Modelling Power Consumption in IEEE 802.16e WiMAX Mobile Nodes

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***Abstract*— Energy availability is the main delimiter for usage time of mobile devices. As wireless network interfaces are usually the most power-demanding subsystem in a mobile device, mechanisms for their power consumption optimization are extensively researched. However, determining the power saving gains from using such optimizations is not an easy task, specially for simulation-based analysis. This work presents an extended power consumption model for the WiMAX interface in Mobile Nodes (MN), capable of capturing minimal contributions such as signalling overhead or burst allocation geometry. Simulation results show an effectiveness comparison of discussed power consumption models.**

***Keywords*— WIMAX; power consumption modeling; 802.16e.**

I. Introduction

Usage time of mobile devices is limited by the capacity of their power supplies, and as such, power consumption efficiency is an important issue. Intense wireless network traffic typically drains considerable amount of power, mostly due to Radio Frequence (RF) amplifiers and baseband coding/decoding chipsets. As power supplies in mobile devices are usually a resource shared with all other components, the total usage time can be said as bounded by the network traffic intensity [1].

Network traffic patterns for current Internet applications are "bursty", with periods of intense usage followed by periods without any activity at all [2]. Reasons include the need to process the information exchanged (e.g. Web browsing), the need for the user to read and understand the received data (e.g. e-mail reading) and even the very same nature of the traffic pattern (e.g. VoIP data generated by voice codecs). However, wireless link-layer technologies demand power consumption even on such "inactivity" periods, as the transmission (Tx) and the reception (Rx) of management messages occurs independently of data exchanges. In order to minimize this power consumption demand, wireless technologies like Wi-Fi, WiMAX and LTE support Power Saving Mechanisms (PSM), where negotiated periods of link-layer traffic inactivity allow devices entering on lower power consumption states. There is also a signalling overhead on using such mechanisms which may not be compensated by the provided energy savings, so using power consumption models for understanding the power saving gains of PSM mechanisms is vital for mobile devices.

This paper addresses the power consumption modelling of WiMAX interfaces in mobile nodes. In order to endorse the model herein presented, this work reviews current literature on power consumption estimation, describing their application context, assumptions and added-value. Discussion on some power consumption abstractions, highlighting their positive and negative points, are also outlined.

II. Power Consumption Analysis and Related Works

Decomposition of modern wireless network interfaces (e.g. Wi-Fi, WiMAX and LTE) in terms of their functional components (see figure 1) allow one to realize distinct power consumption behaviors. For instance, the wireless network I/O bus interface (responsible for communication with the host device) needs to be always turned on for serving the host device at any moment. Functionalities like Media Access Control (MAC) processing may be programmed to be turned off (e.g. implementing PSM mechanisms). Once device is turned on, such functionalities tend to drain a constant amount of energy, no matter if there is data being transferred or received for that node. Other components (e.g. R/F Power Amplifier, RF/IF Converter, IF Modem, Baseband Processor) drain power consumption only when there is actually data being sent or received. Atop those different power consumption facets, features like dynamic voltage scaling make the power consumption behavior even more dynamic.

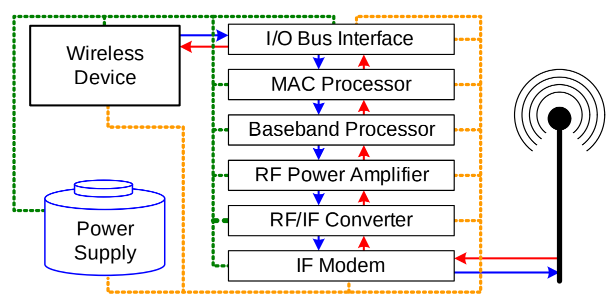


Fig. 1. Power Consumption Elements in Wireless Network Interfaces.

The scope of the power consumption model is one key parameter of any power consumption analysis. System wide-based scopes, measuring the overall consumption of the entire wireless device, are good for minimizing the complexity of the estimation procedure as they measure total system cost [1], [3], [4]. However, the precision of those measurements are very low, as it is not possible to make realistic packed-grained estimations due to concurrent demands that are external to the wireless interface, e.g. processing or memory access. Additionally, the estimations are system-specific, as models are not easily applicable to other devices. For that reason, packet-based scope focus on the measurement of the wireless network interface itself, estimating the power consumption for each packet [5]–[7]. This allows to evaluate specific enhancements on the MAC and Physical (PHY) layers, but has the drawback of focusing on a particular subsystem, not allowing to optimize the overall transmission process of the entire mobile device.

Evaluation metrics for the effectiveness of power consumption models vary, depending on the specific type of study being conducted. For investigations requiring the actual power consumption of the interface at a particular working mode (e.g. Tx, Rx, IDLE, SLEEP) for a particular set of parameters (e.g. Packet Size, Transmission rate, RF Power Level), the Instantaneous Power Consumption is used [5], usually done with a sliding window averaging approach (a number of samples under a specific configuration to form a continuous average). If only the power consumption for the Tx and Rx processes as a whole are required, the Average Power Consumption (including eventual SLEEP and IDLE periods) can be used instead. All the overhead involved in successfully receiving or transmitting one byte of payload (e.g. channel sensing phase, transmission of acknowledgements (ACKs), IDLE times because of inter-frame spaces, packet header/trailer, among others) is accounted on the energy estimation. The power consumption derived from this overhead is important specially when the Network Interface Card (NIC) was constantly in SLEEP mode where there is no data payload being exchanged, but energy being drained. After the power consumption estimation, the Energy Efficiency, measuring the amount of energy required by the interface to transmit/receive one byte of data, could be generated.

As the individual wireless interface sub-components are not modelled, a power consumption profile for each configuration needs to be provided, demanding hence a couple decisions. The first one is whether direct measurements (e.g. via hardware probes) or indirect estimation (e.g. using manufacturer information) could be used. Another is whether the power consumption estimation could be done using a mathematical analysis (e.g. linear equations, probabilistic analysis using Markov chains, etc..) or through simulation (e.g. trace-based approach, or using a more-refined energy models).

To the best of our knowledge, there are no recent publications addressing the power consumption modelling for IEEE 802.16e WiMAX systems. There are several works proposing power saving modes strategies and evaluating their performance by means of simulations [8]–[12], but without a detailed discussion about the power consumption model itself. Some related works could be found by addressing other systems [13]–[16].

III. Power Saving Mechanism in IEEE 802.16e WiMAX

Communication between 802.16e Mobile Nodes (MNs) and Base Stations (BSs) occurs using Time Division Duplex (TDD) multiplexing over an Orthogonal Frequency-Division Multiple Access (OFDMA) channel. The time division groups data in frames, which are then subdivided in subframes for splitting downlink (DL) from uplink (UL) traffic. Each DL or UL subframe is then subdivided in bursts, through which traffic for a specific subset of connections is then transported. Figure 2 presents how this subdivision for OFDMA/TDD works.

Power saving in WiMAX is achieved by turning off parts of the MN network interface in a controlled manner when it is not actively transmitting or receiving data. Mobile WiMAX defines two signalling methods, known as Power Saving Mechanisms (PSM), that allow the MN to retreat into lower power consumption levels during negotiated periods of time [17], as such:

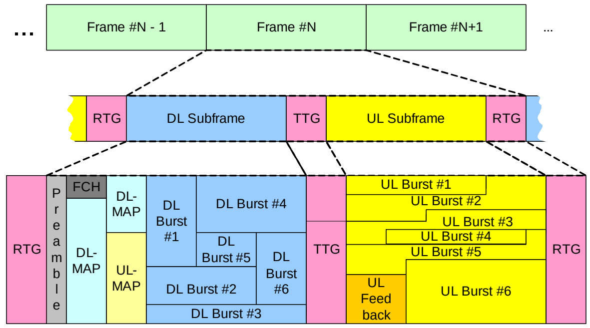


Fig. 2. WiMAX TTD/OFDMA Frame.

- **Sleep mode** allows WiMAX MNs to effectively turns itself off and becomes unavailable for predetermined periods named as Sleep Windows. Additionally, periodic wake-up for listening for BS polling, referred as listening windows, are defined. Three power-saving classes are specified, one for each manner the sleep mode is executed: (i) Class I for fixed listening windows and exponentially increasing sleeping windows, more suited for best-effort (BE) and non-real-time (nRT) traffics where there is no pre-defined interval between bursts; (ii) Class II for fixed-length listening and sleep windows, with the possibility for data exchange during the listening window without deactivating PSM, typically used for Unsolicited Grant Service (UGS) service, where there is a known periodic interval between transmissions; and (iii) Class III for a one-time sleep window followed by PSM deactivation, suitable for multicast traffic or management traffic, when there is no known periodic traffic, but the MN knows when the next traffic is expected;
- **Idle mode** allows even greater power savings. It allows the MN to completely turn off and to not be registered with any BS, and yet receive downlink broadcast traffic. The MN is assigned to a paging group by the BS before going into idle mode, and the MN periodically wakes up to update its paging group. When DL traffic arrives for an idle-mode MN, it is paged by a collection of BSs that form a paging group.

Idle mode saves more power than sleep mode, as the MN does not even have to register or do handoffs. Idle mode also benefits the whole network by eliminating need for handover traffic from inactive MNs. However, signalling overhead is higher with idle mode, as intra-core management negotiation is required (differently from sleep mode). Additionally, transitions between idle mode and active mode are rather slow, especially if the traffic is initiated from the network side and paging is required.

IV. Power Consumption Modelling

This section presents power consumption methodologies for WiMAX 802.16e system, highlighting their characteristics, main assumptions and general recommendations. As an additional contribution of this paper, we propose some refinements based on a careful analysis of existing models.

A. Power Consumption Model based on Inactivity Ratio

The economy in terms of wireless resources obtained from being "offline" during the PSM negotiated periods of inactivity is a good indication of the energy savings. As such, the *Inactivity Ratio* provides an indication of "relative savings" when using PSM, in comparison to a situation where PSM is not used. For that, two metrics are defined. The first one is the activity ratio ($r_{activity}$), derived from the number of total observed WiMAX frames (n_{total}) and the number of frames while in the Awaken Mode (n_{awaken}), which indicates the relative use of frames while MN is not in PSM (sleep and idle modes). The second metric is the inactivity ratio ($r_{inactivity}$), derived from the n_{total} and the number of frames while MN is in PSM ($n_{inactivity}$). See equations 1 and 2.

$$r_{activity} = \frac{n_{awaken}}{n_{total}} \quad (1) \qquad r_{inactivity} = \frac{n_{inactivity}}{n_{total}} \quad (2)$$

The advantage of power consumption model based on inactivity ratio is that a good estimation of the energy saving introduced by the PSM can be rapidly obtained, also demanding fewer changes on simulation tools. One drawback is its lower precision regarding the saved watts, as it does not take under consideration factors like the instantaneous radio configuration, the power consumption required to enter and leave the power saving modes or even the residual power consumption level while using PSM (i.e. from I/O bus interface).

B. Power Consumption Model based on Momentaneous Interface Configuration

In order to better characterize the power consumption, a model based on the *Momentaneous Interface Configuration* can be used. Literature reports at least two distinct approaches [5]. The first one is based on the calculation of *Instantaneous Power Consumption*, using a estimation (usually "smoothed") of the power consumption for a given radio configuration, i.e., a specific working mode (e.g. Tx, Rx, TTG, RTG, Idle, Sleep, etc) and a particular set of parameters (e.g. Packet Size, MCS, RF Power Level). The second approach evaluates the Average Power Consumption in a given configuration, including any Tx/Rx of data and its ACKs, as well as Sleep frames and Idle periods. This approach is performed by averaging the power consumption by a given amount of samples, evaluated to form a continuous estimation for that event during a given amount of time.

Any average power consumption estimation shall be represented in a unit of "expended" energy (e.g. joule). In general, Wireless Network Interfaces operate in a sequence of Rx and Tx operations, each one using a given radio configuration (i.e. Modulation and Coding Scheme (MCS), RF level, etc), yielding in different operation modes with their respective power consumption level. One way to estimate the energy consumption in the wireless network interface for each operation mode is to multiply its power level (in watts) by the time (in seconds) MN operates in that configuration. This way, the total energy power consumption for a given MN can be determined by the sum of the energy consumption for each operation mode that occurred during the observation time.

Power consumption estimations for each modelled radio operation mode could have multiple sources, with each choice relying on the required accuracy level and the technical availability of those estimations. One possible source of information is the manufacturer specifications, generally the mean power consumption peak for some selected RF configurations. Other sources are results found on literature. Finally, measurements on the real device (i.e. using averaged samples) could increase confidence on the results.

The most prominent advantage of using this approach is the improved power consumption estimation quality due to accounting every single possible configuration. The drawbacks include dependence on the availability of the power consumption estimations and the extra calculation overhead for simulators.

C. Proposed Power Consumption model for IEEE 802.16e WiMAX

As previously mentioned, the *momentaneous interface configuration* provides more realistic estimations on the power consumption when compared to the *inactivity ratio* modelling, because its estimations are based on previously known power consumption information associated with the different configurations of the device during normal operation. In this section, we propose some enhancements to the power consumption model based on the *momentaneous interface configuration* for WiMAX systems that we believe provide even more accuracy for the power consumption estimations.

The basic *momentaneous interface configuration* model usually considers two power consumption states, *"during DL subframe"* and *"during UL subframe"*, in which power is drained by elements that are not related to the current RF level (without transmission and reception). We propose a refinement, which is to include a third state, named *"turned on"*, accounting for the energy spent while in Awaken mode but not specifically in DL or UL subframe (i.e. TTG and RTG), where there is residual power consumption by e.g. I/O Bus Interface. We also propose accounting for the power consumption specific for each DL and UL bursts (as represented in figure 3).

For DL, the power consumption for each burst is solely determined by the number of OFDM symbols being processed, as it influences directly the amount of radio and baseband processing at the receiver [18]. On UL, however, the power consumption of the RF amplifier needs to be computed on a per-subchannel basis, therefore the number of subchannels used for UL bursts is also accounted for the power consumption computation.

There is also the need to compute the power consumption associated for staying on Sleep Mode and Idle Mode. Entering on the Sleep Mode power consumption level means that all the parallel connections on the MN entered on Sleep Mode. In the same way, entering on Idle Mode power consumption level means that there is no active connection on the MN, and therefore, the MN is free for turning some elements OFF.

Hence, the energy consumption of PSM windows are defined based on a mapping of operation modes (configurations or events) and their associated power consumption level. This method also demands tracking internal events (e.g. MCS configuration changes, interface turning ON/OFF, Rx-to-Tx and Tx-to-Rx transitions, etc.), so

$$E_{Awaken} = \sum_{f=1}^{F} \left(E_{DL\_Subframe} + \sum_{d=1}^{D} E_{Rx_{d,f}} + E_{Rx \to Tx} + E_{UL\_Subframe} + \sum_{u=1}^{U} E_{Tx_{u,f}} + E_{Tx \to Rx} \right) \quad (3)$$

$$E_{SleepMode} = \sum_{s=1}^{S} E_{Sleep}.W_s + \sum_{l=1}^{L} \left(E_{DL\_Subframe} + \sum_{d=1}^{D} E_{Rx_{d,l}} + E_{Rx->Tx} + E_{UL\_Subframe} + \sum_{u=1}^{U} E_{Tx_{u,l}} + E_{Tx->Rx} \right) \quad (4)$$

$$E_{IdleMode} = \sum_{i=1}^{I} E_{Idle}.T_i + \sum_{p=1}^{P} \left(E_{DL\_Subframe} + \sum_{d=1}^{D} E_{Rx_{d,p}} + E_{Rx->Tx} + E_{UL\_Subframe} + E_{Tx->Rx} \right) \quad (5)$$

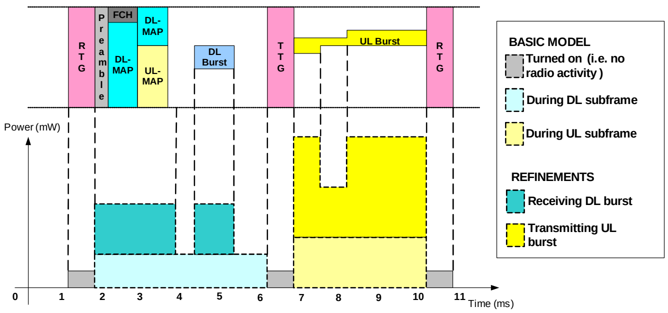


Fig. 3. Extended power consumption mapping/DL and UL bursts.

their associated power consumption can be accounted. The formulations are displayed in equations 3, 4, and 5.

E_{Awaken} is the total energy consumption during "normal" activity (i.e. awaken windows). F means the total number of frames while in "awaken" state, $E_{DL_Subframe}$ means the minimal energy consumed while in DL subframe, D means total number of DL bursts received and processed in a given f-th frame, $E_{Rx_{d,f}}$ means energy for receiving and processing the d-th DL burst on the f-th frame, $E_{Rx \to Tx}$ means energy spent when transiting from DL to UL subframe (i.e. time guard), $E_{UL_Subframe}$ means the minimal energy consumed while in UL subframe, U means total number of UL bursts transmitted in a given f-th frame, $E_{Tx_{u,f}}$ means energy for transmitting the u-th UL burst on the f-th frame and $E_{Tx \to Rx}$ means energy spent when transiting from UL to DL subframe. Note that E_{Awaken} denotes both *data* and *signalling* energy expenditure in the same variable, as $E_{Rx_{d,f}}$ covers even the energy for receiving and processing all preamble, FCH, DL-MAP and UL-MAP DL bursts.

$E_{SleepMode}$ is the energy consumption during Sleep Mode. S means the total number of Sleeping Window occurrences, E_{Sleep} means the energy consumed while in Sleeping Window, W_s means the number of frames of the s-th Sleeping Window, L means the total number of Listening Window occurrences, $E_{Rx_{d,l}}$ means energy for receiving and processing the d-th DL burst on the l-th frame and $E_{Tx_{d,l}}$ means energy for receiving and processing the d-th DL burst on the l-th frame.

$E_{IdleMode}$ is the energy consumption during Idle Mode. I means the total number of Idle Period occurrences, E_{Idle} means the energy consumed (for one second) while in Idle Period, T_i means the duration (in seconds) of the s-th Idle Period, P means the total number of Paging Period occurrences, $E_{Rx_{d,p}}$ means energy for receiving and processing the d-th DL burst on the p-th frame.

Similar to the model presented in section IV-B, the power consumption obtained by using this model are even more accurate as it can indicate facts not clearly evident at first sight. For example, it can reveal that the influence of low power consumption modes are meaningful in a power saving investigation. However, the execution cost of this feature is higher when compared to the post-processing approach required by inactivity ratio. Additionally, there is an even bigger dependency on the existence of previous power consumption estimations for the operation modes.

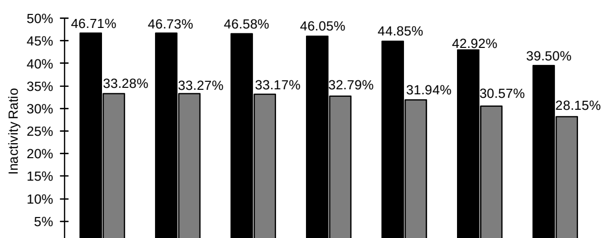
V. Energy Consumption Model in NS-2 and Effectiveness Tests

We implemented the herein proposed power consumption model for the WINSE simulator, a WiMAX extension to the Network Simulator version 2 (ns-2) [19]. Our model receives power consumption relevant events from the WiMAX simulator, whose feed the model's internal state machine. The power consumption relevant events are those associated with transitions between power consumption states, and work as triggers for state transitions. Namely, they are: (i) Turning the MN WiMAX interface ON/OFF; (ii) Start/Finish the DL subframe period; (iii)Start/Finish the DL burst reception; (iv) Start/Finish the UL subframe period; (v) Start/Finish the UL burst transmission; (vi) Start/Finish Sleep Mode; and (vii) Start/Finish Idle Mode.

Power consumption estimations demand chipset power consumption profiles, whose are files containing information about a specific WiMAX chipset's average power consumption for each one of the power consumption states (e.g. Turned On, Sleeping, Idle, etc.) and the average power consumption for each one of the relevant transition events mentioned above. Our power consumption model is fed at the start of the simulation process with the profile information file, from which the chipset power consumption profile information is retrieved. As an advantage of using separate files containing these chipset power consumption profiles, different WiMAX chipsets could be evaluated by simply changing the file contain the chipset power consumption profile.

Transitions on the internal state machine, caused by the power consumption relevant events, generate the associated power consumption estimations, whose are reported back to the simulator as estimated power consumption. After generating each power consumption estimation for a given state or state transition, the power consumption model generates a trace entry containing information associated with this estimated power consumption. Each trace entry associates the power consumption event type, the simulation time in which it occurred, the duration of this state (if it is a state-related estimation) and finally the power consumption in watts.

Figure 4 provides an example of the differences in accuracy between power saving estimations generated from using our proposed power consumption model in comparison with the model based on inactivity ratio, in this case for studying the use of Sleep Mode in the WiMAX simulator. Herein, we fixed all PSM parameters except by the inactivity timer on near-optimal values for HTTP traffic. Looking at results for each single PSM parameter set, one can realize that power economy indications provided by inactivity ratio model are always "more optimistic' than those provided by power savings (from our proposed model). The main reason behind this different is that our model takes into account factors not captured by the inactivity ratio model, for instance, the contribution from the power spent while in Sleep Mode. Additionally, the differences between models' results are also noticeable when we consider the variation of inactivity timer. In this case 7.21% between the first and the last inactivity ratio measurements and 5.13% for power savings measurements. This difference comes from the inability of inactivity ratio model to consider the power spent to enter/leave sleep mode state (i.e. signalling overhead), and means that the perceived gains in power savings from varying the inactivity timer is indeed less effective than what would be expected from just looking at the inactivity ratio. From this single example, one can realize that using more accurate power consumption models like ours is crucial for determining the applicability of PSM in wireless networks.



	0.08	0.16	0.32	0.64	1.28	2.56	5.12
Inactivity Ratio	47%	47%	47%	46%	45%	43%	39%
Power Savings	33%	33%	33%	33%	32%	31%	28%

Inactivity Timer (s)

Fig. 4. Illustration of differences between discussed power consumption models.

VI. CONCLUSIONS

Considering the need for accuracy on the power savings obtained when applying PSM in WiMAX networks, this paper proposes enhancements to the basic *momentaneous interface configuration* power consumption model, provides mathematical modelling of how those enhancements could be computed and compared against the more common metric named *inactivity ratio* using numerical results from a PSM scenario evaluation via simulation tool. An illustrative example indicates that our model is able to captures energy expenditure not accounted by the *inactivity ratio* modelling, such as energy spent while in Sleep Mode, which may be crucial for determining the applicability or not of PSM in different scenarios. As future work, we intend to evaluate the energy savings from different set of PSM parameters in different scenarios, as well as the influence of different power consumption chipset profiles in the power savings from applying PSM.

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