Topic 3: Smart Grid Communications

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Interactions across 7 Smart Grid Domains:

- Each domain involves its own actors and applications.
• **Consumers:**
  
  • The *end* users of electricity.
  
  • May also generate/store electricity.
  
  • Traditionally: Residential, Commercial, and Industrial.

• **Market:**
  
  • Participants in *wholesale market*: day-ahead, hour-ahead,...
  
  • Involves prediction, bidding, auctions, ...
NIST Conceptual Reference Model for Smart Grid

• **Service Providers:**
  - Organizations providing service to:
    - Both utilities and consumers.
    - ISPs, Cell Phone Companies, Aggregators,…

• **Operations:**
  - Independent System Operators (ISOs)
  - Regional Transmission Organization (RTOs)
NIST Conceptual Reference Model for Smart Grid

- **Bulk Generation:**
  - Major Power Plants.

- **Transmission:**
  - Carriers of bulk electricity over long distances.

- **Distribution:**
  - Distribution of electricity to (and from!) consumers.
There are two questions to answer:

- **How** can different smart grid entities exchange messages?
- **What kind** of messages (and **why**) should they exchange?

Our focus in Topic 3 is on the **first question**.

We want to learn which communication technologies may help.
In particular, we cover these communications technologies:

- Sensors
- Operation
- Aggregator
- Substations

Technologies:
- PLC
- IP
- WMN
- IP/IEC

ZigBee (Home Area Network)
ZigBee
ZigBee Overview

• ZigBee is a working group to promote IEEE 802.15.4 standard.

• High level communication

• Small, low-cost, low-power devices

MPR2400 Micaz ZigBee Wireless Sensor Node

www.wsncanada.ca
IEEE 802.15 is for Wireless Personal Area Networking (WPAN)

- 802.15.1: Bluetooth
- 802.15.2: Co-existence (e.g., with WLAN)
- 802.15.3: High Rate WPAN via Ultra wideband (UWB)
- 802.15.4: Low Rate
  
  Low Power Consumption
  
  Long Battery Life
  
  Inexpensive!
ZigBee Overview

- WPAN vs WLAN/WiFi and WMAN/WiMax

<table>
<thead>
<tr>
<th>Parameter</th>
<th>802.16 WiMAX</th>
<th>802.11 WiFi</th>
<th>802.15 WPAN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
<td>2 – 11GHz</td>
<td>2.4GHz</td>
<td>Varies</td>
</tr>
<tr>
<td>Range</td>
<td>31 miles</td>
<td>100 Meters</td>
<td>10 Meters</td>
</tr>
<tr>
<td>Data Rates</td>
<td>70 Mbps</td>
<td>11 - 110Mbps</td>
<td>20k – 55Mbps</td>
</tr>
<tr>
<td>Nodes</td>
<td>Thousands</td>
<td>Dozens</td>
<td>Dozens</td>
</tr>
</tbody>
</table>

* Data for 802.16a and 802.11a
ZigBee Overview

- **ZigBee** (802.15.4)
- **Bluetooth** (802.15.1)
- **IEEE 802.20**
- **WiMax IEEE 802.16**
- **WiFi 802.11**
- **IEEE 802.22**
- **IEEE 802.20**

- **WPAN**
- **WLAN**
- **WMAN**
- **WWAN**

Data Rate (Mbps):
- 0.01
- 0.1
- 1
- 10
- 100
- 1000

www.zigbee.org
ZigBee Overview

• Simpler and Less Expensive than Bluetooth

• **Cost:** One fourth of Bluetooth

• **Complexity:**

  • Complex ZigBee Nodes: 10% Code of a Bluetooth node
  
  • Simple ZigBee Nodes: 2% Code of a Bluetooth node
ZigBee Applications

• A wireless mouse that works for years without new batteries!

• Key Application Areas:
  • Building / Home
  • Energy
  • Health
  • Telecommunications
ZigBee Applications in Smart Grid

• Key Application:
  
  • **Smart Meter** Communications with **Smart Appliances**

• Smart Appliances:
  
  • Washer, Dryer, Dish Washer, Fridge
  
  • Air Conditioning
  
  • Pumps and Water Heaters
  
  • PHEVs
ZigBee Alliance

• Defining Network, Security, and Application **Software**

• Assuring **Interpretability**

• Market **Awareness**

• Managing / Evolving **Standards**

Membership: $3500
<table>
<thead>
<tr>
<th>Scenario</th>
<th>ZigBee Membership Required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Company creating/designing products for sale</td>
<td>Yes</td>
</tr>
<tr>
<td>Company offering services or reselling products</td>
<td>Yes</td>
</tr>
<tr>
<td>Installer</td>
<td>Yes</td>
</tr>
<tr>
<td>Reseller/Retailer</td>
<td>Yes</td>
</tr>
<tr>
<td>User</td>
<td>Yes</td>
</tr>
<tr>
<td>Architect, Designers, Builder, Owner</td>
<td>Yes</td>
</tr>
<tr>
<td>Contractor designing products for ZigBee member</td>
<td>Yes</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>Yes</td>
</tr>
<tr>
<td>Design House</td>
<td>Yes</td>
</tr>
</tbody>
</table>

* Zigbee is an **OPEN** Global Standard
• There are **four layers** in ZigBee Protocol Stack:

![ZigBee Protocol Stack Diagram]

[DE: Data Entity, ME: Management Entity, SAP: Service Access Point]
ZigBee devices may use different frequency bands:

<table>
<thead>
<tr>
<th>PHY</th>
<th>Frequency Band</th>
<th>Channel Numbering</th>
<th>Bit Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>868 MHz</td>
<td>868 – 870 MHz</td>
<td>0</td>
<td>20 kb/s</td>
</tr>
<tr>
<td>915 MHz</td>
<td>902 – 928 MHz</td>
<td>1 - 10</td>
<td>40 kb/s</td>
</tr>
<tr>
<td>2.4 GHz</td>
<td>2.4 – 2.4835 GHz</td>
<td>11 - 26</td>
<td>250 kb/s</td>
</tr>
</tbody>
</table>
ZigBee Wireless Channels

- Frequency channels used by ZigBee devices:

  - Channel 0: 868.3 MHz
  - Channels 1-10: 902 MHz - 928 MHz, 2 MHz bandwidth
  - Channels 11-26: 2.4 GHz - 2.4835 GHz, 5 MHz bandwidth
ZigBee Wireless Channels

• ZigBee may co-exist with other technologies at certain bands.

• Some of the features for co-existence:
  
  • Carrier Sense Multiple Access (CSMA) (Q: Remember?)
  
  • End-to-end ACK and Retransmission
  
  • Built-in Channel Scanning / Find Available Channels
ZigBee Packet Structure

- Packet Fields [specified by IEEE 802.15.4]:
  - Preamble: 32 bits for synchronization (Q: Remember?)
  - Start of Packet Delimiter: 8 bits
  - PHY Header: 8 bits / indicates PSDU length, etc.
  - PSDU: 0 to 127 bytes of data
ZigBee Packet Structure

• Inside PSDU:

- **Preamble**: 6 Bytes
- **Start of Packet Delimiter**: 6 Bytes
- **PHY Header**: 0-127 Bytes
- **PHY Service Data Unit (PSDU)**
- **Link Layer PDU**
- **CRC**

**PC**: Addressing Mode Flags
**ADDR**: Address
**DSN**: Data Sequence Number
**CRC**: Cyclic Redundancy Check
ZigBee Device Addressing

• All Devices Have Address:

  • Two-bytes: We can have up to 65,536 nodes (Q: Why?)

• Addressing Modes:

  • Star
  • Peer-to-Peer
  • Cluster Tree

  Addressing Modes Depend on the Network Topology.

[We will see more on topologies...]
ZigBee Device Classes

• ZigBee has two main Device Classes:
  
  • Full Function Device (FFD)
  
  • Reduced Function Device (RFD)

• **FFD**:
  
  • Available in any topology
  
  • Can become a network coordinator
  
  • Talks to any other device
ZigBee Device Classes

- **RFD**:
  - Limited to star topology
  - **Cannot** become a network coordinator
  - Talks to only a network coordinator
  - Simpler Implementation
  - Less power consumption
ZigBee Device Classes

• Each ZigBee network has **one network coordinator**.

  • It *initiates* network formation.

  • We need **at least one** Full Function Device. *(Q: Why?)*

• Other devices can be either FFD or RFD.

  • FFDs that are not network **coordinator** act as **routers**.

  • Recall that RFDs only talk to the network coordinator.
ZigBee Network Topologies

**Q:** Can we build a mesh topology with RFDs only?
ZigBee Network Topologies

Network Coordinator *initiates* the network formation.
ZigBee routers help expanding the network
ZigBee routers help expanding the network.
We can form Tree Clusters.
ZigBee Tree Clusters

• Each cluster has one FFD as its root.

• The root for the overall tree is the network coordinator.

• They allow routing with minimum overhead.

• The tree may span physically large areas.

• In total, we can have 255 clusters of 254 nodes = 64,770 nodes.
ZigBee Addressing

- For each new node (i.e., associated device):
  - A unique address is allocated by parent (router/coordinator)
  - Recall that the parent can only be a FFD.

- The max number of devices that a parent can support = 32.

- Two types of addresses:
  - Network Address: 16-bit, only unique in this network
  - Extended Address: 64-bit, unique in all networks
The following network attributes are important:

- **nwkcMaxDepth**: The maximum absolute depth allowed in this network.

- **nwkMaxDepth (Lm)**: The maximum absolute depth a particular device can have.

- **nwkMaxChildren (Cm)**: The maximum number of children a device is allowed to have.

- **nwkMaxRouters (Rm)**: The maximum number of routers a device can have as children. It is set by the coordinator for all devices in the network.
• The network attributes for a node/router with **absolute depth** \( d \):
These attributes let us compute the function $C_{skip}(d)$.  

- Size of address block allocated by each parent at depth $d$.

- We have:

$$C_{skip}(d) = \begin{cases} 
1 + Cm \times (Lm - d - 1) & Rm = 1 \\
1 + Cm - Rm - Cm \times Rm^{Lm-d-1} \over 1 - Rm & \text{otherwise}
\end{cases}$$

- A FFD parent with $C_{skip}(d) > 0$ may accept child devices.
A parent assigns addresses to children based on:

- Whether the child is router capable or not.

Let $A_{\text{parent}}$ denote the address of a parent at depth $d$.

**Router Capable Child**: [nth such child at depth $d+1$]

**Address**: $A_n = A_{\text{parent}} + C_{\text{skip}}(d) \times (n - 1) + 1$

**Address Block**: $A_{\text{parent}} + C_{\text{skip}}(d) \times (n - 1) + 1, \ldots, A_{\text{parent}} + C_{\text{skip}}(d) \times n$
ZigBee Addressing

• **End-Device Child**: \([m\)th such child at depth \(d+1\)]

\[
A_m = A_{\text{parent}} + C_{\text{skip}}(d) \times R_m + m
\]

• Note that each child needs an address.

• A router child also needs an address block for its future children.

• Overall Idea: Assure having **unique** addresses for all nodes.
ZigBee Addressing

• Example: \( R_m = 1, \ C_m = 2, \) and \( L_m = 3 \).

• \( C_{skip}(0) = 1 + 2 \times (3 - 0 - 1) = 5 \)
• \( C_{skip}(1) = 1 + 2 \times (3 - 1 - 1) = 3 \)
• \( C_{skip}(2) = 1 + 2 \times (3 - 2 - 1) = 1 \)
ZigBee Addressing

• Consider addressing at the network coordinator with $A_{NC} = 0$.

  • Router Child: $\text{Addr} = 0 + 5 \times (1 - 1) + 1 = 1$
    $\text{Addr Block} = 1 \ldots 5 \times 1 = 1 \ldots 5$

  • End-device Child: $\text{Addr} = 0 + 5 \times 1 + 1 = 6$

![Diagram of ZigBee addressing with nodes labeled 0, 1, 6 and blocks 1...5 with 3 addresses]
ZigBee Addressing

• At the router node at depth 1 with $A_{\text{parent}} = 1$.

  • Router Child: $\text{Addr} = 1 + 3 \times (1 - 1) + 1 = 2$
    $\text{Addr Block} = 2 \ ... \ 1 + 3 \times 1 = 2 \ ... \ 4$

  • End-device Child: $\text{Addr} = 1 + 3 \times 1 + 1 = 5$

![Diagram of ZigBee addressing](image-url)
ZigBee Addressing

• At the router node at depth 2 with $A_{parent} = 2$.

  • Router Child: $Addr = 2 + 1 \times (1 - 1) + 1 = 3$
    $Addr$ Block = $3 \ldots 2 + 1 \times 1 = 3 \ldots 3$

  • End-device Child: $Addr = 2 + 1 \times 1 + 1 = 4$
ZigBee Addressing

• Example: $R_m = 2$, $C_m = 4$, and $L_m = 3$.
  
  • $C_{skip}(0) = (1 + 4 - 2 - 4 \times 2^{3-0-1}) / (1-2) = 13$
  
  • $C_{skip}(1) = $

  • $C_{skip}(2) = $

  • Show how the address blocks are allocated.
Your Job: Choose the addresses and address blocks!
ZigBee Addressing

• Q: What if the topology is not complete?

• Q: What if the topology is not star? Does it affect addresses?
ZigBee Routing

• We need to find a path from a source to a destination node.

• Key observation: For a router device at depth $d + 1$, we have

$$A_n = A_{\text{parent}} + C\text{skip}(d) \times (n-1) + 1$$

Address Block: $A_{\text{parent}} + C\text{skip}(d) \times (n-1) + 1, \cdots, A_{\text{parent}} + C\text{skip}(d) \times n$

• We can rewrite the address block as

$$A_n, \cdots, A_n + C\text{skip}(d) - 1$$

Q: Can we use this observation for routing?
ZigBee Routing

- Assume that such router is searching for a path for address \( D \).

- If the following is True, then \( D \) is a descendent of the router:

\[
A_n < D \leq A_n + C_{skip}(d) - 1 \quad \Rightarrow \quad A_n < D < A_n + C_{skip}(d)
\]

- Otherwise, the router should forward the message to its parent.

- Thus, we can easily find a router with \( D \) as its descendent.
ZigBee Routing

• Next, we should find a way for a router to forward the message:
  • To the right child at next depth level.

• This is trivial if D is the address for an end-device. (Q: Why?)

• Otherwise, the address of the right router child is obtained as

\[
A_n + 1 + \left\lfloor \frac{D - (A_n + 1)}{C_{skip}(d)} \right\rfloor C_{skip}(d)
\]
ZigBee Routing

• Example: Node 13 wants to send a message to node 17.

• Q: Can you explain how the destination is found?

Cskip(0) = 13
Cskip(1) = 5
Cskip(2) = 1

Rm = 2
Cm = 4
Lm = 3
ZigBee Routing

• This routing mechanism is particularly good for tree topologies.

• Although it works for other topologies as well.

• However, for more complex networks, ZigBee uses:
  • AODV: Ad-hoc On-demand Distance Vector
    • Uses Bellman-Ford (BF) Equation as a DV algorithm...
  • But first it requires route discovery on-demand
• AODV route discovery is done using:

  - **Route Request** (RREQ) and **Route Reply** (RREP) Messages

• Source **floods** RREQ messages:
ZigBee Routing

• AODV route discovery is done using:
  
  • Route Request (RREQ) and Route Reply (RREP) Messages

• Revere paths are formed when nodes hear RREQ:
ZigBee Routing

• AODV route discovery is done using:
  
  • Route Request (RREQ) and Route Reply (RREP) Messages

• RREQ flooding continues in the network:

![Diagram of network with nodes A, B, C, D, E, F, G and arrows indicating the route.](image)
ZigBee Routing

- AODV route discovery is done using:
  - Route Request (RREQ) and Route Reply (RREP) Messages
  - Revere paths are formed when nodes hear RREQ:
ZigBee Routing

- AODV route discovery is done using:
  - Route Request (RREQ) and Route Reply (RREP) Messages

- RREP message(s) is/are sent through reverse path(s):

![Diagram of network showing node connections]

- Nodes: A, B, C, D, E, F, G
- Connections: A to B, A to C, B to C, C to D, C to E, E to F, F to G, G to D
ZigBee Routing

• AODV route discovery is done using:

  • Route Request (RREQ) and Route Reply (RREP) Messages

• This will lead to forming / discovering forward path(s):
• **Automatic Notification**: Call the owner if problem occurs.

• **Door Control**: When the door is locked, lights are turned off.
• **Smart appliances** can also communicate with **smart meters**.

• **Example**: They can obtain prices and adjust their **load**. (Topic 4!)
ZigBee Building Solutions

• ZigBee solutions by Texas Instrument (TI) at different layers:

<table>
<thead>
<tr>
<th>Complete ZigBee® Solution</th>
<th>System-on-chip</th>
<th>Co-processor</th>
<th>Dual-chip</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protocol stack</td>
<td>Small footprint</td>
<td>Flexiblo</td>
<td>Ultra low-power or High performance</td>
</tr>
<tr>
<td>Radio</td>
<td>High integration</td>
<td>Easy to use</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Low cost</td>
<td>Reduced time to market</td>
<td></td>
</tr>
</tbody>
</table>

- Application: CC2530
- Protocol stack: ZigBee CC2530
- Radio: ZigBee CC2530ZNP

Refer to TI’s ZigBee pages for more detail.
ZigBee Collocation with WiFi

- ZigBee and WiFi collocate at 2.4 GHz Frequency Band

- In addition to medium access control:
  - They should automatically avoid common channels.
ZigBee Collocation with WiFi

- ZigBee and WiFi collocate at 2.4 GHz Frequency Band

**WiFi:**

<table>
<thead>
<tr>
<th>Channel 1</th>
<th>Channel 6</th>
<th>Channel 11</th>
</tr>
</thead>
<tbody>
<tr>
<td>2400 MHz</td>
<td>2437 MHz</td>
<td>2480 MHz</td>
</tr>
<tr>
<td>2412 MHz</td>
<td>2470 MHz</td>
<td>2483.5 MHz</td>
</tr>
<tr>
<td>2425 MHz</td>
<td>2450 MHz</td>
<td>2480 MHz</td>
</tr>
<tr>
<td>2437 MHz</td>
<td>2455 MHz</td>
<td>(3 Orthogonal Channels)</td>
</tr>
</tbody>
</table>

**ZigBee:**

- ZigBee (or WiFi or both) should search for unused channels.

Ref. P. Yi et al.
ZigBee Collocation with WiFi

- An Algorithm for ZigBee Channel Switching:
  - **PER**: Packet Error Rate
    - To be checked by End-Device
  - **LQI**: Link Quality Indicator
    - To be checked by Router / Coordinator
    - **Strength** of Received Packets
    - From **0 to 255** [Strongest]
  - **ED**: Energy Detection
  - **RSSI**: Received Signal Strength Indicator

Ref: P. Yi et al.
ZigBee Collocation with WiFi

- Experimental Results by P. Yi et al. to obtain:
  - Safe Distance
  - Safe Offset Frequency

- WiFi Uplink and Downlink as source of interference on ZigBee:

![PER vs Distance (Meter)](image)

Ref: P. Yi et al.
• At 7 MHz Frequency Offset, “Safe Distance” is 5 Meter.
ZigBee Collocation with WiFi

- 8 MHz is "Safe Frequency Offset" regardless of Distance.

![Diagram showing PER vs Distance (Meter) with offset frequency 8MHz and legend for downlink and uplink.]  

- We can do similar experiments for other technologies.
- One can also study ZigBee interference on WiFi [the reverse!].
Z-Wave

• An alternative home area networking technology for ZigBee:
  • To resolve ZigBee/WiFi collocation problem.

• Z-Wave operates at around 900 MHz band
  • It does not collocate with WiFi
  • It may compete with some cordless telephones
Z-Wave

• Similar to ZigBee, Z-Wave aims to build a “smart home”:

  • A wireless HAN “ecosystem”

Z-Wave appliances can participate in AMI, AMR, and Demand Response
Wireless Mesh Networks
(Metropolitan Area)
Wireless Mesh Networks (WMNs)

• WMNs are composed of several wireless access points (routers).
  • Usually WiFi or WiMax Routers

• Together, they create a fully wireless communication backbone:
  • To serve wireless mesh clients (fixed / mobile)

• The WMN can be connected to the Internet or other networks:
  • Through a few gateway routers
Wireless Mesh Networks (WMNs)

- Example: a WMN with Internet and Cellular Connectivity:

Ref: Akyildiz et al.
Wireless Mesh Networks (WMNs)

- Example: Wireless Mesh Routers

With Two Network Interface Cards (NICs)

With One Network Interface Card

Q: What is the benefit of having multiple NICs on a Wireless Mesh Router?
Wireless Mesh Networks (WMNs)

- Example: Wireless Mesh Clients

(a) Laptop, (b) PDA, (c) Wi-Fi IP Phone and (d) Wi-Fi RFID Reader.
Some of the Initial Applications of WMNs included:

- Community Networks
- Enterprise Networks
- Local Area Networks for Hotels, Malls, Parks, Trains, etc.
- Metropolitan Area Networks

City-wide WMNs have been deployed in multiple U.S. cities.
City-Wide Wireless Mesh Networking

- Tempe, AZ Wireless Mesh Network
- Nearly 600 Mesh Access Points
- Coverage to an Area of 40 Square Miles
- Project Completed in only 120 days!
WMNs Benefits

- Some of the advantages of WMNs:
  - Low up-front costs
  - Ease of incremental deployment
  - Ease of maintenance

- The wireless mesh clients can also be:
  - Smart Meters, Sensors, Sub-stations, etc.
# Tropos Wireless Mesh Routers for Smart Grid

## Specifications:

<table>
<thead>
<tr>
<th><strong>Wireless Technology</strong></th>
<th>IEEE 802.11b/g/n</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Frequency Band</strong></td>
<td>2.4-2.483 GHz</td>
</tr>
<tr>
<td><strong>Media Access Protocol</strong></td>
<td>CSMA/CA with ACK</td>
</tr>
<tr>
<td><strong>Dimensions</strong></td>
<td>15.16” high x 6.97” wide x 2.01 deep</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>4.0 lbs</td>
</tr>
<tr>
<td><strong>Wind survivability</strong></td>
<td>&gt;165 mph</td>
</tr>
<tr>
<td><strong>Communication Range</strong></td>
<td>About 100 m</td>
</tr>
</tbody>
</table>
WMNs Challenges

• Key challenges in WMNs:
  • Wireless *Interference and Frequent Collisions*
  • Wireless *Multi-hop* Transmissions (e.g., for TCP connections)
  • *Congestion* at Gateways *(Q: Why?)*

• DoE has *requirements for Smart Grid Communications* [will see]:
  • Packet Loss and Delay *(Q: How can we assure these?)*
• Consider two wireless links $i$ and $j$:

  • $P_i$: transmit power of link $i$’s transmitter node

  • $G_{ij}$: channel gain from link $j$’s transmitter to link $i$’s receiver.

• A simple model for $G_{ij} = k (d_{ij})^{-2}$, where $d_{ij}$ is the distance.
Modeling Packet Loss in WMNs

• Received **Signal** Power at link i’s receiver node:

\[ G_{ii}P_i \]

• Received **Interference** Power at link i’s receiver from j’s transmitter

\[ G_{ij}P_j \]

• Similarly, we can obtain interference power from all other links.
We can define signal to interference ratio (SIR) for link $i$ as:

$$SIR_i = \frac{G_{ii}P_i}{\sum_{k \neq i} G_{ik}P_k}$$

- Signal Power
- Aggregate Interference Power

For correct reception of the packet, it is required that

$$SIR_i \geq SIR^{th}$$

(Threshold)

Otherwise, the packet is lost.
The probability of losing the packet on link $i$:

$$O_i = \text{Prob}\{SIR_i < SIR^{th}\}$$

(Outage)

$$= \text{Prob}\left\{G_{ii}P_i < SIR^{th}\sum_{k \neq i} G_{ik} P_k\right\}$$

• **Key Question**: Why are we talking about “probability” here?

• **What is the “stochastic/random” part?**
Modeling Packet Loss in WMNs

• Obviously not all nodes transmit at all times!

• We assume some random distribution for packet transmission.

• If nodes transmit following independent exponential distributions:

\[
O_i = 1 - \prod_{k\neq i}^{\sum} \frac{1}{1 + \frac{SIR_{th} G_{ik} P_k}{G_{ii} P_i}}
\]

[Proof: See Appendix I in IEEE TWC paper by S. Kandukuri and S. Boyd]
Let us consider the packet loss model again:

\[ O_i = 1 - \prod_{k \neq i} \frac{1}{1 + \frac{\text{SIR}^\text{th}_{ik} P_k}{G_{ii} P_i}} \]

Probability of packet loss increases if:

- Link \( i \) transmits with lower power
- Interfering links transmit with higher power
- Interfering links get closer
- There are more interfering links in the neighborhood
Modeling Packet Loss in WMNs

• The model so far only gives “per-link” packet loss.

• **Q:** How about end-to-end packet loss probability?

A fully wireless *multi-hop* communication!
Modeling Packet Loss in WMNs

• End-to-end Probability of Packet Loss (Q: Why?):

\[
O_{Path} = 1 - (1 - O_1)(1 - O_2)(1 - O_3)(1 - O_4)
\]
Modeling Packet Loss in WMNs

• In general, for a path with $R$ as the set of wireless links:

$$O_{Path} = 1 - \prod_{i \in R} (1 - O_i)$$

• For each path in WMN (e.g., AMI), we can calculate $O_{path}$ if we know:
  - Locations of the mesh routers and clients (channel gains)
  - Transmit power of mesh routers and clients
  - The SIR threshold values for the technology being used

[Example: You can check if it satisfies the DoE requirements!]
Modeling Packet Loss in WMNs

- We want low “per-link” loss rates for links closer to aggregator:

![Diagram showing network with Smart Meter and Aggregator with links 1 to 6, and O4 should be low! (Q: Why?)](image)
Modeling Packet Loss in WMNs

• **Q:** How can we assure required packet loss bounds for all path?

• First of all, we should not have paths that are too long!
  • This requires having several gateways in large WMNs.

• Second, we need to do resource management:
  • Power allocation, channel assignment, etc.
• Assume that we use WiFi technology for our WMN.

• Let us look at the available **11 channels** in IEEE 802.11b:

![Channel Diagram]

- **Partially Overlapping**: 1 and 2
- **Non-Overlapping**: 1 and 6 and 11
• We assign different non-overlapping channels to different links:

- Links 1, 2, and 3 will no longer interfere on each other.
- Links 1 and 4 may interfere, but they are far from each other.

Such multi-channel deployment requires mesh routers with multiple NICs. (Q: Why?)
• Same idea applies to a more complex network:

• Channel assignment depends on the number of NICs per node.
• Same idea applies to a more complex network:

• Channel assignment depends on the number of NICs per node.
• Same idea applies to a more complex network:

• Knowing NIC = 2: Q: Do you see more than 2 channels per node?
Channel Assignment in WMNs

• Here, we have three different contention domains:
  • **Channel 1**: Seven Links
  • **Channel 6**: Five Links
  • **Channel 11**: Four Links

• Note that links on channel 1 are far from each other
  • We can better remove interference with more channels/NICs.
ATCP for WMNs

• When it comes to wireless networks:
  • Packet loss due to link failure/interference can affect TCP.
  • The problem: TCP back-off every time a packet is lost.

• One Solution: Ad-hoc Transmission Control Protocol (TCP)

• ATCP uses network feedback:
  • ICMP Destination Unreachable (when a path breaks)
  • Early Congestion Notification (when there is congestion)
• The key idea: We want to distinguish:

  • Packet loss due to congestion

  • Packet loss due to wireless interference/collision

• **ECN Flags**: Indication of congestion

• **Timeout and 3 duplicate ACKs**: Indication of collision/link problem

[Link problems can be because of mobility]
• ATCP in the TCP/IP Stack:

Sender

TCP

A-TCP

IP

Link layer

Receiver

TCP

IP

Link layer

• It only affects the TCP sender side. It is a cross-layer solution.
ATCP for WMNs

- ATCP / TCP Behavior:
  - Timeout and 3\textsuperscript{rd} Duplicate ACK:
    - Retransmit the segment
    - No Congestion Control Reaction
    - Assumed to be due to link collision
  - ACK with ECN Flag:
    - Invokes Congestion Control
ATCP for WMNs

- ATCP / TCP Behavior:

  - **ICMP Destination Unreachable Message:**
    - Stops Transmission
    - Enters “Persist Mode”
    - Starts Persist Timer
      - Probes for Path Availability when Timer Expires
    - Resume Transmission when New Path Found
IEC 61850

(Communications of Substations)
IEC 61850 Overview

- IEC: International Electrotechnical Commission

- IEC 61850

  - Smart Grid Communications Standard

  - Communications across Intelligent Electronic Devices (IEDs)

    - Focus: Sub-stations (but also supports meters, etc.)

  - Runs over TCP/IP networks
IEC 61850 Overview

• Example Sub-station:

Ref: ABB Switzerland Ltd Corporate Research
• IEC 61850 Aims to provide inter-operability

• **Key focus:** IEC 61850 provides a comprehensive model for how power system devices should organize data in a manner that is consistent across all types and brands of devices.

• The IEC 61850 devices are intended to be plug-and-play.

• They are configured by uploading simple configuration files.
IEC 61850 Overview

• IEC 61850 Network Architecture:

  Physical Device (Data Concentrator) -> XCBR
  Physical Device (Data Concentrator) -> MMXU1
  Physical Device (Data Concentrator) -> MMXU2

  Logical Devices / Nodes:
  XCBR
  MMXU1
  MMXU2

• XCBR: Circuit Breaker, MMXU1: Measurement Unit for Feeder 1, ...
IEC 61850 Overview

- Data types to be transmitted for each logical device:

  - Should follow **certain specifications**:

<table>
<thead>
<tr>
<th>OBJECT NAME</th>
<th>COMMON DATA CLASS</th>
<th>DESCRIPTION</th>
<th>T</th>
<th>MANDATORY/OPTIONAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>LNName</td>
<td>Secure</td>
<td>Shall be inherited from Logical-Node Class (see IEC 61850-7-2)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Data Class Name (Data Structure)**

Object Name
• Data types to be transmitted for each logical device:

<table>
<thead>
<tr>
<th>DATA NAME</th>
<th>COMMON DATA CLASS</th>
<th>DESCRIPTION</th>
<th>T</th>
<th>MANDATORY/OPTIONAL</th>
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</thead>
<tbody>
<tr>
<td>Controls</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pos</td>
<td>DPC</td>
<td>Switch position</td>
<td>Mandatory</td>
<td></td>
</tr>
<tr>
<td>BlkOpn</td>
<td>SPC</td>
<td>Block opening</td>
<td>Mandatory</td>
<td></td>
</tr>
<tr>
<td>BlkCls</td>
<td>SPC</td>
<td>Block closing</td>
<td>Mandatory</td>
<td></td>
</tr>
<tr>
<td>ChaMotEna</td>
<td>SPC</td>
<td>Charger motor enabled</td>
<td>Optional</td>
<td></td>
</tr>
<tr>
<td>Metered Values</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>SumSwARs</td>
<td>BCR</td>
<td>Sum o Switched Amperes, resetable</td>
<td>Optional</td>
<td></td>
</tr>
<tr>
<td>Status Information</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CBOpCap</td>
<td>INS</td>
<td>Circuit breaker operating capability</td>
<td>Mandatory</td>
<td></td>
</tr>
<tr>
<td>POWCap</td>
<td>INS</td>
<td>Point on Wave switching capability</td>
<td>Optional</td>
<td></td>
</tr>
<tr>
<td>MaxOpCap</td>
<td>INS</td>
<td>Circuit breaker operating capability when fully charged</td>
<td>Optional</td>
<td></td>
</tr>
</tbody>
</table>

Object Name ———— Data Class Name (Data Structure)
### IEC 61850 Data Classes

- **Example:** **SPS:** Single Point Status

#### SPS Class

<table>
<thead>
<tr>
<th>ATTRIBUTE NAME</th>
<th>ATTRIBUTE TYPE</th>
<th>FUNCTIONAL CONSTRAINT</th>
<th>TRGOP</th>
<th>VALUE / VALUE RANGE</th>
<th>MANDATORY/ OPTIONAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>DataName</td>
<td>Inherited from Data Class (see IEC 61850-7-2)</td>
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<td></td>
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</table>

**DATA ATTRIBUTE**

<table>
<thead>
<tr>
<th>Status</th>
<th>Attribute Type</th>
<th>Functional Constraint</th>
<th>TRGOP</th>
<th>Value / Value Range</th>
<th>Mandatory</th>
</tr>
</thead>
<tbody>
<tr>
<td>sVal</td>
<td>BOOLEAN</td>
<td>ST</td>
<td>dchg</td>
<td>TRUE</td>
<td>FALSE</td>
</tr>
<tr>
<td>q</td>
<td>Quality</td>
<td>ST</td>
<td>qchg</td>
<td></td>
<td>Mandatory</td>
</tr>
<tr>
<td>t</td>
<td>TimeStamp</td>
<td>ST</td>
<td></td>
<td></td>
<td>Mandatory</td>
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</table>

**Substitution**

<table>
<thead>
<tr>
<th>subSta</th>
<th>BOOLEAN</th>
<th>SV</th>
<th>TRUE</th>
<th>FALSE</th>
<th>PICS_SUBST</th>
</tr>
</thead>
<tbody>
<tr>
<td>subSta</td>
<td>BOOLEAN</td>
<td>SV</td>
<td>TRUE</td>
<td>FALSE</td>
<td>PICS_SUBST</td>
</tr>
<tr>
<td>subSta</td>
<td>Quality</td>
<td>SV</td>
<td></td>
<td></td>
<td>PICS_SUBST</td>
</tr>
<tr>
<td>subSta</td>
<td>VISIBLE STRING64</td>
<td>SV</td>
<td></td>
<td></td>
<td>PICS_SUBST</td>
</tr>
</tbody>
</table>

**Configuration, description and extension**

<table>
<thead>
<tr>
<th>d</th>
<th>VISIBLE STRING255</th>
<th>DC</th>
<th>Text</th>
<th>Optional</th>
</tr>
</thead>
<tbody>
<tr>
<td>dU</td>
<td>UNICODE STRING255</td>
<td>DC</td>
<td></td>
<td>Optional</td>
</tr>
<tr>
<td>dcdNs</td>
<td>VISIBLE STRING255</td>
<td>EX</td>
<td>AC_DLINDA_M</td>
<td></td>
</tr>
<tr>
<td>dcdName</td>
<td>VISIBLE STRING255</td>
<td>EX</td>
<td>AC_DLINDA_M</td>
<td></td>
</tr>
<tr>
<td>doLatNc</td>
<td>VISIBLE STRING255</td>
<td>EX</td>
<td>AC_DLINDA_M</td>
<td></td>
</tr>
</tbody>
</table>

- **ST:** Status
- **DC:** Description
- **SV:** Substitution
IEC 61850 Data Classes

• Other Data Classes:

  • Status information (binary, integer):
    • **SPS**: Single Point Status
    • **DPS**: Double Point Status
    • **INS**: Integer Status
    • **ACT**: Protection Activation info
    • **ACD**: Activation Info Directional Protection
    • **SEC**: Security Violation Counting
    • **BCR**: Binary Counter Reading
IEC 61850 Data Classes

• Other Data Classes:

  • Control Status:
    • **SPC**: Single Point Control
    • **DPC**: Double Point Control
    • **INC**: Integer Status Control
    • **BSC**: Binary Controlled Step Position Info
    • **ISC**: Integer Controlled Step Position Info

  • Just like the example for SPS, each item has a data structure.
• Recall that we used names XCBR, MMXU1, ... for logical nodes.

• The first letter indicates the type for the logical node:
  
  • X: Switchgear  
  • M: Metering and Measurement  
  • A: Automatic Control  
  • C: Supervisory Control  
  • G: Generic Function
• Recall that we used names XCBR, MMXU1, ... for logical nodes.

• The first letter indicates the type for the logical node:
  • I: Interfacing
  • P: Protection
  • S: Sensors
  • T: Instrument Transformer
  • Y: Power Transformers
  • Z: Other devices
**Example:** Can you identify different logical nodes?
IEC 61850 Logical Nodes

• IEC 61850 gives an object-oriented model for communications.

• Example for Object Names:

  Relay1/XCBR1$ST$Loc$stVal

  Logical Device
  Logical Node
  Functional Constraint
  Data
  Attribute

• We would like to know if the circuit breaker logical node XCBR1 in logical device Relay 1 is in the remote or local mode of operation.
• The object names are used to form MMS messages:
  
  • MMS: Manufacturing Messaging Specification

• The messages are exchanged as application-layer messages.

• The MMS messages are exchanged over TCP/IP networks
  
  • LAN

  • Web-Based
Power Line Communications
• Power Line Communications (PLC):
  • Carrying data on a conductor also used for power transmission

• PLC is a wired communications technology
  • But it can compete with wireless technologies with low cost
  • Because the infrastructure already exists

• Harsh environment of the power transmission lines.
PLC Overview

• Idea:
  • Digital signal to be transmitted is modulated over power line.
  • This is done by a proper coupler device.
  • The signal is propagated over the power line.
  • It will be decoupled and decoded at the receiver side.

![Inductive coupler](plc-modem.png)

Inductive coupler
PLC-Modem
• Harsh Noise Environment:

Power spectral densities of noise due to various sources
Three classes of PLC Technologies:

- **Broadband (BB):**
  - Operating at 1.8 – 250 MHz.
  - Data Rate: Up to 200 Mbps
  - Initial Application: Residential Internet Access
  - Short Communication Range (few kilometers)
  - Good for AMI/AMR, Not Good for sub-stations *(Q: Why?)*
• Three classes of PLC Technologies:
  
  • **Broadband (BB):**

Example: Residential broadband access / AMI / AMR
• Three classes of PLC Technologies:

  • **Narrowband (NB):**
    
    • Operating at 3 – 500 kHz.
    
    • United States FCC: 10-490 kHz
    
    • Data Rate: Up to 500 kbps (usually several kbps)
    
    • Considered for sub-station communications
• Three classes of PLC Technologies:

  • Ultra Narrowband (UNB):
    • Operating at 30 Hz – 3 kHz.
    • Data Rate: Up to 100 bps (very low, but good enough!)
    • Communication Range: 150 km or more

  • Current Applications:
    • AMI, AMR, Demand Response (Direct Load Control)
HomePlug

• HomePlug is an industry Alliance to enable and promote PLC:

  • **HomePlug 1.0**: Residential Internet

  • **HomePlug AV**: Residential Cable TV

  • **HomePlug Green PHY**: Smart Grid Applications (in-home)

    • Wired alternative/addition to ZigBee and Z-Wave for HAN
DoE Requirements for Smart Grid Communications
## DoE Smart Grid Communication Requirements

<table>
<thead>
<tr>
<th>Application</th>
<th>Network Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Bandwidth</strong></td>
<td><strong>Latency</strong></td>
</tr>
<tr>
<td>AMI</td>
<td>10-100 kbps/node</td>
</tr>
<tr>
<td>Demand Response</td>
<td>14kbps-100 kbps/node</td>
</tr>
<tr>
<td>Wide Area Situational Awareness</td>
<td>600-1500 kbps</td>
</tr>
<tr>
<td>Distribution Energy Resources and Storage</td>
<td>9.6-56 kbps</td>
</tr>
<tr>
<td>Electric Transportation</td>
<td>9.6-56 kbps</td>
</tr>
<tr>
<td>Distribution Grid Management</td>
<td>9.6-100 kbps</td>
</tr>
</tbody>
</table>

Not that high!
Other Smart Grid Communications Technologies
### Other Smart Grid Communication Technologies

<table>
<thead>
<tr>
<th>Type/Name of Standards</th>
<th>Details</th>
<th>Application</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEC 61970 and IEC 61969</td>
<td>Providing Common Information Model (CIM): IEC 61970 works in the transmission domain and IEC 61969 works in the distribution domain</td>
<td>Energy management systems</td>
</tr>
<tr>
<td>IEC61850</td>
<td>Flexible, future proofing, open standard, communication between devices in transmission, distribution and substation automation systems</td>
<td>Substation Automation</td>
</tr>
<tr>
<td>IEC 60870-6/TASE.2</td>
<td>Data exchange between utility control centers, utilities, power pools, regional control centers</td>
<td>Inter-control center communications</td>
</tr>
<tr>
<td>IEC 62351 Parts 1-8</td>
<td>Defining cyber security for the communication protocols</td>
<td>Information Security Systems</td>
</tr>
<tr>
<td>IEEE P2030</td>
<td>A Guide for smart grid inter-operability of energy technology and IT operation with the electric power system (EPS)</td>
<td>Customer-side applications</td>
</tr>
<tr>
<td>IEEE P1901</td>
<td>High speed power line communications</td>
<td>In-home multimedia, utility and smart grid applications</td>
</tr>
<tr>
<td>ITU-T G.9955 and G.9956</td>
<td>ITU-T G.9955 and G.9956 contain the physical layer specification and the data link layer specification</td>
<td>Distribution Automation, AMI</td>
</tr>
<tr>
<td>OpenADR</td>
<td>Dynamic pricing, Demand Response</td>
<td>Price Responsive and Load Control</td>
</tr>
<tr>
<td>BACnet</td>
<td>Scalable system communications at customer side</td>
<td>Building automation</td>
</tr>
<tr>
<td>HomePlug</td>
<td>Powerline technology to connect the smart appliances to HAN</td>
<td>HAN</td>
</tr>
<tr>
<td>HomePlug Green PHY</td>
<td>Specification developed as a low power, cost-optimized power line networking specification standard for smart grid applications</td>
<td>HAN</td>
</tr>
<tr>
<td>U-SNAP</td>
<td>Providing many communication protocols to connect HAN devices to smart meters</td>
<td>HAN</td>
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Ref: V.C. Güngör et al.
# Other Smart Grid Communication Technologies

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<td>Providing many communication protocols to connect HAN devices to smart meters</td>
<td>HAN</td>
</tr>
<tr>
<td>ISA100.11a</td>
<td>Open standard for wireless systems</td>
<td>Industrial Automation</td>
</tr>
<tr>
<td>SAE J2293</td>
<td>Standard for the electrical energy transfer from electric utility to EVs</td>
<td>Electric Vehicle Supply Equipment</td>
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<tr>
<td>ANSI C12.22</td>
<td>Data network communications are supported and C12.19 tables are transported</td>
<td>AMI</td>
</tr>
<tr>
<td>ANSI C12.18</td>
<td>Data structures transportation via the infrared optical port han</td>
<td>AMI</td>
</tr>
<tr>
<td>ANSI C12.19</td>
<td>Flexible metering model for common data structures and industry &quot;vocabulary&quot; for meter data communications</td>
<td>AMI</td>
</tr>
<tr>
<td>Z-Wave</td>
<td>Alternative solution to ZigBee that handles the interference with 802.11/b/g</td>
<td>HAN</td>
</tr>
<tr>
<td>M-Bus</td>
<td>European standard and providing the requirements for remotely reading all kinds of utility meters</td>
<td>AMI</td>
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<tr>
<td>PRIME</td>
<td>Open, global standard for multi-vendor interoperability</td>
<td>AMI</td>
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<tr>
<td>G3-PLC</td>
<td>Providing interoperability, cyber security, and robustness</td>
<td>AMI</td>
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<tr>
<td>SAE J2836</td>
<td>Supporting use cases for plug-in electric vehicles communication</td>
<td>Electric Vehicle</td>
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<tr>
<td>SAE J2847</td>
<td>Supports communication messages between PEVs and grid components</td>
<td>Electric Vehicle</td>
</tr>
</tbody>
</table>

Ref: V.C. Güngör et al.


References

• Department of Energy, “Communications Requirements of Smart Grid Technologies”, October 5, 2010.


References

