Principles of Wireless Sensor Networks

http://www.ee.kth.se/~carlofi/teaching/pwsn-2011/wns_course.shtml

Lecture 8
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Routing, Zigbee, and RPL

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Today's learning goals

- What are the basic routing options for sensornet?
- How to compute the shortest path?
- How to compute multipath routings?
- Which routing is used in standard protocols?
Today’s lecture

- Previous lecture
  - MAC protocols, IEEE 802.15.4

- Today’s lecture will focus on routing
Outline

1. Classification of routing protocols for WSNs
2. The shortest path routing
3. Multipath routing
4. Routing algorithms in standardized protocol stack
Routing protocols

- **Goal:** Derive a mechanism that allows a packet sent from an arbitrary node to arrive at some arbitrary destination node

  - **The routing & forwarding problem**
  - **Routing:** Construct data structures (e.g., tables) that contain information how a given destination can be reached
  - **Forwarding:** Consult these data structures to forward a given packet to its next hop

- **Challenges**
  - Nodes may move around, neighborhood relations change
  - Optimization may be difficult
Ad hoc routing protocols – classification

- When does the routing protocol operate?

- Option 1: Routing protocol *always* tries to keep its routing tables up-to-date
  - Protocol is proactive (active before tables are actually needed)

- Option 2: Route is only determined when actually needed
  - Protocol operates on demand

- Option 3: Combine these behaviors
  - Hybrid protocols
Proactive protocols - DSDV

- Destination Sequence Distance Vector (DSDV)
  - Based on Bellman Ford procedure (see later on)
  - Add *aging* information to route information propagated by distance vector exchanges; helps to avoid routing loops
  - Periodically send full route updates
  - On topology change, send incremental route updates
  - Unstable route updates are delayed
On Demand protocols – AODV

- **Ad hoc On Demand Distance Vector** routing (AODV)
  - Popular routing protocol on sensor networks
  - Route discovery procedure by special packets
  - Nodes maintain routing tables instead of source routing
  - Nodes remember from where a packet came and populate routing tables with that information
Geographic routing

- Routing tables contain information to which next hop a packet should be forwarded
  - Explicitly constructed
- Alternative: Implicitly *infer* this information from physical placement of nodes
  - Position of current node, current neighbors, destination known - send to a neighbor in the right direction as next hop
- Options
  - Send to any node in a given area - *geocasting*
  - Use position information to aid in routing - *position-based routing*
    - Might need a *location service* to map node ID to node position
Problem: dead ends

- Simple strategies might send a packet into a dead end
Many options for routing

- Maximum total available battery capacity
  - Path metric: Sum of battery levels
  - Example: A-C-F-H
- Minimum battery cost routing
  - Path metric: Sum of reciprocal battery levels
  - Example: A-D-H
- Conditional max-min battery capacity routing
  - Only take battery level into account when below a given level
- Minimize variance in power levels
- Minimum total transmission power
Many options for routing

- Is there a basic way to model all these options?

- Yes, the shortest path problem...
Outline

• Classification of routing protocols for WSNs

• The shortest path routing

• Multipath routing

• Routing algorithms for standardized protocol stack
Some definitions

- \( N \) number of nodes
- \( N \) set of nodes
- \( A = \{(i, j)\} \) set of arcs
- \( G = (N, A) \) network
- \( a_{ij} \) routing cost on the link \( ij \)

Question: what is the shortest (minimum cost) path from source to destination?
The shortest path problem

\[ \min_x \sum_{(i,j) \in A} a_{ij} x_{ij} \]

s.t. \[ \sum_{j: (i,j) \in A} x_{ij} - \sum_{j: (j,i) \in A} x_{ij} = s_i \]

\[
\begin{cases}
1 & \text{if } i = s \\
-1 & \text{if } i = t \\
0 & \text{otherwise.}
\end{cases}
\]

\[ x_{ij} \geq 0 \quad \forall (i,j) \in A \]

- \( x_{ij} \) binary variable. It can be also real, but remarkably if problem feasible, the unique optimal solution is binary.

- The optimal solution gives the shortest path source-destination.
Applications of the shortest path problem

- The solution to this problem is very general and can be applied to
  1. Routing over WSNs, used in WirelessHART, RPL, ...
  2. Dynamic programming
  3. Project management
  4. The paragraphing problem
  5. ...

- In the following, we see the basic algorithm to solve the problem
The solution of the problem can be achieved by combinatorial algorithms that don’t use optimization.

We consider now a generic algorithm based on node labelling, the Generic shortest path algorithm.

The algorithm is the foundation of other more advanced algorithms widely used for routing such as:

1. Dijkstra method
2. Bellman-Ford method
A label associated to a node $d_j = \begin{cases} \text{a scalar} \\ \infty \end{cases}$

**Proposition:** Let $d_1, d_2, \ldots, d_N$ be scalars such that

$$d_j \leq d_i + a_{ij}, \quad \forall (i, j) \in A.$$ 

Let $P$ be a path starting at a node $i_1$ and ending at a node $i_k$. If

$$d_j = d_i + a_{ij}, \quad \forall (i, j) \text{ of } P,$$

then $P$ is a shortest path from $i_1$ to $i_k$. 

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Generic shortest path algorithm: the idea

- Complementary Slackness conditions (CS) is the foundation of the generic shortest path algorithm.

- Some initial vector of labels is assigned \((d_1, d_2, \ldots, d_N)\).

- The arcs \((i, j)\) that violate the CS condition \(d_j > d_i + a_{ij}\) are selected and their labels redefined so that
  \[d_j := d_i + a_{ij}\]

- This is continued until the CS condition \(d_j \leq d_i + a_{ij}\) is satisfied for all arcs \((i, j)\).
Let initially be $V = \{1\}$, $d_1 = 0$, $d_i = \infty$, $\forall i \neq 1$.

**Iteration of the Generic Shortest Path Algorithm**

Remove a node $i$ from the candidate list $V$. For each outgoing arc $(i, j) \in A$, if $d_j > d_i + a_{ij}$, set

$$d_j := d_i + a_{ij}$$

and add $j$ to $V$ if it does not already belong to $V$.

Node removal rule gives Dijkstra method or Bellman-Ford method.
An example

![Graph Diagram]

<table>
<thead>
<tr>
<th>Iter. #</th>
<th>Candidate List $V$</th>
<th>Node Labels</th>
<th>Node out of $V$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>{1}</td>
<td>$(0, \infty, \infty, \infty, \infty, \infty)$</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>{2, 3}</td>
<td>$(0, 2, 1, \infty, \infty)$</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>{3, 5}</td>
<td>$(0, 2, 1, \infty, 2)$</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>{5}</td>
<td>$(0, 2, 1, \infty, 2)$</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>$\emptyset$</td>
<td>$(0, 2, 1, \infty, 2)$</td>
<td></td>
</tr>
</tbody>
</table>
Convergence of the algorithm (a)

Proposition: Consider the generic shortest path algorithm.

(a) At the end of each iteration, the following conditions hold:

(i) If \( d_j < \infty \), then \( d_j \) is the length of some path that starts at 1 and ends at \( j \).

(ii) If \( i \not\in V \), then either \( d_i = \infty \) or else

\[
d_j \leq d_i + a_{ij}, \quad \forall j \text{ such that } (i, j) \in A.
\]
Convergence of the algorithm (b)

(b) If the algorithm terminates, then upon termination, for all $j$ with $d_j < \infty$ $d_j$ is the shortest distance from 1 to $j$ and

$$d_j = \begin{cases} 
\min_{(i,j) \in A}(d_i + a_{ij}) & \text{if } j \neq 1 \\
0 & \text{if } j = 1 
\end{cases}$$

Furthermore, $d_j = \infty$ if and only if there is no path from $i$ to $j$.

The Bellman-Ford equation
(c) If the algorithm does not terminate, then there exists some node $j$ and a sequence of paths that start at 1, ends at $j$, and have a length diverging to $-\infty$.

(d) The algorithms terminates if and only if there is no path that starts at 1 and contains a cycle with negative length.
Outline

• Classification of routing protocols for WSNs

• The shortest path routing

• Multipath routing

• Routing algorithms for standardized protocol stack
The shortest path algorithm gives the best path from source to destination.

The shortest path algorithm can be used to compute the first best, the second best, and so on paths.

Sending messages over multiple paths introduces diversity.
Multipath routing

- Instead of only a single path, it can be useful to compute multiple paths between a source-destination pair.

Disjoint paths

Source - Primary path - Sink

Secondary path

Braided paths

Source - Primary path - Sink
How to split optimally the messages over multiple paths?

- Of course, see Bertsekas and Titsiklis, Parallel and Distributed Computation, Numerical Methods:
  1. Constrained optimization, pages 210-212
  2. Distributed routing protocol over data networks, pages 414-418
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ZigBee

http://www.zigbee.org/

ZigBee covers the networking and application layers on top of IEEE 802.15.4

Nodes:
- IEEE 802.15.4 nodes
- ZigBee coordinator: starts the network
- ZigBee router

Networks:
- Star network
- Tree network
- Mesh network

Routing
- No transport protocol for end-to-end reliability (only hop-by-hop).
- Tree routing: packets are sent to the coordinator, and then to the destination.
- Mesh routing: AODV protocol for route discovery
ISA SP-100

- [http://www.isa.org](http://www.isa.org)

- Standard for non-critical process applications tolerating delays up to 100ms.

- It is based on IEEE 802.15.4 plus a new data link layer and adaptation layer between MAC and data link
  - Frequency hopping
WirelessHART

- http://www.hartcomm.org/

- Released in September 2007 as part of HART 7 specifications

- An open communication standard designed for process measurements and control applications
  - strict timing requirements
  - security concerns
WirelessHART network

- Field device, attached to the plant process
- Handheld, a portable computer to configure devices, run diagnostic and perform calibrations
- Gateway, that connect host applications to field devices
- Network manager, responsible for configuring the network, scheduling and managing communication
WirelessHART network

- Topology: Star, Cluster, Mesh

- Central network manager: maintains up-to-date routes and communication schedules for the network

- Basic functionalities:
  - Timer
  - Network wide synchronization
  - Communication security
  - Reliable mesh networking
  - Central network management
### A Five Layers Architecture

<table>
<thead>
<tr>
<th>OSI Layer</th>
<th>HART</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>Command Oriented. Predefined Data Types and Application Procedures</td>
</tr>
<tr>
<td>Presentation</td>
<td>Auto-Segmented transfer of large data sets, reliable stream transport, Negotiated Segment sizes</td>
</tr>
<tr>
<td>Session</td>
<td></td>
</tr>
<tr>
<td>Transport</td>
<td></td>
</tr>
<tr>
<td>Network</td>
<td>Power-Optimized Redundant Path, Mesh to the edge Network</td>
</tr>
<tr>
<td>Data Link</td>
<td>Secure, Time Synched TDMA/CSMA, Frequency Agile with ARQ</td>
</tr>
<tr>
<td>Physical</td>
<td>Simultaneous Analog &amp; Digital Signaling 4-20mA Copper Wiring</td>
</tr>
<tr>
<td></td>
<td>2.4 GHz Wireless, 802.15.4 based radios, 10dBm Tx Power</td>
</tr>
</tbody>
</table>

**Wired FSK/PSK & RS 485**

**Wireless 2.4 GHz**
Layers

- Physical layer:
  - similar to IEEE 802.15.4
  - 2.4-2.4835 GHz, 26 channels, 250 Kbps per channel

- Data link layer:
  - Network wide synchronization (a fundamental functionality)
  - TDMA with strict 10ms time slots
  - Periodical superfames
  - Channel blacklisting: the network administrator removes the channels with high interference.
  - Pseudorandom change of the channel for robustness to fading
  - TDMA security: industry-standard AES-128 ciphers and keys
WirelessHART MAC

Network Layer
Interface to Network Layer

Queue
Timer
Link Scheduler

State Machine
Link Table
Superframe Table
Neighbor Table
Graph Table
PIB

Message Handling Module

Wireless HART MAC
Interface to Physical Layer

Physical Layer

Queue
WirelessHART Routing

- **Graph Routing:**
  - A graph is a collection of paths that connect network nodes.
  - The paths in each graph is created by the network manager and downloaded to each individual network device.
  - To send a packet, the source device writes a specific graph ID (determined by the destination) in the network header.
  - All network devices on the way to the destination must be pre-configured with graph information that specifies the neighbors to which the packets may be forwarded.

- **Source Routing:**
  - Supplement of the graph routing aiming at network diagnostics.
  - To send a packet to its destination, the source device includes in the header an ordered list of devices through which the packet must travel.
  - As the packet is routed, each routing device utilizes the next network device address in the list to determine the next hop until the destination device is reached.
ROLL: Routing over Low Power Lossy Networks

- ROLL is a Working Group of the Internet Engineering Task Force
- RPL, routing protocols for low power and lossy networks in Industrial and home automation, healthcare, smart grids

Network assumption
- Many embedded devices with limited power, memory, and processing
- Interconnection by a variety of links, such as EEE 802.15.4, Bluetooth, Low Power WiFi, wired or other low power Powerline Communications
- End-to-end IP-based solution to avoid the problem of on-interoperable networks interconnected by protocol translation gateways and proxies
Summary

- We have studied routing protocol
  - Proactive
  - Reactive
  - Geographic

- The basic mechanism of routing is the shortest path optimization problem

- Once shortest paths are available, multipath routing can increase diversity

- These mechanisms are included in standards such as ZigBee, ISA100, WirelessHart and RPL
Project presentations, Nov. 15

Make a presentation of max 15 minutes including questions

- Phd Students
  - Motivation
  - Problem formulation
  - Approach to the solution
  - Results
  - Conclusions

- Master Students:
  - Didactic overview of the investigated material

Email by tonight title of the presentation and speakers
Basics of position-based routing

- “Most forward within range r” strategy
  - Send to that neighbor that realizes the most forward progress towards destination
  - NOT: farthest away from sender!

- Nearest node with (any) forward progress
  - Idea: Minimize transmission power

- Directional routing
  - Choose next hop that is angularly closest to destination
  - Choose next hop that is closest to the connecting line to destination
  - Problem: Might result in loops!