Converged, configurable LPWAN architecture for IoT devices

Ingrid Moerman, Jeroen Hoebeke, Eli De Poorter
iMinds – Ghent University
OUTLINE

• LP WAN: what and why?
• Challenges
• Vision
• Activities @ iMinds
LPWAN - WHAT AND WHY?
LOW POWER WIDE AREA NETWORKS

Mobile Broadband
(Mobile, SIM Card)

LPWAN

Fixed Broadband
(Security, Comfort, Safety...)

Source: Actility
WIRELESS COMMUNICATION LANDSCAPE

Opportunities

LPWAN

Low data rate TV
Whitespace M2M
STDs, e.g.
Weightless

Cellular
(HSXPA, LTE, LTE+, etc.)

Proprietary
Sub-GHz
2.4GHz

Wi-Fi®
802.11 a,b,g,n, ac, ad, ah

RF4CE
ZigBee®
Bluetooth®

NFC
LPWAN CHARACTERISTICS

• **Low date rate** (few kbps, few messages/day)
• **Long range** (up to 10 km, ubiquitous coverage)
• **Low power** (multi-year battery)
• **Low cost** (hardware, installation, maintenance)
• **License free spectrum**
LPWAN MARKETS

http://www.analysysmason.com/Research/Content/Reports/Low-powered-wireless-solutions-have-the-potential-to-increase-the-M2M-market-by-over-3-billion-connections/

iMinds
LPWAN TECHNOLOGIES

- SigFox
- LoRa
- Ingenu (former OnRamp)
- Nwave (Weightless-N)
- M2COMM (Weightless-P)
- SilverSpring’s Starfish (IEEE 802.15.4g)
- Cyan’s Cynet
- Accellus
- Telensa
- DART
- WaveloT
- Qowisio
- Wi-Fi HaLow (IEEE 802.11 ah)
- ...

iMinds
LPWAN TECHNOLOGIES

- SigFox
- LoRa
- Ingenu (former OnRamp)
- Nwave (Weightless-N)
- M2COMM (Weightless-P)
- SilverSpring’s Starfish (IEEE 802.15.4g)
- Cyan’s Cynet
- Accellus
- Telensa
- DART
- WaveloT
- Qowisio
- Wi-Fi HaLow (IEEE 802.11 ah)
- ...
SigFox
SigFox

• Claims to be "the first and only company providing global cellular connectivity for the Internet of Things."

  • Radio frequency
    • 868 MHz (Europe)
    • 915 MHz (North America)
    • Ultra-narrow band signals (100 Hz)

  • Typical TX powers
    • 14 dBm (@45 mA) or 0 dBm (@10 mA)
    • Receiver sensitivity:
      -129 dBm RX @ 600 bps

  • Throughput:
    • max 12 byte packets
    • ~ 1 message / 10 min
    • Up to 100 bits per second

  • Cost:
    • Radio chip: < 5 dollar
    • Licensing: 1 €/year/device
SigFox

- Long range behavior
  - France: 83% of territory covered with 770 BSs
SigFox

Coverage (2015)

60 countries
5 years
SigFox

- **Main advantages**
  - Easy to deploy
    - Leverage on existing cellular network and software backbone
    - Several radio chips available, Arduino boards available
  - Relatively cheap
  - No technical knowledge required
  - Extreme low energy consumption
    - Battery lifetime: from several years to decades
- **Main disadvantages**
  - Very small packets
  - No two-way communication (only uplink)
  - Yearly fees
  - Limited in terms of reliability, security, throughput, …
  - Scalability towards higher densities, more users?
  - Only via operators
LoRa
LoRa – Technical Highlights

• Proprietary chirp spread spectrum (CSS) modulation (Semtech)
  • At +14dbm output power, 868MHz:
    • >2km dense urban, >15km suburban, >80km VLOS
  • Receiver sensitivity: -148dBm (< noise floor)

• LoRaWAN = communication protocol (MAC) and system architecture for the network
  • Open, open source implementations available

• Adaptive Data Rate: network instructs node to adapt transmission rate

<table>
<thead>
<tr>
<th>Application</th>
<th>LoRa® MAC</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAC options</td>
<td></td>
</tr>
<tr>
<td>Class A (Baseline)</td>
<td>Class B (Baseline)</td>
</tr>
</tbody>
</table>

10 channels

Regional ISM band

EU 868 EU 433 US 915 AS 430 —

LoRa® Modulation

2D simulation (flat environment)
LoRa – Network architecture + security

End Nodes
- pet tracking
- smoke alarm
- water meter
- trash container
- vending machine
- gas monitoring

Concentrator /Gateway
- LoRa® RF LoRaWAN™

Network Server
- 3G/ Ethernet Backhaul
- TCP/IP SSL LoRaWAN™
- TCP/IP SSL Secure Payload

Application Server
- iMinds
LoRa

### Additional advantages
- Per device adaptive transmission power and data rate
  - Good for scalability
- Larger packet sizes
- More complex modulation
  - Better throughput than SigFox
  - More interference robust
- In-built security
- Support for multiple communication patterns
  - Class A (all) / Class B (beacon) / Class C (mains powered actuators)
- Support for mobility
- Geolocalisation as of 2016
- More open source

### Disadvantages
- Single chip manufacturer (Semtech)
- Due to broadband CDMA, less suited for dense deployments.
- Slower roll-out
  - Belgium: Proximus
  - Should be available end 2016
- Higher energy consumption
IEEE 802.15.4g
IEEE 802.15.4g

- Promoted by Wi SUN Alliance
- Focus on smart utility and smart city
- Support for Global and Regional frequency bands
  - 902-928 MHz in US and many other regions
  - 863-870 MHz Europe
- **Physical layer**
  - 2-level or 4-level FSK modulation
  - Data rates from 50 kbps to 400 (200) kbps
  - Range up to several kilometres
  - Optional forward error correction for better link margin

3 PHY formats supported:
- MR-FSK: 2FSK and 4FSK
- MR-OFDM: available but not popular
- MR-O-QPSK: DSSS and multiplexed DSSS
IEEE 802.15.4g

- Promoted by Wi SUN Alliance
- Focus on smart utility and smart city
- Support for Global and Regional frequency bands
  - 902-928 MHz in US and many other regions
  - 863-870 MHz Europe
- MAC
  - Frame supports full IP payloads (> 1500 bytes)
  - 4 octet FCS (Frame Check Sequence) for good error detection
  - De-centralised frequency hopping
  - Channel blacklisting for interference mitigation
  - Optional L2 multi-hop layer

3 PHY formats supported:
- MR-FSK: 2FSK and 4FSK
- MR-OFDM: available but not popular
- MR-O-QPSK: DSSS and multiplexed DSSS
IEEE 802.15.4g

**Main advantages**
- Benefits from the widespread popularity of IEEE 802.15.4 IoT technologies
- Built-in support for multi-hop
- IPv6 addressable through 6LoWPAN
- Packet size up to 2047 bytes
- Fully open standard

**Main disadvantages**
- Lower range than e.g. SigFox and LoRa (but still further than traditional Wi-Fi)
- Potentially higher energy consumption
IEEE 802.11ah (HaLow)
Long-range Wi-Fi – IEEE 802.11af

- **White-Fi**
  - Operates in TV white space spectrum between 54 and 790MHz
  - Uses cognitive radio technology

- **MAC**
  - Based on OFDM (802.11ac)
  - Channel bandwidth: 6 or 8MHz

- **Alternative in unlicensed spectrum: 802.11ah**
Long-range Wi-Fi – IEEE 802.11ah

- Lower frequency bands → longer range
IEEE 802.11ah features

- Based on legacy IEEE 802.15.4 concepts, with several improvements
  - Large # stations, throughput enhancements, power saving, etc.
- Sub-GHz frequencies (Europe: 863 – 868 Mhz)
- Standard to be approved in July 2016
  - No devices yet (devices expected to come on market 2017/2018)
- Adaptive link
  - Modulation: BPSK, QPSK, 16-QAM, 64-QAM, 256-QAM
  - Bandwidth per channel: 1, 2, 4, 8 or 16 MHz
  - Transmission technique: OFDM
- Packet length ~ 100 bytes
- Range 100-1000 m
- Bandwidth: 0.15 – 7.8 Mbps

<table>
<thead>
<tr>
<th>COUNTRY</th>
<th>BAND LIMITS (MHZ)</th>
</tr>
</thead>
<tbody>
<tr>
<td>China</td>
<td>755 - 787</td>
</tr>
<tr>
<td>Europe</td>
<td>863 - 868</td>
</tr>
<tr>
<td>Japan</td>
<td>916.5 - 927.5</td>
</tr>
<tr>
<td>Korea</td>
<td>917.5 - 923.5</td>
</tr>
<tr>
<td>Singapore</td>
<td>866 - 869 &amp; 920 - 925</td>
</tr>
<tr>
<td>USA</td>
<td>902 - 928</td>
</tr>
</tbody>
</table>
IEEE 802.11ah transmission range

• **Adaptive link configuration**
  • Frequency, modulation and bandwidth all influence the throughput and range

### 802.11ah supported modulation and Coding Scheme (MCS) combinations

<table>
<thead>
<tr>
<th>MCS Index</th>
<th>Modulation</th>
<th>Code Rate</th>
<th>$N_{SD}$</th>
<th>$N_{DBPS}$</th>
<th>Data Rate (Mbps)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Normal GI</td>
</tr>
<tr>
<td>0</td>
<td>BPSK</td>
<td>1/2</td>
<td>52</td>
<td>26</td>
<td>0.65</td>
</tr>
<tr>
<td>1</td>
<td>QPSK</td>
<td>1/2</td>
<td>52</td>
<td>52</td>
<td>1.3</td>
</tr>
<tr>
<td>2</td>
<td>QPSK</td>
<td>3/4</td>
<td>52</td>
<td>78</td>
<td>1.95</td>
</tr>
<tr>
<td>3</td>
<td>16-QAM</td>
<td>1/2</td>
<td>52</td>
<td>104</td>
<td>2.6</td>
</tr>
<tr>
<td>4</td>
<td>16-QAM</td>
<td>3/4</td>
<td>52</td>
<td>156</td>
<td>3.9</td>
</tr>
<tr>
<td>5</td>
<td>64-QAM</td>
<td>2/3</td>
<td>52</td>
<td>208</td>
<td>5.2</td>
</tr>
<tr>
<td>6</td>
<td>64-QAM</td>
<td>3/4</td>
<td>52</td>
<td>234</td>
<td>5.85</td>
</tr>
<tr>
<td>7</td>
<td>64-QAM</td>
<td>5/6</td>
<td>52</td>
<td>260</td>
<td>6.5</td>
</tr>
<tr>
<td>8</td>
<td>256-QAM</td>
<td>3/4</td>
<td>52</td>
<td>312</td>
<td>7.8</td>
</tr>
<tr>
<td>9</td>
<td>256-QAM</td>
<td>5/6</td>
<td>Not valid</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
IEEE 802.11ah transmission range

- Adaptive link configuration
  - Frequency, modulation and bandwidth all influence the throughput and range
IEEE 802.11ah MAC

- **Support large number of stations**
  - Association Identifier for each associated station
    - Up to 8191 \(2^{13}-1\) Association Identifiers (AIDs)
  - Hierarchical structure
    - Page – block - sub-block - station’s index in sub-block
  - Purpose
    - Address multiple stations at once e.g. using sub-block ID
    - Cluster according to traffic patterns, location
    - Power saving
IEEE 802.11ah

• **Main advantages**
  • Fully open standard
  • Support both low and high date-rate
    • Supports higher bitrates suitable for e.g. IoT video cameras
    • Support for heterogeneous traffic types
  • Support of QoS
  • Likely candidate for integration in 3-band WiFi access points (868 MHz, 2.4 GHz and 5 GHz)

• **Main disadvantages**
  • Lower range than e.g. SigFox and LoRa (but still further than traditional WiFi)
  • Potentially higher energy consumption
  • No chips on the market yet (expected in 2017)
## Characteristics of main LPWAN technologies

<table>
<thead>
<tr>
<th></th>
<th>SIGFOX</th>
<th>LoRa</th>
<th>IEEE 802.15.4g</th>
<th>IEEE 802.11ah</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Open vs closed nature</strong></td>
<td>- Open hardware</td>
<td>- Patented PHY</td>
<td>Fully open standard</td>
<td>Fully open standard</td>
</tr>
<tr>
<td></td>
<td>- Closed (patented) MAC and higher layers</td>
<td>- Open software and management stack</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Operator model</strong></td>
<td>Worldwide single operator</td>
<td>- Availability of multiple network operators</td>
<td>Possibility to install and maintain your own network</td>
<td>Possibility to install and maintain your own network</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Possibility to install and maintain your own network</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Unique valorization potential</strong></td>
<td>Cross-country monitoring with roaming IoT devices</td>
<td>Dense IoT devices in larger premises (several square kilometer)</td>
<td>Inherent multi-hop capabilities for infrastructureless communications</td>
<td>Heterogeneous and high-throughput IoT devices and devices requiring QoS</td>
</tr>
</tbody>
</table>
### LPWAN technologies in the 868 MHz band

<table>
<thead>
<tr>
<th>Technology</th>
<th>Bandwidth</th>
<th>Data rate</th>
<th>Range</th>
<th>Multihop</th>
<th>Remarks</th>
</tr>
</thead>
<tbody>
<tr>
<td>SigFox</td>
<td>100Hz</td>
<td>100bps</td>
<td>3-50km</td>
<td>No</td>
<td>Single operator, 12 bytes messages</td>
</tr>
<tr>
<td>LoRaWAN</td>
<td>125kHz/250kHz</td>
<td>250bps - 5.5kbps / 11kbps / 50kbps</td>
<td>2-15km</td>
<td>No</td>
<td>Open system specification</td>
</tr>
<tr>
<td>IEEE 802.15.4g</td>
<td>200kHz - 1.2MHz</td>
<td>50kbps - 1Mbps</td>
<td>1000m</td>
<td>Yes</td>
<td>Part of widely adopted 802.15.4 family</td>
</tr>
<tr>
<td>IEEE 802.11ah</td>
<td>1/2/4/8/16 MHz</td>
<td>150kbps - 78Mbps</td>
<td>100 - 1000m</td>
<td>2 hops</td>
<td>Part of widely adopted Wi-Fi family</td>
</tr>
</tbody>
</table>
CHALLENGES
CHALLENGES

• Spectrum is ISM bands is scarce
  • sub GHz spectrum has small available bandwidth (3 MHz in 868 band in Europe)
  • Sub GHz spectrum is more and more utilized
• Uncoordinated deployment, operation and management,
  • many network providers and administrators
• Large impact of interference
  • long propagation range
  • significant performance degradation

unlicensed sub GHz bands will soon be considerably congested and unusable!
**VISION**

**virtualized network management and intelligence**
fault detection, root-cause analysis, self-healing, application-aware QoS, network virtualization and slicing, …

**cross-technology optimization and control**
interference avoidance, multi-protocol radios, hybrid MAC scheduling, cross-technology handovers…

**intra-technology optimization and control**
power control, adaptive modulation, QoS-aware MAC scheduling, salability, energy optimization…

---

**Network coexistence controller of operator A**

- Control of private network
- Control of operator A technology 1 network
- Control of operator A technology 2 network
- Control of operator B network

**Network coexistence controller private network**

**Network coexistence controller operator B**

**inter-operator virtual network slice with specific QoS guarantees**

**inter-technology virtual network slice with specific QoS guarantees**

**technology-neutral APIs**

**technology-specific APIs**

---

**Operator A Technology 1**

**Private network**

**Operator A Technology 2**

**Operator B**
ACTIVITIES @ iMinds
Abstractions & adaptors for IoT devices
Enabling smooth Internet/Web integration

GET /s/t

CoAP

2.05 Content text/plain

CLIENT

23.2°C

SERVER

History

Select the amount of rows to show: 5

<table>
<thead>
<tr>
<th>Timestamp</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2013-06-20 13:54:12</td>
<td>22.1</td>
</tr>
<tr>
<td>2013-06-20 13:54:07</td>
<td>21.6</td>
</tr>
<tr>
<td>2013-06-20 13:54:02</td>
<td>22.1</td>
</tr>
<tr>
<td>2013-06-20 13:53:57</td>
<td>22.4</td>
</tr>
<tr>
<td>2013-06-20 13:53:52</td>
<td>22.1</td>
</tr>
</tbody>
</table>

Graph

Select a type of graph: Line

History of fetched values

22.4
22.2
22.0
21.8
21.6
Problem statement

No transparency in interactions

Routing problems in LAN settings

Sensing devices

Cloud

Sensor network

LAN

VARIETY OF INTERACTION MODELS, CHANGING IP, CLASS 0 DEVICES (SigFox), TEMPORARY OFFLINE (BLE)

NO OUT-OF-THE-BOX COMMUNICATION POSSIBLE
Abstraction layer @ GW, Edge or Cloud

Sensing devices

Abstraction layer

UNIFORM VIEW & ACCESS

HIDING UNDERLYING COMPLEXITY OR DETAILS

Cloud/LAN

CLIENT PERCEIVES END-TO-END CONNECTION (cfr. data center)
Abstraction layer @ GW, Edge or Cloud

- CoAP client
  - A) POST
    - coap://[2001:6a8:1d80:600::24]/toggle
  - B) OBSERVE
    - coap://[2001:6a8:1d80:600::22]/s/t
    - coap://[2001:6a8:1d80:600::24]/s/t

- 6LoWPAN/RPL border router

- Access Layer

- Abstraction Layer

- 2001:6f8:202:85cc::/64
- 802.15.4 WSN
- PUT
  - Sleeping (push)
- Always on (pull)
Abstraction layer @ GW, Edge or Cloud

ALL TRAFFIC IS PASSING HERE

CoAP client

A) POST
coap://[2001:6a8:1d80:600::24]/toggle

B) OBSERVE
coap://[2001:6a8:1d80:600::22]/s/t

6LoWPAN/RPL border router

802.15.4 WSN

2001:6f8:202:85cc::/64

PUT
Sleeping (push)

Always on (pull)
**Abstraction layer @ GW, Edge or Cloud**

<table>
<thead>
<tr>
<th>ALL TRAFFIC IS PASSING HERE</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SENSOR FUNCTION</strong></td>
</tr>
<tr>
<td><strong>VIRTUALIZATION</strong></td>
</tr>
<tr>
<td><strong>TRAFFIC OPTIMIZATION</strong></td>
</tr>
<tr>
<td><strong>IMPROVED USER INTERACTIONS</strong></td>
</tr>
<tr>
<td><strong>...</strong></td>
</tr>
</tbody>
</table>

| **Offload functionality or implement advanced features (e.g. fine-grained access ctrl)** |
| **Control load in LLN, dynamically adjust network parameters, etc.** |
| **Advanced proxying, payload rewriting, virtual sensors, etc.** |
| **...** |
Adapter example – DTLS termination

User

GET coaps://[aaaa::1]/s/t

Internet

Trusted gateway

WSAN

1

aaaa::/64

ACL

CA

DTLS
Adapter example – DTLS termination

- **Benefits** → Reduced latency

E2E: end-to-end DTLS session between client and WSN node
TER1: terminate DTLS session, new long-lived session with node
TER: terminate DTLS session, reuse long-lived session with node
PLT: plain text (i.e. no DTLS)
Adapter example – DTLS termination

- Benefits ➔ Reduced load in LLN ➔ Reduced energy consumption
Low cost spectrum sensing
RSSI-based Recognition of OFDM technologies

• Motivation
  • An increasing number of OFDM technologies is expected to use the ISM bands (WiFi, LTE-U, …)
  • Little research about cheap (suitable for embedded devices) technology recognition for OFDM technologies

• Example OFDM packet
RSSI-based Recognition of OFDM technologies

- **Observations**
  - Not all OFDM technologies use padding to ensure all subcarriers are filled
  - If subcarriers are not filled, RSSI distributions are impacted
RSSI-based Recognition of OFDM technologies

- Realization
- Detection of technology based on RSSI histogram features
RSSI-based Recognition of OFDM technologies

- **Realization**
- **Possible to differentiate between LTE, DVB-T & WiFi**
  - > 90% detection rate

<table>
<thead>
<tr>
<th>ACT</th>
<th>Wi-Fi</th>
<th>LTE</th>
<th>DVB-T</th>
<th>Noise</th>
<th>Unknown</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wi-Fi</td>
<td>92.6%</td>
<td>1.85%</td>
<td>0%</td>
<td>3.7%</td>
<td>1.85%</td>
</tr>
<tr>
<td>LTE</td>
<td>0%</td>
<td>100%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>DVB-T</td>
<td>0%</td>
<td>1.85%</td>
<td>98.15%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Noise</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>Unknown</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
</tr>
</tbody>
</table>

**Algorithm 1** RSSI-based technology identification

Input: $\overrightarrow{R}$ // a vector of RSSI measurements

Output: sig // the identified signal type

Variables:
- $\overrightarrow{H}$ ← Histogram($\overrightarrow{R}$)
- stddev ← StdDeviation($\overrightarrow{R}$)
- noiseloc ← LocOfLeftmostPeak($\overrightarrow{H}$)
- noisepeak ← AmpOfLeftmostPeak($\overrightarrow{H}$)
- npks ← TotalNumOfPeaks($\overrightarrow{H}$)

Function:

if noiseloc ≤ THR_NL & noisepeak ≥ THR
   if stddev ≥ Wi-Fi.mindev then
      sig ← Wi-Fi
   else
      sig ← noise
   end if
else
   if stddev ≥ (LTE.mindev + DVB-T.maxdev)
      sig ← LTE
   else
      if npks ≤ DVB-T.maxpk then
         sig ← DVB-T
      else
         sig ← unknown
      end if
   end if
end if
Cross-technology communication
MOTIVATION

• Cross-technology coordination of medium access is nearly non-existing
  → Cross-technology interference
  → Degraded performance
  → Non-deterministic behaviour

GOAL

• Investigate the impact of cross-technology interference
  • Setup of interference scenarios
  • Monitoring channel condition
  • Measuring network performance

• Apply network control to avoid interference
  • Sharing of medium access information
  • Changing medium access scheme
  • Using WiSHFUL unified interfaces

The research leading to these results has received funding from the European Horizon 2020 Programme under grant agreement n°645274 (WiSHFUL project).
Legacy (CSMA/CA) operation
collisions between Wi-Fi and sensor nodes
Sensor throughput reduced by factor 4 in case of Wi-Fi interference
CROSS-TECHNOLOGY COORDINATION

• Scenario: coexistence of IEEE-802.11 (green) and IEEE-802.15.4 (grey) networks

[Diagram showing cross-technology synchronization and TDMA schedule on the left, and cross-technology monitoring and channel blacklisting on the right.]
Cross-technology synchronisation and TDMA schedule
Cross technology monitoring and channel blacklisting

- TSCH no Wi-Fi
- TSCH with WiFi interference
- TSCH with WiFi and blacklisting
Testbeds
Experimental facilities

Office environment

Pseudo-shielded environment

HomeLab
UGent LoRa network
Portable testbed: packaging & transport

Multiple flight cases
THANK YOU