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Evaluation of Joint Sleep and Idle Mode in IEEE 802.16e WIMAX

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Abstract

As energy availability limits usage time for mobile devices, modern wireless systems implement Power Saving Mechanisms (PSMs). Determining optimal PSM parameters and switch points when applying all PSM mechanisms jointly in the same scenario is a trade-off between power savings and system performance degradation. This work presents an unpublished performance study of the joint operation of Sleep Mode and Idle Mode on an accurate 802.16e PSM NS-2 simulation implementation, with the MS experiencing two different classes of Internet traffic, namely HTTP Web Browsing and Always-On traffic. We first determine which set of PSM parameters influence the most on power savings and performance degradation (in terms of TCP retransmissions) via a 2k.r factorial analysis. Then, we explore those PSM parameters via full factorial analysis in order to determine optimal transition points between Sleep Mode and Idle Mode, such that we achieve power savings without high performance degradation. Results showed that although we managed to obtain good power saving results for a wide range of PSM parameters, performance degradation can be substantial if the Sleep Mode Inactivity Timer is such that PSM is activated within TCP RTT or the timers for Sleep Mode and Idle Mode are such that there is a “competition” between which PSM mechanism should be activated. Under established conditions, we observe a significant power saving gains followed by a surprising system performance enhancement.

Keywords: *power saving mechanism, IEEE 802.16e, WIMAX, Sleep mode, Idle mode.*

1. 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 Frequency (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.

Network traffic patterns for some Internet applications are “bursty”, with periods of intense usage followed by periods without any activity at all. Reasons include the time needed to process received data (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 even on such “inactivity”’ periods, as the transmission (Tx) and the reception (Rx) of link-layer management messages is orthogonal to data exchanges. In order to minimize power consumption, modern wireless technologies (e.g. WiFi, WIMAX and LTE) support PSM, where negotiated periods of link-layer traffic inactivity allow devices entering on lower power consumption states.

2. WiMAX PSM Analysis and Related Works

Decomposing modern wireless network interfaces in terms of their functional components allows one to realize distinct power consumption behaviors. For instance, the wireless network I/O bus interface (responsible for communication with the host device) requires being always turned on for always serving the host device whenever necessary. On the other hand, functionalities such as Media Access Control (MAC) processing may be programmed to be turned off (e.g. implementing PSM mechanisms) while other components (e.g. R/F Power Amplifier, RF/IF Converter, IF Modem, baseband Processor) drain power 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.

The definition of *sleeping* intervals is one key parameter of any PSM strategy. Many researchers have developed methods for efficient determining sleep intervals [1], [2]. Moreover, those studies are based on a simple energy consumption model, Markov-chain simulations or analytical performance evaluations. Evidently, there is a *trade-off* between power saving and response delay, and the performance of a power saving mechanism depends on user traffic characteristics and how well the power saving mechanism can predict the termination time of an idle period. Then, traffic profile is other important aspect for the analysis of PSM strategies. Authors in [3], [4] provide performance analysis of sleep mode for WIMAX for Best Effort (BE) traffic, while others try to explore the relationship among traffic load, power consumption and idle check time (e.g. in [4]). There are other works (e.g. [3], [5]) providing analytical and numerical examples to show the usefulness of the proposed schemes, but in general all such works do not consider Idle Mode.

In this contribution, we propose to jointly evaluate the dynamics of Sleep Mode and Idle Mode, considering a power consumption model based on *momentaneous interface configuration* [6], where its estimations are based on previously known power consumption information associated with the different configurations of the device during normal operation. Our evaluation considers a complete model of WIMAX signalling implemented on the NS-2 simulator as well as HTTP and always-on modern traffic services like VoIP, e-mail and RSS reading application. To the best of our knowledge, there are no similar work on literature addressing a detailed power consumption modeling for IEEE 802.16e WIMAX systems including the simultaneous operation of Sleep Mode and Idle Mode. There are several works proposing power saving modes strategies and evaluating their performance by means of simulations [7], [8], but without a detailed discussion about the power consumption model itself.

3. Power Saving Mechanism in IEEE 802.16e

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. Time division groups data in *frames*, which are then subdivided in *subframes* for splitting downlink (DL) traffic 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 1 presents how this subdivision for OFDMA/TDD works.

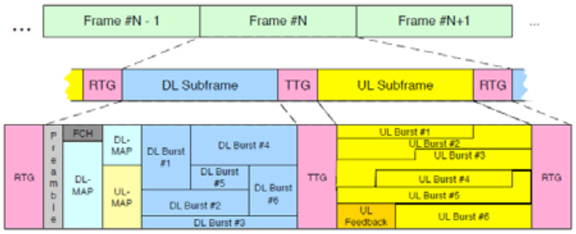


Fig. 1. WIMAX TTD/OFDMA Frame.

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. As previously mentioned, mobile WIMAX defines two signalling methods, known collectively as PSM, that allow the MN to retreat into lower power consumption levels during negotiated periods of time [9], as such:

- **Sleep mode** allows MNs to effectively turns itself off and becomes unavailable for predetermined periods named as SleepWindows. Additionally, periodic wake-up for listening to 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 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 or management traffics, 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 [10], 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.

4. Power Consumption Modeling

This section presents the methodology for evaluating power consumption of WIMAX 802.16e system, highlighting its characteristics, main assumptions and general recommendations. As an additional contribution of this work, we propose modeling refinements based on a careful analysis of existing models.

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 [11]. The first one is based on the 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). 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 number of samples, evaluated to form a continuous estimation for that event during a given amount of time.

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 [6]. 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 2).

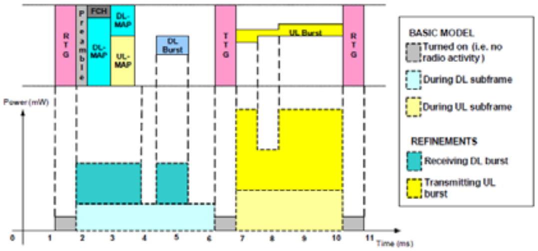


Fig. 2. Extended power consumption mapping/DL and UL bursts.

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. On UL, 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 their associated power consumption can be accounted. The formulations of the proposed power consumption model are displayed in equations 1, 2, and 3.

$$\begin{aligned} E_{Awaken} = \sum_{f=1}^{F} \Bigg(& E_{DL\_Subframe} + \sum_{d=1}^{D} E_{Rx_{d,f}} + \\ & E_{Rx \to Tx} + E_{UL\_Subframe} + \sum_{u=1}^{U} E_{Tx_{u,f}} + E_{Tx \to Rx} \Bigg) \end{aligned} \tag{1}$$

$$\begin{aligned} E_{SleepMode} = \sum_{s=1}^{S} E_{Sleep}.W_s + \sum_{l=1}^{L} \Bigg(& E_{DL\_Subframe} + \sum_{d=1}^{D} E_{Rx_{d,l}} + \\ & E_{Rx->Tx} + E_{UL\_Subframe} + \sum_{u=1}^{U} E_{Tx_{u,l}} + E_{Tx->Rx} \Bigg) \end{aligned} \tag{2}$$

$$\begin{aligned} E_{IdleMode} = \sum_{i=1}^{I} E_{Idle}.T_i + \sum_{p=1}^{P} \Bigg(& E_{DL\_Subframe} + \sum_{d=1}^{D} E_{Rx_{d,p}} + \\ & E_{Rx->Tx} + E_{UL\_Subframe} + E_{Tx->Rx}) \end{aligned} \tag{3}$$

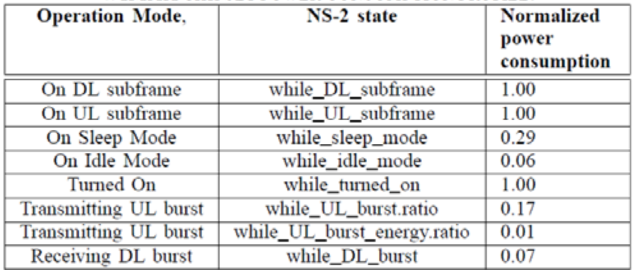
E_{Awaken} is the total energy consumption during “normal” activity (i.e. awaken windows). F means the total number of frames while in “awaken” state, $E_{DL\_Subframe}$ means the minimal energy consumed while in DL subframe, D means total number of DL bursts received and processed in a given f-th frame, $E_{Rx_{d,f}}$ 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.

5. Performance Evaluation of PSM

5.1 PSM operation parameters

For this paper, we use the normalized chipset power consumption profile presented in Table I.

TABLE I
WIMAX CHIPSET POWER CONSUMPTION PROFILE.



Operation Mode,	NS-2 state	Normalized power consumption
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

For Sleep Mode, the IEEE 802.16e standard [9] defines three system parameters, which are:

- Initial sleeping window: duration of initial sleeping window.
- Listening window: frame duration of MS listening window.
- Final sleeping window: the biggest possible size for a sleeping window. It is composed by two factors, final sleeping window base and final sleeping window exponent.

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.

Idle Mode provides a mechanism for the MS to become periodically available for DL broadcast traffic messaging without registration at a specific BS [9]. This mechanism 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 [9] defines three system parameters, which are:

- Paging cycle: the cycle (number of frames) in which the paging message is transmitted within the paging group.
- Paging interval: the duration during which the MS must listen for BS broadcast paging messages to check for pages.
- Paging offset: used to determine the starting frame of the BS paging interval used to transmit paging messages for the MS.

Literature recommends defining another parameter for Idle Mode, the *Idle Timer*, which is the time interval during which no connection activity should be noted prior to putting MS on Idle Mode.

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.

5.2 Evaluation Methodology

In order to evaluate the joint operation of WIMAX PSM Sleep Mode and Idle Mode, we need to determine its “upper limit” performance, so we choose to use an optimal scenario, with perfect channel and a single mobile user. We evaluate four different traffic patterns, namely HTTP web traffic and e-mail (modeled in accordance with [12]), RRS and VoIP presence models (as found in [13] and [14], respectively). For each selected 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.

All simulation campaigns had two phases. Phase 1 (P1) focuses on *$2^k.r$ factorial analysis* and Phase 2 (P2) focuses on *full factorial analysis* [15]. *$2^k.r$ factorial analysis* [15] is a preliminary analysis technique generally used on evaluation of system models to classify *primary* and *secondary factors* according to their impact on the performance for some response variables. The main purpose of such technique is to provide an insight on what are the most important parameters (primary factors) that contribute to the results of the selected metrics. Regarding the scope of this paper, the procedure of $2^k.r$ factorial analysis involves varying all the *k*-th PSM parameters ($k = 8$) from their smallest to their largest possible values, and obtain the average performance results from r simulation instances for each of these configurations in order to achieve a desired statistical confidence level ($r = 3$). The *k*-th PSM parameters used for the $2^k.r$ factorial analysis in this study as well as their parameter ranges evaluated are listed on Table II.

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

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* [15]. 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.

5.3 Performance Results and Discussions

We have conducted the 2k.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 in this table are relative to the case where all PSM parameters are set to their lowest possible value (configuration C0). Then, the gain/loss is evaluated comparing the performance of C0 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%

We can see clearly that increasing *Idle Timer* makes power savings decrease 23.15 % when comparing with the PSM configuration C_0, which indicates that we need to define the lowest *Idle Timer* as possible. Additionally, we can notice that increasing the *Idle Timer* also increases the TCP RTT by 2.21%. This clearly shows a trade-off between power savings performance and the system Quality of Service (QoS). For the *Transport Inactivity Timer*, we have power saving losses on the order of -1.11%, indicating that it has not as much significance for power saving. Looking at the TCP RTT increase, we can see that *Transport Inactivity Timer* actually provides a QoS depreciation, increasing artificially the RTT by 29.22% when comparing with C_0.

As a consequence, the *Transport Inactivity Timer* should be defined the lowest as possible. For the *Initial Sleeping Window*, as it provides some power saving gains on the order of 1.43%, one could be led to believe that setting it to a higher value would be beneficial, but it is important to observe that for a higher Initial Sleeping Window, we have a depreciation on the QoS (i.e., increase in TCP Retransmission Rate of 43.46%). Then, there is clearly a trade-off 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 C0. As for the *Final Sleeping Window*, setting it to a higher value only makes it depreciate QoS without providing relevant power savings, so we should only 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.

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

Name	Value(s)
Inactivity Timer for Transport Connections (transport_inactivity_timer)	0.02, 0.04, 0.08, 0.16, 0.32, 0.64 seconds
Initial Sleeping Window (initial_sleeping_window)	2, 4, 8, 16, 32, 64, 128, 256 frames
Listening Window (listening_window)	2 frames
Final Sleeping Window (final_sleeping_window)	2.56 seconds
Inactivity Timer for Basic Management Connection (bmc_inactivity_timer)	0.16 seconds
Idle Timer (idle_timer)	0.25 and 2 seconds
Paging Cycle (idle_paging_cycle)	4 seconds
Paging Interval (idle_paging_interval)	2 frames

For the other PSM parameters, they were set at their best values (higher or lower) according to the results from the 2^k.r factorial analysis. Figures 3, 4 and 5 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 4 and 5 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 interesting phenomenon 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.

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.

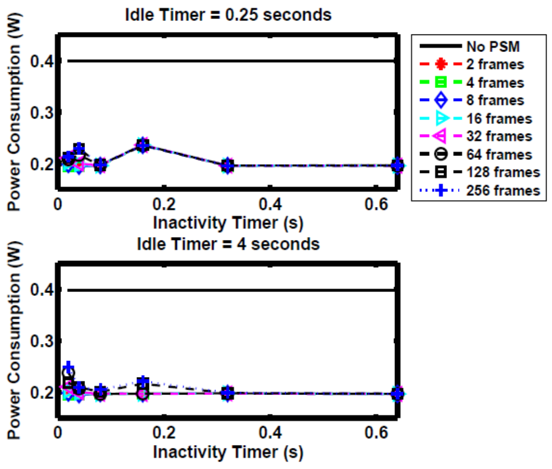


Fig. 3. Power Consumption.

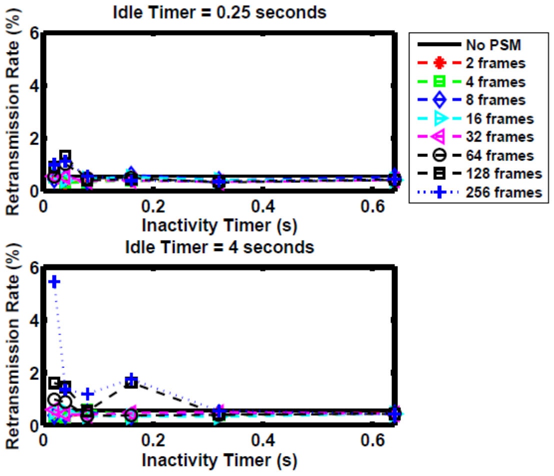


Fig. 4. TCP retransmission rate.

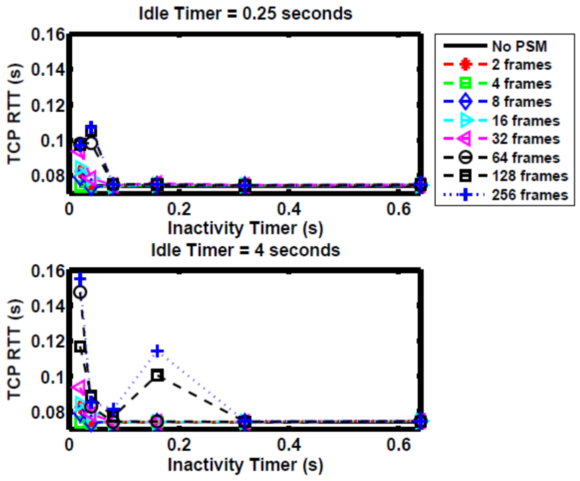


Fig. 5. TCP Round Trip Time (RTT).

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 6).

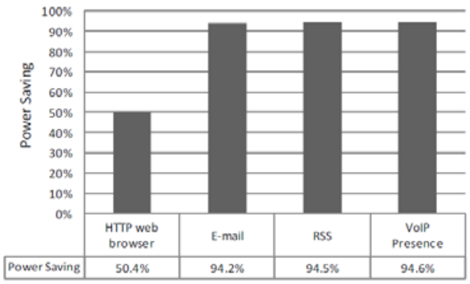


Fig. 6. Power saving on Mixed Sleep Mode/ Idle Mode (parameters defined by full factorial analysis).

6. Conclusions

This paper proposes evaluating the joint performance, in terms of power savings and QoS degradation, of both Mobile WIMAX (802.16e) PSMs, namely Sleep Mode and Idle Mode, 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 after the employment of 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 the energy savings on dynamic simulation scenarios with multiple MSs, multiple traffic patterns and realistic channel simulation. Then, we will continue to study the efficiency of PSM investigating methods to automatically determine optimal PSM parameters for a given observed scenario (e.g. via Machine Learning techniques).

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