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

The Cellular IoT White Paper demonstrates that there is a huge opportunity for Mobile Network Operators to exploit the emerging IoT market.

However, this opportunity is critically dependent on achieving the following:

- Ultra-low cost terminals (module cost less than $5)
- Battery life of > 10 years (assuming 100 bytes/hour uplink)
- 20 dB extended link budget versus existing cellular technologies to ensure reliable coverage into difficult locations

An inability to meet these objectives will result in much of the potential market for Cellular IoT being absorbed by alternative technologies such as WiFi, Zigbee, Bluetooth Smart and proprietary 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 simply due to the inevitable overheads and inefficiencies that will result from trying to adapt a very high data rate broadband delivery system to support low data rate IoT applications.

What is needed is an optimised solution for Cellular IoT that can be deployed using existing cellular infrastructure, and which is superior to alternative technologies for a large segment of IoT applications.
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, whilst supporting a huge number of terminals per cell (tens of thousands)
  - Modulation methods chosen specifically to minimise potential coexistence issues with technologies operating at adjacent frequencies

- **Optimized for ultra-low terminal cost** (< $5)
  - Designed from the ground-up to deliver the required performance for IoT at very low cost
  - Removes unnecessary complexity that is not required for IoT applications
  - Simple air-interface should greatly reduce potential IPR licensing costs
  - No cost overhead due to legacy

- **Optimised for very long terminal battery life** (> 10 years)
  - Efficiently supports very low duty cycle modes, while terminals remain “connected” to network
  - 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)
  - Supports higher data rates where path loss permits, but can configure cell-edge terminals for much lower data rates to increase processing gain and hence improve link budget
Downlink channelization

- Each 180 kHz resource block is split into 12 downlink channels, spaced by 15 kHz
  - Allows access through FDMA and TDMA
  - One downlink channel is reserved for synch / broadcast for efficient network acquisition
- Each basestation sector can be assigned a subset of downlink channels
  - Supports flexible frequency re-use
  - Allows frequency diversity through frequency hopping
- Downlink channels are individually modulated and pulse-shaped to minimise spectral side-lobes
  - Reduces coexistence issues with adjacent systems
  - Receiver equalisation is simple (single-carrier, with low bandwidth)
- 3 dB bandwidth for each channel is 12 kHz
  - Modulation is 16QAM, QPSK and BPSK
  - Spreading / repetition for processing gain
  - Coding is convolutional to minimise terminal receiver complexity
Uplink channelization

- Each 180 kHz resource block is split into many uplink channels
  - 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
- 3 dB bandwidth for each channel is 2 kHz or 3.75 kHz
  - Modulation is (D)QPSK, (D)BPSK or GMSK
  - Very low or zero PAPR, for high transmitter efficiency (similar to GPRS/EDGE)
  - Spreading / repetition for processing gain
  - Coding is convolutional or turbo, depending on burst type
- Uplink channels may be bonded by x2, x4 or x8
  - Still single-carrier, but provides higher uplink data rates when path loss permits
- Maximum uplink data rate is 45 kbps, minimum uplink data rate is 250 bps
Deployment in GSM sub-carrier

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

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
Deployment in LTE guard bands

Implemented in LTE-FDD, i.e. with M2M downlink in LTE downlink guard bands
Co-existence examined in detail and effective mitigation strategies available

Licensed by Mobile Network Operator in LTE700, LTE800 or LTE900
9MHz occupied by OFDM Resource Elements

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

LTE in adjacent channel

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
20 dB coverage enhancement

<table>
<thead>
<tr>
<th>Transmitter</th>
<th>Downlink</th>
<th>Uplink</th>
</tr>
</thead>
<tbody>
<tr>
<td>(0) Max Tx power (dBm)</td>
<td>46</td>
<td>23</td>
</tr>
<tr>
<td>(1) Actual Tx power (dBm)</td>
<td>35.2</td>
<td>23</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Receiver</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<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</td>
<td>-124.2</td>
<td>-133.3</td>
</tr>
<tr>
<td>= (2) + (3) + (4) + 10 log((5)) (dBm)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(7) Required SINR (dB)</td>
<td>-2.8</td>
<td>-6</td>
</tr>
<tr>
<td>(8) Receiver sensitivity</td>
<td>-127</td>
<td>-139.3</td>
</tr>
<tr>
<td>= (6) + (7) (dBm)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Maximum coupling loss (MCL)
= (1) – (8) (dB)

<table>
<thead>
<tr>
<th>Downlink</th>
<th>Uplink</th>
</tr>
</thead>
<tbody>
<tr>
<td>162.2</td>
<td>162.3</td>
</tr>
</tbody>
</table>

Simulation parameters:

Uplink: GMSK modulation, 1/3 code rate Turbo coding, 80 ms frame length, x8 repetition, 1T2R

Downlink: QPSK modulation, 1/3 code rate Turbo coding, 25 ms frame length, x8 spreading factor + x2 repetition, 2T1R

Graphs show SNR threshold for 10% BLER using EPA1Hz channel with 100 Hz residual frequency offset

20 dB coverage enhancement is achieved versus LTE/GSM (according to 3GPP 36.888, the maximum coupling loss is 140.7 dB for LTE, and is 139.4 dB for GSM)
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
- Includes 30% overheads for uplink
- Assumes 15 uplink channels (so frequency reuse is 1/4 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
- Path loss = 120.9 + 37.6 \log_{10}(R_{km}), plus log-normal fading with 8 dB sigma
- Curves show additional 0, 20, 30 and 40 dB penetration/path loss (3GPP case3 corresponds to 20 dB curve)
- Excludes out-of-range terminals
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
## Power consumption analysis

<table>
<thead>
<tr>
<th>Coverage enhancement vs. GSM</th>
<th>6 reports/hour</th>
<th>1 report/hour</th>
<th>1 report/day</th>
</tr>
</thead>
<tbody>
<tr>
<td>GSM + 0 dB</td>
<td>6.7 years</td>
<td>&gt; 20 years</td>
<td>&gt; 20 years</td>
</tr>
<tr>
<td>GSM + 10 dB</td>
<td>3.0 years</td>
<td>14.7 years</td>
<td>&gt; 20 years</td>
</tr>
<tr>
<td>GSM + 20 dB</td>
<td>0.4 years</td>
<td>2.3 years</td>
<td>&gt; 20 years</td>
</tr>
</tbody>
</table>

**Assumptions:**

- 3GPP traffic model
- +23 dBm transmission power with x8 spreading / repetition for 20 dB enhanced coverage
- +13 dBm transmission power with no spreading / repetition for 0 dB enhanced coverage
- Battery self-discharge is not included

<table>
<thead>
<tr>
<th>Assumptions</th>
<th>Voltage (V)</th>
<th>Tx 23dBm (mA)</th>
<th>Tx 13dBm (mA)</th>
<th>Rx (mA)</th>
<th>Idle/sleep (uA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3</td>
<td>190</td>
<td>80</td>
<td>20</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>

- Battery life of > 10 years for terminals that require up to 10 dB coverage enhancement versus GSM, for hourly reporting
- Battery life will be < 10 years for terminals that require > 10 dB coverage enhancement versus GSM, for hourly reporting, so longer report period may need to be considered
Coexistence with GSM

- Benefits of using narrow signal bandwidths to improve coexistence:
  - Up-sampling in digital domain can be used to perform pulse shaping and digital filtering
  - Multi-stage digital filter reduces the side-lobes and images of the spectrum
  - Far-out from the narrow band signal is below -70dBc, so meets the GSM spectrum mask

- Only a marginal GSM performance loss is introduced due to interference from Clean-Slate Cellular IoT waveforms
  - Performance loss is < 1 dB
  - Based on both link simulations and system simulations
Module cost analysis

Module ASP estimate is for 2016
(excludes IPR licensing – should be modest)

Single-chip RF/BB IC
- Area estimate (excl. scribe & seal):
  - 9.2 mm² on 90nm
  - 7.0 mm² on 65nm
- Assumed functionality includes:
  - 700-960 MHz transceiver
  - Integrated power management from battery
  - DSP core for software defined modem, plus custom digits for filtering and accelerators
  - ARM M0 core for protocol stack and space for 3rd party application code

<table>
<thead>
<tr>
<th>eBOM</th>
<th>2016 Estimates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Single chip RF/BB</td>
<td>$0.95</td>
</tr>
<tr>
<td>16Mb NOR flash</td>
<td>$0.20</td>
</tr>
<tr>
<td>PA/switch module</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>Total eBOM</td>
<td>$2.37</td>
</tr>
</tbody>
</table>

Mechanical, Assembly & Test
- PCB (4 layer FR4, 175mm²)   | $0.13          |
- Shield                       | $0.04          |
- Assembly                     | $0.45          |
- Test                         | $0.10          |
- Yield loss (2%)              | $0.06          |
- Packaging/labelling          | $0.10          |
- CEM margin (5%)              | $0.17          |
| Total ex-works price         | $3.43          |

OEM value-added
- Freight (shipped)            | $0.20          |
- Allowance for swap/RMA (2%)  | $0.07          |
- OEM margin (10%)             | $0.37          |
| Total expense to MNO or VAR  | $4.07          |

Module ASP is ~ $4 excluding licensing, so will be significantly below $5 target.
Approach to standardisation and roadmap

- 2014: 3GPP Network Devices
- 2015: R13
- 2016: R13/R14 Evolved Core
- 2017: 1st Commercial Network
- 2018: Samples
- 2019: Commercial
Summary

- The proposed clean-slate radio access technology offers substantial benefits:
  - IoT network can be deployed in a very small bandwidth (DL: 180 kHz, UL: 180kHz)
  - Optimized for ultra-low terminal module cost (< $5)
  - Optimised for very long terminal battery life (> 10 years)
  - 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

- 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