Fixed WiMAX Profit Maximisation with Energy Saving through Relay Sleep Modes and Cell Zooming

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1. Evolution towards Wireless Broadband Systems
2. Fixed/mobile WiMAX spectrum and demonstrator
3. The challenge from relays & different frame formats
4. Formulation for the supported cell/sector throughput
5. Comparison between the absence and presence of Relay Stations (RSs)
6. Economic and environmental impact of cell zooming and sleep modes
7. Conclusions
Evolution of Wireless towards Wireless Broadband Systems

Radio access Technologies
- TDMA
- QPSK
- Adaptive QAM
- OFDM/QAM
- Adaptive coding
- MIMO
- Adaptive array

Data Rate
- ~40k
- 2M
- 14M
- 54M
- 100M
- 1G

Spectral Efficiency
- 0.4
- 0.4
- 2.8
- 2.7
- 5

Stationary
- PDC/GSM/IS-95
- W-CDMA/HSDPA
- CDMA2000 EV-DO/DV
- Bluetooth
- ZigBee
- UWB

Vehicular
- AMPS
- ETACS
- NTT
- 1G (Analog)
- 2G (Digital)
- 3G (IMT2000)
- 802.16-2004
- 802.16e
- B3G/LTE
- IMT-2000
- System Beyond IMT2000

Pedestrian
- Cellular
- 1995
- 2000
- 2010

Cellular
- 1G
- 2G
- 3G
- 3G

Wireless Broadband Systems
- 1G
- 2G
- 3G
- B3G/LTE

Mobility
- Stationary
- Vehicular
- Pedestrian
- Cellular
2-6 GHz band available for WiMAX

ISM: Industrial, Scientific & Medical Band
UNII: Unlicensed National Information Infrastructure band

Licensed Band

Unlicensed Band

US WCS
2.305 – 2.320 GHz
2.345 – 2.360 GHz

MMDS
2.5 – 2.69 GHz

ISM
2.4 – 2.48 GHz

3.3 – 3.4 GHz

3.4 – 3.6 GHz

WRC
5.47 – 5.725 GHz

UNII
5.15 – 5.35 GHz

UNII/ISM
5.7255 – 5.85 GHz

ISM: Industrial, Scientific & Medical Band
UNII: Unlicensed National Information Infrastructure band
Point-to-multipoint demonstrator at 3.5 GHz, Health Science Faculty
Signal-to-noise ratio, SNR, measurements
Detailed measurements of SNR in DL

Frequency license bands:
3543-3567.5 MHz
3443-3467.5 MHz

Throughput_{max} = 230 kB/s = 1840 kb/s (per SU)
16-QAM with several coding rates; however it increased to ~ 6 Mb/s after QoS classes were configured
The frequency reuse problem ...

- $I$ - interference power
- $N$ - noise power
- $C$ - power of the received carrier
Challenge: Coverage Scenario with Relays

- DL Scenario and 240º sector coverage in Relay Station (RS) coverage area
- The central coverage area BS may have omnidirectional or tri-sectorial antenna

\[ D = 3\sqrt{k} \cdot R \]

\[ \frac{C}{I} = \frac{R^{-\gamma}}{2(D - 0.8372R)^{-\gamma} + (D + 0.09535R)^{-\gamma} + (D + 0.8866R)^{-\gamma}} \]

D: reuse distance
R: coverage distance or cell radius

UL freq. "FDD+TDD"
Other Challenges

• Structure of the frames to support the use of relays:
  – Different frame formats are enabled for omni-directional and tri-sectored central coverage zones
  – The main improvement of the “tri-sectored” frame corresponds to increase the throughput by a factor $N_{sec}=3$ (due to a more favourable frame format)

• Full frame usage with no relays:
  – Is the dynamic adaptation of the frame formats enabled?
The WiMAX frame is divided into DL and UL sub-frames which, in turn, include the following sub-divisions:

- BS to SS communication
- BS to RS communication
- SS to BS communication
- RS to SS communication
- SS to RS communication
- RS to BS communication

The UL sub-frame supports DL communications from the RS to the SS (FDD in conjunction with TDD); assuming an asymmetry factor of 1:5 between the UL and DL, as shown in the Figure, the UL sub-frame can make extra resources available to DL RS communications.
The use tri-sect. increases the throughput by a factor $N_{sec}$ 
(at the cost of additional bandwidth)
- Each sector only communicates with one relay
- The area covered by one relay is twice the one covered by the sector in the central coverage zone
Adaptive modulation and coding schemes

<table>
<thead>
<tr>
<th>Modulation &amp; coding</th>
<th>Net PHY Bit Rate [Mbps]</th>
<th>Sensitivity [dBm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPSK 1/2</td>
<td>1.41</td>
<td>-100</td>
</tr>
<tr>
<td>BPSK 3/4</td>
<td>2.12</td>
<td>-98</td>
</tr>
<tr>
<td>QPSK 1/2</td>
<td>2.82</td>
<td>-97</td>
</tr>
<tr>
<td>QPSK 3/4</td>
<td>4.23</td>
<td>-94</td>
</tr>
<tr>
<td>QAM 16 1/2</td>
<td>5.64</td>
<td>-91</td>
</tr>
<tr>
<td>QAM 16 3/4</td>
<td>8.47</td>
<td>-88</td>
</tr>
<tr>
<td>QAM 64 2/3</td>
<td>11.29</td>
<td>-83</td>
</tr>
<tr>
<td>QAM 64 3/4</td>
<td>12.27</td>
<td>-82</td>
</tr>
</tbody>
</table>

3.5GHz *Alvarion* equipment (3.5 MHz bandwidth)
Step distances for CNIR vs supported Physical throughput

- There are $J$ different coverage rings in a cell, each supporting a different MCS (for instance, $J = 4$ in Figure).
- The distances that correspond to the steps between consecutive MCS are represented by $d_j$, $j = 1, 2, \ldots, J$. Here we denote the order of the MCS as $MCS_j$.
- The supported throughput is obtained as

$$R_{b_{\text{sup}}} = \frac{\int_0^L R_b(d, R, K) dxdy}{\frac{3\sqrt{3}}{2} \cdot R^2} = \sum_{j=1}^J \left( \frac{3\sqrt{3}}{2} \cdot (d_j^2 - d_{j-1}^2) \cdot (R_b)_{MCS1 + 1-j} \right)$$

where $(R_b)_{MCS1 + 1-j}$ is the throughput for the $j^{th}$ coverage ring.
**Rings vs supported PHY throughput**

\[
MCS_j(CNIR_{[dB]}) = \begin{cases} 
0, & CNIR < 3.3 \\
1, & 3.3 \leq CNIR < 5.5 \\
2, & 5.5 \leq CNIR < 6.5 \\
3, & 6.5 \leq CNIR < 8.9 \\
4, & 8.9 \leq CNIR < 12.2 \\
5, & 12.2 \leq CNIR < 15.0 \\
6, & 15.0 \leq CNIR < 19.8 \\
7, & 19.8 \leq CNIR < 21.0 \\
8, & CNIR > 21.0 
\end{cases}
\]

\[d_j = cnir^{-1}\left(\min\left(CNIR\left(R_{b,MCS_{j+1}}\right]\right)\right), \quad j = 1, \ldots, J.\]
Correspondence between CNIR and throughput for tri-sectored BS antennas, UL, $K=3$ and subchannelisation.

The supported throughput is computed according to the formulation of the two previous slides.

$P_t = -2$ dBW  \hspace{1cm} N_f = 3$ [dB]  
$G_t = 17$ dBi  \hspace{1cm} f = 3.5$ GHz  
$G_r = 9$ dBi  \hspace{1cm} \gamma = 3  
$b_{rf} = 3.5$ MHz. *(no relays)*
Contributions from the central coverage zone and RS-zone to the throughput

\[
\left( R_{b\text{-sup}} \right)_{equiv} = \frac{R_{b\text{-tot}}}{3} = \frac{N_{sec} \cdot R_{b\text{-central}} + 3 \cdot R_{b\text{-RS-zone}}}{3} = \frac{1}{2} \cdot N_{sec} \cdot R_{b\text{-central-norm}} + R_{b\text{-RS-zone}}
\]

3 equivalent cells

\[P_t = -2 \text{ dBW}\]
\[G_t = 17 \text{ dBi (RS->SS)}\]
\[G_r = 28 \text{ dBi (BS<->RS)}\]
\[b_{rf} = 3.5 \text{ MHz.}\]
Equivalent Supported Throughput for Tri-sectored Cells and Relays in DL
Central coverage zone zooms out when RSs go to sleep mode

\[ A_{\text{multi-hop}} = \frac{3}{2} \sqrt{3} R^2 = 3 \times A_{\text{single-hop}} \]
Equivalent Supported Throughput with Relays and Zoomed-out Cells, $K=3$

*(here frames aren’t dinamically adapted)*
## Costs with relays with different antennas and $K=1$ (one carrier per cell/sector)

<table>
<thead>
<tr>
<th>Costs</th>
<th>Omnidirectional</th>
<th>Tri-sectored</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{fi}$ [€/km²]</td>
<td>15.63</td>
<td>47.14</td>
</tr>
<tr>
<td>$C_{BS}$ [€]</td>
<td>7680</td>
<td>6800</td>
</tr>
<tr>
<td>$C_{Inst}$ [€]</td>
<td>1333.33</td>
<td>2000</td>
</tr>
<tr>
<td>$C_{bh}$ [€]</td>
<td>833.33</td>
<td>833.33</td>
</tr>
<tr>
<td>$C_{M&amp;O}$ [€/year]</td>
<td>833.33</td>
<td>833.33</td>
</tr>
</tbody>
</table>

**Equivalent cell / BS**

### Revenues

A given price for 1 MB of information is assumed, e.g., 0.005 €/MB

- $C_{fi}$ – fixed term of the costs
- $C_{BS}$ – cost per BS
- $C_{Inst}$ – installation cost
- $C_{bh}$ – cost for the normal backhaul
- $C_{M&O}$ – cost of the maintenance and operation
Revenue and Profit

- The cost per unit area is given by:
  \[ C_{[\text{€/km}^2]} = C_{fi} [\text{€/km}^2] + C_b \cdot N_{cell/\text{km}^2} \]
  where \( C_{fi} \) is the fixed term of the costs, \( C_b \) is the cost per BS

- The cost per BS is given by:
  \[ C_b = \frac{C_{BS} + C_{bh} + C_{Inst}}{N_{year}} + C_{M&O} \]

- The (absolute) profit is given by (\( R_v \) is the revenue per unit area):
  \[ P_{[\text{€/km}^2]} = R_v - C, \]
  from which, the profit in percentage terms is given by:
  \[ P_{[\%]} = \frac{R_v - C}{C} \cdot 100. \]
Energy saving when RSs are switched-off

• An additional challenge has been to optimize the energy saving when RSs are switched-off during either the night period or the weekends, when the traffic load is low.

• In these periods:
  – although the value for the BS transmitter power is kept the same, the central coverage zone of the cell is zoomed out.
  – the offered traffic significantly decreases and RSs may sleep whilst increasing the range of the central coverage zone of the cell; when a RS is working at the sleep mode, the air-conditioner and other energy consuming equipment can be switched-off.

• The coverage zones of the RSs in the sleep mode zooms in to 0 and the central BS coverage zone zooms out to guarantee the coverage of the cell.
### Power consumption parameters for the BSs and RSs

<table>
<thead>
<tr>
<th>Station</th>
<th>BS</th>
<th>RS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Tri-sectored</td>
<td>Omni.</td>
</tr>
<tr>
<td>Power for the full chassis [W]</td>
<td>420</td>
<td>80</td>
</tr>
<tr>
<td>Number of sectors</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Power for the outdoor unit(s) [W]</td>
<td>120</td>
<td>40</td>
</tr>
<tr>
<td>Total power of BS/RS equipment alone [W]</td>
<td>540</td>
<td>460</td>
</tr>
<tr>
<td>Power consumption for the router/switch [W]</td>
<td>100</td>
<td>-</td>
</tr>
<tr>
<td>Power consumption for the ventilator [W]</td>
<td>40</td>
<td>20</td>
</tr>
<tr>
<td>Total power consumption for the stations [W]</td>
<td>680</td>
<td>600</td>
</tr>
<tr>
<td>Annual energy consumption [kW·h]</td>
<td>6000</td>
<td>5250</td>
</tr>
</tbody>
</table>

- During whole year, the total energy waste in RSs is $24 \cdot 365 \cdot 540 = 4730.4$ kW·h $\rightarrow$ electricity cost = 473.04 €/year (@ 0.10 €/kW·h)
- If the RSs are switched-off overnight (for eight hours each night during the working days) and during the whole weekend (48 hours) $=>$ the energy is saved for $5 \cdot 8 + 2 \cdot 24 = 88$ hours (against 80 hours of full functionality cell operation), i.e., 47.6% (~50%) of the time in full operation.
Economic and environmental impact of cell zooming

• Therefore, by switching-off the three RSs of each cell there is a reduction in the annual cost per cell of 247.17 €/year

• The aforementioned reduction in the cost per cell corresponds to a reduction of the operation costs of the ‘equivalent BS’ of $\frac{247.17}{3} = 82.62$ €/year (~10% of $C_{M&O}$)

• NOTE:
  – We assume here the DL sub-frame format cannot be changed (to a more favourable one) when the RSs are switched-off
  – Note the ~ 83 €/year reduction in the operation and maintenance costs are reflected in the computations for the zoomed out central BS coverage zone cell (in the no RSs case).
Comparison between omni. (3 carr.) and tri-sect. (1 carr./sect.) with *Cell Zooming*
Conclusions

• Relays are cheaper than full-functionality BSs
• With Relays, the need of resources for BS-to-RS communications causes a decrease in throughput (only partially compensated by sectorization)
• During the low traffic periods, zooming out the central coverage zone and zooming the RS coverage zone in to 0 yields 50% of energy saving in RSs (~25% saving in the whole cell with relays)
• If the dynamic adaptation of frames is not allowed, as the throughput decreases, the economic performance is lower (but still kept at reasonable values)
Conclusions (cont.)

- However, it is important to highlight that in the absence of RSs, in the case of the zoomed out central BS coverage zone (with these RSs in the sleeping mode and its cooling system switched-off), the economic performance is still reasonable.

<table>
<thead>
<tr>
<th>Type of cell</th>
<th>With RSs</th>
<th>Cell Zooming</th>
</tr>
</thead>
<tbody>
<tr>
<td>Omnidirectional</td>
<td>900</td>
<td>400-450</td>
</tr>
<tr>
<td>Tri-sectored</td>
<td>~1000</td>
<td>700-800</td>
</tr>
</tbody>
</table>

- As, during the night and weekends the offered traffic is low, the switch-off of the RSs has the clear advantage of the power saving, and yields an important economic impact.
Mobile WiMAX BS at 5.4 GHz

Thank you!
Equivalent Supported Throughput for Cells with Relays and Zoomed-out Cells

(frames may be dynamically adapted)

![Graph showing throughput for different cell configurations and zoomed-out cells.](image)
Comparison between omni. (3 carriers) and tri-sect. (1 carrier/sect.)

...but better coverage is achieved with RSs