On the Effectiveness of Switched Beam Directional Antennas in Indoor Environments

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Why Directional Antennas?

- Last-mile network access predominantly 802.11
  - High bandwidth, low/no cost

- 802.11 Success → Changing requirements
  - Spatial reuse [Navda07, Choudhury06], Localization [Sayrafian-Pour06, Niculescu04], Security [Carey04]

100 million WiFi handsets over the next 5 years. Source: IDC, Frost & Sullivan, Infonetics

- Directional antennas can meet several requirements
  - How? Directional antennas reduce the wireless *footprint*
Application Scenarios

- **Spatial Re-use: Increased # (simultaneous transmissions)**
  - Energy focused in one direction and suppressed in others

- **Node localization**
  - Using increased signal strength in the direction towards a client.
Effectiveness in Indoor Environments?

**Focus:** Most 802.11 deployments today are indoors.

**Challenge:** indoor environments rich in Multipath reflections → limit the benefits of directionality

**Objective:** Evaluate the effect of multipath reflections on directionality in indoor environments

**Related work:**
- [Navda07, Raman05, Ramanathan05] – outdoor studies
  - Not applicable due to differing radio propagation characteristics
Background: Types of Directional Antennas

- **OMNI**: Low Flexibility / Efficiency, high Implementation Complexity
- **PATCH**: High Flexibility / Efficiency, low Implementation Complexity
- **SWITCHED BEAM**: Medium Flexibility / Efficiency, medium Implementation Complexity
- **ADAPTIVE BEAM**: Highest Flexibility / Efficiency, highest Implementation Complexity

A more optimal beam is formed
A more optimal beam is selected

NEC Laboratories America
Relentless passion for innovation
Switched Beam Antennas: Background

- Commonly realized using a *phased array*.
  - Antenna pattern formed by signals sent to elements
  - Signals weighted in magnitude and phase

\[
A(k) = a_0 e^{jkd_0} + a_1 e^{jkd_1} + \ldots + a_{N-1} e^{jkd_{N-1}}
\]

- Beams can be changed by modifying amplitude and phase of array coefficients \(a_0, a_1, \ldots\)
Switched Beam Antennas: Background

Example pattern:

<table>
<thead>
<tr>
<th></th>
<th>Magnitude</th>
<th>Phase (deg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>a0</td>
<td>100</td>
<td>-166</td>
</tr>
<tr>
<td>a1</td>
<td>100</td>
<td>-69</td>
</tr>
<tr>
<td>a2</td>
<td>100</td>
<td>69</td>
</tr>
<tr>
<td>a3</td>
<td>100</td>
<td>166</td>
</tr>
<tr>
<td>a4</td>
<td>100</td>
<td>166</td>
</tr>
<tr>
<td>a5</td>
<td>100</td>
<td>69</td>
</tr>
<tr>
<td>a6</td>
<td>100</td>
<td>-69</td>
</tr>
<tr>
<td>a7</td>
<td>100</td>
<td>-166</td>
</tr>
</tbody>
</table>

Energy cannot be fully eliminated in undesired directions

- Results in spill-over or side-lobes
- As main lobe is made more focused, spill-over increases
**Experimental Objective**

Evaluate the effect of multipath on the directionality of switched beam antennas under varying parameters such as:

- **Beam width**
- **Front-to-side-lobe ratio (FSR)**
- **Location**
- **Transmit Power**

- Thin beams = reduced multipath?
- Effect of side lobes
- LOS = strong directionality and NLOS = weak directionality?
- Can we combine transmit power and directionality?
Application-specific Requirements

For spatial reuse:
- “Very few” beams with signal stronger than OMNI
- “Large number” of beams with signal weaker than OMNI

For localization:
- Beam with largest gain = geographical beam towards RX.
Experimental Setup

- One transmitter (AP)
  - Phocus Array – cycles through directions (or beams).
  - Pseudo-IBSS + monitor mode.
  - Broadcasts 128 byte UDP packets.

- Eleven receivers
  - OMNI antenna (6dBi “rubber-duck”)
  - Monitor mode and tcpdump.

Indoor Office Testbed
Black dots = receivers
AP = transmitter
Experimental Setup (continued)

Three pattern sets (p1, p2, p3) used:

- **P1** (BW = 45°, FSR = 8dB)
- **P2** (BW = 45°, FSR = 8dB)
- **P3** (BW = 60°, FSR = 18dB)

- **All nodes**
  - Use Linux v2.4.26 with mini-PCI 802.11 b/g (Atheros, MadWifi)
  - Use channel 6 after office hours
Results

- Degree of directionality
- Potential for Spatial Re-use
- Accuracy of Node Localization
Degree of directionality – Results (p3)

(a) Location a, LOS

(b) Location b, NLOS

(c) Location c, NLOS

(d) Location d, NLOS

(e) Location e, NLOS

(f) Location f, LOS

(g) Location g, LOS

(h) Location h, LOS

(i) Location i, NLOS
Degree of directionality – Results (p3) (continued)

- Strong signal in few directions and weak in rest
  - In many locations (LOS and NLOS)
  - For all three patterns

- Propagation characteristics based on location (LOS or NLOS) alone – hard to predict
Spatial reuse – Results and Observations

- For spatial reuse, RSSI should be lower than OMNI by a considerable amount
  - We choose 3dB threshold (half the received power).

- More than 5 locations have >= 3 directions showing reduced interference relative to OMNI
  - Over 45% of locations indicate chances of spatial reuse
Node localization

- **Assumption:** Beam with highest RSSI = geographical beam towards client – results in loss of accuracy

- Across patterns, very few clients get wrongly positioned
  - Note that RSSI difference is minor in most cases

- Techniques should choose across best beams and patterns for improved accuracy
Degree of directionality – Effect of thinner beams

(a) Location a  
(b) Location b  
(c) Location c

Do thinner beams change observations drastically?
- Use a 17° patch antenna and repeat experiment

Observations:
- Thinner beam widths yield better directionality
- Multipath effects not fully eliminated
Combining directionality and transmit power

- Can we exploit directional gain to reduce transmit power (for increased battery life and reduced interference)?

- TX can reduce transmit power to achieve same performance as OMNI and meet client requirements
  - Transmit power control reduces side lobes as well
Conclusion

- Multipath in indoor environments does not completely negate the benefits of directionality

- Definition of directionality is dependent on application requirements
  - For spatial reuse, the potential exists at many locations (LOS and NLOS)
  - For localization, most clients get correctly positioned

- Thinner beam widths yield greater directionality but fail to completely eliminate impact of reflections

Future Work

- Effectiveness of beams formed in signal space in indoor environments
Questions?
Comparison with MIMO

- **Multiple-input, multiple-output (MIMO) – can exploit multipath indoors**

- **However, for spatial reuse and node localization, MIMO may not work as,**
  - In open-loop mode, it can only improve single link performance
  - In closed-loop mode, it requires significant channel feedback and receiver modifications to enable adaptive beamforming

- **Interesting avenue for future work**
  - When hardware and software become friendly for experimentation
Fidelity Comtech’s Phased Array (Phocus)

- Single board computer (SBC) connected to eight-element circular phased array
  - At most $360° / 8 = 45°$ beam width, 15dBi gain
  - Atheros 802.11 b/g radio

- Electronically steerable
  - Switch between beams at 250μs intervals