Spatially Adaptive Ad-Hoc Networks

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Robot Network Agents

• First responder applications
  – Access area too small, too hot, dangerous.

• Human – Robot network

• Robot communication relays and sensor nodes deployed by a human in field to augment communication and sensing capabilities

• Military applications
  – Landroid program
Vision

• A Network that can sense, move and reason augmenting the capabilities of the network user.
Challenge

- Maintain information flow throughout the robot-sensor network as nodes move around.
- Optimize the network, as robots move around and sensors are deployed within a dynamic, potentially hazardous environment.
- Use mobility to maintain network communication.
- Extend network dimension as nodes move away from command and control center.
Robot behavior

- Robots in teams, create a dynamic multi-robot network maintaining connectivity at all times.
- Proactive motion and cooperation between robot nodes may be necessary.
Network
Key Requirements

• Self-Configuration
• Self Localization
• Self-Optimization
• Self-Healing
• Dynamic network radius
• Intelligent Power Management
• Low memory footprint
• Low Complexity
Remove the line of sight constraint

- Most systems assume a predefined minimum communication radius and add a line of sight constraint between cooperating nodes.
- Network nodes can be shadowed by large obstacles removing direct line of sight.
  - Most indoors environments.
Key Design Decisions

• Dynamic Distributed Address Allocation
  – Low complexity
  – Low energy
  – Strong DAD

• Hybrid Cluster Tree – Mesh architecture

• Policy based and Quality of service driven routing decisions (Multipath Routing)

• Fast recovery from node and link failures

• Mobility is not accidental. Take advantage of node mobility.

• Multichannel MAC
SomsNET Node
SOMSNet
Building the network
Failure and Recovery

(a) initial topology
(b) gateway node 2 fails
(c) topology change
(d) final topology
Cluster Tree Topology
Dynamic Address Space

Root       Root Node
B, C, E    Router Node
A, D, G, F End Node

Child Connect
Gateway Connect

130.191.103.5
  Root
  01:FE

01:01
  A

01:02
  B
  02:FE

02:01
  D

02:02
  E
  04:FE

04:01
  G

01:03
  C
  03:FE

03:01
  F
Address Allocation (Network)
Address Allocation Latency (Node)

\[ P_{\text{noinv}} = (1 - P_{\text{inv}})^N + \sum_{i=2}^{N} P_{\text{inv}} \times (1 - P_{\text{inv}})^{N-i} \]

\[ P_{\text{pfail}} = P_{\text{loss}} + (1 - P_{\text{loss}}) \times P_{\text{loss}} + (1 - P_{\text{loss}}) \times (1 - P_{\text{loss}}) \times P_{\text{loss}} \]

\[ P_{\text{address}} = (1 - P_{\text{pfail}}) \times P_{\text{one}} \]

\[ P_{\text{address}} = (1 - P_{\text{pfail}}) \times N \times P_{\text{inv}} \times (1 - P_{\text{inv}})^{N-1} \]

\[ A = P_{\text{address}} \times 0 + (1 - P_{\text{address}}) \times (A + 1) \]

\[ A = P_{\text{address}}^{-1} - 1 \]

\[ T_{\text{one}} = \left[ \frac{T_{\text{inv}}}{2} + \frac{L_{\text{inv}} + L_{\text{join}} + L_{\text{ack}}}{C} + 2 \times IIFG \right] \]

\[ T_{\text{ave}} = T_{\text{one}} + A \times T_{\text{inv}} \]
Address Allocation Latency (Node)

Experimental measurements on the network resulted in latencies under 1 second.
Address Allocation Latency (Network)

- Depends on the depth of the tree

\[ H = \sum_{i=1}^{\text{Depth}} \frac{C_i}{\sum_{j=1}^{\text{Depth}} C_j} \times i \]

- H is the average number of hops to the root
- C is the average number of child clusters spanned off a cluster head

\[ P_{\text{success}}(H) = (1 - P_{\text{loss}})^H \]

\[ A = P_{\text{success}}^{-1} - 1 \]
Address Allocation Latency (Network)
Routing – Mesh

```
<table>
<thead>
<tr>
<th>LINK</th>
<th>SRC</th>
<th>NEXT HOP</th>
<th>DEST</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>4:1</td>
<td>4:254</td>
<td>3:1</td>
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<tr>
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<td>4:1</td>
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<tr>
<td>3</td>
<td>4:1</td>
<td>3:1</td>
<td>3:1</td>
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</table>
```
Routing

• If destination is in neighbor list, next hop is destination
• If destination is not in neighbor list but destination cluster head is, next hop is destination cluster head
• Next hop is source cluster head
• Routing is performed by source cluster head.
Multichannel Network

• Each new network is created on its own home channel.
• To communicate with a node on a different frequency, jump to its home frequency.
• Channel allocated when network ID is created.
• Nodes need to synchronize to their cluster head.
Multichannel Network

• Guaranteed time slot for cluster-head to parent network
• Probabilistic channel access (CSMA/CA) among nodes in the same network
• Funnel effect as we get closer to the root
  – Data aggregation
  – Bandwidth allocated proportional to the network size
Network Example
Network Example
Network Example
Network Example
Network Example
Take Your Children With You

• When a cluster head is disconnected, it will move on and reconnect to another branch of the tree.

• As a cluster head moves around, it takes its children with it.

• Reduces network convergence time and control traffic
An Instance of the network before node failure
An Instance of the network after recovery from failure
Location Matters

• At 2.4 GHz a high variance in RSS can typically occur within short distances. One-half to one-quarter of a wavelength are reasonable distances in which to expect variance in a multi-path setting.

• Small changes in location can greatly impact signal strength

• The multipath environment may enhance or degrade communication.
SDSU Engineering 4th Floor
TelosB

- IEEE 802.15.4
- 2.4 to 2.4835 GHz
- 250 kbps data rate
- Integrated onboard antenna
- 8 MHz TI MSP430 microcontroller with 10kB RAM
- Low current consumption
- TinyOS
Direct-Ray model - RSSI

• Calculate the signal path loss based on parameters determined from the shortest straight line connecting the transmitting and receiving antennas.

• Frii’s transmission equation, calculates the received signal power according to the signal loss in free space using:

\[ P_{RX} = P_{TX} \times G_{TX} \times G_{RX} \times \left( \frac{\lambda}{4\pi d} \right)^2 \]

\[ RSSI = 10 \times \log \frac{P_{RX}}{P_{Ref}} \]
Path Loss

\[
PathLoss = -10 \times \log_{10} \frac{P_R}{P_T}
\]

\[
PathLoss = -10 \times \log_{10} \frac{G_T G_R \lambda^2}{(4\pi)^2 d^2}
\]

\[
PathLoss = -10 \times \log_{10} \frac{\lambda^2}{(4\pi)^2 d^2}
\]
Log Normal Model

• Propagation models use the close-in distance, $d_0$, as the received-power reference point.
• Calculate the received power, $PR(d)$, at any distance greater than the received-power reference point with reference to $PR(d_0)$

$$PR(d) = PR(d_0) \times \left(\frac{d_0}{d}\right)^2$$

The reference distance for practical systems operating at 1 to 2 GHz is 1m for indoor environments and 100m for outdoor environments
Path Loss – Indoor Channels

\[ P_L(d) = P_L(d_0) + 10 \times n \times \log_{10}\left(\frac{d}{d_0}\right) + X_\sigma \]

\[ \text{PathLoss} = 10 \times n \times \log_{10}\left(\frac{d}{d_0}\right) + 20 \times \log_{10}\left(\frac{4 \times \pi \times d_0}{\lambda}\right) + X_\sigma \]

Using a reference distance of 1 m

\[ P_L(d) = 20 \times \log_{10}(f_{\text{MHz}}) + 10 \times n \times \log_{10}(d) - 28 + X_\sigma \]

Value of n depends on the surrounding
Signal is effected by

- Reflections on metallic objects
- Superposition of electro-magnetic fields
- Diffraction at edges
- Refraction by media with different propagation velocity

RSSI has a very high variance and low entropy
Robot Path 1
RSS measured by the robot
Out of line of sight
Robot Path 2
RSSI Measured Along Robot Path 2
LQI Measured Along Robot Path 2
SDSU Engineering 4th Floor
LQI vs Packet Loss
RSSI – LQI
Correlation
LQI vs Seq Num

LQI vs Seq No -- Blue - Moving Node Red - Fixed Node
RSSI – Both classrooms
RSSI vs Packet Loss

Bin Size: 20
LQI vs Packet Loss
RSSI – LQI Correlation
The slope of the best-fit line to an N-length segment of data is given by $b$. The slope is of importance since it will hint of possible link loss for mobile nodes.
Slope of regression line for Measured RSSI values from a LOS source
Unfiltered RSSI data collected over robot path 2
Piecwise Regression Line with a window size of 7 measurements
Change in Slope of the Regression Line with a window size of 7
Change in bias of the regression line with a window size of 7
Exploiting Multipath
Improve RSSI by Moving
Improve RSSI by Moving
RSSI and LQI Between Beacon 1 and Robot
RSSI and LQI Between Beacon 2 and Robot
RSSI and LQI Between Beacon 3 and Robot
Conjugate Directions Search Pattern

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<tr>
<td>78.0000</td>
<td>72.0000</td>
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Partial RSSI Maps from three Beacons

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<td>65.0000</td>
<td>62.0000</td>
<td>67.0000</td>
<td></td>
</tr>
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Is the location optimal for Beacon 1 good for the other beacons as well?
Improving RSSI for Beacon 1

- Path optimizing RSSI for Beacon-1

Improvement in RSSI as robot move
Improving RSSI for Beacon 2

Path optimizing RSSI for Beacon-2

Improvement in RSSI as robot move
Improving RSSI for Beacon 3

Path optimizing RSSI for Beacon-3

Improvement in RSSI as robot move
Multiple Nodes

• The RSSI patterns observed at a mobile station from multiple fixed/mobile nodes is different – as expected. A move to optimize the RSSI for one node may result in reducing the RSSI for another one.
• Multinode Optimization is a challenge – can be done for a single node at some cost
Optimize Multi Node Channel

- For optimization of the channel between multiple nodes and the mobile node we applied the gradient descent algorithm on the combined RSSI maps from multiple nodes. The RSSI values at each location from multiple nodes are added using a weight for each beacon as given:

\[
RSSI_c = \frac{1}{N} \times \sum_{i=1}^{i=N} W_i \times RSSI_i
\]

\(W_i\) is the weight for each node depending on their role in the network. Nodes with a role of router will have a heavier weight than those that are not.
DYNAMICALLY WEIGHTED RSSI OPTIMIZATION

\[
\text{\textit{RSSI}}_{\text{combined}} = \sum_{i=1}^{I} \frac{R(i)}{\sum_{j=1}^{I} R(i)} \times R(i) \times \left(1 + \log \left( \frac{R(i)}{R_{th}} \right) \right)
\]

- The first term in equation will weigh the contribution of RSSI values with respect to the current value of the RSSI.
  - If the RSSI between two nodes is -80 dBm, it will have more impact on the relocation decision than a node with -50 dBm.
- The second term in parenthesis further improves this. This term awards the RSSI contribution of any node which has a lower RSSI than \( R_{th} \) while it decreases the contribution of any node which has an RSSI value higher than the threshold, \( R_{th} \).
Multinode Optimization with Weighted RSSI

Change in combined cost function – Multi node

Change in combined cost function – Individual node
Multinode Optimization with Weighted RSSI

RSSI Map between beacon 1 and Robot node

Combined RSSI Map computed using $R_{th} = -70$ dBm

Change in combined cost function Multinode
Back to Tethering
Tethering

- Combine robot mobility and a directional antenna
Optimize location

As robot groups spread out it may be necessary to deploy additional robots or relocate robots to improve connectivity.

The mobile routers should move to extend the radius of the network.
Optimize location

As robot groups spread out it may be necessary to deploy additional robots or relocate robots to improve connectivity.
Mobile routers deployed should seek a position to improve connectivity and reduce power while achieving connectivity at all times.
Optimize location

source

relay

dest
RF antenna pattern

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
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<tbody>
<tr>
<td>Frequency range (Mhz)</td>
<td>2400~2500</td>
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<tr>
<td>Polarization</td>
<td>Vertical</td>
</tr>
<tr>
<td>Gain (dBi)</td>
<td>6</td>
</tr>
<tr>
<td>Electrical downtilt (°)</td>
<td>0</td>
</tr>
<tr>
<td>Half-power beam width (°)</td>
<td>Hor: 65, Ver: 65</td>
</tr>
<tr>
<td>Front-to-back ratio (dB)</td>
<td>&gt;= 20</td>
</tr>
<tr>
<td>Impedance (Ω)</td>
<td>50</td>
</tr>
<tr>
<td>VSWR</td>
<td>&lt;= 1.4</td>
</tr>
<tr>
<td>Maximum input power (W)</td>
<td>100 W</td>
</tr>
<tr>
<td>Lightening</td>
<td>DC Ground</td>
</tr>
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</table>
Localization – Angle of Arrival

\[ \begin{align*}
\alpha &= \text{Angle of Arrival for Beacon 1} \\
\beta &= \text{Angle of Arrival for Beacon 2} \\
\gamma &= \text{Angle of Arrival for Beacon 3}
\end{align*} \]
AoA localization

\[ y_1 = m_1 \times x_1 + b_1 \quad \quad b_1 = y_1 - m_1 \times x_1 \]

\[ y_2 = m_2 \times x_2 + b_2 \quad \quad b_2 = y_2 - m_2 \times x_2 \]

\[ y_u = m_2 \times x_u + b_2 \quad y_u = m_1 \times x_u + b_1 \]

The location of the robot can be computed at the intersection of the two lines
Angle of Arrival

\[ \angle B_1R_2B = A = \beta - \alpha \]

\[ \angle B_2R_3B = B = \gamma - \beta \]

\[ \angle B_3R_1 = (360 - (A + B)) \]
Angle of Arrival

- **Beacon 1**: $(P_x, P_y)$
- **Beacon 2**: $(K_x, K_y)$
- **Beacon 3**: $(Z_x, Z_y)$

- **Lines**:
  - Line 1: $Y = m_1 X + b_1$
  - Line 2: $Y = m_2 X + b_2$
  - Line 3: $Y = m_3 X + b_3$

- **Angles**:
  - $\alpha$: Slope $m_1 = \tan \alpha$
  - $\beta$: Slope $m_2 = \tan \beta$
  - $\gamma$: Slope $m_3 = \tan \gamma$

- **Initial Orientation**: The mobile rover $(U_x, U_y)$ is shown with an initial orientation.
Angle of Arrival

 LOS = Line of sight
 \( \alpha \) = Angle of Arrival for beacon 1
 \( \beta \) = Angle of Arrival for beacon 2
 \( \gamma \) = Angle of Arrival for beacon 3

\[
(R_x, R_y) = \left\{ \frac{(X_1 + X_2 + X_3)}{3}, \frac{(Y_1 + Y_2 + Y_3)}{3} \right\}
\]
Indoor Experiments

Indoor Experiment # 1

\[ \alpha_1 = 21.8^\circ \]
\[ \beta_1 = 171.87^\circ \]
\[ \gamma_1 = 240.25^\circ \]

Indoor Experiment # 2

\[ \alpha_1 = 284.03^\circ \]
\[ \beta_1 = 190^\circ \]
\[ \gamma_1 = 231.34^\circ \]
Due to multipath angle of arrival localization is not consistent.
Outdoor Experiments

Outdoor Experiment # 1

Outdoor Experiment # 2

$\alpha_1 = 307^\circ$
$\beta_1 = 53.13^\circ$
$\gamma_1 = 180^\circ$

$\alpha_1 = 22.62^\circ$
$\beta_1 = 157.38^\circ$
$\gamma_1 = 202.62^\circ$
RSSI versus Direction of Robot – Beacon 1

Angle Vs RSSI Value

RSSI

Angle
RSSI versus Direction of Robot – Beacon 2

Angle Vs RSSI Value

RSSI

Angle

RSSI Value
Outdoor Localization Experiments
Outdoor Experiments

Soccer Field Experiment

RSSI in dBm vs. Angle of Arrival

- Beacon 1
- Beacon 2
- Beacon 3
Outdoor Experiments

Rotation # 1

RSSI in dBm

Angle of Arrival

- Beacon1
- Beacon2
- Beacon3
Outoor Experiments
Outdoor Experiments

Rotation #3

RSSI in dBm vs Angle of Arrival

- Beacon 1
- Beacon 2
- Beacon 3
## AoA Estimation Accuracy

<table>
<thead>
<tr>
<th>Rotations</th>
<th>AoA measurement</th>
<th>Accuracy (Δθ) %</th>
<th>Average Orientation Error</th>
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<tr>
<td>1</td>
<td>153°</td>
<td>90.72</td>
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<tr>
<td>5</td>
<td>144°</td>
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</table>

![Graph showing AoA estimation accuracy vs number of spins around axis]
Hallway experiments
Hallway experiments

Hallway Exp. # 1

RSSI in dBm

Line of sight Angle of Arrival

-95
-94
-93
-92
-91
-90
-89
-88
-87
-86

RSSI from Beacon
Hallway experiments
Extending the network
Current Research

• Autonomous decision making among a group of robots to optimize the location