Performance of NB-IoT

The technology that aims to reach the 5G-IoT requirements

Wednesday, December 1st, 2021

Romain Barbau
Agenda

01 NB-IoT Context : 5G & IoT

02 NB-IoT Inside the Communication Procedure

03 Our Model

04 Performance Evaluation
Internet of Things
IoT
An emblematic use case: The Connected Cow
**Evolution of Cellular Technologies**

1991

- **GSM (2G):**
  - Global System for Mobile communications
  - Perfect for «Voice» type communication

2000

- **UMTS (3G):**
  - Universal Mobile Telecom System
  - From F/TDMA to W-CDMA
  - Frequency re-use + bitrate

2010

- **LTE (4G):**
  - Long Term Evolution
  - From W-CDMA to OFDMA (DL) and SC-FDMA (UL)
  - 3 times more spectral efficiency and so + bitrate
  - Flexibility in the allocation of bandwidth for a cell.

**NB-IoT Context**
GSM (2G): Global System for Mobile communications
- Perfect for « Voice » type communication

UMTS (3G): Universal Mobile Telecom System

LTE (4G): Long Term Evolution
- From W-CDMA to OFDMA (DL) and SC-FDMA (UL)
- 3 times more spectral efficiency and so + bitrate
- Flexibility in the allocation of bandwidth for a cell.

Sigfox: Non-3GPP

LoRa(WAN): Non-3GPP

Evolution of Cellular Technologies

1991

2000

2010

2013 2014

Rel. 13 2016

Rel. 15 2018

LTE-M

NR (5G)

3GPP

NB-IoT

3GPP

NB-IoT Context
**NB-IoT Context**

**NB-IoT Objectives**

**IoT Key Metrics**

- Low Data rate
- Low Battery
- Latency non-sensitive
- High concentration of devices
- Wide Coverage

- Playing on both metrics
- 10 years on 4AA batteries
- 1 million devices per km²
- +20dB coverage compared to LTE
- +14dB compared to GSM

(5) TR 45.820
(6) IMT-2020
How does 3GPP foresee the IoT in the future 5G ecosystem?
<table>
<thead>
<tr>
<th>01</th>
<th>NB-IoT Context : 5G &amp; IoT</th>
</tr>
</thead>
<tbody>
<tr>
<td>02</td>
<td>NB-IoT Inside the Communication Procedure</td>
</tr>
<tr>
<td>03</td>
<td>Our Model</td>
</tr>
<tr>
<td>04</td>
<td>Performance Evaluation</td>
</tr>
</tbody>
</table>
PHY Layer

→ Same as LTE
But with a narrower transmission bandwidth = more power per symbol (increase the coverage)
MAC Layer and Communication Procedure
Communication Procedure with connection

1. Random Access Preamble
2. Random Access Response
3. RRC-ConnectionRequest
4. RRC-ConnectionSetup
5. RRC-ConnectionSetupComplete
6. RRCConnectionRelease
Channels

- **NPBCH**: Broadcasts info for system access.
- **NPCCH**: Control. UL and DL scheduling info.
- **NPSCH**: Shared. Dedicated and common Data.
- **NPSS/NSSS**: time and frequency synchronization.

**Downlink Carrier**

1 ms

180 kHz

**Uplink Carrier**

1 ms

180 kHz
Communication Procedure

Downlink Carrier

180 kHz
1 ms

Uplink Carrier

180 kHz

Connection Establishment

Message 1: Preamble
DL Grant
Message 2: RAR
Connection Request
DL Grant
Message 3: RRC
Connection Setup
UL Grant
Message 4: RRC
Setup Request
Message 5: RRC

NB-IoT Insides
**Communication Procedure**

**Downlink Carrier**
- 1 ms
- 180 kHz

**Uplink Carrier**
- 180 kHz

**Data Report**
- UL Grant
- Data + buffer status
- UL Grant
- Data
- UL Grant
- Data
- ...
Communication Procedure

Downlink Carrier

Uplink Carrier

End of Connection

DL Grant

Message 6: RRC Connection Release

NB-IoT Insides
## Message Exchanges during Connection Establishment, Data Report and Connection Termination

<table>
<thead>
<tr>
<th>Channel</th>
<th>Message</th>
<th>Payload Size (bits)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Uplink</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Connection establishment</td>
<td>Message 1: Preamble</td>
<td>92 bits</td>
</tr>
<tr>
<td>NPDCCH</td>
<td>Downlink Grant</td>
<td>531 bits</td>
</tr>
<tr>
<td>NPUSCH</td>
<td>Message 2: Random Access Response</td>
<td>-</td>
</tr>
<tr>
<td>NPDCCH</td>
<td>Message 3: RRC Connection Request</td>
<td>-</td>
</tr>
<tr>
<td>NPDSCH</td>
<td>Downlink Grant</td>
<td>-</td>
</tr>
<tr>
<td>NPUSCH</td>
<td>Message 4: RRC Connection Setup</td>
<td>-</td>
</tr>
<tr>
<td>NPDCCH</td>
<td>Uplink Grant</td>
<td>-</td>
</tr>
<tr>
<td>NPUSCH</td>
<td>Message 5: RRC Setup Complete</td>
<td>128</td>
</tr>
<tr>
<td></td>
<td>Additional Signalling</td>
<td>≈344</td>
</tr>
<tr>
<td>Releasing</td>
<td>Message 6: RRC Connection Release</td>
<td>92 bits</td>
</tr>
<tr>
<td>NPDCCH</td>
<td>Downlink Grant</td>
<td>531 bits</td>
</tr>
<tr>
<td>NPUSCH</td>
<td>RRC Connection Release</td>
<td>-</td>
</tr>
</tbody>
</table>

### Connection Overhead

- **NPDCCH**: 92 bits + data grant
- **NPDSCH**: 1458 bits + data block
- **NPUSCH**: 531 bits + data block

1 million devices per km²
Agenda

01. NB-IoT Context: 5G & IoT
02. NB-IoT Inside the Communication Procedure
03. Our Model
04. Performance Evaluation
How to compute the capacity in terms of terminal per km²?

→ 3GPP methodology:
  • Traffic definition (payload size, communication interval)
  • Coverage definition (SINR distribution and cell area)
  • Set a number N of device in the cell
  • Implement an algorithm to compute the reliability $r$
  • If $r > 0.99$ : increase N
  • else: decrease N
  • Loop until r matches 0.99
  • Compute capacity
Modelling the use of time/frequency resources

<table>
<thead>
<tr>
<th>Contention Phase</th>
<th>Congestion Phase</th>
</tr>
</thead>
<tbody>
<tr>
<td>Poisson arrivals on slots</td>
<td>Each UE demand is composed of resource blocks assigned to the different contention-free queues. If the sojourn time exceeds impatience on one of the blocks, the demand is dropped.</td>
</tr>
</tbody>
</table>

Outputs:

- Collision and Congestion probabilities $\Rightarrow$ reliability
Found in literature [2] – M/M/1-FIFO with impatience
- Exponential arrivals - M
- Exponential services - M
- FIFO

What we proposed – M/D/1-PS with impatience
- Exponential arrivals - M
- Deterministic services - D
- Processor Sharing - PS

Idea: we use an approximation for the impatience probability
Impatience Rates

Our Model

Graph showing the relationship between Impatience Rate (τq) and the Load of the System (ρ). The graph includes three curves:
- M/D/1/PS our approximation for Impatience
- M/M/1 with Impatience from [31]
- M/D/1/PS Impatience simulation
Ideas:
- several servers
- each communication can be segmented in $n$ blocks

What we did next – M/D/H/K
- Exponential arrivals - M
- Deterministic services - D
- Several subcarriers/servers - H
- A queue with a limited size - K

Our Model

$block_i$

$block_{i+1}$

$block_{i+K-1}$

Exponential arrivals - M
Deterministic services - D
Several subcarriers/servers - H
A queue with a limited size - K

$n$ times
We know the duration of a block so we know when the new blocks will be served and can compute the impatience rate $\tau$. 

Our Model
Benefits of using M/D/H/K:

• Avoid modelling the possibility of zero useful traffic
• Compute the impatience probability
• Precision – knowing how many blocks have been served
### Agenda

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</tr>
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<tbody>
<tr>
<td>01</td>
<td>NB-IoT Context : IoT &amp; 5G</td>
</tr>
<tr>
<td>02</td>
<td>NB-IoT Insides : PHY &amp; MAC layers</td>
</tr>
<tr>
<td>03</td>
<td>C-IoT optimizations</td>
</tr>
<tr>
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<td>Performance Evaluation</td>
</tr>
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</table>
Traffic and Cell definition

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Payload UL/DL</td>
<td>32 bytes / 0 bytes</td>
</tr>
<tr>
<td>Communication Interval</td>
<td>2 hours</td>
</tr>
<tr>
<td>Cell Radius - r</td>
<td>500 meters</td>
</tr>
</tbody>
</table>
## Performance according our model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication per second r=0.99</td>
<td>22.05</td>
</tr>
<tr>
<td>Capacity per carrier</td>
<td>182,900 devices/km²</td>
</tr>
<tr>
<td>Nb of carrier needed to reach 5G-IoT requirements</td>
<td>6</td>
</tr>
<tr>
<td>Total bandwidth needed</td>
<td>2,160 kHz</td>
</tr>
</tbody>
</table>
User Plane Optimization
Sequence Diagram

**Classic - LTE**

1. Random Access Preamble
2. Random Access Response
3. RRC-ConnectionRequest
4. RRC-ConnectionSetup
5. RRC-ConnectionSetupComplete
   - Additional Signaling
6. RRCConnectionRelease
   - UL and DL data

**User Plane Optimization**

1. Random Access Preamble
2. Random Access Response
3. Msg3 = RRC-ConnectionResumeRequest
4. Msg4 = RRC-ConnectionResume
5. Msg5 = RRC-ConnectionResumeComplete
   - UL data
   - More UL and DL data
6. RRCCConnectionRelease

**Performance Evaluation**

- Terminal
- Base station

- Terminal
- Base station
Performance according our model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication per second $r=0.99$</td>
<td>61.95</td>
</tr>
<tr>
<td>Capacity per carrier</td>
<td>515 000 devices/km²</td>
</tr>
<tr>
<td>Nb of carrier needed to reach 5G-IoT requirements</td>
<td>2</td>
</tr>
<tr>
<td>Total bandwidth needed</td>
<td>720 kHz</td>
</tr>
</tbody>
</table>
Early Data Transmission

Or the ultimate way to reduce connection overhead
**User Plane Optimization**

1. Random Access Preamble
2. Random Access Response
3. Msg3 = RRC-ConnectionResumeRequest
4. Msg4 = RRC-ConnectionResume
5. Msg5 = RRC-ConnectionResumeComplete
   + UL data
   More UL and DL data
6. RRCConnectionRelease

**Early Data Transmission**

1. Random Access Preamble
2. Random Access Response
3. Msg3 = RRC-ConnectionResumeRequest
4. Msg4 = RRC-Conn.Release or RRC-Conn.Resume]
   + DL data
   UE goes back to idle if indicated in Msg4
5. Msg5 = RRC-ConnectionResumeComplete
   + UL data
   More UL and DL data
6. RRCConnectionRelease
Performance according our model

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication per second $r=0.99$</td>
<td>139.5</td>
</tr>
<tr>
<td>Capacity per carrier</td>
<td>1 159 800 devices/km$^2$</td>
</tr>
<tr>
<td>Nb of carrier needed to reach 5G-IoT requirements</td>
<td>1</td>
</tr>
<tr>
<td>Total bandwidth needed</td>
<td>360 kHz</td>
</tr>
</tbody>
</table>
5G and IoT

Access technologies addressing different IoT areas

- Dual-mode 5G Cloud Core
- 5G architecture options:
  - Option 1
  - Option 3 (NSA)
  - Option 2 (SA)

- 5G RAN
  - NB-IoT
  - LTE-M
  - LTE
  - NR

Performance Evaluation

Critical IoT
- Bounded latencies
- Ultra-reliable data delivery
- Ultra-low latency

Broadband IoT
- High data rates
- Large data volumes
- Low latency (best effort)

Massive IoT
- Low-cost devices
- Small data volumes
- Extreme coverage

https://www.ericsson.com/
Overview of our other research activities

Or the teasing of the thesis defence
I. Deep study on the limitation of NB-IoT capacity
Thank you