Introduction to “Clean-Slate” Cellular IoT radio access solution

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Introduction and motivation

- There is a huge opportunity for Mobile Network Operators to exploit the emerging IoT market, including the mass volume, low data rate segment.

- However, this opportunity is critically dependent on achieving the following:
  - Much lower terminal cost compared with GPRS
  - Vastly improved battery life versus GPRS
  - Enhanced indoor coverage versus GPRS

- Otherwise much of the potential market for Cellular IoT will be absorbed by PAN technologies (WiFi, Zigbee, Bluetooth Smart) and proprietary WAN systems.

- Although an evolution of LTE might appear initially attractive due to a convenient standardisation path, it will most likely prove impossible to meet these objectives.
  - This is due to its starting point as a very high data rate broadband delivery system.

**What is needed is an optimised solution for Cellular IoT that can be deployed using existing cellular infrastructure.**
Key features of clean-slate solution

- **IoT network can be deployed in a very small bandwidth** (180 kHz downlink, 180 kHz uplink)
  - Offers a wide range of deployment options
  - Capacity for huge numbers of terminals per cell (tens of thousands)
  - Modulation methods minimise coexistence issues with adjacent bands

- **Optimized for ultra-low terminal cost** (< $4 ASP)
  - Designed from the ground-up to deliver the required performance for IoT at very low cost
  - Removes unnecessary complexity and legacy overhead
  - Simple air-interface should greatly reduce IPR licensing costs compared with LTE

- **Optimised for very long terminal battery life** (10 years feasible in many scenarios)
  - Efficiently supports very low duty cycle modes
  - Supports both scheduled and event driven traffic
  - Single-carrier modulation allows high efficiency, high power transmitters (similar to GPRS)

- **Extended coverage compared with existing cellular** (20 dB enhancement)
  - Provides deep indoor penetration
  - Very flexible trade-off between data rate and link budget
Downlink channelization

- Each 180 kHz resource block is split into 12 downlink channels, spaced by 15 kHz
  - Conceptually similar to OFDM
  - Allows access through FDMA and TDMA
  - Trivial equalisation at receiver
  - One downlink channel is reserved for synch / broadcast for efficient network acquisition

- Each basestation sector can be assigned a subset of downlink channels
  - Supports very flexible frequency re-use
  - Allows frequency diversity through hopping

- Channels are individually modulated (BPSK, QPSK, 16QAM) and pulse-shaped to minimise spectral side-lobes
  - Reduces coexistence issues with adjacent systems

- Maximum PHY data rate per channel is 36 kbps; minimum PHY data rate per channel is 375 bps
Uplink channelization

- Each 180 kHz resource block is split into 36 uplink channels, spaced by 5 kHz
  - Conceptually similar to OFDMA
  - Allows access through FDMA and TDMA
  - Provides high uplink capacity and very flexible frequency re-use
- Uplink channels are individually modulated and pulse-shaped to minimise inter-user interference
  - Avoids feedback loops for frequency correction or timing advance, unlike OFDMA or SC-FDMA
- Modulation is (D)QPSK, (D)BPSK or GMSK
  - Very low or zero PAPR, for high transmitter efficiency (similar to GPRS)
- Uplink channels may be bonded by x2, x4 or x8
- Maximum PHY data rate per bonded channel is 45 kbps; minimum PHY data rate per channel is 250 bps
Deployment in GSM sub-carrier

Licensed by Mobile Network Operator (e.g. GSM850 or GSM900)

Multiple GSM sub-carriers, with 200 kHz spacing

M2M network is deployed in a single re-farmed GSM sub-carrier

Each single-carrier is individually pulse-shaped to avoid spectral spillage

Can also be deployed in left-over spectrum following 2G/3G re-farming

Implemented as FDD, i.e. with M2M downlink in GSM downlink sub-carrier group

Single-carrier, pulse-shaped modulation avoids spectral side-lobes so minimises co-existence issues
Deployment in LTE guard bands

More challenging than deployment in GSM carriers, due to co-existence issues, but effective mitigation strategies are being studied.

M2M network is deployed in LTE guard bands

Each single carrier is individually pulse-shaped to avoid spectral spillage

Use of both guard bands provides frequency diversity

LTE Physical Resource Blocks (50 PRB x 180 kHz in 10 MHz)

Licensed by Mobile Network Operator in LTE700, LTE800 or LTE900

9MHz occupied by OFDM Resource Elements

LTE in adjacent channel

Power

Frequency (MHz)
## 20 dB coverage enhancement

<table>
<thead>
<tr>
<th>Cellular IoT link budget</th>
<th>Downlink</th>
<th>Uplink</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(0) Total Tx power (dBm)</td>
<td>43</td>
<td>23</td>
</tr>
<tr>
<td>(1) Tx power per channel (dBm)</td>
<td>32.2</td>
<td>23</td>
</tr>
<tr>
<td>Receiver</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(2) Thermal noise density (dBm/Hz)</td>
<td>-174</td>
<td>-174</td>
</tr>
<tr>
<td>(3) Receiver noise figure (dB)</td>
<td>9</td>
<td>5</td>
</tr>
<tr>
<td>(4) Interference margin (dB)</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(5) Occupied channel bandwidth (kHz)</td>
<td>12</td>
<td>3.75</td>
</tr>
<tr>
<td>(6) Effective noise power = (2) + (3) + (4) + 10 log((5)) (dBm)</td>
<td>-124.2</td>
<td>-133.3</td>
</tr>
<tr>
<td>(7) Required SINR (dB)</td>
<td>-4.7</td>
<td>-5.0</td>
</tr>
<tr>
<td>(8) Receiver sensitivity = (6) + (7) (dBm)</td>
<td>-128.9</td>
<td>-138.3</td>
</tr>
<tr>
<td>Maximum coupling loss (MCL) = (1) – (8) (dB)</td>
<td><strong>161.1</strong></td>
<td><strong>161.3</strong></td>
</tr>
</tbody>
</table>

Simulation parameters:
- Uplink is GMSK, 1/3 code rate, x4 spreading/repetitions, 1T2R
- Downlink is BPSK, 1/2 code rate, x16 spreading/repetitions, 1T1R
- Channel model is 3GPP EPA 1 Hz
- Base station Tx power is same as typical GSM
- UE Tx power is +23 dBm, so typical of a low cost terminal
- Base station and UE receiver noise figures are taken from 3GPP specs to allow a fair comparison with GSM and LTE

From 3GPP 36.888:
- GSM MCL is 139.4 dB
- LTE MCL is 140.7 dB

20 dB coverage enhancement is achieved versus LTE/GSM specs
Cell capacity analysis
Served uplink users per hour per 180 kHz

- Shows number of users served with 100 byte uplink payload per 180 kHz per hour
- Assumes 9 uplink channels (so frequency re-use is ¼ to mitigate inter-cell interference)
- Terminal transmit power is +23 dBm with -4 dB antenna gain
- Base station noise figure is 4 dB with +14 dB antenna gain
- 3GPP macro cell path loss model plus 0, 20, 30 or 40 dB indoor penetration loss
- 6 dB margin for modulation rate adaption relative to theoretical SNR threshold
Cell coverage analysis
Percentage users that can be reached

- Shows percentage of terminals that can be reached, assuming uniform density.
- Modelling assumptions are the same as for the Cell Capacity Analysis slide.
- Minimum uplink data rate is set as:
  - 250 bps = 32 bytes/sec (raw PHY rate after FEC)
  - ~20 bytes/sec after overheads
- Terminals that cannot support this minimum data rate are considered to be not covered.

![Cell coverage analysis graph](image)

- 3GPP macro cell model + 20 dB penetration loss
- 3GPP macro cell model + 40 dB penetration loss
- 1732m inter-site distance

0 dB 20 dB 30 dB 40 dB
Power consumption analysis

<table>
<thead>
<tr>
<th>Coverage enhancement vs. GSM</th>
<th>Battery life for 5 Wh capacity</th>
<th>Assumptions</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Report = 20 bytes uplink, 20 bytes downlink</td>
<td>+23 dBm transmit power at 33% efficiency</td>
</tr>
<tr>
<td></td>
<td>4 reports/hour</td>
<td>1 report/hour</td>
</tr>
<tr>
<td>GSM + 0 dB</td>
<td>&gt; 10 years</td>
<td>&gt; 10 years</td>
</tr>
<tr>
<td>GSM + 10 dB</td>
<td>4 years</td>
<td>&gt; 10 years</td>
</tr>
<tr>
<td>GSM + 20 dB</td>
<td>0.5 years</td>
<td>2 years</td>
</tr>
</tbody>
</table>

Assumptions:
- Voltage (V): 3.3
- Tx: +23dBm (mA): 180
- Rx (mA): 30
- Idle/sleep (mA): 0.005

- 10 years battery life is achievable depending on required coverage enhancement and reporting interval, assuming a 5 Wh battery capacity
- For extreme coverage (GSM + 20 dB), reporting interval must be quite low or battery capacity must be increased to achieve 10 year battery life
Module cost analysis

Estimated module ASP is ~ $4

- Based on 2016 costs, including margin

Assumes single-chip RF/BB IC

- 700-960 MHz transceiver
- Integration level comparable with low cost PAN technologies (< 10 mm² on 65 or 90 nm)
- Software defined modem for flexibility, given low data rates
- Embedded flash and OTP
- Integrated secure element
- Integrated power management
- Ability to execute 3rd party application code and to interface directly to sensors

<table>
<thead>
<tr>
<th>eBOM</th>
<th>2016 Estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single chip RF/BB (incl. margin)</td>
<td>$ 0.95</td>
</tr>
<tr>
<td>RF FEM</td>
<td>$ 0.50</td>
</tr>
<tr>
<td>26MHz XO</td>
<td>$ 0.20</td>
</tr>
<tr>
<td>32kHz XO</td>
<td>$ 0.12</td>
</tr>
<tr>
<td>RF filter</td>
<td>$ 0.15</td>
</tr>
<tr>
<td>Other discretes</td>
<td>$ 0.25</td>
</tr>
<tr>
<td><strong>Total eBOM</strong></td>
<td><strong>$ 2.17</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Mechanical, Assembly &amp; Test</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>PCB (4 layer FR4, 175mm²)</td>
<td>$ 0.13</td>
</tr>
<tr>
<td>Shield</td>
<td>$ 0.04</td>
</tr>
<tr>
<td>Assembly</td>
<td>$ 0.45</td>
</tr>
<tr>
<td>Test</td>
<td>$ 0.10</td>
</tr>
<tr>
<td>Yield loss (2%)</td>
<td>$ 0.06</td>
</tr>
<tr>
<td>Packaging/labelling</td>
<td>$ 0.10</td>
</tr>
<tr>
<td>CEM margin (5%)</td>
<td>$ 0.17</td>
</tr>
<tr>
<td><strong>Total ex-works price</strong></td>
<td><strong>$ 3.23</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>OEM value-added</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Freight (shipped)</td>
<td>$ 0.20</td>
</tr>
<tr>
<td>Allowance for swap/RMA (2%)</td>
<td>$ 0.07</td>
</tr>
<tr>
<td>OEM margin (10%)</td>
<td>$ 0.37</td>
</tr>
<tr>
<td><strong>Total expense to MNO or VAR</strong></td>
<td><strong>$ 3.87</strong></td>
</tr>
</tbody>
</table>
Summary

- The proposed clean-slate radio access technology offers some key benefits:
  - IoT network can be deployed in a small bandwidth (180 kHz x 2)
  - Optimised for ultra-low terminal module cost (< $4 ASP)
  - Optimised for very long terminal battery life (10 years is feasible in many scenarios)
  - Extended coverage compared with existing cellular (20 dB enhancement)

- These benefits are very hard to achieve through the evolution of existing cellular radio access technologies
  - Because the IoT requirements are so different from mobile broadband / voice
  - And existing systems require too much legacy support and performance compromise

- Deployment options include re-farming of GSM sub-carriers, LTE guard bands, and left-over fragments of spectrum during re-farming of 2G/3G to 4G

- Proposed standardisation route is through 3GPP GERAN (see “study item description” submitted by Vodafone to the recent GERAN meeting in Valencia, which was approved)