the received SNR

- **Data Demodulation**
  - Goal: Retrieve the local sensing data (1? 0?)
  - How? Track the peak

Round-trip Radio Link

6~16dB/km @ 60-GHz band

$$\frac{P_r}{P_t} = D_{TX} D_{RX} D_{sens}^2 G_{sens} \left(\lambda_{up} \lambda_{down}\right)^2 \frac{e^{-2\alpha R}}{(4\pi R)^4}$$

60-GHz

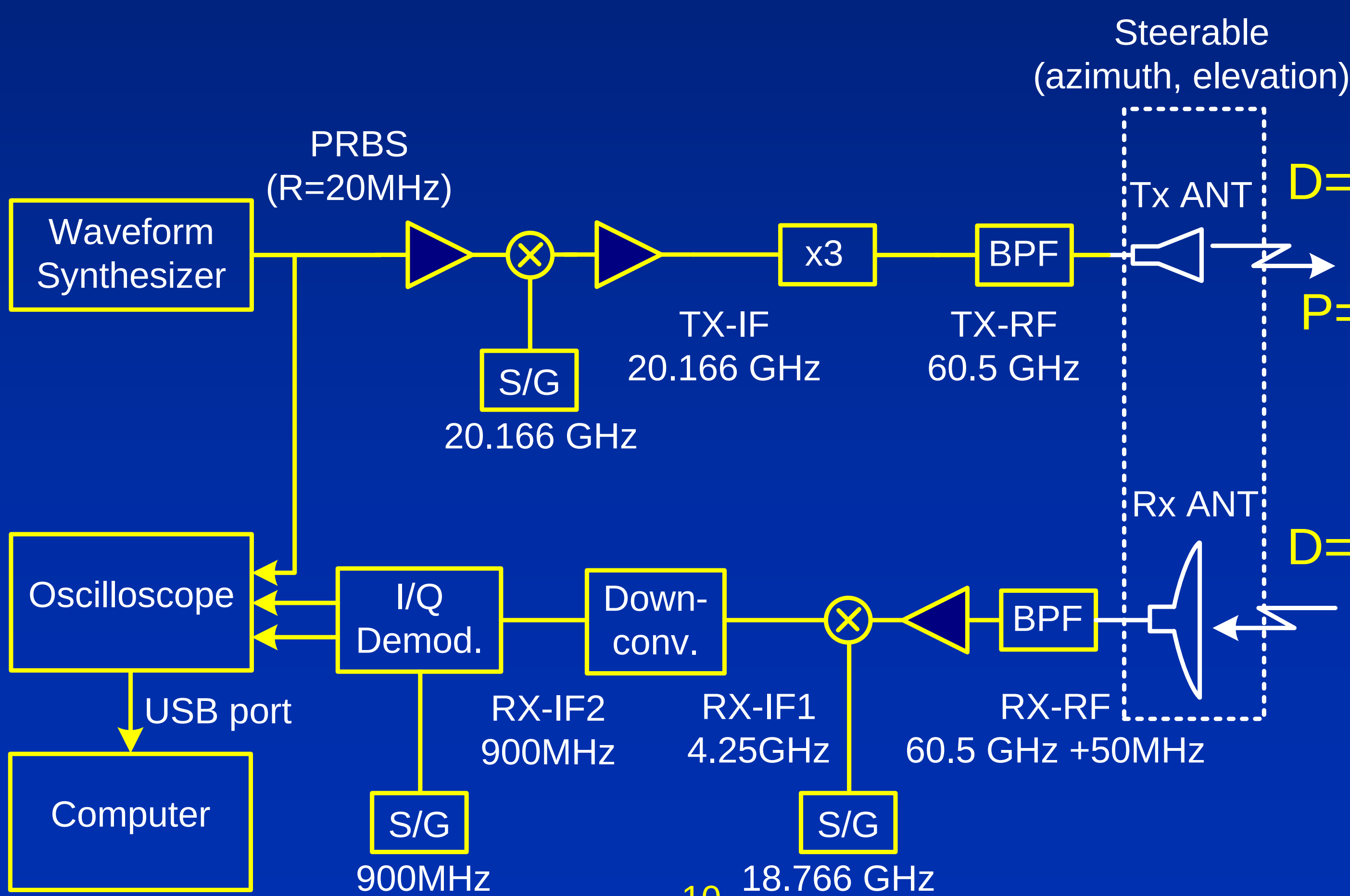
60-GHz +/- f_{delta}

P_t	D_{TX}	D_{RX}	D_{sens}	G_{sens}	R_{max} @10kbps, BER $= 10^{-6}$
7dBm	23dBi	40dBi	7dBi	-3dB	**25m** (current prototype)
25dBm	40dBi	40dBi	7dBi	-3dB	**200m** (possible ext.)
25dBm	40dBi	40dBi	7dBi	80dB	**1,600m** (“active” sensor)

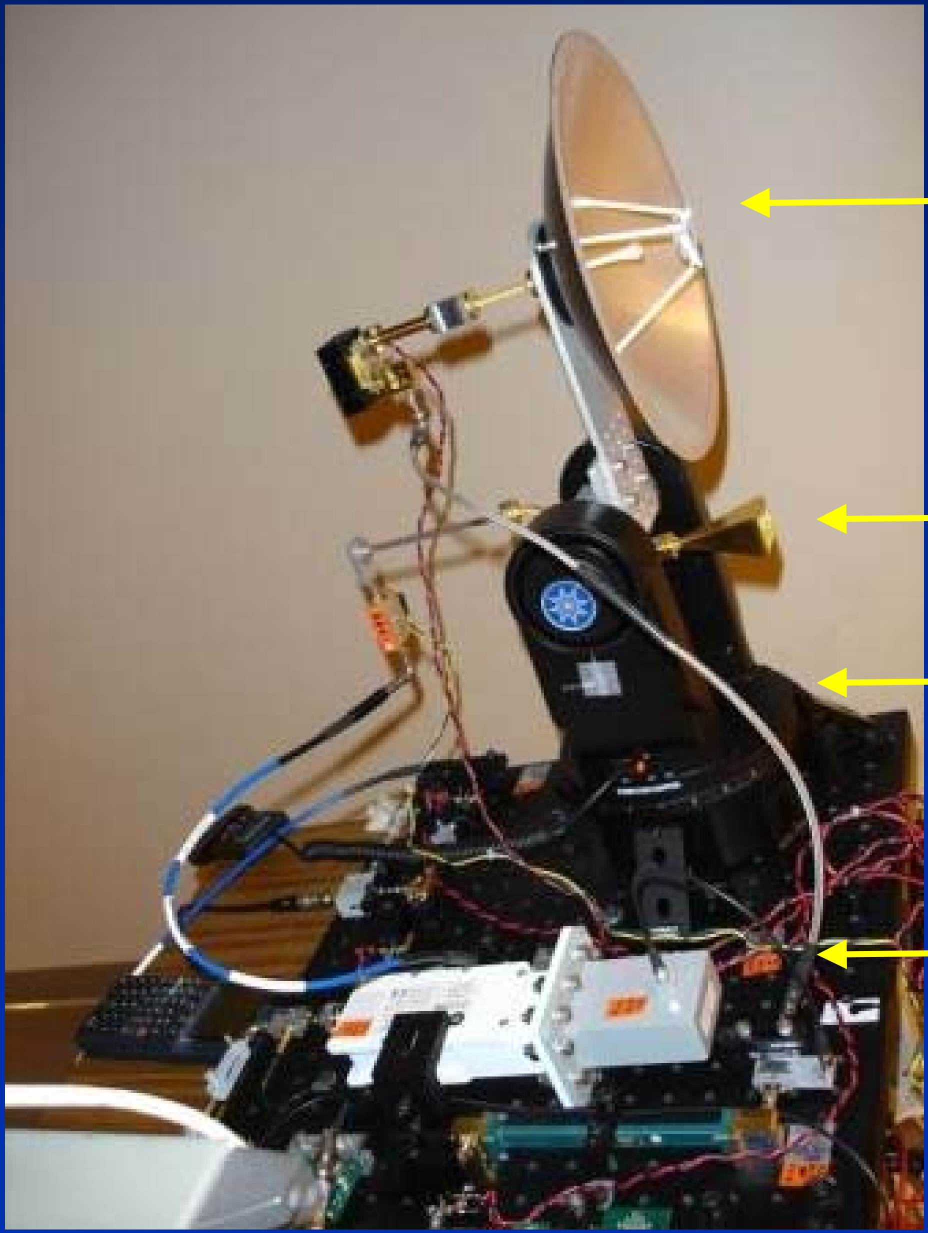
60-GHz Collector Block Diagram

Range code: 20-MHz PRBS (2^6-1)
Single-chip= 7.5m,
Max. field size= 470m

Directivity= 40dB (2 deg)
0.4m@R=10m
4.0m@R=100m



60-GHz Collector Transceiver



Rx Antenna (40dB)

Tx Antenna (23dB)

Remote-controlled Positioner (Az, El)

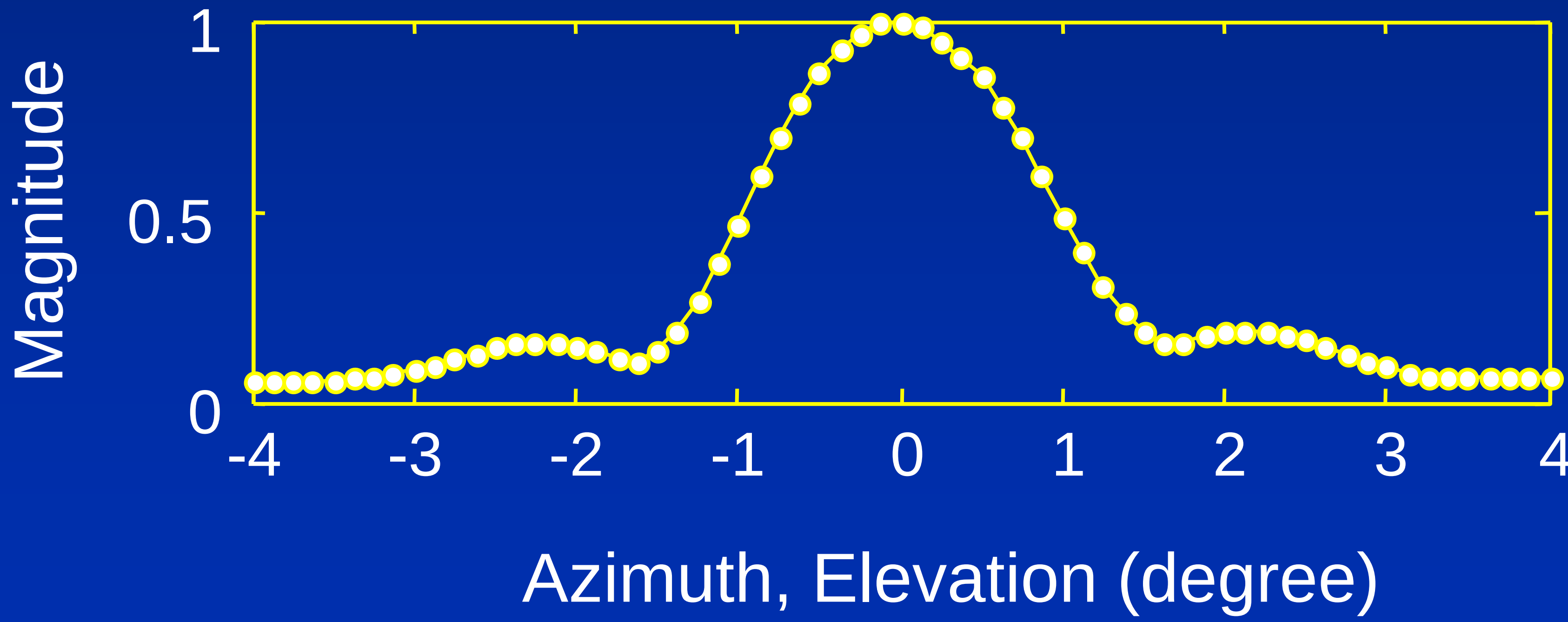
Transceiver board

60-GHz Collector System

- Transceiver with all required instruments.
- Mounted on a mobile cart.

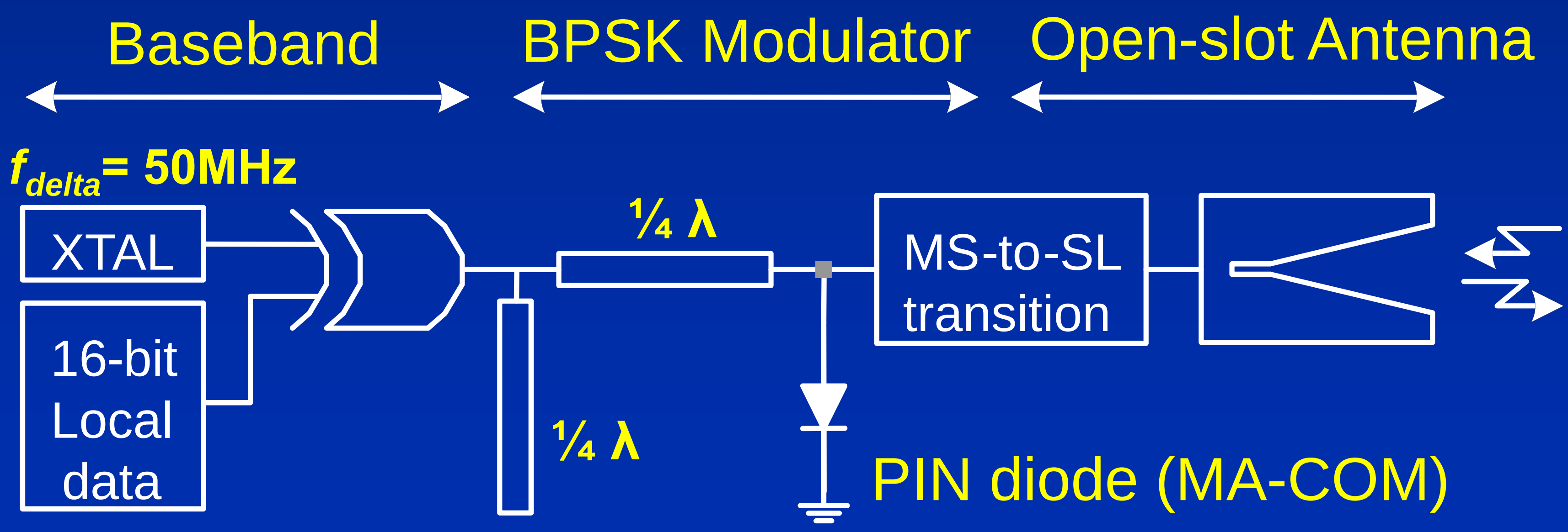
Measured Antenna Gain Function (AGF)

AGF = (TX ANT) (RX ANT)
= (23dB Horn) (40dB Cassegrain)

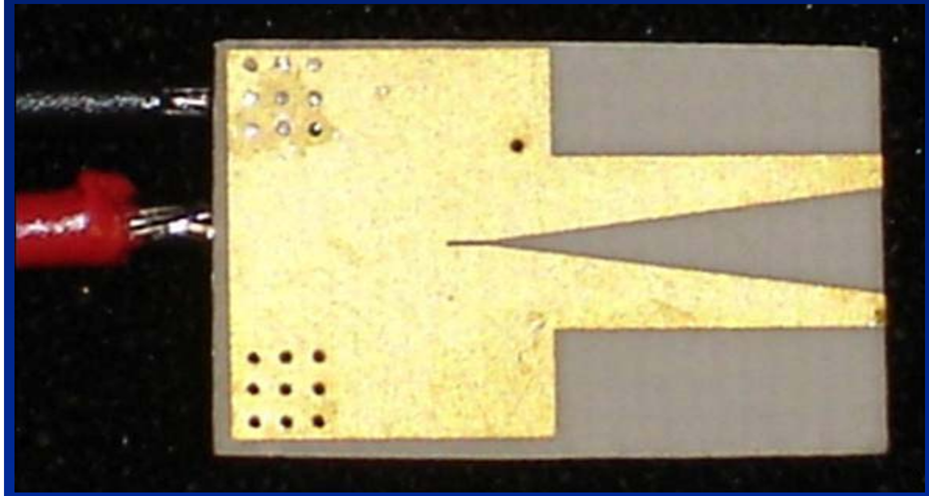


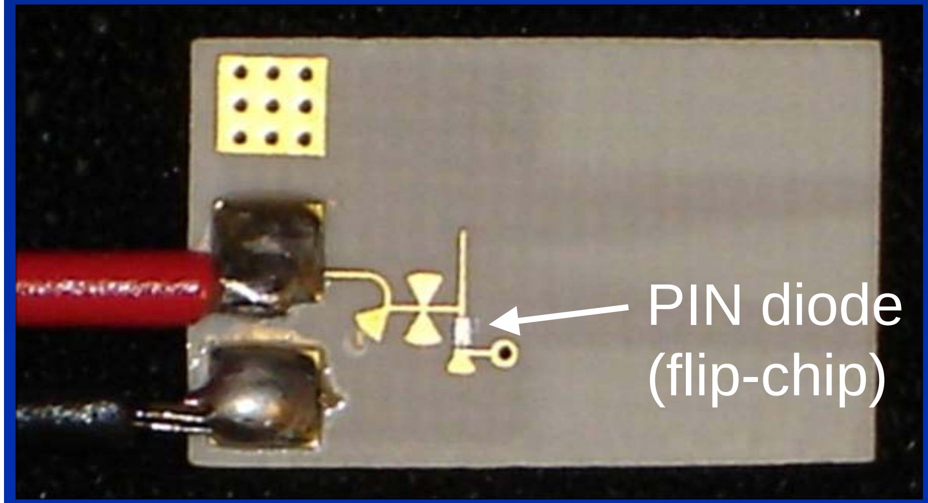
60-GHz Passive Sensor: Block Diagram

- Receive, modulate and re-radiate the beam
- **Simplicity, low cost, robustness**, etc



60-GHz Passive Sensor: Considerations

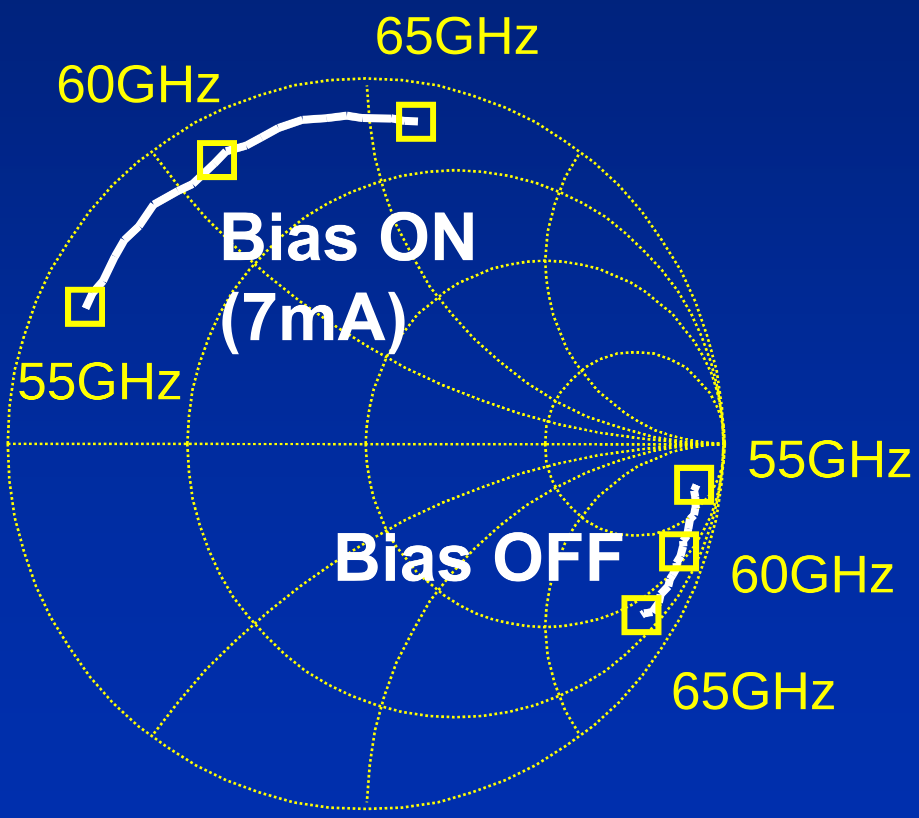




Size: 15mm x 10mm

- Antenna
  - Patch type?
  - Slot-type?
  - ***Open-slot*** type?
- Substrate: RO4003C
  - 0.2mm, Er=3.38
  - Loss= 0.07dB/mm, Q=20
- Standard low-cost PC-board manufacturing
  - Min. line width/spacing = 5mil (125um)
  - This favors high Z0 (=90ohm)

Modulator Impedance



$$b = \Gamma_{\mathrm{mod}}\left(V_{\mathrm{mod}}\right)a$$

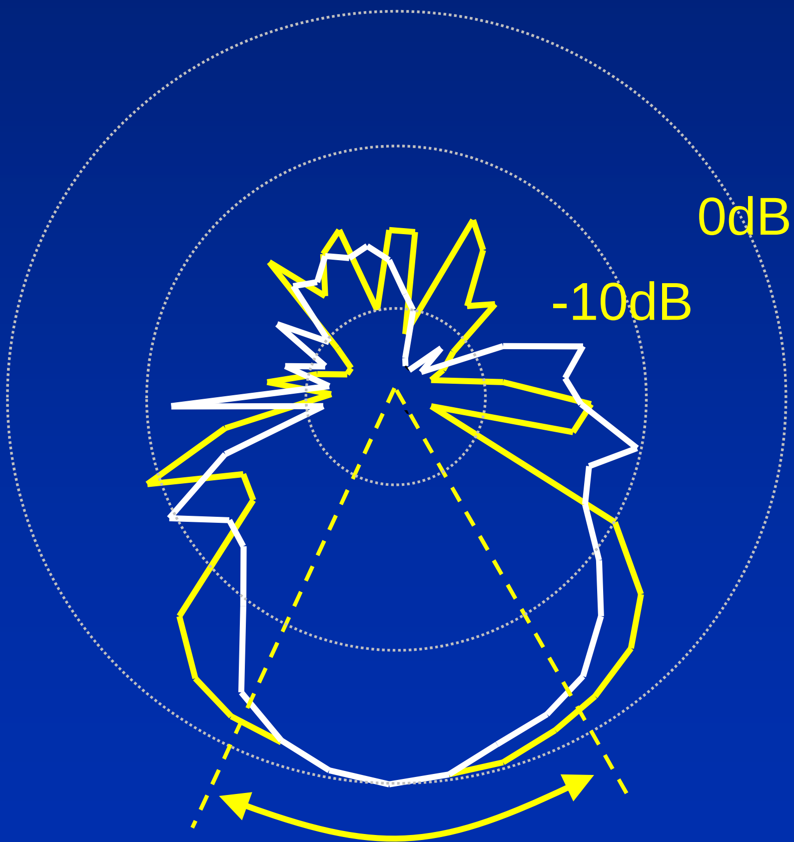
a : indident wave

b : reflected wave

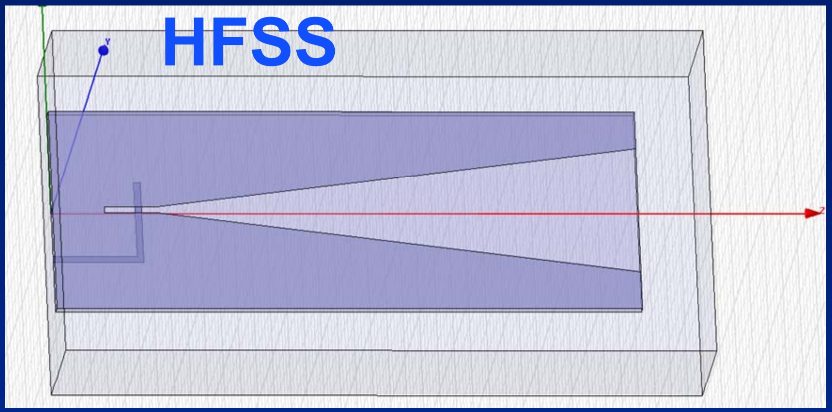
- Switches between two impedance states.
- ~180 degree relative phase shift
- **BPSK Modulation**

Linearly-Tapered Open-Slot Antenna

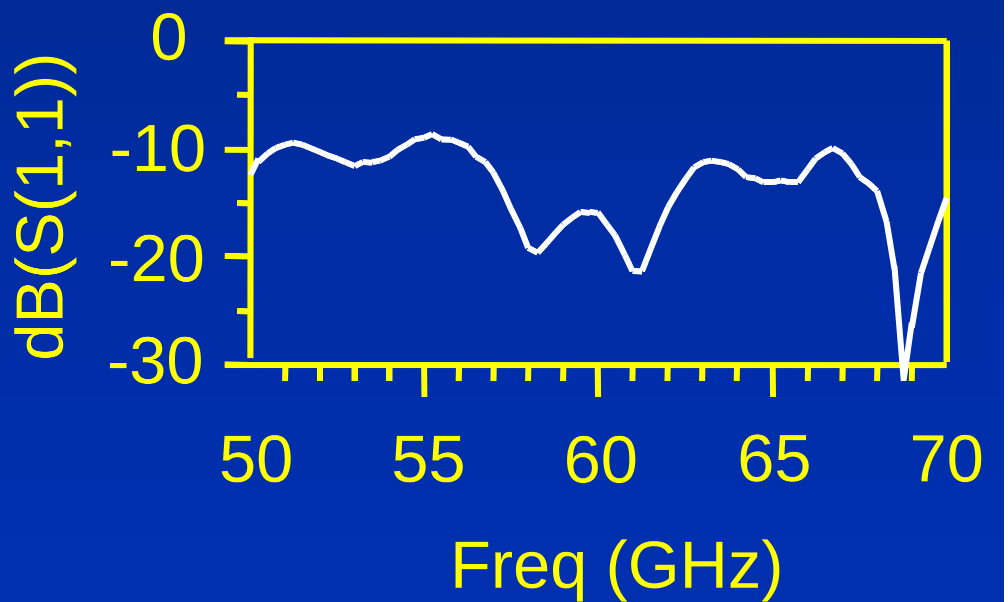
Beam Pattern (7dBi)



HPBW= 50 deg



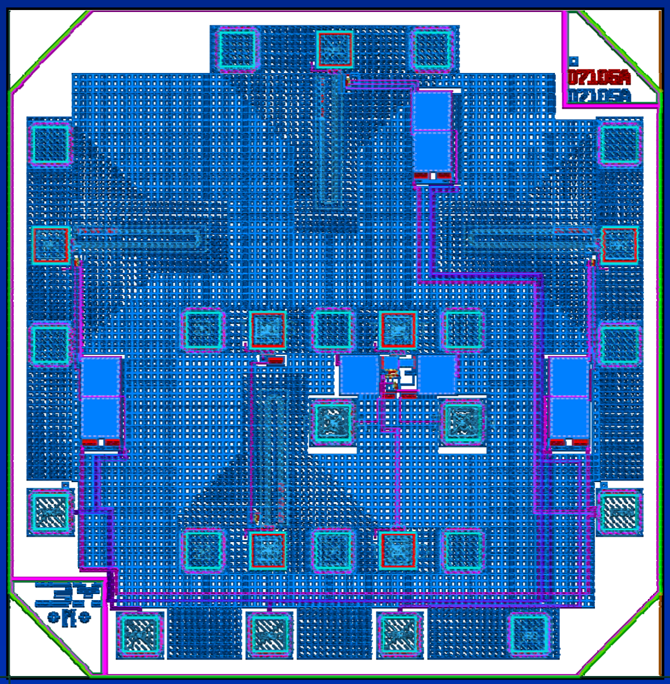
Input Match



CMOS Passive Sensor (under fab.)

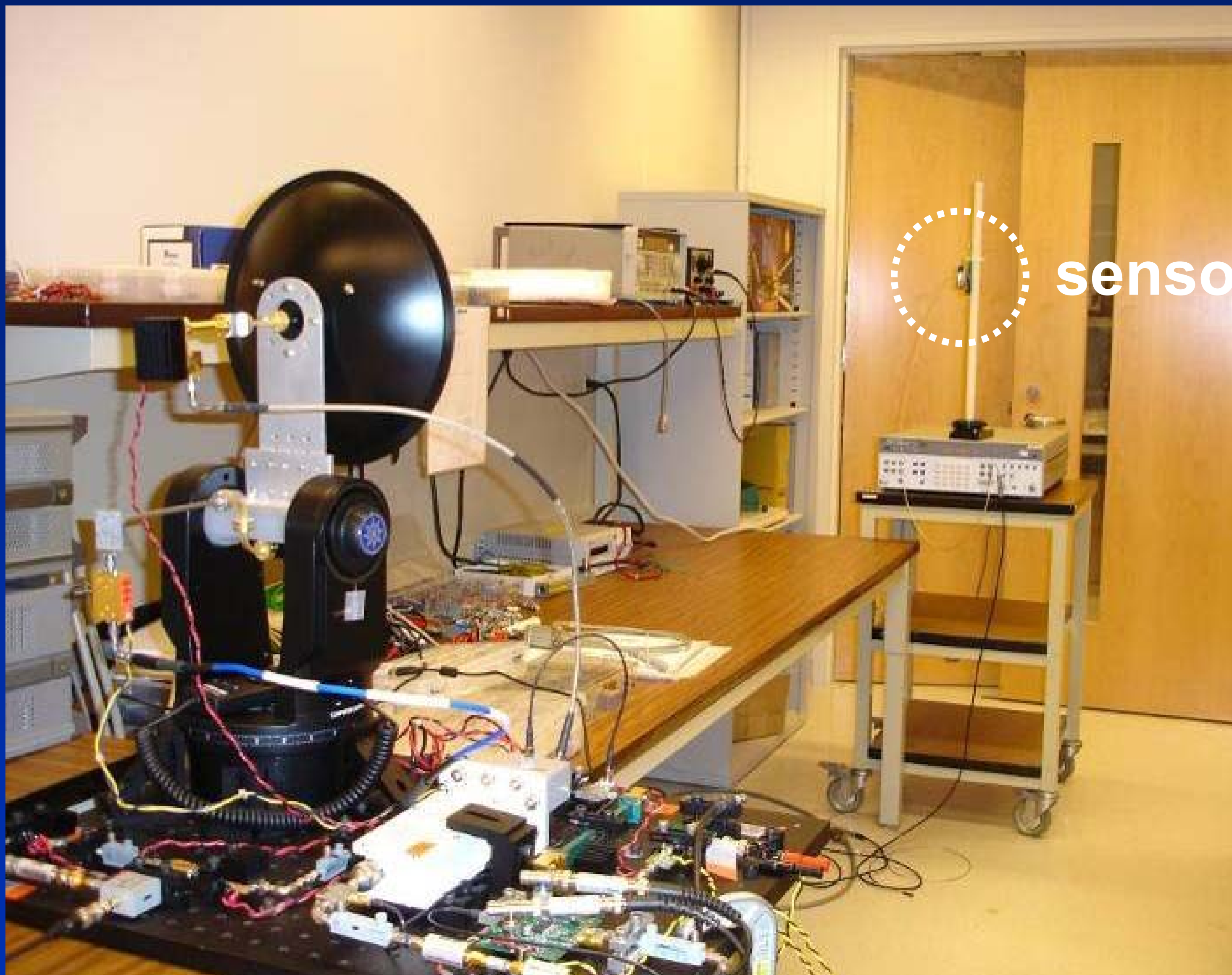
For low-power operation, CMOS integration is necessary

Layout (1mm^2)

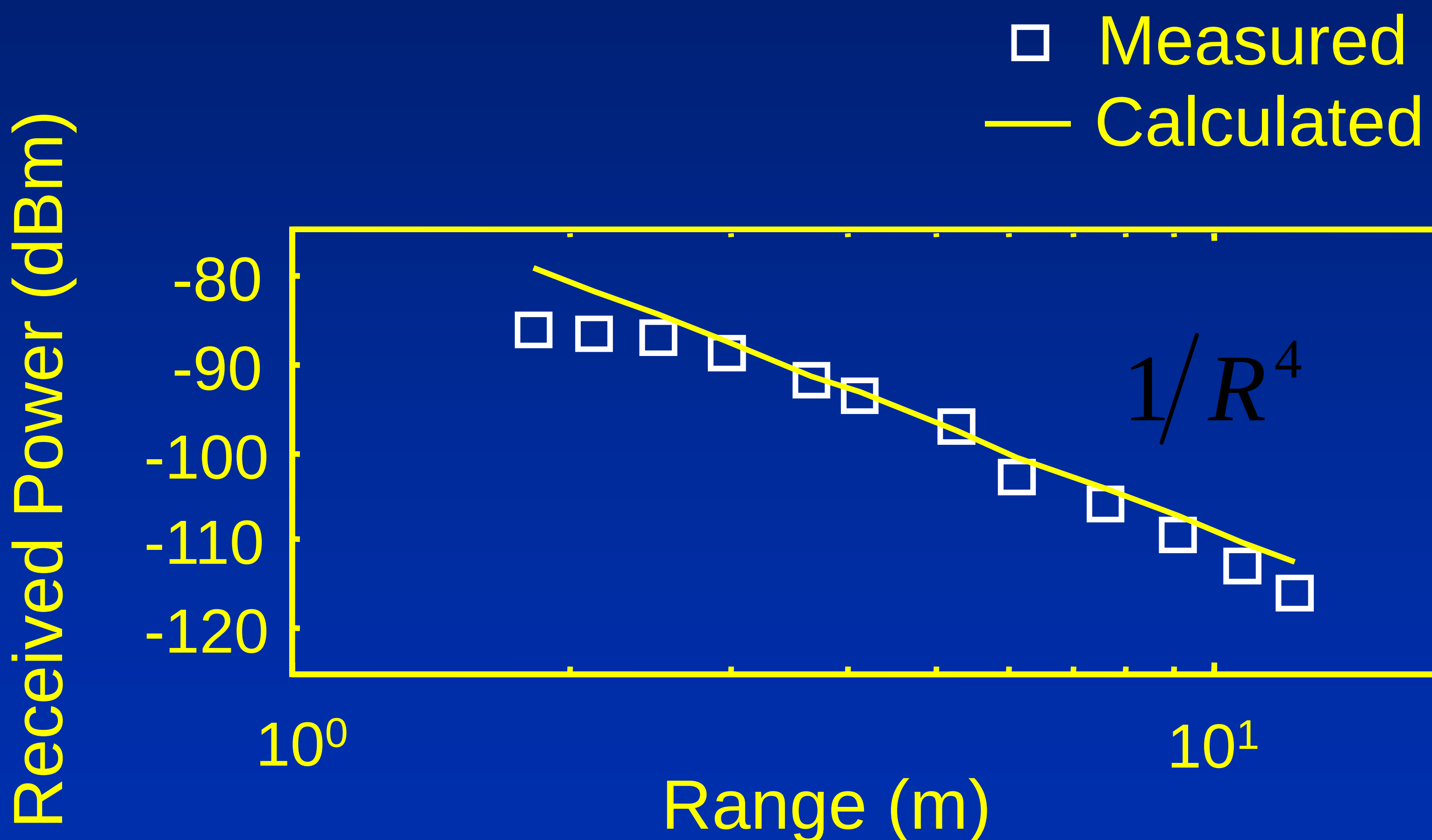


- 3-channel sensor (90-nm CMOS)
- **dc power = 0.5~3uW**
- Contains a BPSK modulator and low-power, voltage-controlled ring-oscillator
- Flip-chip interface to ANT.

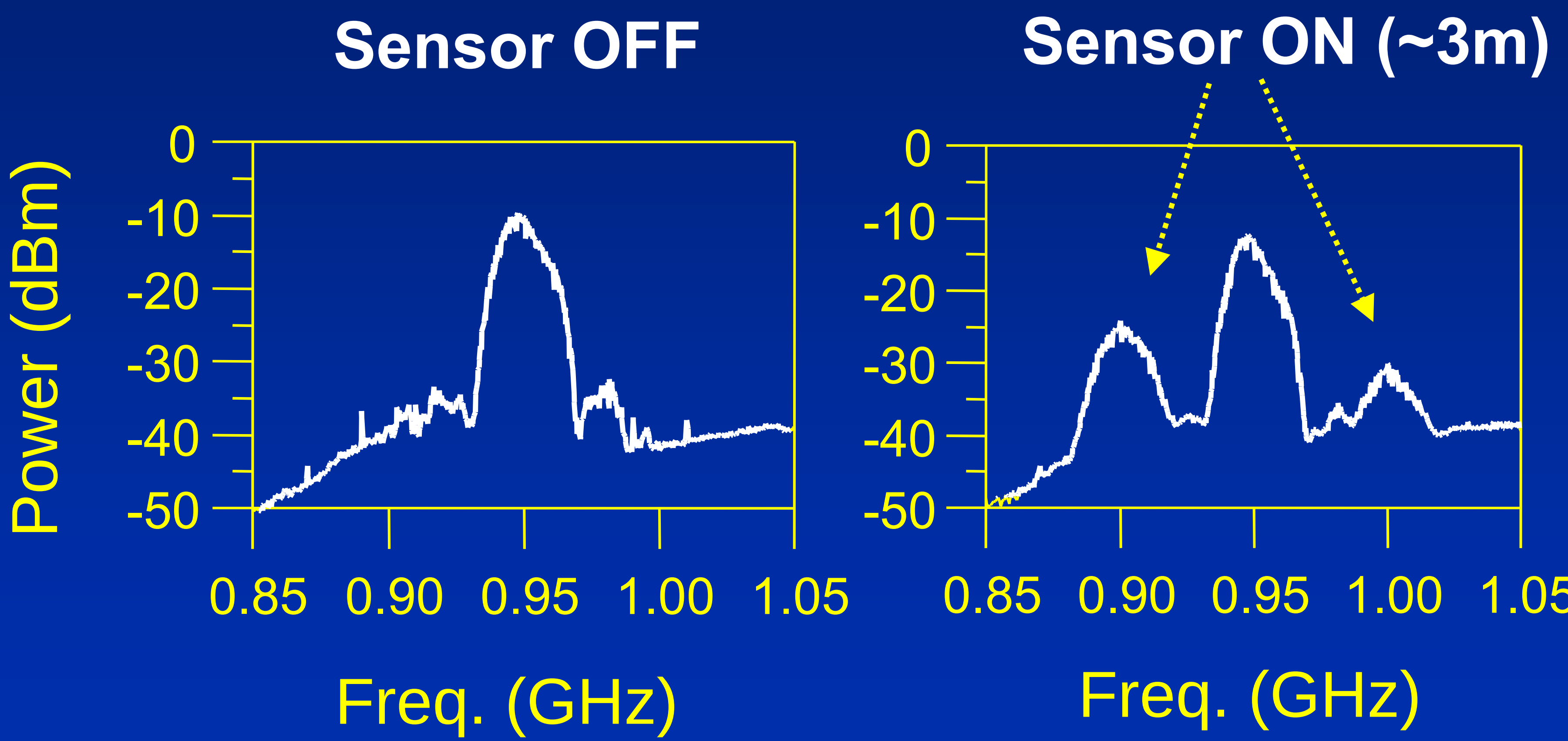
Indoor Radio Experiment



Received Power vs Range

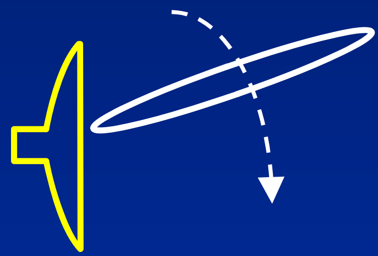


Received Spectrum (RX-IF2)

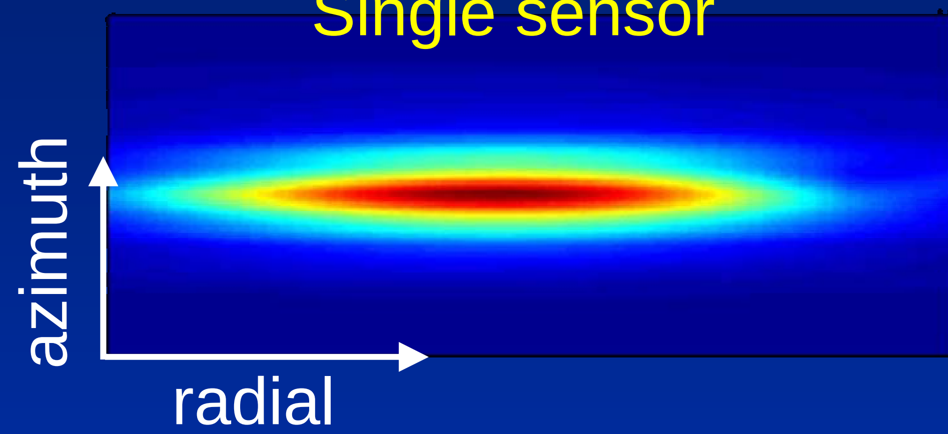


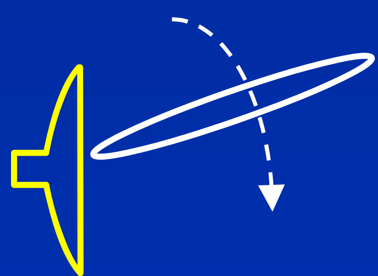
2-D Localization (M/F output)

Sweep 15.6 deg
Step= 0.6 deg

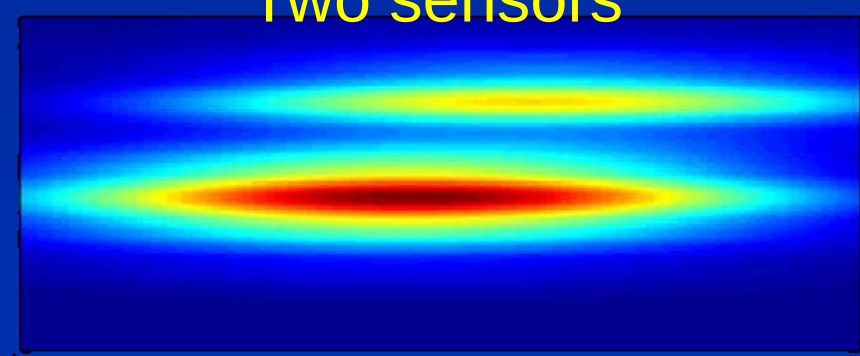


Single sensor



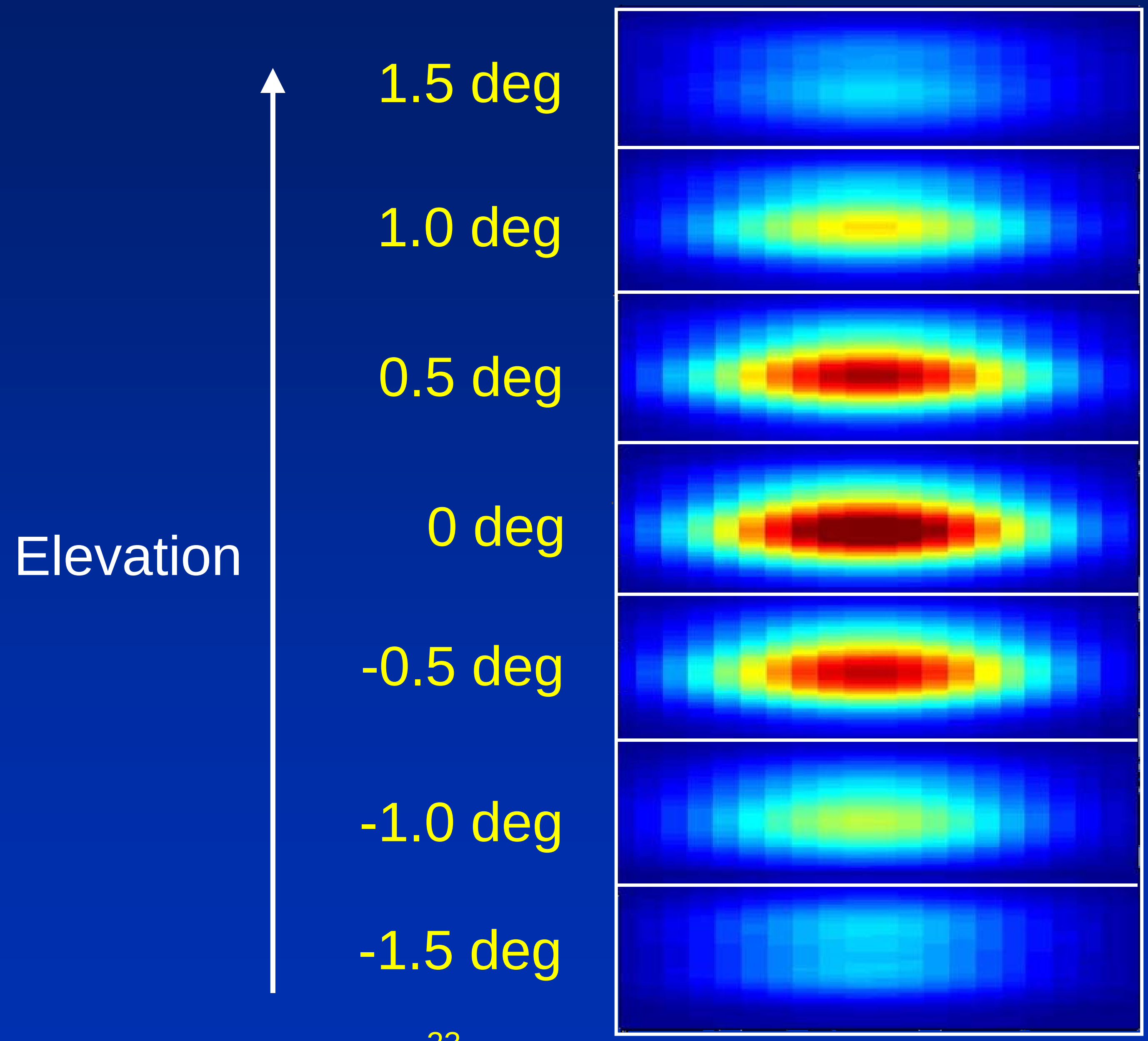


Two sensors



Field size: 12x0.6 m^2

3-D Localization (M/F output)



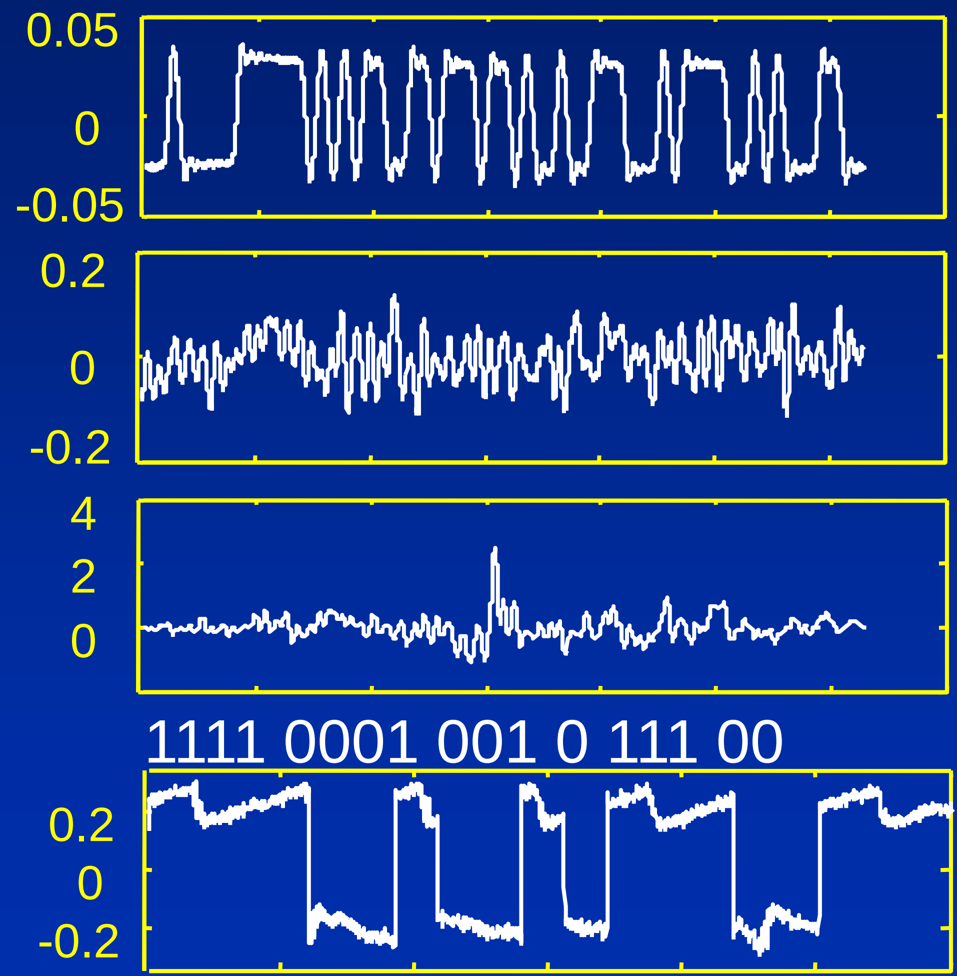
Data Demodulation

Reference PRBS

Received signal (I)

Cross-correlation

Demodulated Data
(10kbps)



Summary

- Millimeter-wave wireless sensor network
  - Large-scale network w/ simplistic sensors
- 60-GHz prototype
  - Collector
  - PIN-diode based passive sensor
  - CMOS sensor (dc power: uW level)
- Indoor radio experiment (<12m)
  - Data demodulation, 3D localization
- ***Next***
  - uW CMOS sensor module
  - Large-scale radio experiment

Thank you.

Questions?