Ad hoc Network Communications for Collaborative Mobile Robots

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Network Communications Goals

- Support self-forming, autonomous and ad hoc network domains
- Allow for intermittent connections to the Operator Control Unit
- Provide a survivable networking infrastructure to support collaborative experiments
- Adjust network topology dynamically based on robot functions, behaviors and mission reconnaissance gathering
Outline

- Ad hoc routing overview
- Routing Enhancements and Signal Strength Visualization
- Network deployment strategies
- Indoor Signal Strength Measurement
- Power Consumption Measurements
- Node Scheduling Strategies

Routing Overview and Enhancements
**Ad-Hoc Wireless Network Overview**

**Basic Idea**
- Given a set of wireless nodes in an infrastructure-less environment, these nodes shall self-organize into a network in such a way that
  - Nodes not in the same radio range communicate by multi-hopping.
  - Mobile nodes, dynamic network topology.

**Benefits from Infrastructure-less approach**
- Easy communication network deployment.
- No access point routers
- Fault Tolerance
- Extends LOS

**MANET Protocols (Multi-hop routing protocols):**
- Proactive approach:
  - Every node stores routes for all possible destinations
  - Nodes constantly exchanges route information.
  - Pros and Cons:
    - (+) Minimum initial delay
    - (-) More memory to store routes which may not be used.
    - (-) A lot of 'control message' traffic to update topology changes.
  - Examples: OLSR

- Reactive approach: On-demand:
  - Nodes stores route entries as needed.
  - Far less topology update messages.
  - Pros and Cons:
    - (-) relatively long initial delay.
    - (+) Less memory for route entries
    - (+) Less bandwidth usage on topology updates.
  - Examples: AODV, DSR
Ad-Hoc Wireless Network Overview

- **AODV**: (Ad-hoc On Demand Distance Vector)
  - Messages:
    - Neighbor Connectivity: local broadcast “Hello” message
    - Path finding and maintenance: RREQ, RREP, RREP-ACK, RERR
  - Operations:
    - Neighbor Connectivity: A node notices its neighbors by ‘Hello’ messages.
    - Path discovery:
      - A node broadcasts RREQ if it does not know how to reach the destination.
      - A node unicasts RREQ if it knows how to get to the destination.
    - Path maintenance:
      - RERR is used to notified link break. It helps the source node to reinitiate Path discovery.

AODV Implementation on IPAQs

- Ported NIST AODV to IPAQ
  - Identified and fixed bugs in NIST AODV
- Extended AODV for minimizing uni-directional links
- Topology Visualization Tool
  - Signal strength measured only on arrival of AODV packets
  - Visualization tool for network topology.
  - Database to allow other applications to query network topology and signal strength between nodes.

Signal quality – 92 (highest)
Routing Optimization

Network optimizations based on above observations:
- Power Consumption:
  - Highly dense and relatively stationary network \(\rightarrow\) multiple routing paths between data source and data sink
  - However, most are idle
  - Alleviate power consumption without losing network connectivity?
  - Ideas: Load balance routing load by policy based routing.
  - Routing Cost Metric: a combination of power level, transmitted packets (size), etc.

Routing Optimization

- Routing Enhancement:
  - Most sensors are stationary
  - Enhance routing efficiency?
  - Example: prolong route entry timeout, multipath routing.
  - Longer route entry cache time or having multi-route entries to prevent path-seeking.
  - Metrics: path-request processing time
Handling Unidirectional Links

**Causes:**
- unbalanced power transmission or interferences/packet collisions.
- In a highly dense environment, if nodes request for non-existent destination, flooding requests may temporarily create unidirectional links in the network.

**AODV is based on bi-directional links which is not practical.**

**Solutions:**
- From AODV protocol draft: passive handling:
  - hand-shaking mechanism: RREQ, RREP, RREP-ACK
  - If RREP sender does not receive RREP-ACK, the next-hop is in the blacklist, the node ignores any RREQ from that next-hop node.
  - Partial solution to the problem:
    - B can successfully identify A as an unidirectional link only if A have ever sent a RREQ and B sends back RREP to A directly (not via C).
    - Otherwise, B has no way to know there exists an unidirectional link.
    - Communication from B to A always fails.
### Handling Unidirectional Links

- **The solution we used:** proactive handling.
  - Proactively identify unidirectional links and ignore them.
  - Still based on the existence of bi-directional links.
  - Algorithm: Each node sends out the neighbor list. For each receiver, it compares itself against the list. If the receiver is not in the list, the link to the neighbor is an 'unidirectional link'.
  - Use bitmap for neighbor list to reduce message size:
    - Number of nodes is less than 256.
    - RREP (Hello message) is 52 bytes (20 bytes + 32 bytes)
  - Can and Can't:
    - Can provide communications as long as bi-directional links exist.
    - Can’t, if no bi-directional links exist.

### Other enhancements

- Reduce dependence on hello messages
  - Extends route-entry lifetime as long as a packet from the node.
- Increase hello message interval and route-entry lifetime:
  - Network is highly dense
  - Nodes not moving very fast.
- Dynamic configuration:
  - Turn on/off signal measurement on demand
  - Turn on/off debug messages on demand.
- Fixed many other bugs:
  - Memory allocation
  - Linked-list
  - Byte-order...etc
Deployment Strategies in Robotics
Sensor Networks

Main Issues

- Mobile Robots Deployed at Random
- Create Self supporting, autonomous system
  - Auto configuration of system parameters
  - Automatic management of the system
  - Adaptive to environment condition and robot applications
  - Intelligent decision making system
- Deployment should meet application constraints
  - Coverage
  - Assurance, Reliability
  - Fault tolerance
- System Constraints
  - Power, memory, processor and sensing capabilities present in the system
- Algorithmic issues
  - Distributed algorithms
Overview of the work

Goal: A distributed algorithm to explore the in-door network deployment based on radio range to maximize network coverage

Deployment strategy
- Potential field method (Howard’s Work)
- Random Walk

Algorithms have to adhere to constraints
- Should Cover as much monitoring region as possible
- Should maintain connectivity
- Should set up ad-hoc networking for communication purposes

Model Indoor radio model
- Ranging
- Communication

Implementation Issues
- Integration with NS2 to perform networking tests with mobile robots

Robot Network Deployment Strategies

Network Deployment – Random walk
- Ideas: The nodes purely random walk in the environment until the criteria are satisfied.
- Criteria:
  - The range of signal strength
  - The number of neighbors
- Pros:
  - Easy to implement
- Cons:
  - Forms isolated islands.
  - Not even distribution
Potential Fields Method for deployment

- Physical obstacles (Walls or other nodes) together form a ‘force’ which pushes the node itself away.

Criteria:
- Force from the walls
- Force from other nodes
- Sticky parameter to ‘stop’ the node

Pros:
- Even distribution of nodes
- Better connected network

Cons:
- Require the distances to the obstacles.
- Radios can penetrate walls
- The shape of the walls may cause isolated islands

Implementation of the Potential Fields Method

- Perl script
- Visualization of the robot movement for deployment
- Input parameters in GUI
- Requires Image of floor plan
- Number of nodes
- Potential field parameters
Implementation of the Potential Field Method

Methodology
- Use image segmentation (edge extraction) to recognize walls
- Each image pixel tagged as a wall or not
- For each node find the virtual force corresponding to other nodes and each pixel which is tagged as a wall

Problems
- Image segmentation and storage of walls as pixels is slow
- Does not incorporate indoor radio model
- Nodes and signals can cross wall boundaries
- Implementing algorithm to bounce off nodes from the walls would be really expensive

Current Implementation Details
- A C++ code with command line arguments for simulation parameters
  - Number of Nodes
  - Communication Range
  - Sensor Range
  - Type of ranging
    - Radio Signal Strength (Lot of errors)
    - SONAR (more accurate)
  - Simulation duration
  - Floor Plan
    - A text file with list of walls described by position of endpoint
  - Output files
    - Animation file (NAM format)
    - Traffic file (to use in NS2 simulations)
## Current Implementation Details: Radio Model

- **Radio Model**
  - Signal Strength attenuation due to walls
  - Procedure to incorporate results of experiments on signal strength measurements
    - Can plug in other attenuation models to simulate the network environment
  - Include random error in measured signal strength in simulations

- **Simulating Ranging functions**
  - Ranging approximation
    - Prone to error since input is erroneous signal strength
  - Use intersection algorithm with walls to simulate the signal strength received

## Implementation Details: Potential Field

- **Based on distances from obstacles and other nodes**
- **Walls**
  - Inversely proportional to the perpendicular distance from walls
  - Only when inside communication range
  - Force only perpendicular to the plane of the wall
- **Nodes**
  - Inversely proportional to the distance from other nodes
  - Direction: along the line joining two nodes
  - Repulsive force when inside communication range
  - Attractive force when outside communication range to bring nodes inside communication region
Implementation Details: Motion

- Based on the force vector compute the next destination for node
- Movement bounded by a small step
  - Step should be much smaller than the communication range so that nodes do not go out of range
- Movement may also be bounded in time
  - Have a constant velocity
  - Move either to the destination or for the fixed time period
  - To simulate periodic computation of potential fields
  - **Not implemented currently**
- Before moving compute if new location is a feasible region
  - If occupied by some other node
  - If it is crossing any wall boundary
  - Find the best new feasible region
  - Uses line intersection finding algorithms

Floor Plan

- Input changed from image file to a text file with a list of walls described by endpoints
- Storing floor-plan as an image: Cons
  - Takes a long time to simulate
  - Segmentation method not accurate and time consuming
  - Difficult to implement intersection finding algorithm
    - For radio model
    - To bounce nodes from the walls
- Storing floor-plan as an image: Pros
  - We may directly apply some real image of a floor plan
- Storing image as a list of lines
  - Faster routines for wall intersection, ranging
  - Have to manually write the floor plan
  - Good for simulation purposes
Integration with NS2

Visualization with Network Animator (NAM)
- Wall information read from input file
  - Nam commands logged in output file to draw the walls
- The movement computed from force equations translated to
  - Velocity of motion for animation
  - Virtual system time
  - NAM command formats for movements

Generating Traffic File for Simulations
- NS2-TCL commands for node movement
- NS2-TCL Commands to update GOD information
  - For connectivity computation
- Compute and log Virtual system time to be used in simulations
- Commands to send packets periodically to simulate periodic computation of signal strengths and potential fields
  - Not Implemented Currently

Future Work

Current walls are straight lines
- Include walls with different shapes
- Three dimensional

Plug in various radio models and ranges to test the performance of potential fields method

Performance of method in more complex floor plans

Implement Communication protocol on top of deployment algorithm
- Communication while moving

Generate ad-hoc map of the floor-plan from explored regions
- Use these maps to take decisions for deployment

Implementation in mobile robots
Indoor Signal Strength Measurement (in Telcordia AR Labs)
- Signal Strength range >> sensor range  \( \rightarrow \) sensor range is the driving factor in network deployment

- Discussions on Indoor Signal Strength Measurement
  - Signal strength:
    - \( > 10 \) \( \rightarrow \) reliable communication
    - \( > 5 \) \( \rightarrow \) not stable communication (due to interference)
  - Signal range: (>> sensor range)
    - Straight distance: 190 feet while maintaining signal strength ~ 20
    - Corner: 114 feet while signal strength ~ 12
    - Open vs. closed door: seems no significant impact on signal strength.
  - Dynamic Obstacles:
    - Much less impact on communication network than on sensor network.
    - Response to Dynamic Obstacles: If radio signal strength significantly downgrades due to dynamic obstacles, the node locally wanders until the signal strength criteria are satisfied.
Power Consumption Strategies in Robotics Sensor Networks

- Observations
  - Radio range >> sensor range
  - Highly dense communication network (because sensor range is the driving factor)
  - Stationary sensor nodes once deployment is done.
  - Limited battery life.
  - Power consumption on communication:
    - Idle: Receive: Transmit = 1: 2: 2.5  [O. Kastern. Energy Consumption]
Robot Power Consumption: Experiments

- Radio Off v.s Radio Idle --> ~ 6% power saving
- Radio Idle v.s. Lightweight Traffic (Ping [9 bytes] v.s. AODV) --> ~ same
- Light (9 bytes) v.s Heavy (64 bytes) --> ~ 20% power saving.

Power Consumption in Multi-Hop Wireless Networks

- Number of Hops Between Source and Destination
  - Communication overhead increases with hops
- Channel Error
  - number of retransmissions for reliable packet delivery increases with error
  - Increases significantly with increase in number of hops
- Communication Range
  - Determines Transmit Power Level
- System Idle Power
  - Can be reduced by putting redundant nodes to sleep mode
- Data Processing, Computation
  - Depends on Protocol complexity
Power Conservation Approaches

- Transmit Power Control
  - Find optimal transmission power for minimum power consumption
- Node Scheduling
  - Put redundant nodes to sleep mode
  *General idea is to reduce the density of the network to reduce power consumption*

Transmit Power Control

- Reduce transmit power to optimal level
- Reduced received power consumption since lesser number of nodes receive packets
- Increases hop distance between nodes
- Presence of channel errors leads to different analysis
- Lot of work in literature
Node Scheduling

- Switch off redundant nodes for packet forwarding purposes
- Minimize the number of active nodes required for communication purposes
- Switching nodes off leads to increase in average path lengths
  - Increase in overhead for communication
  - In the presence of channel errors increased path lengths have adverse effects on reliable packet transmission overhead
  - Not studied in literature

Node Scheduling Strategies

- Generally uses Minimum Connected Dominating Sets (MCDS)
  - Construct a backbone of the network comprising of MCDS
  - Switch off all nodes for forwarding purposes which are not part of the MCDS
  - Constructs a network with the minimum possible density while still maintaining connectivity
  - Minimizes power consumed while receiving packets

- Problems with the MCDS approach
  - Significant increase in hop lengths
  - Minimum density of the network may not have optimal power consumption
  - More so in the presence of channel errors
### Problem Statement

- Large density leads to lot of useless received power dissipation
- Small density increases average hop lengths
- Exploiting the tradeoff:
  - *What is the optimal density of nodes needed to be active so that the power consumption for reliable packet delivery is minimum?*

### Main Contributions

- Formulation of power consumption equation for node scheduling algorithms
  - Average hop distances (decreasing function of density)
  - Received Power Consumption (increasing function of density)
  - Power consumption for reliable transmissions (function of channel error rates and hop distances $\Rightarrow$ decreasing function of density)
  - Idle Power consumption: (increasing function of density)
- Conditions for minimum power consumption
  - Find optimal density
- How to schedule nodes at the optimal density
  - The Concept of Minimum Virtual Connected Dominating Sets (MVCDS)
Impact of Density on Hop Distance

- Assuming active nodes are uniformly distributed with a lesser density than actual distribution of nodes

![Graph showing expected hops as a function of density](image)

Formulation of Power Consumption

- $P_T = \text{Transmit power consumption}$
- $P_R = \text{Receive power consumption}$
- $P_I = \text{Power consumption in Idle Mode}$
- $P_S = \text{Power consumption in Sleep mode}$
- $\lambda_p = \text{packet generation frequency per node}$
- $X = \text{fraction of nodes with receivers turned off}$

\[
P_{\text{Total}} = \lambda_p \left( P_T O_{\text{Transmissions}} + P_R O_{\text{Receptions}} \right) + P_I (1 - X) + P_S X
\]
Reliable Transmission Schemes

- **End-To-End Retransmissions**
  - For a correctly received packet, the destination sends an acknowledgement to the source.
  - Source stops retransmission when it receives the acknowledgement packet.
    - Due to channel error acknowledgement packet may also be dropped.
  - Overhead increases exponentially with hop distance.
    - Increased hop distance at low density has significant impact.

- **Hop-By-Hop Retransmissions**
  - Intermediate nodes send acknowledgements for a correctly received packet (Link layer retransmissions).
  - Reliable delivery on a hop by hop basis.
    - Much lesser overhead.
    - More suitable for wireless networks.

Comparison of the Retransmission Schemes

- **Overhead (EER): Impact of channel errors**
- **Overhead (HRR): Impact of Channel errors**

![Graphs showing comparison of overhead impacts]
Exploiting the Wireless Broadcast

- Since wireless is a broadcast medium when a packet is transmitted all neighbors can receive it.
  - Intuitively this amounts to automatic redundancy in packet forwarding
  - The probability of getting forwarded is higher since multiple nodes receive a packet
  - If at least one of the next hop neighbors forward the packet it travels with a gradient towards the sink
  - Number of retransmissions can be reduced

Hop-By-Hop Broadcast Protocol

- A node broadcasts while forwarding a packet
- A subset of neighbors receive the packet correctly
- All next-hop neighbors which receive the packet correctly probabilistically forwards the packet
- Forwarding probability such that on an average only one node forward a packet
- A next hop neighbor which forwards a packet sends a confirmation packet back to the previous hop node
Derivation of the Expected Overhead of HHB

- **Expected number of next hop neighbors, \( k_i \)**

![Graph showing expected number of next hop neighbors](image)

- **Total Packet Overhead**

\[
P_{HHB} = \lambda_p \left( P_i \sum_{j=1}^n \frac{2 - f_k}{1 - f_k} + P_d \sum_{i=1}^n \frac{2 - f_k}{1 - f_k} \right) + P_r (1 - X) + P_s X
\]

![Graph showing overhead (HHB): Impact of Channel Errors](image)

**Comparison: HHR vs HHB**

![Graph showing comparison between HHR and HBB](image)
We found the optimal density of active nodes at which different schemes, EER, HHR, and HHBR have minimum overhead.

How do we make MCDS based node scheduling algorithms use these results to create topology at the optimal density?

- Note that MCDS only creates a topology at the minimum possible density.

We define a notion of dominating sets at multiple densities:

**A Minimum Virtual Connected Dominating Set**

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**Minimum Virtual Dominating Set: MVDS**

- Disk Graph $G(V, E(R))$
- Virtual Graph $G(V, E(r))$
  - Virtual Range, $0 \leq r \leq R$
  - $MVDS(r)$ = minimal dominating set of the virtual graph.

Minimum Backbone

```
 r=R
```

All Nodes

```
 r=0
```
Properties of MVCDS

- Analytical models assume that the distribution of the dominating set follows a Uniform Distribution
  - The formulation of the power consumption equation was based on such uniformity assumptions of the Active node set
  - If MVCDS also has properties similar to a uniformly distributed set of nodes, if can be used to construct topology at the optimal density

- Expected cardinality of MVCDS
- Expected Hop Distance

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- Expected cardinality of MVCDS
- Expected Hop Distance
We use the plots of the analytical functions derived for Hop-By-Hop Broadcast Protocol to find the optimal density at which it has minimum expected overhead.

- Find the virtual range \( r \) corresponding to the optimal density from the analytical model of MVCDS.
- Construct the MVCDS \( (r) \) based on the computed virtual range.
- Switch off all nodes not belonging to the MVCDS for forwarding purposes.
  - Nodes in sleep mode may wake up any time and transmit a packet, but they do not receive any packet to forward.
- We compute the overhead for reliably transmitting packets between randomly selected source and a sink.
Program Overview | SW Architecture | Network Comm | User Interface | Adj Autonomy | Localization | Discussion
---|---|---|---|---|---|---

**Simulation Results**

**Overhead (HBB): Impact of Power Ratio**

- \( P_r = 0.1 \)
- \( P_r < 0.2 \)
- \( P_r < 0.1 \)
- \( P_r = 1.0 \)

**Comparison of Overhead**

- Using MCDS
- Using MVCDS at optimal density

**Ratio of Transmit and Receive Power**

**Summary of Results**

- The expected overhead of reliable transmission in multi-hop wireless networks a function of:
  - Density of active nodes
  - Average hop distance (a function of density)
  - Channel Error conditions
  - Average traffic volume

- Overhead of reliable transmissions can be reduced by exploiting the broadcast redundancy in wireless channel
  - The Hop-By-Hop Broadcast Protocol

- Minimum density as Constructed by Minimum Dominating sets not optimal for power consumption

- Connected Dominating set can be created at the optimal density using the concept of Minimum Virtual Connected Dominating Sets
  - MVCDS created has approximately uniform distribution
  - Properties of MVCDS make it applicable to construct topology at optimal density