# Performance of Power Saving Modes in IEEE 802.16e System

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***Abstract*—To extend battery life, modern wireless systems implement Power Saving Mechanisms (PSMs). This work presents a performance evaluation of HTTP Web Browsing and Always-On traffic whithin joint IEEE 802.16e Sleep Mode and Idle Mode operation, on an accurate 802.16e PSM NS-2 simulation implementation. We first determine the most influencial PSM parameters in terms of power savings and performance degradation, for then determining optimal transition points between Sleep Mode and Idle Mode. Results show that although power savings can be achieved, performance degradation can be substantial for a wide range of PSM parameters, if (a) Sleep Mode Inactivity Timer are such that PSM is activated within TCP RTT, or (b) timers for PSM modes are such that there is a "competition" between which PSM mechanism should be activated. Also, under established conditions, we observe a significant power saving gains followed by a surprising system performance enhancement.**

***Index Terms*—802.16e, Power Saving Mode, Power Savings**

## I. Introduction

Power efficiency is an important issue for mobile devices, since their usage time is limited by their power supplies. As power supplyies are usually a shared resource, total usage time can be said to be bounded by wireless traffic intensity [1]. Traffic patterns for some Internet applications are "bursty", with intense usage periods followed by inactive periods. However, wireless interfaces demand power even on such "inactivity" periods, as the exchange of control signaling messages is orthogonal to data exchanges. To minimize power consumption, modern wireless technologies (e.g. WiFi, WIMAX and LTE) support Power Saving Mechanisms (PSMs), where negotiated periods of inactivity allow wireless devices to enter on lower power consumption states.

In this work, we propose to jointly evaluate the dynamics of IEEE 802.16e Sleep Mode and Idle Mode joint operation, considering a power consumption model based on *momentaneous interface configuration* [2] Our evaluation considers a complete model of WIMAX signalling, implemented on the NS-2 simulator, as well as HTTP Web and Always-On traffic services like VoIP, e-mail and RSS reading application. To the best of our knowledge, no similar work on literature addresses a detailed power consumption modeling for IEEE 802.16e WIMAX systems including the simultaneous operation of Sleep Mode and Idle Mode.

## II. Power Saving Mechanism in IEEE 802.16e

Communication between IEEE 802.16e (WiMAX) Mobile Nodes (MNs) and Base Stations (BSs) may occur using eiither Frequency Division Duplex (FDD) or Time Division Duplex (TDD) multiplexing over an Orthogonal Frequency-Division Multiple Access (OFDMA) channel. For WiMAX TDD, traffic is divided into *frames*, which are subdivided into *subframes* for splitting downlink (DL) traffic from uplink (UL) traffic. Each subframe is further subdivided into *bursts* occupying resources in frequence and time, through which traffic for MN *connections* is then transported. Reception Time Guard (RTG) and Transmission Time Guard (TTG) periods of variable size are inserted between UL and DL subframes.

Power saving is achieved by turning off parts of the MN network interface in a controlled manner when it is not actively transmitting or receiving data. 802.16e defines two signalling methods, known collectively as Power Saving Mechanisms (PSMs), that allow the MN to retreat into lower power consumption levels during negotiated periods of time [3]:

- **Sleep mode** allow MNs to become unavailable for predetermined periods, known as *sleep windows*. Periodic wake-ups for listening to BS polling, known as *listening windows*, are also defined. Three Sleep Mode classes are specified: (i) Class I for fixed listening windows and exponentially increasing sleeping windows, suited for best-effort and non-real-time (nRT) traffics ; (ii) Class II for fixed-length listening and sleep windows, with data exchange allowed during listening windows (without deactivating PSM), suited for Unsolicited Grant Service (UGS) service ; and (iii) Class III for a one-time sleep window followed by PSM deactivation, suited for multicast or management traffics;
- **Idle mode** allows even greater power savings. It allows the MN to become not registered with any specific BS within a *paging group*, for then completely turn off the radio and yet receive downlink broadcast traffic notifications periodically. MN is assigned to a paging group by BS before going into Idle Mode, and MN periodically wakes up to update its paging information. When DL traffic arrives for an idle MN, it is paged by a collection of BSs that form that paging group.

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There are three standardized [3] Sleep Mode parameters:

- Initial sleeping window;
- Listening window;
- Final sleeping window (base and exponent).

Paging period on Idle Mode allows a MS to enter on a lower power consumption state, while it transverses an air link environment populated by multiple base stations. The IEEE 802.16e standard [3] defines three system parameters:

- Paging cycle: the cycle (number of frames) in which the paging message is transmited within the paging group.
- Paging interval: period during which the MS listens for BS broadcast paging messages.
- Paging offset: starting frame of BS paging interval.

Literature recommends defining another parameter for Sleep Mode, known as *Inactivity Timer*, which corresponds to the time interval during which no connection activity should be noted prior to putting MS on Sleep Mode. Literature also recommends defining an *Idle Timer*, i.e. the time interval during which no connection activity should be noted prior to putting MS on Idle Mode.

## III. Bibliography on PSM

Literature reports that Idle Mode allows saving more power than Sleep Mode while the whole network is benefited [4], as inactive MNs do not have to register or do handoffs. 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 (in comparison with e.g. TCP RTT), especially if traffic is initiated from network side and therefore paging is required to wake-up the MN.

The *sleeping* interval is one key parameter to be determined in any PSM strategy. Many researchers have developed methods for efficient determining sleep intervals [5], [6]. Moreover, those studies are based on simplistic energy consumption models, or use Markov-chain simulations or analytical performance for their evaluations.

User traffic profile is another important aspect for the analysis of PSM strategies. Authors in [7], [8] provide performance analyses of WiMAX Sleep Mode for Best Effort (BE) traffic, while others explore the relationship among traffic load, power consumption and idle check time (e.g. in [8]). Other works (e.g. [7], [9]) provide analytical and numerical examples to show the usefulness of the proposed PSM schemes, but those in general do not consider Idle Mode.

Finally, several works study WiMAX PSM strategies and evaluate their performance by means of simulations [10], [11], but without a detailed discussion about the power consumption model itself. Some other related works could be found by addressing other systems [12], [13].

In addition, literature reports at least two distinct approaches for characterizing power consumption of wireless network interfaces [14]: (i) calculation of *instantaneous power consumption*, using an 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), or (ii) evaluation 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.

## IV. IEEE 802.16e Power Consumption Modeling

We propose an enhanced power consumption model based on the *momentaneous interface configuration* for WIMAX systems that, we believe, provide even more accuracy for the power consumption estimations [2]. This model considers two basic 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 1).

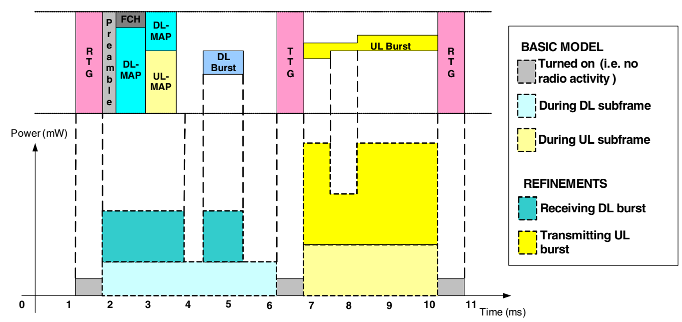


Fig. 1. Extended power consumption mapping/DL and UL bursts.

For DL, power consumption for each burst is determined by the no. of OFDM symbols processed, as it influences directly the amount of radio and baseband processing at the receiver. On UL, power consumption of the RF amplifier is computed on a per-subchannel basis, therefore the no. of subchannels used by UL bursts is accounted for power consumption computation. There is also the need to compute power consumption associated to staying on Sleep/Idle Modes. Power consumption on Sleep Mode is accounted when all the parallel connections on the MN entered on Sleep Mode, while power consumption on Idle Mode is accounted when there are no active connections on the MNs so they are free for turning off some of the wireless interface elements.

Hence, energy consumption in our proposed model is 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 their associated power consumption can be accounted.

## V. PERFORMANCE EVALUATION METHODOLOGY

For this work, we use the chipset power consumption profile presented in Table I, devised from measurements in a Nokia N900 device and normalized by the highest value.

TABLE I
WIMAX CHIPSET POWER CONSUMPTION PROFILE.

| Operation Mode, | NS-2 state | Norm. Power |
|---|---|---|
| On DL subframe | while_DL_subframe | 1.00 |
| On UL subframe | while_UL_subframe | 1.00 |
| On Sleep Mode | while_sleep_mode | 0.29 |
| On Idle Mode | while_idle_mode | 0.06 |
| Turned On | while_turned_on | 1.00 |
| Transmitting UL burst | while_UL_burst.ratio | 0.17 |
| Transmitting UL burst | while_UL_burst_energy.ratio | 0.01 |
| Receiving DL burst | while_DL_burst | 0.07 |

Joint use of both Sleep Mode and Idle Mode PSMs on the same scenario is expected for WIMAX terminals. In these scenarios, Sleep Mode would be activated first for the inactive connections, and as soon as total absence of traffic is noted for a period of time equal to the Idle timer, the terminal would then activate the Idle Mode. In order to determine the "upper limit" performance of joint operation of WIMAX PSM Sleep Mode and Idle Mode, we need to evaluate a more controlled scenario, so we choose to use an "idealistic" scenario, with "perfect channel" and a single MN and one BS.

We evaluate four different traffic patterns: HTTP web traffic, e-mail (both as in [15]), RRS and VoIP presence models (as in in [16] and [17], respectively). In all traffic models, TCP Reno was used as transport protocol. Also, for each traffic pattern, we have one WIMAX BS, one WIMAX MS and one server at the backend. RTT between the WIMAX BS and the backend server (7 ms) and channel related parameters - OFDMA bandwidth (10 MHz) and OFDMA frames per second (200 Frames/s, or 1 frame each 5 ms) - are set to fixed values. Downlink (DL)/Uplink (UL) ratio is equal to $29/18$, and we use PUSC for both DL and UL.

Our simulation campaigns have two phases. Phase 1 (P1) focuses on $2^k.r$ *factorial analysis*, while Phase 2 (P2) focuses on *full factorial analysis* [18]. $2^k.r$ *factorial analysis* [18] is a preliminary analysis technique, used to classify *primary* and *secondary factors* according to their impact on the performance for some response variables. Its purpose is to provide an insight on what are the most important parameters (primary factors) that contribute to the results of the selected metrics. On this work, $2^k.r$ factorial analysis involves varying all $k$-th PSM parameters ($k$ = 8) from their smallest to their largest possible values, obtaining for each of these configurations the average results from $r$ simulation instances to achieve a desired statistical confidence interval ($r$ = 3). The $k$-th PSM parameters used for the $2^k.r$ factorial analysis in this work as well as their parameter ranges are listed on Table II.

After we define the factors which had more impact on performance metrics via the $2^k.r$ factorial analysis, we intend to use the so-called *full factorial analysis* [18]. For this method, parameters that have lesser impact on the performance are fixed with their best suited values, and we shall only vary the primary factors (parameters) with more samples per factor.

TABLE II
PSM PARAMETERS FOR $2^k.r$ FACTORIAL ANALYSIS.

| | Parameter Name | Parameter Range |
|---|---|---|
| Sleep Mode | Transport Connection Inactivity Timer | [0.04, 0.64] seconds |
| | Basic Management Connection Inactivity Timer | [0.04, 0.16] seconds |
| | Initial Sleeping Window | [2,8] frames |
| | Listening Window | [2,8] frames |
| | Final Sleeping Window | [0.64, 2.56] seconds |
| Idle Mode | Idle Timer | [0.5, 8] seconds |
| | Paging Cycle | [1, 4] seconds |
| | Paging Interval | [2, 8] frames |

## VI. RESULTS FROM PERFORMANCE EVALUATION

We have conducted the $2^k.r$ factorial analysis for HTTP Web traffic after the employment of the Mixed Sleep Mode/Idle Mode in order to classify primary and secondary factors using their impact on PSM performance. Table III presents the gain/loss in Power Saving, RTT Retransmission Rate and TCP RTT identifying candidates to primary factors. Values are gains/losses relative to the case where all PSM parameters are set to their lowest possible value, hereforth named configuration $C_0$. Then, gains/losses are evaluated by comparing the performance of $C_0$ with a case where we changed the candidate to primary factor to its highest value.

TABLE III
RESULTS OF $2^k.r$ FACTORIAL ANALYSIS FOR WEB HTTP TRAFFIC.

| Output metric: Power Saving | |
|---|---|
| **Parameter** | **Change from $C_0$** |
| Idle Timer | -23.15% |
| Transport Inactivity Timer | -1.11% |
| Initial Sleeping Window | 1.43% |
| **Output metric: TCP Retransmission Rate** | |
| **Parameter** | **Change from $C_0$** |
| Initial Sleeping Window | 43.46% |
| Final Sleeping Window | 58.57% |
| BMC Inactivity Timer | -36.48% |
| **Output metric: TCP RTT** | |
| **Parameter** | **Change from $C_0$** |
| BMC Inactivity Timer | -1.29% |
| Idle Timer | 2.21% |
| Transport Connection Inactivity Timer | 29.22% |

One can see that increasing *Idle Timer* makes power savings decrease 23.15 % when comparing with $C_0$, indicating that *Idle Timer* should be defined the lowest as possible. However, one can also notice that increasing *Idle Timer* also increases the TCP RTT by 2.21%, which may lead to TCP performance depreciation due to spurious TCP Retransmission Timeouts (RTOs). This clearly shows a trade-off between power savings performance and the system Quality of Service (QoS).

For the *Transport Inactivity Timer*, the same situation occurs, i.e. an increase in TCP RTT of 29.22% can be observed when comparing with $C_0$, while actual power saving losses of $-1.11\%$ are observed, indicating that it has not as much significance for power saving. As a consequence, the *Transport Inactivity Timer* should be defined the lowest as possible.

For the *Initial Sleeping Window*, power saving gains of 1.43% could be observed, at the cost of a depreciation on the QoS (i.e., increase in TCP Retransmission Rate of 43.46%); again, a clear trade-off is involved. *Basic Management Connection (BMC) Inactivity Timer* provides a decrease in the TCP Retransmission Rate, which indicates that by setting it at the lowest value we can provide better QoS when comparing with $C_0$. As for the *Final Sleeping Window*, setting it to a higher value only makes it depreciate QoS without power savings, so we set it to the lowest possible value.

With those results in mind, we decided to evaluate on Phase 2 the trade-off between performance and QoS depreciation for *Idle Timer* and *Initial Sleeping Window*, and also evaluate the scale of performance and QoS depreciation that the *Transport Inactivity Timer* may have. Then, we intend to evaluate those three parameters in greater granularity for Phase 2 full factorial analysis, as shown in Table IV, while the other PSM parameters were set at their best values (higher or lower) according to the results from the $2^k.r$ factorial analysis.

TABLE IV
PSM PARAMETERS - PHASE 2: FULL FACTORIAL ANALYSIS.

| **Name** | **Value(s)** |
|---|---|
| Inactivity Timer for Transport Connections | 0.02, 0.04, 0.08, 0.16, 0.32, 0.64 seconds |
| Initial Sleeping Window | 2, 4, 8, 16, 32, 64, 128, 256 frames |
| Listening Window | 2 frames |
| Final Sleeping Window | 2.56 seconds |
| Inactivity Timer for Basic Management Connection | 0.16 seconds |
| Idle Timer | 0.25 and 2 seconds |
| Paging Cycle | 4 seconds |
| Paging Interval | 2 frames |

Figures 2, 3 and 4 show the tradeoff between Power Consumption versus TCP Retransmission Rate obtained for Phase 2 (full factorial analysis). Each line represents one value of *Initial Sleeping Window*, as shown in the figures legend. A performance degradation is only clearly noticed for really higher values of *Initial Sleeping Window* (see lines in figures 3 and 4 for 128 and 256 frames). This results indicates that 64 frames is a good choice for *Initial Sleeping Window* in this scenario. Additionally, TCP RTT increase due to *Idle Timer* increase is not noticeable, so we can set it to a higher value without worrying about QoS degradation.

One phenomena occurs when the *Transport Inactivity Timer* is analyzed. There is a performance degradation for values lower than twice of the RTT between the BS and the server (which is 0.14 s). This may indicate that the transport connection, used by the MS to carry TCP data packets, is put to Sleep Mode within an RTT interval when *Transport Inactivity Timer* is set to a low value. As consequence, an ACK may take longer to be sent because the connection is on Sleep Mode, therefore degrading QoS performance. From this, we claim that the *Transport Inactivity Timer* can be set to a low value, but higher than twice of the TCP RTT.

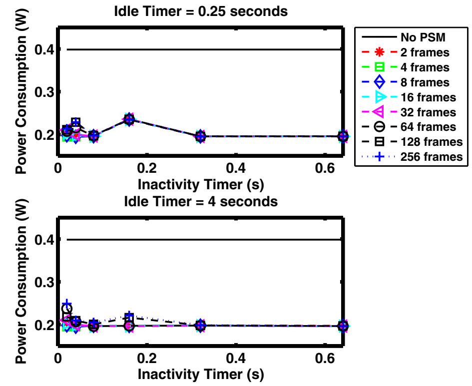


Fig. 2. Power Consumption.

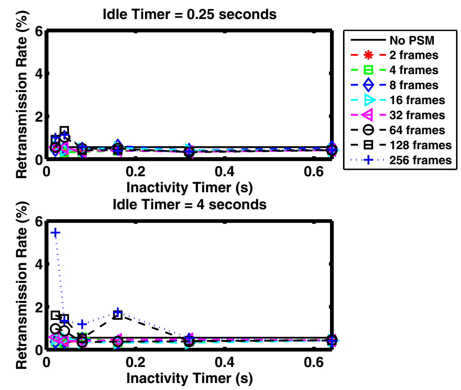


Fig. 3. TCP retransmission rate.

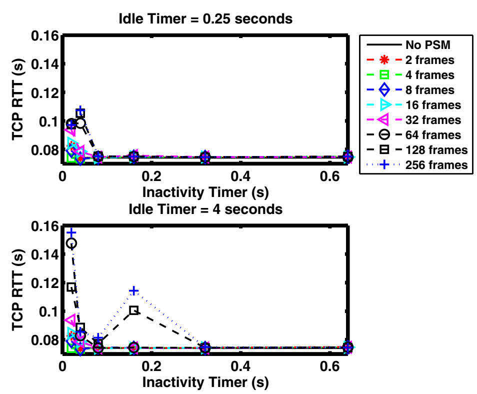


Fig. 4. TCP Round Trip Time (RTT).

Another phenomenon occurs when *Idle Timer* and the duo *Transport Inactivity Timer* plus *Initial Sleeping Window* are on the same time scale. A performance degradation is observed due to the fact that both timers are "disputing" for the inactivity periods. Then, in order to avoid this undesirable situation, we advocate that the *Idle Timer* should be set to a high value while keeping the *Transport Inactivity Timer* in the lowest value (observing the RTT), as analyzed before.

Obeying previously conditions, we can surprisingly see an enhancement not only in terms of power saving, but in TCP performance (i.e., smaller TCP RTT) when compared to the situation without using PSM parameter. We claim that this overall gain is caused by the following situation. When the MS is in Sleep Mode or Idle Mode, incoming TCP data packets are buffered on the BS. When the MS awakens to receive those packets, the TCP layer receives a “burst” of incoming TCP packets which are ACK’ed cumulatively with a singled TCP ACK packet. As a consequence, the probability of TCP RTO being triggered is decreased, yielding in a lower perceived TCP Retransmission Rate. Then, by applying PSM, potential performance degradation introduced by the WIMAX MAC layer, especially due to the bandwidth request mechanism, may be diminished by the use of PSM. Although this performance gain can be achieved by other means, it displays one unexpected benefit for using PSM.

Qualitatively speaking, we can find similar conclusions considering always-on traffic applications like e-mail, RSS and VoIP presence. The main difference between HTTP and always-on traffic is the amount of power saved by PSM. As expected, we observe lower power wasting for low-traffic demanding applications when PSM is applied (see figure 5).

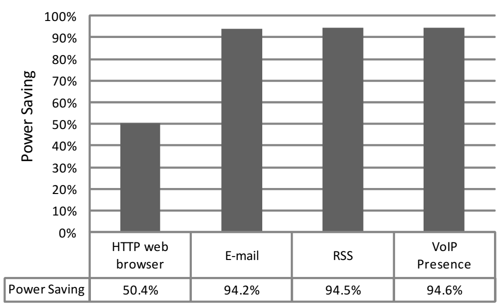


Fig. 5. Power saving on Mixed Sleep Mode/ Idle Mode

## VII. Conclusions

This paper proposes evaluating the joint performance, in terms of power savings and QoS degradation, of both Mobile WIMAX (802.16e) PSMs, when applied simultaneously on the same scenario. We propose using an enhanced *momentaneous interface configuration* power consumption model which better captures energy expenditure due to refined system modeling. We evaluate PSM parameters via a two-phase approach, starting with a $2^k.r$ *factorial analysis* to determine primary and secondary parameters and concluding with a *full factorial analysis* of the primary parameters. Results indicate that a set of guidelines for PSM parameters setting can be derived, such as avoiding timer collision for Sleep Mode and Idle Mode and avoiding Sleep Mode timers being smaller than twice of TCP RTT. We also observe an unexpected QoS performance enhancement with PSM, followed by 50% of power saving in web HTTP scenarios and about 90.5% for always-on traffic applications like email, RSS and VoIP presence. As future work, we intend to evaluate energy savings on dynamic simulation scenarios with multiple MSs, traffic patterns and realistic channel simulation. We will continue to study how to automatically determine optimal PSM parameters for a given observed scenario (e.g. via Machine Learning).

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