Energy efficiency of multi-standard mobile devices in Heterogeneous Wireless Networks

Jacek Kibiłda

Wrocławskie Centrum Badań EIT+, Trinity College Dublin

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The big picture

- Mobile data traffic has grown 6x between 2008 and 2010 for most of the regions world-wide. Cisco predicts further increase by 18x between 2011 and 2016.
- In December 2011 there were more than 1 million apps, available in Apple store (745 new apps per day), and Google Play (543 apps per day).
- In 2012 there were around 845 million Facebook users, of which approx. 50% login daily.
- Mobile devices are equipped with multiple radio interfaces: GSM, UMTS, LTE, WLAN, Bluetooth, GPS, ...
- Mobile devices are equipped with: HD cameras, touch screens, large LCDs, torches (!?), ...
- Mobile devices are equipped with quad-core processors, clocked at over 1 GHz
Laws driving mobile technology growth

- **Moore’s Law** - processor performance doubles every 18 months!
- **Cooper’s Law** - wireless capacity doubles every 30 months!

**But:**
- Battery capacity has increased only by 80% over the last decade,
Battery operational time for smartphones

Smartphones are well-designed to handle idle state during which they can survive even several days on a single battery charging, however, they can stay permanently active for few hours only.

<table>
<thead>
<tr>
<th></th>
<th>iPhone 3G(^1)</th>
<th>Nokia N96(^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Standby</td>
<td>300h</td>
<td>230h</td>
</tr>
<tr>
<td>Active</td>
<td>5h</td>
<td>4h</td>
</tr>
</tbody>
</table>

\(^1\)3G/UMTS  
\(^2\)2G/GSM
Light-weight design vs. battery size

Figure: Evolution of iPhone’s battery capacity, and weight.
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Power consumption of a mobile device

\[ P_{tot} = \sum_{n=1}^{N} P_{nIC}^n + P_{CPU} + P_{GR} + P_{DISP} + P_{OTHER} \]

- \( P_{tot} \) - total power consumption of a mobile device
- \( N \) - number of radio interfaces
- \( P_{nIC}^n \) - power consumption of an n-th radio interface
- \( P_{CPU} \) - power consumption of a CPU unit and RAM unit
- \( P_{GR} \) - power consumption of a graphics unit
- \( P_{DISP} \) - power consumption of a display unit, including backlight
- \( P_{OTHER} \) - other components, e.g. flash memory, SD card
Some example power consumption measurements

Overall power consumption measurement [Caroll and Heiser]:

Figure: Idle state power consumption: a) suspended mode (68 mW), b) idle mode (268 mW).

Figure: Active state power consumption: a) video playback (543 mW), b) GSM phone call (1054 mW).
Some example power consumption measurements II

Power consumption measurements for GSM and UMTS [Perrucci et al]:

<table>
<thead>
<tr>
<th>Scenario</th>
<th>GSM</th>
<th>UMTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiving a voice call</td>
<td>612.7</td>
<td>1224.3</td>
</tr>
<tr>
<td>Making a voice call</td>
<td>683.6</td>
<td>1265.7</td>
</tr>
<tr>
<td>Idle mode</td>
<td>15.1</td>
<td>25.3</td>
</tr>
</tbody>
</table>

Figure: Energy consumed for transmission of 200 bytes for GSM and UMTS.
Power consumption measurements for WLAN [Pedersen et al] :

<table>
<thead>
<tr>
<th>State</th>
<th>Power value [W]</th>
<th>Data rate [Mbps]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sending (d=3m)</td>
<td>1.645</td>
<td>4.781</td>
</tr>
<tr>
<td>Sending (d=30m)</td>
<td>1.674</td>
<td>2.387</td>
</tr>
<tr>
<td>Receiving (d=3m)</td>
<td>1.449</td>
<td>4.745</td>
</tr>
<tr>
<td>Receiving (d=30m)</td>
<td>1.329</td>
<td>2.392</td>
</tr>
<tr>
<td>Idle mode</td>
<td>1.027</td>
<td>-</td>
</tr>
<tr>
<td>Sleep mode</td>
<td>0.04</td>
<td>-</td>
</tr>
</tbody>
</table>

Power consumption measurements for LTE dongle [Jensen et al]:

<table>
<thead>
<tr>
<th>State</th>
<th>Power value [W]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uplink (50 PRB, tx power = -10dBm)</td>
<td>1.91</td>
</tr>
<tr>
<td>Uplink (50 PRB, tx power = 15dBm)</td>
<td>3.00</td>
</tr>
<tr>
<td>Downlink (rx power = -40dBm)</td>
<td>1.98</td>
</tr>
<tr>
<td>Downlink (rx power = -80dBm)</td>
<td>2.02</td>
</tr>
</tbody>
</table>
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C2POWER expects to **design methods that will increase energy efficiency of wireless communications systems** based on multi-standard mobile devices. C2POWER makes use of the two complementary techniques:

- **Cooperative wireless communications** between mobile devices using low-power short-range interfaces.

- **Cognitive handover mechanisms** to select the RAT, which offers the best energy efficiency while providing the required quality of service.
C2POWER scenarios

Figure: C2POWER scenarios: a) cooperative communications in homogeneous network, b) cooperative communications in heterogeneous network, c) vertical handovers.
C2POWER architecture

Figure: C2POWER architectural framework.
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Energy inefficiency of WiFi MAC protocol I

The scenario:

Figure: WiFi dual-link congestion scenario.
CSMA/CA protocol basics:

Figure: CSMA/CA protocol.
Self-enforced cooperative relaying MAC protocol for WiFi

Figure: SECR-MAC protocol.

Figure: Relay-contention window.
Self-enforced cooperative relaying MAC protocol for WiFi - results I

Figure: Energy efficiency for a scenario with a direct path of 1 Mbps and with a relay link of: a) 11-11 Mbps, b) 5.5-5.5 Mbps.
Self-enforced cooperative relaying MAC protocol for WiFi - results II

Figure: Energy efficiency for a scenario with a direct path of 1 Mbps and with a relay link of: a) 5.5-2 Mbps, b) 1-1 Mbps.
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C2POWER framework

Steps to perform energy efficient vertical handover:

1. **Discover** available networks in the vicinity, e.g. by network scanning
2. **Extract** context information, e.g. measured power consumption, data rate
3. **Estimate** energy consumption of each available access network, and **select** the least energy consuming one
4. **Execute** handover, i.e. connect to the network of choice, and gracefully disconnect with the previously selected network
Simplified energy consumption model of a radio interface

In a mobile device the radio interface energy consumption can be calculated:

\[ E_i = T_{Tx} P_{Tx} + T_{Rx} P_{Rx} + (T_c - T_{Tx} - T_{Rx}) P_{idle} \quad i \in N \]

\[ T_{Tx/Rx} = \begin{cases} \frac{L}{R_{uplink}} & \text{if traffic is variable bit rate} \\ \frac{L^*}{R_{uplink}} & \text{if traffic is constant bit rate} \end{cases} \]

- \( P_{Tx/Rx/Idle} \) - measured device’s power consumption in transmission, reception and idle states
- \( T_{Tx/Rx} \) - transmission/reception time
- \( L \) - transmission size in bits
- \( L^* = D T_c \) - transmission size in bits for constant rate traffic, corresponds to the application rate times the connection duration
- \( R_{uplink/downlink} \) - idle power consumption of a radio interface
Figure: Energy consumption bounds for 3G and 802.11n case: a) 3G only, b) WiFi only, c) VHO random decision, d) VHO decision mismatch, e) VHO exact decision.
Energy consumption metric I

After some reformulations:

$$\bigwedge_{i \in N} E_i = \frac{D}{R_{\text{uplink/downlink}}} \left( P_{i\text{Tx}}^i - P_{i\text{idle}}^i \right) + P_{i\text{idle}}^i$$

where:

- $N$ - is the number of available access networks

The network selection criterion:

$$\arg \min_{i \in N} (E_i)$$
Handover decision as an MDP

However, we may look at the vertical handover decision making process from the perspective of a certain time horizon. We can formulate this process as a Markov Decision Process (MDP).

Figure: An example of MDP model for vertical handover decision making.
Energy consumption metric with MDP

Markovian rules are of the form:

$$\delta_t : X_t \rightarrow K_t(x_t)$$

A set of rules forms a policy:

$$\pi_i = \delta_1, \delta_2, \ldots, \delta_n, i \in (N \times n), n \in (1, \infty)$$

Utility coming from each policy $\pi_i$ can be described in terms of total expected reward:

$$\vartheta^{\pi_i} = E^{\pi_i} \{ E_n[\rho(n)r_n(X_t)] + \sum_{t=1}^{n-1} \rho(n)r_t(X_t, K_t) \}$$

Our goal is to find a policy that will maximize the total expected reward:

$$\pi^* = \arg \max_{i \in N} \{ \vartheta^{\pi_1}, \ldots, \vartheta^{\pi_N} \}$$
Energy consumption metric II

Reward:
\[ r(x_t, k_t) = -(e(x_t, k_t) + g(x_t, k_t)) \]

Action cost:
\[ g(x_t, k_t) = \begin{cases} 
0 & x_t = x_{t+1} \\
e_{ho} & x_t \neq x_{t+1} 
\end{cases} \]

Transition probability:
\[ P(x_{t+1}^* | x_t, k_t) = \begin{cases} 
0 & x_{t+1}^* = k_t \\
p_{x_{t+1}, x_t} & x_{t+1}^* \neq k_t 
\end{cases} \]

Discount factor:
\[ \rho(n) = (1 - \delta)\delta^{n-1}, \quad n = 1, 2, ... \]
Energy consumption metric II cont.

For geometrically distributed connections (with mean connection duration $\delta$):

$$\vartheta^{\pi_i} = E^{\pi_i}\left\{ \sum_{n=1}^{\infty} \sum_{t=1}^{n} r_t(X_t, K_t)(1 - \delta)\delta^{n-1} \right\}$$

After some transformations:

$$\vartheta^{\pi_i} = E^{\pi_i}\left\{ \sum_{t=1}^{\infty} \delta^{n-1} r_t(X_t, K_t) \right\}$$

Finally, the network of choice is the one that:

$$\pi^* = \arg \max_{k_t \in K} \left\{ r_t(x_t, k_t) + \delta \sum_{x_{t+1} \in X} P[x_{t+1}^*|x_t, k_t] \vartheta(x_{t+1}^*) \right\}$$
Simulation scenario

Figure: WiMAX-WLAN single user simulation scenario.

<table>
<thead>
<tr>
<th>Traffic profile</th>
<th>Main characteristics</th>
<th>Distributions</th>
<th>Direction</th>
</tr>
</thead>
<tbody>
<tr>
<td>VoIP</td>
<td>call duration</td>
<td>exponential</td>
<td>bidirectional</td>
</tr>
<tr>
<td>VoD</td>
<td>session duration</td>
<td>exponential</td>
<td>unidirectional</td>
</tr>
<tr>
<td>FTP</td>
<td>file size, reading time</td>
<td>truncated lognormal, exponential</td>
<td>unidirectional with ACK</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Interface</th>
<th>Transmission state [mW]</th>
<th>Reception state [mW]</th>
<th>Sleep state [mW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>WiMAX</td>
<td>1500</td>
<td>1500</td>
<td>25</td>
</tr>
<tr>
<td>WLAN 802.11a</td>
<td>1920</td>
<td>1400</td>
<td>75</td>
</tr>
</tbody>
</table>
Simulation results I

(a) VoD traffic; gains 32-52%.

(b) FTP traffic; gains 32-34%.

Figure: Energy efficiency for two traffic types VoD and FTP.
Simulations results II

Figure: Energy efficiency for VoIP traffic; gains 0%.
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Various techniques for saving energy

- **Application layer:**
  - Aggregation - aggregation of database queries, peer-2-peer status information exchange
  - Load partitioning - passing of processing load to BS units
  - Network-supported access network discovery, e.g. ANDSF\(^3\)

- **Transport layer:**
  - Aggregate or minimize retransmissions
  - Decrease backoff

- **Network layer:**
  - Energy efficient network selection, e.g. energy efficient handovers

- **MAC:**
  - Idle state management
  - Discontinuous reception mechanism
  - Cooperative communication, e.g. cooperative relay

- **PHY:**
  - Uplink power control mechanisms
  - More efficient waveform design (possibly adaptive), e.g. OFDM adjacent channel leakage and high PAPR
  - Techniques that increase SINR: MIMO, beamforming, network coding, etc.

\(^3\) It can be perceived as an improvement to MAC.
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