Implementation and Performance Evaluation of IEEE 802.15.4k LECIM DSSS PHY at 2.4 GHz

Felix Wunsch | 09/14/2017
Agenda

1. Low Power Wide Area Networks
2. A new GNU Radio module: gr-lpwan
3. IEEE 802.15.4k LECIM DSSS PHY
4. Measurements
5. Conclusion
Low Power Wide Area Networks

Some possible business cases for IoT applications:

- **Transport and logistics**: Fleet management, Goods tracking
- **Utilities**: Smart metering, Smart grid management
- **Agriculture**: Climate/agriculture monitoring, Livestock tracking
- **Environment**: Flood monitoring/alerts, Environmental monitoring (water, air, noise etc.)
- **Industrial**: Process monitoring and control, Maintenance monitoring
- **Consumers**: Wearables, Kids/senior tracker, Medical monitoring
- **Smart buildings**: Smoke detectors, Alarm systems, Home automation
- **Smart cities**: Parking sensors, Smart bicycles, Waste management, Smart lighting

Source: Ericsson
Low Power Wide Area Networks

Common characteristics of many potential applications:

- (Very) low data rates
- Relaxed requirements for latency and reliability
- Strict power and size constraints
- Expected to run on a single battery for up to 15 years without maintenance
Low Power Wide Area Networks

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Those can not be served efficiently by existing wireless technologies!

New paradigm: Low Power Wide Area Networks (LPWAN)

- Usually star topology
- Cell radius of up to 15 km
- Tens of thousands of devices per cell
Low Power Wide Area Networks

Many players with different approaches competing for market shares

- Standardized vs. proprietary technology
- Licensed vs. unlicensed bands
- Spread spectrum vs. (Ultra) Narrow Band
Motivation:

- LPWAN technology is evolving rapidly
- Many open questions, e.g., regarding interference, performance and scalability
- No quantitative comparison between competing technologies available

Goal: Create an open-source testbed to facilitate field tests

First project: IEEE 802.15.4k LECIM DSSS PHY

- Only LPWAN technology using the 2.4 GHz ISM band
- Spreading factor of up to $2^{15} \rightarrow 45$ dB processing gain!
- Compatible to Ingenu’s Random Phase Multiple Access (RPMA)
- Implemented at CEL (KIT) by Kristian Maier (GitHub: @krmaier)
IEEE 802.15.4k LECIM DSSS PHY

**Modulator:** Standard

- **Frame format**

<table>
<thead>
<tr>
<th>Bytes: 0/2/4</th>
<th>0/1</th>
<th>16/24/32</th>
</tr>
</thead>
<tbody>
<tr>
<td>Preamble</td>
<td>SFD</td>
<td>PHY payload</td>
</tr>
</tbody>
</table>

- **Block diagram**

```
Payload ➔ Convolutional FEC ➔ Interleaver ➔ Differential encoder ➔ Binary bit-to-symbol mapper ➔ Gold code ➔ OVSF code ➔ Transmit signal s[k]
```

```
SHR ➔ Differential encoder ➔ Binary bit-to-symbol mapper ➔ Gold code ➔ OVSF code ➔ SHR insertion ➔ BPSK/OQPSK modulation ➔ Transmit signal s[k]
```
IEEE 802.15.4k LECIM DSSS PHY

**Modulator:** GNU Radio / GRC hierarchical block
IEEE 802.15.4k LECIM DSSS PHY

Synchronization:

1. Correlate with spreading sequence
   \[ \varphi_k[l] = \sum_{n=0}^{SF-1} r[n + l] \cdot c^*[n]e^{-j2\pi f_\Delta / f_s \cdot k \cdot n} \]
   2-D search required due to frequency offset

2. Differential decoding: \[ \varphi_{\text{dec},k}[l] = \varphi_k[l] \cdot \varphi_k^*[l + M \cdot SF] \]

3. Correlate with preamble symbols
   \[ \psi_k[l] = \sum_{n=0}^{L_{\text{SHR}}-1} \varphi_{\text{dec}}[l + n \cdot M \cdot SF] \cdot p^*[n] \]

4. Find frame start: \( \hat{l}, \hat{k} = \arg \max_{k,l} |\psi_k[l]| \)

5. Find frequency offset: \[ \hat{f}_o = \hat{k} \cdot f_\Delta + \frac{\angle \psi_k[l]}{2\pi \cdot SF} \]
IEEE 802.15.4k LECIM DSSS PHY

Preamble correlation example: SNR = -16 dB, SF = 1024
IEEE 802.15.4k LECIM DSSS PHY

Receiver: GRC hierarchical block

4 MS/s Matched Filter

Frame Detection, Time & Freq. Sync.

Payload Despreading and DLL

Deinterleaving

Convolutional Decoding

Differential Decoding
IEEE 802.15.4k LECIM DSSS PHY

Transceiver:

```
LPWAN LECIM DSSS OQPSK PHY
Chiprate: 2M
RX Data Goldcode Seed: ...43M
TX Data Goldcode Seed: ...43M
FEC Tailbiting: True
Max. frequency deviation (Hz): 5
OVSF Code Index: 0
OVSF Log Spreading Factor: 0
Preamble Length: 32
RX Preamble Goldcode Seed: 12.34...5k
TX Preamble Goldcode Seed: 54.32...1k
PSDU Length: 32
RRC Roll Off: 1
SFD Present: False
Spreading Factor: 256
Samples Per Symbol: 4
```
Measurements

- Transmitter set up on a high building on KIT campus
- Four different receive locations
  1. 350m distance, Campus, near-LOS, many co-located WiFi APs
  2. 450m distance, Campus, NLOS, many co-located WiFi APs
  3. 2100m distance, Commercial area, NLOS, few WiFi APs
  4. 3800m distance, apartment building, LOS, many uncoordinated WiFi APs
Measurements

Transmitter

Receiver
Measurements

Results for the different receive locations at 2.45 GHz

Configuration:
- 1 MHz bandwidth
- 16 byte payload
- OQPSK modulation
- 5 dBm transmit power
- omnidirectional antennas

Frame Success Rate

<table>
<thead>
<tr>
<th>Location</th>
<th>SF=256</th>
<th>SF=1024</th>
<th>SF=4096</th>
</tr>
</thead>
<tbody>
<tr>
<td>Campus LOS</td>
<td>0.80</td>
<td>0.80</td>
<td>0.80</td>
</tr>
<tr>
<td>Campus NLOS</td>
<td>0.85</td>
<td>0.85</td>
<td>0.85</td>
</tr>
<tr>
<td>Commercial</td>
<td>0.82</td>
<td>0.82</td>
<td>0.82</td>
</tr>
<tr>
<td>Suburban</td>
<td>0.78</td>
<td>0.78</td>
<td>0.78</td>
</tr>
</tbody>
</table>

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IEEE 802.15.4k: Implementation and Evaluation
Measurements

Impact of WiFi interference

(a) Neighboring WiFi APs
(Image: Wifi Analyzer)
Measurements

Impact of WiFi interference

(c) Neighboring WiFi APs
(Image: Wifi Analyzer)

(d) FSRs at the suburban apartment house. WiFi channels 1, 6, 11 at 2412, 2436, and 2462 MHz show severe degradation.
Conclusion

Summary

- New OOT module: gr-lpwan
  - Implements IEEE 802.15.4k LECIM PHYs
    - Complete DSSS PHY including fragmentation sublayer
    - First standards-compliant and open source implementation
    - FSK PHY is WIP
  - Available on GitHub: https://github.com/kit-cel/gr-lpwan
- DSSS PHY field tests in 2.4 GHz ISM band
  - Cross-technology interference can be challenging
  - Large spreading factors needed to overcome shadowing
  - LOS links over many km possible

Outlook

- Investigation and characterization of cross-technology interference
- Investigation of self-interference / MAI effects on the scalability
Thank you for your attention!
Questions?