Internet of Things (IoT): Wide-area IoT protocols*

*Long-range IoT radio access technologies (RATs)

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People-centric IoT applications and services

CONSUMER context

- Personalized advertisements
- Wearable camera
- AR glasses
- Smart watch
- Smart commuting
- Social discovery
- Pet tracking

INDUSTRIAL context

- Mission-critical alerts
- Smart tracking
- Health monitoring
- Smart logistics
Features of long-range IoT radio access technologies (RATs)

- Massive amount of connected devices (we currently talk about ~0.01-10 devices per square meter)
- Specific traffic characteristics
- Stringent requirements of the end devices
  - Energy consumption / battery lifetime
  - Communication range
  - Simplicity of the solution / low cost
- Therefore, we end up designing dedicated RATs for IoT, preferably, long-range.
Historical insights..

- Originally, there was no common understanding that dedicated technologies are needed.

- Approach 1: Let machines talk “conventional” Wi-Fi
- Approach 2: Let machines talk “conventional” LTE

- Below, we discuss, why this idea is not nice at all 😊
Approach 1 motivation (Conventional Wi-Fi for IoT)

- Mitigate technology fragmentation by *reusing existing deployments*
Problem statement

- Wi-Fi – *de-facto* technology for WLANs
- Expected to *minimize time-to-market* for various MTC applications
- *Assessing* their *performance* is important

Network architecture

Cloud environment. MTC services

Ethernet

Fiber optics

AP1

AP2

WiFi

Ethernet

Router

MTC cluster

Human-oriented cluster
Challenges

- Application challenges
  - Small burst transmissions
  - Large number of devices
  - Tight battery budget

- Technology challenges
  - Contention-based access
  - High signaling overhead
Assessment methodology

References

- IEEE 802.11 Conventional Model
- 802.16 M2M Technical Report
- Internet of Things SRA

Expected number of MTC devices

Maximum number of MTC devices

Application assessment

IEEE 802.11 Test Bench

Goodput estimation technique

PER

Goodput estimation

Goodput

Maximum number of MTC devices calculation
IEEE 802.11 test bench

Measurement of PER
1. MTC aware use case
2. State-of-the-art technology
3. Saturated queues
4. Two signaling schemes

Open-source driver: \textit{ath9k}
- Manual rate control
- No retries (genuine statistics)
PER measurements

Basic scheme

- RTS/CTS scheme

- Realistic levels of PER estimated
**Optimistic scenario:**
- Full-buffer traffic
- Single link
- Fixed data rate
- Maximum power

$$S = \frac{8 \cdot l_{data} \cdot (1 - p_e)}{(\frac{W_0}{2} \cdot t_{slot} + t_s) \cdot (1 - p_e) + t_e \cdot p_e \cdot \frac{p_e^{N-1}}{p_e - 1} + W_0 \cdot t_{slot} \cdot p_e \cdot \frac{(2 \cdot p_e)^{N-1}}{2 \cdot p_e - 1}}$$

$$S^* = \frac{8 \cdot l_{data} \cdot (1 - p_e)}{(\frac{W_0}{2} \cdot t_{slot} + t_s + t_h) \cdot (1 - p_e) + (t_e + t_h) \cdot p_e \cdot \frac{p_e^{N-1}}{p_e - 1} + W_0 \cdot t_{slot} \cdot p_e \cdot \frac{(2 \cdot p_e)^{N-1}}{2 \cdot p_e - 1}}$$
Goodput estimation

Basic scheme

Semi-analytical model verified

Goodput accuracy

Acceptable accuracy level

$$Pr\{S \notin \left( \frac{8 \cdot l_{data}}{d_b + \sigma_b/3}; \frac{8 \cdot l_{data}}{d_b - \sigma_b/3} \right) \leq \frac{9}{M} \approx 10^{-8}$$
Reference MTC device

<table>
<thead>
<tr>
<th>A typical MTC device</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traffic rate</td>
</tr>
<tr>
<td>Message size</td>
</tr>
</tbody>
</table>

Deployment requirements

- Wi-Fi coverage area ~50 meters
- ~200 MTC devices per cluster

Conventional system

- Scales poorly
- Too much overhead
Aggregation techniques

- **MAC layer aggregation**
  - Defined by IEEE 802.11-2007
  - Defined by IEEE 802.11n-2009

- **PHY layer aggregation**
  - Defined by IEEE 802.11-2007
  - Defined by IEEE 802.11n-2009

*Defined by IEEE 802.11-2007*
Aggregation results (asymptotic)

Potential for some improvement

Table of expected number of MTC devices vs. aggregation threshold (bytes)
Numerical results (optimistic)

Scalable MTC support is challenging.

<table>
<thead>
<tr>
<th>Data rate (Mbps)</th>
<th>No aggregation</th>
<th>Aggregation at MAC layer</th>
<th>Aggregation at PHY layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>8</td>
<td>25</td>
<td>55</td>
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<tr>
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<td>8</td>
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<td>40</td>
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<tr>
<td>54</td>
<td>10</td>
<td>40</td>
<td>314</td>
</tr>
</tbody>
</table>

**TABLE II**

Maximum supported number of MTC devices. RTS/CTS scheme

<table>
<thead>
<tr>
<th>Data rate (Mbps)</th>
<th>No aggregation</th>
<th>Aggregation at MAC layer</th>
<th>Aggregation at PHY layer</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
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<tr>
<td>54</td>
<td>7</td>
<td>39</td>
<td></td>
</tr>
</tbody>
</table>
Approach 1. Major conclusions

- Main results
  - Conventional IEEE 802.11-2007 scales poorly for MTC
  - IEEE 802.11n-2009 aggregation looks promising, but still non-sufficient
Approach 2. Use “conventional” LTE for IoT.

System topology

- Aggregated traffic (M2M applications)
  - Traffic analysis (numerous devices)
    - Performance metrics analysis
      - Throughput
      - Mean delay
      - Energy efficiency

- Target:
  - Performance evaluation

- Challenges
  - Overload protection
  - Energy efficiency
  - Small data transmission

Approach 2. Use “conventional” LTE for IoT.
Approach 2. Initial network entry

Traffic arrival

Scheduling opportunity

Scheduling request

Scheduling grant (SG)

Data transmission

Scheduling opportunity

UE

eNodeB

Traffic arrival

Ramping failure

Ramping failure

Msg1: Preamble

Collision

Msg1: Preamble retransmission

RAR Rx + processing

SG Rx + processing

Response window + backoff window

Delay

Periodicity+

UE

eNodeB

Traffic arrival

RAR Rx + processing

Msg2: Random access response (RAR)

Msg3: Layer 3 message

Msg4: Contention resolution identity

Delay
LTE RACH model

Specialty:
- dependant queues
- ~30000 sources
- 54 preambles

Metrics (closed-form approximation)
- throughput
- energy expenditure
- energy efficiency
Delay is too high for all the schemes...
Approach 2 numerical results (2)

- Energy efficiency is too low for all the schemes...

![Individual power consumption, mW vs Number of MTC devices graph]

- PUCCH
- PRACH
- COBALT
- Theory
Approach 2. Major conclusions

- Main results
  - Conventional LTE scales poorly for MTC
  - LTE-Advanced with certain channel access enhancements scales better, but still not sufficient
Therefore, novel IoT-specific radio access technologies are proposed

- **Due to the abovementioned limitations of “conventional” RATs for IoT, novel IoT-specific radio access technologies were proposed**

- **These are, including but not limited to:**
  - **SIGFOX**
  - **LoRaWAN**
  - **IEEE 802.11ah (branded as Wi-Fi HaLow)**
  - **NB-IoT (roughly, IoT version of LTE)**
SIGFOX

- Band: SubGHz ISM
  - Carrier: 868 MHz
- Rate: 100 bps uplink
  - 600 bps downlink
- Tx power: 14 dBm
- Link budget: 156 dB
- Range: over 30 km
- Devices in a cell: millions
- Chipset price: 2-5 EUR
- Features:
  1) Single MCS
  2) Multi-channel ALOHA MAC
LoRaWAN

**Band:** SubGHz ISM
**Carrier:** 433/868 MHz

**Rate:** 293-50 000 bps
**uplink/downlink**

**Tx power:** up to 20 dBm
**Link budget:** 117-156 dB
**Range:** over 30 km

**Devices in a cell:** millions

**Chipset price:** 2-5 EUR

**Features:**
1) 8 MCSs
2) Multi-channel ALOHA MAC
Wi-Fi HaLow (IEEE 802.11ah)

- **Band:** SubGHz ISM
- **Carrier:** 868 MHz
- **Rate:** 150-7 800* kbps
  *Single spatial stream*
- **Tx power:** up to 14 dBm
- **Link budget:** 72-115 dB
- **Range:** up to 1 km
- **Devices in a cell:** up to 8192
- **Chipset price:** 4-8 EUR
- **Features:**
  1) Over 30 MCSs
  2) OFDM
Narrow band IoT (NB-IoT)

**NB-IoT**

- **Band**: licensed UHF
- **Carrier**: 0.7-2.1 GHz
- **Rate**: 20-250K bps uplink
  - 35-226 700 bps downlink
- **Tx power**: up to 20 dBm
- **Link budget**: < 164 dB
- **Range**: over 30 km
- **Devices in a cell**: millions
- **Chipset price**: 2-5 EUR
- **Features**:
  1) Over 10 MCSs
  2) OFDM / SC-FDMA
Motivation to go lower in carrier and bandwidth

- Why do we move from 2.4GHz to 900MHz?

- Why do we move from 5MHz channel bandwidth in LTE to 180kHz channel bandwidth in NB-IoT?
Motivation to go lower in carrier and bandwidth

- **Why do we move from 2.4GHz to 900MHz?**
  
  **Answer:** lower path loss -> greater comm. range

- **Why do we move from 5MHz channel bandwidth in LTE to 180kHz channel bandwidth in NB-IoT?**
Motivation to go lower in carrier and bandwidth

- Why do we move from ~2GHz to ~900MHz?
  
  **Answer:** lower path loss -> greater comm. range

- Why do we move from 5MHz channel bandwidth in LTE to 180kHz channel bandwidth in NB-IoT?
  
  **Answer:** higher Tx power spectral density -> greater comm. range
Long-range IoT technologies comparison

Diagram showing the comparison of various IoT technologies such as SIGFOX, LoRaWAN, Wi-Fi HaLow, and NB-IoT. The diagram compares parameters like bandwidth, cell range, carrier band, devices per cell, chipset price, and years in deployment.
Long-range IoT RATs vs short-range IoT RATs

- **Long-range strengths:**
  - More devices connected to a single access point -> economical gains
  - Greater communication range -> more applications/services supported
  - ...

- **Short-range strengths:**
  - Ability to control/modify internal parameters and the topology -> Greater level of flexibility
  - Shorter communication range -> higher security
  - ...