Chapter 4
Routing Protocols
(Part II)
4.1 Routing Challenges and Design Issues in WSNs
4.2 Flat Routing
4.3 Hierarchical Routing
4.4 Location Based Routing
4.5 QoS Based Routing
4.6 Data Aggregation and Convergecast
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4.8 ZigBee
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Chapter 4.6
Data Aggregation and Convergecast
Aggregation in Sensor Networks

- Traditional Address-Centric routing
  - IP address routing
  - Not suitable in large scale sensor networks
- Data-Centric Routing
  - Content-based routing
  - Enhance the data aggregation opportunity

![Diagram showing Address-Centric (AC) Routing and Data-Centric (DC) Routing]

- a) Address-Centric (AC) Routing
- b) Data-Centric (DC) Routing
Theoretical Results on Aggregation

- Let there be $k$ sources located within a diameter $X$, each a distance $d_i$ from the sink. Let $N_A$ and $N_D$ be the number of transmissions required with AC and optimal DC protocols, respectively.

1. The following are bounds on $N_D$:
   
   $N_D \leq (k - 1)X + \min(d_i)$
   
   $N_D \geq \min(d_i) + (k - 1)$

2. Asymptotically, for fixed $k, X$, as $d = \min(d_i)$ is increased,
   
   $$\lim_{d \to \infty} \frac{N_D}{N_A} = \frac{1}{k}$$

3. Although the problem is NP-hard in general, the optimal data aggregation tree can be formed in polynomial time when the sources induce a connected sub-graph on the communication graph.
Aggregation Techniques

In general the formation of the optimal aggregation tree is NP-hard. Some suboptimal DC routing heuristics as follows:

- **Center at Nearest Source (CNSDC)**
  - All sources send the information first to the source nearest to the sink, which acts as the aggregator.

- **Shortest Path Tree (SPTDC)**
  - Opportunistically merge the shortest paths from each source wherever they overlap.

- **Greedy Incremental Tree (GITDC)**
  - Start with path from sink to nearest source. Successively add next nearest source to the existing tree.

- **Address Centric (AC)**
  - No aggregation, distinct shortest paths from each source to sink.
Performance Study

Event-Radius model

Random Sources model
Performance Study (cont.)

Sensing Range = 0.2

Energy Costs

Event-Radius model

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Energy Costs

Number of Sources = 9

- AC
- CNSDC
- SPTDC
- GITDC
- lower bound

Random Sources model
Conclusions

- Data aggregation can result in significant energy savings for a wide range of operational scenarios.
- The gains from aggregation are paid for with potentially higher delay. It should be possible to design routing algorithms for sensor networks in which this tradeoff is made explicitly.
Reference

Chapter 4.7
Data centric networking
4.7.2 Data-centric Storage

- Data centric storage
  - Data is stored inside the network.
  - All data with the same name (or data range) will be stored at the same sensor network location

- Why data centric storage?
  - Energy efficiency
  - Robustness against mobility and node failures
  - Scalability
One-dimensional Data Storage

- Data-Centric Storage in Sensornets with GHT, a Geographic Hash Table (GHT [Ratnasamy et al. 2003])
  - Data Storage and Retrieval
  - Perimeter Refresh Protocol
  - Structured Replication
One-dimensional Data Storage

- **GHT**
  - \( \text{Put}(k, v) \)- stores \( v \) (observed data) according to the key \( k \)
  - \( \text{Get}(k) \)- retrieve whatever value is associated with key \( k \)
- **Hash function**
  - Hash the key into the geographic coordinates
  - \( \text{Put}() \) and \( \text{Get}() \) operations on the same key “\( k \)” hash \( k \) to the same location

**An example for GHT**

- \( \text{Put} \) ("elephant", data)
- \( \text{Get} \) ("elephant")
- Hash ("elephant")=(12,24)
Perimeter Refresh Protocol

- Assume key $k$ hashes at location $L$

- $A$ is closest to $L$ so it becomes the home node
Structured Replication

- Augment event name with hierarchy depth
- Given root $r$ and given hierarchy depth $d$
  - Compute $4^d - 1$ mirror images of $r$

Example of structured replication with a 2-level decomposition

- root point
- level 1 mirror points
- level 2 mirror points
Conclusions

- Data centric storage entails naming of data and storing data at nodes within the sensor network.
- GHT uses Perimeter Refresh Protocol and structured replication to enhance robustness and scalability.
- DCS is useful in large sensor networks and there are many detected events but not all event types are queried.
Multi-dimensional Data Storage

- Multi-Dimensional Range Queries in Sensor Networks (DIM [Li et al. 2003])
  - Building Zones
  - Data Insertion
  - Query Propagation
Building Zones

- Divide network into zones.
- Each node mapped to one zone.
- Encode zones based on division.
- Each zone has a unique code.
- Map m-d space to zones.
- Zones organized into a virtual binary tree.

$L$: Light, $T$: Temperature
Data Insertion

- Encode events
- Compute geographic destination
- Hand to GPSR
- Intermediate nodes can refine the destination estimation

$L$: Light, $T$: Temperature
Query Propagation

- Split a large query into smaller sub-queries.
- Encode each sub-query.
- Process sub-queries separately, resolving locally or forwarding to other nodes based on their codes.

$L$: Light, $T$: Temperature

\begin{align*}
Q_{11} &= <.5, \cdot .75, .5, 1> \\
Q_{12} &= <.75, \cdot .75, 1>
\end{align*}
Conclusions

- **DIM** resolves multi-dimensional range queries efficiently.

- **Work that still needs to be done**
  - Skewed data distribution
    - These can cause storage and transmission hotspots.
  - Existential queries
    - Whether there exists an event matching a multi-dimensional range.
  - Node heterogeneity
    - Nodes with larger storage space assert larger-sized zones for themselves.
Chapter 4.8
ZigBee
The ZigBee Standard

- ZigBee is a low cost, low power, low complexity, and low data rate wireless communication technology at short range. Based on IEEE 802.15.4, it is mainly used as a low data rate monitoring and controlling sensor network.

![Diagram of Zigbee stack](image-url)
The Network Layer

- ZigBee identifies three device types
  - The ZigBee coordinator (one in the network) is an FFD managing the whole network
  - A ZigBee router is an FFD with routing capabilities
  - A ZigBee end-device corresponds to a RFD or FFD acting as a simple device

- The ZigBee network layer supports three types of network configurations:
  - *Star topology*
  - *Tree topology*
  - *Mesh topology*
The Network Layer (cont.)

(a) Star network
(b) Tree network
(c) Mesh network

ZigBee coordinator
ZigBee router
ZigBee end device
Network Formation and Address Assignment

- Before forming a network, the coordinator determines
  - Maximum number of children of a router ($C_m$)
  - Maximum number of child routers of a router ($R_m$)
  - Depth of the network ($L_m$)
- Note that a child of a router can be a router or an end device, so $C_m \geq R_m$
- The coordinator and routers can each have at most $R_m$ child routers and at least $C_m - R_m$ child end devices
Network Formation and Address Assignment (cont.)

- For the coordinator, the whole address space is logically partitioned into $Rm + 1$ blocks.
- The first $Rm$ blocks are to be assigned to the coordinator’s child routers and the last block is reserved for the coordinator’s own child end devices.
- From $Cm$, $Rm$, and $Lm$, each router computes a parameter called $Cskip$ to derive the starting addresses of its children’s address pools.

$$Cskip(d) = \begin{cases} 
1 + Cm \times (Lm - d - 1), & \text{if } Rm = 1 \\
1 + Cm - Rm - Cm \times Rm^{Lm-d-1} \frac{1}{1-Rm}, & \text{Otherwise}
\end{cases}$$
The coordinator is said to be at depth $d = 0$, and $d$ is increased by one after each level.

Address assignment begins from the ZigBee coordinator by assigning address 0 to itself.

If a parent node at depth $d$ has an address $A_{parent}$, the $n$-th child router is assigned to address $A_{parent} + (n - 1) \times Cskip(d) + 1$.

$n$-th child end device is assigned to address $A_{parent} + Rm \times Cskip(d) + n$. 


Network Formation and Address Assignment (cont.)

\[
A_{\text{parent}} + (n - 1) \times C\text{skip}(d) + 1
\]

\[
A_{\text{parent}} + Rm \times C\text{skip}(d) + n
\]

- ZigBee coordinator
- ZigBee router
- ZigBee end device

\[
Cm = 5 \quad Rm = 4 \quad Lm = 2
\]
ZigBee Routing Protocol

- In a ZigBee network, the coordinator and routers can directly transmit packets along the tree.
- When a device receives a packet, it first checks if it is the destination or one of its child end devices is the destination.
- If so, this device will accept the packet or forward this packet to the designated child. Otherwise, it forwards the packet to its parent.
If a device \( n \) receives a packet with destination \( A_{dest} \). Assume that the depth of the device \( n \) is \( d \) and its address is \( A \). This packet is for one of its descendants if the destination address \( A_{dest} \) satisfies \( A < A_{dest} < A + Cskip(d - 1) \), and this packet will be relayed to the child router with address

\[
A_r = A + 1 + \left[ \frac{A_{dest} - (A + 1)}{Cskip(d)} \right] \times Cskip(d)
\]

If the destination is not a descendant of this device, this packet will be forwarded to its parent.
ZigBee Routing protocol (cont.)

\[ C_m = 6 \]
\[ R_m = 4 \]
\[ L_m = 3 \]

\[ A_r = A + 1 + \left[ \frac{A_{dest} - (A + 1)}{Cskip(d)} \right] \times Cskip(d) \]

\[ A < A_{dest} < A + Cskip(d - 1) \]
## Route Discovery

<table>
<thead>
<tr>
<th>Field Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Destination Address</td>
<td>16-bit network address of the destination</td>
</tr>
<tr>
<td>Next-hop Address</td>
<td>16-bit network address of next hop towards destination</td>
</tr>
<tr>
<td>Entry Status</td>
<td>One of Active, Discovery or Inactive</td>
</tr>
</tbody>
</table>

### Routing Table in ZigBee
# Route Discovery (cont.)

<table>
<thead>
<tr>
<th>Field Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>RREQ ID (route request)</td>
<td>Unique ID (sequence number) given to every RREQ message being broadcasted</td>
</tr>
<tr>
<td>Source Address</td>
<td>Network address of the initiator of the route request</td>
</tr>
<tr>
<td>Sender Address</td>
<td>Network address of the device that sent the most recent lowest cost RREQ</td>
</tr>
<tr>
<td>Forward Cost</td>
<td>The accumulated path cost from the RREQ originator to the current device</td>
</tr>
<tr>
<td>Residual Cost</td>
<td>The accumulated path cost from the current device to the RREQ destination</td>
</tr>
</tbody>
</table>

Route Discovery Table
Route Discovery (cont.)

**RREQ message**

- **RDQ entry exists for this RREQ?**
  - **Yes**: Update RDT entry with better fwd path cost
  - **No**: Create RDT entry and record fwd path cost

- **Does RREQ report a better fwd path cost?**
  - **Yes**: Send RREP
  - **No**: Drop RREQ

- **Is RREQ for local node or one of end-device children?**
  - **Yes**: Create RT entry (Discovery_Underway) And rebroadcast RREQ
  - **No**: The RREQ processing continues...
Route Discovery (cont.)

Discard route request

Unicast
Broadcast
Without routing capacity

S
A
D
C
B
T
References


Conclusions

- Routing in sensor networks is a new area of research, with a limited but rapidly growing set of research results.
- We highlight the design trade-offs between energy and communication overhead savings in some of the routing paradigm, as well as the advantages and disadvantages of each routing technique.
- Overall, the routing techniques are classified based on the network structure into four categories: flat, hierarchical, and location-based routing, and QoS based routing protocols.
- Although many of these routing techniques look promising, there are still many challenges that need to be solved in sensor networks.