Implementation of an IEEE 802.15.4 and ZigBee Protocol using the OPNET simulator

Mohammad Reza Sahraei

http://www.sfu.ca/~mrs16/ensc835.htm
mrs16@sfu.ca
Road map

- Introduction:
  - Overview
  - ZigBee vs. Bluetooth
- Performance evaluation:
  - Simulation scenarios and parameters
  - Simulation results
- Conclusions
- Unfinished work:
  - Simulation scenario and parameters
  - Implementations details
- Future work
- References
Introduction - overview

- Transmission bands:
  - 868 MHz
  - 915 MHz
  - 2459 MHz

- Device type:
  - Full-function device (FFD)
    - PAN coordinator (IEEE 802.15.4) or ZC (ZigBee)
    - Coordinator (IEEE 802.15.4) or ZR (ZigBee)
  - Reduced-function device (RFD)
    - Device (IEEE 802.15.4) or ZED (ZigBee)

ZC: ZigBee Coordinator, ZR: ZigBee Router, ZED: ZigBee End Device
PAN: Personal Area Network
Introduction - overview

- **Application layer features:**
  - Generating and receiving application traffic
  - Initiating network discovery and network join
  - Failing and recovering ZigBee devices

- **Network layer features:**
  - Establishing a network
  - Joining a network and permitting network joins
  - Assigning an address
  - Maintaining a neighbor table
  - Mesh Routing Process
  - Network Broadcast
  - Tree routing process
  - Transmitting and receiving data
  - Mobility
  - Beacon scheduling

- **MAC layer features:**
  - Channel Scanning
  - CSMA/CA (Contention-based operation mode)
# Introduction – ZigBee vs. Bluetooth

<table>
<thead>
<tr>
<th></th>
<th><strong>ZigBee</strong></th>
<th><strong>Bluetooth</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmission band</td>
<td>868, 915, and 2459 MHz</td>
<td>2.4 GHz</td>
</tr>
<tr>
<td>Data rate</td>
<td>250 Kbps (at 2.4 GHz)</td>
<td>1 Mbps</td>
</tr>
<tr>
<td>Operational range</td>
<td>10 – 75 m (1500 m for ZigBee Pro)</td>
<td>1, 10, and 100 m</td>
</tr>
<tr>
<td>Configuration</td>
<td>Master-slave</td>
<td>Peer-to-peer, master-slave</td>
</tr>
<tr>
<td>Maximum child</td>
<td>254</td>
<td>7 (active) + 255 (inactive)</td>
</tr>
<tr>
<td>Maximum power</td>
<td>1 mW</td>
<td>1, 2.5, and 100 mW</td>
</tr>
<tr>
<td>Wake up delay</td>
<td>15 msec</td>
<td>3 sec</td>
</tr>
<tr>
<td>Protocol stack</td>
<td>30 kwords</td>
<td>256 kwords</td>
</tr>
<tr>
<td>Protocol complexity</td>
<td>Lower</td>
<td>Higher</td>
</tr>
<tr>
<td>Price</td>
<td>less expensive</td>
<td>more expensive</td>
</tr>
</tbody>
</table>
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Simulation scenarios and parameters

Simulation scenarios:
- Star, Tree, and Mesh topologies
- Single and multiple ZC

Parameters:
- 1,000 s simulated time
- Destination: random
- Packet inter-arrival time: constant, mean 1.0 s
- Packet size: 1024 bytes, constant
- Start time: uniform min 20 s, max 21 s

ZC: ZigBee Coordinator
Simulation scenarios and parameters

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ZC: ZigBee Coordinator
Star topology

ZC: ZigBee Coordinator
ZR: ZigBee Router
ZED: ZigBee End Device
Tree topology

ZC: ZigBee Coordinator
ZR: ZigBee Router
ZED: ZigBee End Device
Mesh topology

ZC: ZigBee Coordinator
ZR: ZigBee Router
ZED: ZigBee End Device
Network structure

<table>
<thead>
<tr>
<th>Device Name</th>
<th>PAN ID</th>
<th>Parent</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Star</td>
<td>Tree</td>
</tr>
<tr>
<td>zc_fixed_1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>zed_mobile_1</td>
<td>1</td>
<td>93</td>
</tr>
<tr>
<td>zr_fixed_1</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>zr_mobile_1</td>
<td>3</td>
<td>47</td>
</tr>
<tr>
<td>zr_fixed_3</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>zed_fixed_1</td>
<td>5</td>
<td>46</td>
</tr>
<tr>
<td>zed_fixed_5</td>
<td>6</td>
<td>92</td>
</tr>
<tr>
<td>zed_fixed_2</td>
<td>7</td>
<td>23</td>
</tr>
<tr>
<td>zr_fixed_5</td>
<td>8</td>
<td>24</td>
</tr>
<tr>
<td>zr_fixed_2</td>
<td>9</td>
<td>3</td>
</tr>
<tr>
<td>zr_fixed_4</td>
<td>10</td>
<td>48</td>
</tr>
<tr>
<td>zed_fixed_3</td>
<td>11</td>
<td>69</td>
</tr>
<tr>
<td>zed_fixed_4</td>
<td>12</td>
<td>45</td>
</tr>
</tbody>
</table>

ZC: ZigBee Coordinator, ZR: ZigBee Router, ZED: ZigBee End Device
PAN ID: Personal Area Network Identifier
Simulation parameters

<table>
<thead>
<tr>
<th>ZigBee Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Star</td>
</tr>
<tr>
<td>Maximum children</td>
<td>255</td>
</tr>
<tr>
<td>Maximum routers</td>
<td>0</td>
</tr>
<tr>
<td>Maximum depth</td>
<td>1</td>
</tr>
<tr>
<td>Achieved depth</td>
<td>1</td>
</tr>
<tr>
<td>Mesh routing</td>
<td>Disabled</td>
</tr>
<tr>
<td>Transmit power</td>
<td>0.05</td>
</tr>
<tr>
<td>Transmit band</td>
<td>2450 MHz</td>
</tr>
<tr>
<td>PAN ID</td>
<td>Auto assigned</td>
</tr>
</tbody>
</table>

PAN ID: Personal Area Network Identifier
Road map

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- Performance evaluation:
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- Conclusions

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Simulation results

- Mesh routing table
- End-to-end delay
- Number of hops
- Throughput - ZC
- Throughput - global

ZC: ZigBee Coordinator
# Mesh routing table

<table>
<thead>
<tr>
<th>Source</th>
<th>Destination</th>
<th>Next Hop</th>
</tr>
</thead>
<tbody>
<tr>
<td>Office Network zr_fixed_1</td>
<td>Office Network zr_fixed_4</td>
<td>Office Network zr_fixed_4</td>
</tr>
<tr>
<td>Office Network zr_fixed_1</td>
<td>Office Network zr_fixed_3</td>
<td>Office Network zr_fixed_3</td>
</tr>
<tr>
<td>Office Network zr_fixed_1</td>
<td>Office Network zr_fixed_2</td>
<td>Office Network zr_fixed_2</td>
</tr>
<tr>
<td>Office Network zr_fixed_1</td>
<td>Office Network zr_fixed_5</td>
<td>Office Network zr_fixed_5</td>
</tr>
<tr>
<td>Office Network zr_fixed_1</td>
<td>Office Network zr_mobile_1</td>
<td>Office Network zr_mobile_1</td>
</tr>
<tr>
<td>Office Network zr_fixed_1</td>
<td>Office Network zr_fixed_1</td>
<td>Office Network zr_fixed_1</td>
</tr>
<tr>
<td>Office Network zr_fixed_1</td>
<td>Office Network zr_mobile_1</td>
<td>Office Network zr_mobile_1</td>
</tr>
<tr>
<td>Office Network zr_fixed_1</td>
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<td>Office Network zr_fixed_1</td>
<td>Office Network zr_fixed_1</td>
</tr>
</tbody>
</table>
End-to-end delay

- Star and Mesh topologies have similar end-to-end delay in this simulation.
- Tree topology has a higher end-to-end delay of 50% and it is increasing.
Number of hops

- Average number of hops for **Mesh** topology is the same as **Star** topology.
- **Tree** topology has a higher average number of hops of 75%.
The Coordinator in **Star** topology has the highest throughput (bits/sec).

The Coordinator in **Tree** topology has the second highest throughput (bits/sec).

The Coordinator in **Mesh** topology has the lowest throughput (bits/sec).

**ZC:** ZigBee Coordinator
Throughput - global

- **Tree** topology has the highest global throughput (bits/sec)
- **Mesh** topology has the second highest global throughput (bits/sec)
- **Star** topology has the lowest global throughput (bits/sec)
Simulation scenarios and parameters

- Simulation scenarios:
  - Star, Tree, and Mesh topologies
  - Single and multiple ZC

- Parameters:
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ZC: ZigBee Coordinator
Multiple ZC – tree topology

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ZC: ZigBee Coordinator
Simulation results

- End-to-end delay
- Throughput - ZC

ZC: ZigBee Coordinator
End-to-end delay

- **Ds_0**: end-to-end delay of the network with a single PAN
- **Dm_0**: end-to-end delay of PAN_0 in the network with two PANs
- **Dm_1**: end-to-end delay of PAN_1 in the network with two PANs

- \( Ds_0 > Dm_0 \)
- \( Ds_0 > Dm_1 \)
- \( Ds_0 < Dm_0 + Dm_1 \)

PAN: Personal Area Network
Throughput - ZC

- **Ts_0**: throughput of ZC in the network with a single PAN
- **Tm_0**: throughput of ZC in PAN_0 of the network with two PANs
- **Tm_1**: throughput of ZC in PAN_1 of the network with two PANs

\[(Ts_0 * 1.25) = Tm_1 + Tm_2\]

PAN: Personal Area Network
ZC: ZigBee Coordinator

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Conclusions

- **End-to-end delay**
  - Star and Mesh topologies are similar
  - Tree is higher

- **Average number of hops**
  - Star and Mesh topologies are similar
  - Tree is higher

- **ZC throughput (bits/sec)**
  - Star topology has the highest
  - Tree has the second highest
  - Mesh has the lowest

- **Global throughput (bits/sec)**
  - Tree topology has the highest
  - Mesh has the second highest
  - Star has the lowest

ZC: ZigBee Coordinator
Conclusions - single vs. multiple ZC

- End-to-end delay
  - The network with a single PAN has lower than the network with two PANs

- Throughput ZC
  - The network with a single PAN has lower than the network with two PANs

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Unfinished work - simulation scenario and parameters

Simulation scenario:
- ZC failure and quick recovery using ZC backup (ZCB)

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Unfinished work - implementation details
Unfinished work - implementation details

static void failNode(void * ptrVoid, int iCode);
void wpan_prj_init();
...
void wpan_prj_init() {
    double dInterruptTime = 100.0; // time is second that the interrupt is scheduled
    int iCode = 0; // verification code
    void * ptrVoid = 0; // data structure to send to the called function

    FIN (wpan_prj_init());
    dInterruptTime += op_sim_time();
    op_intrpt_schedule_call(dInterruptTime, iCode, failNode, ptrVoid);

    FOUT;
}
...
static void failNode(void * ptrVoid, int iCode) {
    Objid iObjId;
    Objid iParentObjId;

    FIN (failNode);

    if (((0 == my_pan_id) && (0 == my_network_address)) && (-1 == my_parent_address)) {
        printf("Node: Coordinator with PAN_ID: 0\n");
        ...
        op_ima_obj_attr_set(op_intrpt_source(), "condition", OPC_BOOLINT_DISABLED);
    }
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Future work

- Access to OPNET source code of the network and the application layers
- Complete ZC backup (ZCB) concept:
  - Monitor and mirror ZC data
  - Substitute ZC in case of failure
- Implement and analyze the concept in ns-2

ZCB: ZigBee Coordinator Backup
References