Routing Protocols for Ultra-Wideband Mobile Ad Hoc Networks

Samer Bali

Dissertation Presentation
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Outline

- Introduction
- Investigations & Performance Evaluation
- Mathematical Model of Channel Capacity
- New Developed Routing Protocol (AOMSR)
- Conclusions
Main Characteristics:
- Formed by self-configurable (mobile) devices with wireless capabilities
- Do not require pre-existing infrastructure
- Have a dynamic topology due to node mobility
- All nodes operate as routers to forward packets to each other using multi-hop communications
- **Routing Protocols** are needed to establish and maintain connections between nodes
Main Goal:
- To develop efficient routing protocol for UWB Mobile Ad Hoc Network in a factory scenario (industrial indoor application)

Research Questions:
- Why UWB technology is considered in this work?
  - UWB is suitable for indoor applications (robust performance under fading conditions, low transmission power and large channel capacity)
  - Production Line in a factory is a viable indoor application
- Is there routing protocol suitable for the production line scenario?
  - Need Investigations (most research considers random way point scenario)
- How can routing protocols be developed?
  - Two main mechanisms: **Route Discovery** and **Route Maintenance**
Ad hoc routing protocols are classified in 2 main categories:

- **Proactive**: each node retains routes to all other nodes in all times
- **Reactive**: a route is only discovered when it is actually needed

MANET group is trying to standardize only two protocols:

- OLSRv2 (proactive) & DYMO (reactive)
- They are still immature in terms of implementation
- They are basically developed from AODV, DSR and OLSR

<table>
<thead>
<tr>
<th>AODV</th>
<th>DSR</th>
<th>OLSR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactive</td>
<td>Reactive</td>
<td>Proactive</td>
</tr>
<tr>
<td>Hop-by-hop routing</td>
<td>Source routing</td>
<td>Hop-by-hop routing</td>
</tr>
<tr>
<td>Flooding</td>
<td>Flooding</td>
<td>Multi-Point Relay (MPR)</td>
</tr>
<tr>
<td>One route per destination</td>
<td>Multi-route per destination</td>
<td>One route per destination</td>
</tr>
<tr>
<td>Timer for route entry</td>
<td>No timer for route entry</td>
<td>No timer for route entry</td>
</tr>
</tbody>
</table>
Methodology

- Define & simulate the production line network scenario as basis for investigations
  - Considering realistic UWB radio model
  - Considering realistic node positions and traffic patterns

- Carry out performance evaluation of AODV, DSR & OLSR
  - Propose approach to develop efficient routing protocol for the production line network scenario

- Develop a mathematical model for channel capacity as tools for benchmarking & validation of simulation results

- Develop efficient routing protocol for the production line scenario based on the proposed approach
Network Scenario

Production Line in a Factory

- **Machine (fixed node)**
- **Material Box (mobile node)** moved by a conveyor belt with speed of 1m/s from one side to the other

**Purpose:** interconnect machines through the moving boxes between them

**Traffic:** each machine sends basically one data packet (1024 Bytes) every 30s to the next machine containing information (codes)

i.e., **basic data rate** of 0.27Kbps which is low enough to be used in WPAN (IEEE802.15.4a) network with a noisy environment
Simulation Tools (1/2)

■ **NS-2 Simulator:**
  - software developed by UWB research group at EPFL-IC
    - Joint PHY/MAC architecture for 802.15.4a-like UWB networks
    - PHY: TH-IR-UWB technique, fading channel model (shadowing model)
    - MAC: dynamic channel coding (bit rate adaptation), interference mitigation scheme
  - WLAN (IEEE 802.11a) code was used for comparison

■ **UWB main parameters:**
  - Tx Power: 1 µW
  - Tx Range *average*: ~ 10 m (depends on bit rate)
  - Bit rate: [1.8-18] Mb/s (depends on channel coding)
  - Bandwidth: 1GHz
  - Center Frequency: 5 GHz

TH-IR-UWB: one data bit ($T_s = N_s \cdot T_f$)

$$T_f = M_f \cdot T_c$$
Simulation Experiments
- Simulation time was 750s (including a warming up period of 150s)
- Each simulation experiment was repeated 50 times (average was used)
- 90% confidence intervals are included in the plots

Investigations
- Multi-hop effect
- Data rate effect
- Scalability effect

Main Performance Metrics
- Packet Delivery Ratio (PDR) = \( \frac{\text{received data packets}}{\text{sent data packets}} \)
- Normalized Throughput (NTh) = \( \frac{(\text{received data packets (bits) / simulation time (s)})}{\text{data rate (bits/s)}} \)
- Routing Overhead Ratio (ROR) = \( \frac{\text{routing packets (bytes)}}{\text{routing packets (bytes) + sent packets (bytes)}} \)
One data traffic flow (fixed)

Basic data rate of 0.27Kbps (fixed)

Distance between fixed nodes is (variable)

Distance between mobile nodes is (variable)
Multi-Hop Investigation (2/2)

- **AODV-10m (1-Hop)**
- **AODV-20m (2-Hops)**
- **AODV-30m (3-Hops)**

(a) AODV-10m (1-Hop)

- UWB
- WLAN

(b) AODV-20m (2-Hops)

- UWB
- WLAN

(c) AODV-30m (3-Hops)

- UWB
- WLAN

Introduction
Investigations & Performance Evaluation
Mathematical Model of Channel Capacity
New Proposed Routing Protocol (AOMSR)
Conclusions

Leibniz Universität Hannover
- UWB: Ultra-Wideband
- WLAN: Wireless Local Area Network
- AODV: Ad Hoc On Demand Distance Vector Routing
- OLSR: Optimized Link State Routing

15-Sep-08
■ One data traffic flow (fixed)
■ Data rate is (variable)
■ Distance between fixed nodes is 30m (fixed)
■ Distance between mobile nodes is (variable)
Data Rate Investigation (2/4)

(a) UWB-AODV

(b) UWB-DSR

(c) UWB-OLSR

Introductions & Performance Evaluation
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AODV: Ad Hoc On Demand Distance Vector Routing
DSR: Dynamic Source Routing
OLSR: Optimized Link State Routing

UWB: Ultra-Wideband
Data Rate Investigation
(3/4)

(a) UWB-AODV

(b) UWB-DSR

(c) UWB-OLSR

- AODV: Ad Hoc On Demand Distance Vector Routing
- DSR: Dynamic Source Routing
- OLSR: Optimized Link State Routing

• UWB: Ultra-Wideband

Introduction
Investigations & Performance Evaluation
Mathematical Model of Channel Capacity
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Data Rate Investigation (4/4)

(a) UWB-AODV-0.27 Kbps

(b) UWB-DSR-0.27 Kbps

(c) UWB-OLSR-0.27 Kbps

Distance between Mobile Nodes (m)
1, 3 and 8 data traffic flows (variable) (1 & 3 are shown)
- Basic data rate of 0.27Kbps (fixed)
- Distance between fixed nodes is 30m (fixed)
- Distance between mobile nodes is 1m-30m (variable)
Scalability Investigation (2/2)

Introduction
Investigations & Performance Evaluation
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• UWB: Ultra-Wideband
• AODV: Ad Hoc On Demand Distance Vector Routing
• OLSR: Optimized Link State Routing
UWB achieves higher throughput than WLAN in multi-hop communications

AODV outperforms DSR in the production line scenario

Also, AODV outperforms OLSR in small network size with low data rates (less than almost 1Kb/s). When data rate increases (larger than 1Kb/s) without increasing the network size, OLSR outperforms AODV.

However, the performance of OLSR degrades as network size increases and AODV again outperforms it.

Proposal for enhancement

- Combine some routing mechanisms from AODV, DSR & OLSR in one routing protocol:
  - Timer to delete out-of-date routes (AODV mechanism)
  - Multipath routing (DSR mechanism) to resolve link breaks quickly
  - Source routing (DSR mechanism) to solve some problems easily
  - Reliable route paths (OLSR mechanism) to control packet forwarding

AODV: Ad Hoc On Demand Distance Vector Routing
DSR: Dynamic Source Routing
OLSR: Optimized Link State Routing
UWB: Ultra-Wideband
WLAN: Wireless Local Area Network
■ Nodes are distributed along a line at regular distance $\Delta$
■ From the view point of node $n_0$, other nodes are placed on the diameter endpoints of co-centered rings, represented by gray circles
■ Number of nodes is $N = 1 + 2K$; where $K$ is number of rings.
■ Coverage area is represented by black circle of radius $R$ and it includes $\alpha$ rings

Pathloss power law model is used: $P = c(d)^{-\beta}$; where $c$ : constant that determines transmission power level, $d$ : distance, $\beta$ : pathloss exponent
■ Two routing methods: Energy Conservation and Minimum Hop-Count
■ The first method is used if $\alpha$ is 1. Otherwise, the second method is used
■ If $\alpha \neq 1$, number of relay nodes is $N_r = 1 + 2\left\lfloor \frac{K}{\alpha} \right\rfloor$. Otherwise $N_r = N$
Nodes generate new traffic according to Poisson distribution independently.

Total traffic per node consists of own traffic and relay traffic. i.e.:

\[
\begin{align*}
    r_o &= r_b + r_b(E[h]-1) = r_b \cdot E[h]
\end{align*}
\]

where \( E[h] \) is the expected hop-count of the network.

Closed-form formula for \( E[h] \) can be found, if the exact hop-count distribution \( h \) is found for several network sizes.

For example:

\[
\begin{align*}
    K &= 2 \\
    \alpha &= 1 \\
    N &= N_r = 5 \\
    E[h] &= 2
\end{align*}
\]

In general:

\[
E[h] = \frac{N_r + 1}{3} + 2\left(1 - \frac{N_r}{N}\right)
\]
Channel capacity (in bits/s) between any two neighbor nodes is governed by Shannon formula that can be expressed in the form:

\[ C = W \cdot \log_2 (1 + E[S / I]) \]

- **\( W \): Channel Bandwidth, \( E[S / I] \): Expected Signal to Interference Ratio**
- **Transmission technique** and **medium access scheme** impose some modifications to this formula
  - In spread-spectrum systems, interference power is reduced by a factor called **processing gain** (\( g \)).
  - Medium access scheme affects channel capacity in two ways: **channel utilization factor** (\( u \)) & **amount of interference** (\( I \))
- Considering these effects, capacity formula is then:

\[ C = u \cdot W \cdot \log_2 (1 + g \cdot E[S / I]) \]

- To find a closed-form formula for \( C, E[S / I] \) is found based on **UWB** (TH-IR-UWB) & **WLAN** using (CSMA/CA)
Expected Signal Power: UWB & WLAN

Signal Power (1st ring): $S_1 = c(\Delta)^{-\beta}$

1st ring probability: $p_1 = 2 / 2\alpha$

$$E[S] = \sum_{j=1}^{\alpha} \frac{c(j \cdot \Delta)^{-\beta}}{\alpha}$$

Expected Interference Power: UWB

$$E[I] = \sum_{j=1}^{K} p_{tr} \cdot 2 \cdot c(j \cdot \Delta)^{-\beta}$$

Expected Interference Power: WLAN

$$E[I] = \sum_{j=1}^{\frac{K}{\alpha+1}} p_{tr} \cdot 2 \cdot c(j(\alpha+1)\Delta)^{-\beta}$$

- UWB: Ultra-Wideband
- WLAN: Wireless Local Area Network
Capacity Computation (3/4)

**UWB**

\[
C = W \cdot \log_2\left(1 + \frac{\sum_{j=1}^{\alpha} g^{j-\beta}}{2\alpha \cdot p_{tr} \sum_{j=1}^{\beta}}\right)
\]

**WLAN**

\[
C = \frac{W}{1+2\alpha} \cdot \log_2\left(1 + \frac{\sum_{j=1}^{\alpha} g^{j-\beta}}{2\alpha \cdot p_{tr} (\alpha+1)^{-\beta} \sum_{j=1}^{\beta}}\right)
\]

where \( g = \begin{cases} 1000 & \text{for UWB} \\ 11 & \text{for WLAN} \end{cases} \)

- **UWB**: Ultra-Wideband
- **WLAN**: Wireless Local Area Network
Capacity Computation (4/4)

WLAN

- \( r = 1 \text{Mb/s} \)
- \( \beta = 2.15 \)
- \( r_b = 50 \text{Kb/s} \)

UWB

- UWB: Ultra-Wideband
- WLAN: Wireless Local Area Network
The line topology with 11 relay nodes was simulated for verification.

It resembles the production line with one traffic flow.
WLAN

- $r = 1\text{Mb/s}$
- $\beta = 2.15$
- $N_r = 11$
- $N_r = 1 + 2\left\lfloor K / \alpha \right\rfloor$

UWB

- $r = 1\text{Mb/s}$
- $\beta = 2.15$
- $N_r = 11$
- $N_r = 1 + 2\left\lfloor K / \alpha \right\rfloor$
Spread-Spectrum Scheme and Medium Access Scheme play an important role in channel capacity computation. As a result, the output throughput per node is limited mainly by the transmission bit rate in case of UWB technology, while it is limited mainly by the very low channel capacity in case of WLAN technology. This explains why UWB achieves much higher throughput than WLAN in multi-hop communications.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TH-IR-UWB</th>
<th>WLAN (CSMA/CA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$g$</td>
<td>&gt;1000</td>
<td>11</td>
</tr>
<tr>
<td>$u$</td>
<td>100%</td>
<td>&lt;33%</td>
</tr>
</tbody>
</table>
Some routing mechanisms from AODV, DSR & OLSR are combined in one enhanced routing protocol:

- Timer to delete out-of-date routes (AODV mechanism)
- Multipath routing (DSR mechanism) to resolve link breaks quickly
- Source routing (DSR mechanism) to solve some problems easily
- Reliable route paths (OLSR mechanism) to control number of forwarding nodes

The resulting protocol is called: Ad Hoc On-Demand Multipath Source Routing (AOMSR)
Multipath routing:
+ If a route breaks, a route can be found quickly without initiating a new route discovery procedure
- Multipath routing may lead to loop problem (simply solved by source routing mechanism)

Source routing:
+ Solve loop problem easily
+ Reliable route paths can be easily chosen (disjoint paths)
- Increase routing overhead (acceptable in our network scenario)

Timers:
+ Delete out-of-date routes
### Route Table Entry

<table>
<thead>
<tr>
<th>destination</th>
<th>sequence number</th>
<th>path list</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>nodes along path1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>nodes along path2</td>
</tr>
<tr>
<td></td>
<td></td>
<td>timeout1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>timeout2</td>
</tr>
</tbody>
</table>

(a) RREQ Propagation

(b) RREP Propagation
Route Update Algorithm

01: if route has larger sequence number (more fresh)
02: {
03:     delete all old paths in the route entry list and add the new fresh path
04: }
05: elseif route has same sequence number and path is loop-free
06: {
07:     if the new path is disjoint [using nodes along path information in the packet header]
08:         add the new path to route entry list
09:     }
10: }
11: }
- **Route Maintenance Mechanism**

  - A path is used until it expires or breaks (confirmed by error message)

  - If a path becomes unavailable, then the next path in the list is used

  - When there are no more paths in the list, then a route discovery procedure is initiated

![Diagram showing route maintenance mechanism](attachment://route_maintenance_diagram.png)
## AOMSR Performance in Data Rate Investigation

<table>
<thead>
<tr>
<th>Data Rate (Kbps)</th>
<th>Ratio of max. <strong>PDR</strong> of AOMSR to that of:</th>
<th>Ratio of max. <strong>NTh</strong> of AOMSR to that of:</th>
<th>Ratio of min. <strong>ROR</strong> of AOMSR to that of:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>AODV</td>
<td>DSR</td>
<td>OLSR</td>
</tr>
<tr>
<td>0.27</td>
<td>1.29</td>
<td>2.31</td>
<td>1.24</td>
</tr>
<tr>
<td>0.82</td>
<td>1.58</td>
<td>4.00</td>
<td>1.19</td>
</tr>
<tr>
<td>1.64</td>
<td>2.02</td>
<td>5.57</td>
<td>1.12</td>
</tr>
</tbody>
</table>

*30m* distance between fixed nodes

One Data Traffic Flow *(0.27, 0.82 and 1.64) Mbps*

30m distance between mobile nodes *(1m-30m)*
AOMSR Performance in Scalability Investigation

<table>
<thead>
<tr>
<th>Flow Type</th>
<th>NTh of AOMSR (Ratio to AODV)</th>
<th>ROR of AOMSR (Ratio to OLSR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1Flow</td>
<td>0.98 1.93</td>
<td>3.00 0.64</td>
</tr>
<tr>
<td>3Flows</td>
<td>1.24 1.90</td>
<td>2.00 0.61</td>
</tr>
<tr>
<td>8Flows</td>
<td>1.30 2.10</td>
<td>2.00 0.61</td>
</tr>
</tbody>
</table>

- **NTh**: Normalized Throughput
- **ROR**: Routing Overhead Ratio
- **AOMSR**: Ad Hoc On Demand Multipath Source Routing
- **AODV**: Ad Hoc On Demand Distance Vector Routing
- **OLSR**: Optimized Link State Routing
Conclusions

- UWB has large channel capacity because of its large processing gain and large channel utilization factor.
- UWB is suitable for indoor multi-hop applications with noisy environment.
- Routing overhead can be acceptable to a certain extent in UWB ad hoc networks because of its large channel capacity.
- But delay in establishing routes prevents nodes from utilizing the large capacity of UWB.
- This led to develop AOMSR (based on AODV, DSR and OLSR):
  - It reduces time of route establishment.
  - Although it may increase routing overhead in comparison with AODV, it still achieves same or better throughput than other protocols.
  - It enhances throughput up to 150% in some situations.

- UWB: Ultra-Wideband
- AOMSR: Ad Hoc On Demand Multipath Source Routing
- AODV: Ad Hoc On Demand Distance Vector Routing
- OLSR: Optimized Link State Routing
- DSR: Dynamic Source Routing
Thank You for Your Attention
Scalability Investigation (1/2)  EXAMPLE