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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 😞

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

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!
  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

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

<table>
<thead>
<tr>
<th>$P_t$</th>
<th>$D_{TX}$</th>
<th>$D_{RX}$</th>
<th>$D_{sens}$</th>
<th>$G_{sens}$</th>
<th>$R_{\text{max}}$ @10kbps, BER = 10^{-6}</th>
</tr>
</thead>
<tbody>
<tr>
<td>7dBm</td>
<td>23dBi</td>
<td>40dBi</td>
<td>7dBi</td>
<td>-3dB</td>
<td>25m (current prototype)</td>
</tr>
<tr>
<td>25dBm</td>
<td>40dBi</td>
<td>40dBi</td>
<td>7dBi</td>
<td>-3dB</td>
<td>200m (possible ext.)</td>
</tr>
<tr>
<td>25dBm</td>
<td>40dBi</td>
<td>40dBi</td>
<td>7dBi</td>
<td>80dB</td>
<td>1,600m (“active” sensor)</td>
</tr>
</tbody>
</table>
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

Steerable
(azimuth, elevation)

D=23dBi
P=7dBm
D=40dBi
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

Baseband → BPSK Modulator → Open-slot Antenna

- $f_{\text{delta}} = 50\text{MHz}$
- $\frac{1}{4} \lambda$
- $\frac{1}{4} \lambda$
- MS-to-SL transition
- PIN diode (MA-COM)
60-GHz Passive Sensor: Considerations

- **Antenna**
  - Patch type?
  - Slot-type?
  - *Open-slot* type?

- **Substrate: RO4003C**
  - 0.2mm, $\varepsilon_r=3.38$
  - Loss = 0.07dB/mm, $Q=20$

- **Standard low-cost PC-board manufacturing**
  - Min. line width/spacing = 5mil (125um)
  - This favors high $Z_0$ (=90ohm)

Size: 15mm x 10mm
Modulator Impedance

Bias ON (7mA)

Bias OFF

\[ b = \Gamma_{\text{mod}} (V_{\text{mod}}) a \]

\[ a : \text{incident wave} \]

\[ b : \text{reflected wave} \]

- Switches between two impedance states.
- \(~180\) degree relative phase shift
- BPSK Modulation
Linearly-Tapered Open-Slot Antenna

Beam Pattern (7dBi)

HFSS

Input Match

HPBW = 50 deg
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

$\frac{1}{R^4}$

Received Power (dBm)

Range (m)
Received Spectrum (RX-IF2)

Sensor OFF

Sensor ON (~3m)

Power (dBm)

Freq. (GHz)

Freq. (GHz)
2-D Localization (M/F output)

Sweep 15.6 deg
Step = 0.6 deg

Field size: 12x0.6 m²
3-D Localization (M/F output)

Elevation

- 1.5 deg
- 1.0 deg
- 0.5 deg
- 0 deg
- -0.5 deg
- -1.0 deg
- -1.5 deg
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?