Joint Optimization of Power Saving Mechanism in the IEEE 802.16e Mobile WiMAX

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Abstract—The IEEE 802.16e mobile WiMAX technology aims to provide with an energy efficient communication platform for various mobile applications. In the standard, the sleep mode feature with three Power Saving Classes (PSCs) is designed to compensate for the power saving as the target. Prior work has shown that the proposed Markov Decision Process (MDP) approach can achieve the optimal performance in terms of energy consumption and packet delay through the optimal PSC selection. In this paper, we further consider the design of when to sleep and how to sleep in the system to achieve better tradeoffs between the switching frequency during idle mode and mean power consumption in overall. First, we present our optimal timeout scheme designed based on the previous proposed MDP approach, which can help the system determine when to sleep as well as how to sleep optimally with less switching frequency intuitively. To guarantee the optimality, we show the equivalency of the MDP approach and our optimal timeout scheme that both can achieve the optimal performance in terms of energy consumption level. Also, we demonstrate the performance of our proposed scheme through numerical analysis and validate it with simulation experiments using ns-2 compared with the MDP approach. Finally, we evaluate the impact of Poisson and non-Poisson traffic on our proposed optimal scheme.

Index Terms—Energy-efficiency wireless, IEEE 802.16e, mobile WiMAX, timeout scheme, Markov Decision Process, sleep mode, power management and optimization.

I. INTRODUCTION

Minimizing energy consumption in battery-powered mobile devices is utmost important in broadband wireless network technology. As the IEEE 802.16e [1] standard known as mobile WiMAX continues to its convergent direction in the industry, designing a mobile system with high energy efficiency to provide with QoS guarantee for various applications is a duty-bound work in our research community.

In the past couple years, researches have been dedicated in studying and developing the best-fit power saving mechanism for the mobile WiMAX platform. According to the original standard, the sleep mode feature has been adopted to be the key solution to power saving. In the sleep mode operation, three Power Saving Classes (PSCs) of type I, II, and III are available to save the energy consumption based on the different types of traffic. These three PSCs are differed with their growth of sleeping windows. For PSCs of type I, the size of sleeping window is doubled each time when no traffic is detected. It grows exponentially until it reaches the maximum allowable size. For type II and III, the sleeping window is constant. The only difference between these two is that the sleep mode in type III contains one sleeping window only, while type II allows the station to stay in the sleep mode with the same sleeping window when no traffic is sensed.

Referring to the standard specification, it does not provide any algorithm on deciding when a mobile station should go to sleep mode, as well as which class it should pick to optimize the performance such as the delay, energy consumption, and sleep ratio. Previously, a well-known "timeout" scheme was studied to illustrate the different timeout values which can affect the system performance significantly [7]. When running this scheme, after a certain time interval when no traffic arrives, the system will switch to sleep mode. Indeed, this scheme can be categorized as a static approach, meaning the timeout value is predetermined before switching to the sleep mode. However, this static timeout scheme can only solve the problem of when to perform the sleep mode switching. At the end, the system still does not know which PSC should choose after the timeout.

Because of the inadequacy of timeout scheme, an optimal solution was proposed known as the Semi-Markov Decision Process (Semi-MDP) approach [8] to investigate the optimal PSC selection issue. Originally, the problem was formulated as a policy optimization (PO) problem under uncertainty subject to certain constraints such as delay and energy cost. Then later on, a novel PO solver algorithm [9] was proposed to search for the optimal policy for choosing PSCs in a more efficient way. Through this MDP approach, we were able to determine the optimal PSC selection based on the energy and delay constraints.

Yet, one downside of this approach is to introduce the frequent switching during the idle mode due to the high frequency of decision making. Therefore, we further extend the work and propose a joint optimal scheme in this paper so that a mobile station can know how long it should be waiting before making the decision to sleep. With less switching frequency, a system can still achieve the optimal performance but with higher efficiency in short run. In this paper, our main target is to join studying the two schemes and show the equivalence between the pure MDP approach and our proposed optimal scheme in terms of energy consumption. Through comparative study, we will demonstrate the performance of the proposed scheme and compared with the previous approach through numerical analysis and simulation using ns-2. In our definition,
we emphasize that this is a joint scheme because we involve MDP-based PO algorithm and the traditional timeout scheme in our run-time approach for the system optimization.

The rest of this paper is organized as follows. In section II, we briefly mention the recent related works. In sections III, summary of the previous models are discussed. Then, we propose a joint optimal timeout scheme to take the advantages of two schemes in section IV. Afterward, we present our numerical and simulation results in section V. We will conclude this paper in section VI.

II. RELATED WORKS

The IEEE 802.16e provides with flexible PSCs that are able to deal with different service requirements. Many research works have been done on the sleep mode operation. Several of them have served as the foundation of our proposed schemes. In [2] and [3], the authors propose an analytical model of PSC of type I to capture the energy consumption levels including both incoming and outgoing frames. This is the founder of sleep mode operation research as it sets the fundamental model for analysis. Similar to another well-known proposed analytical designs [4] and [5], these works provide with the performance analysis on the original PSC of type I with a brief discussion of how the effect of selecting different operational parameters. However, they were unable to resolve the issues of when to sleep and how to sleep both at the same time.

More recently in [6], we studied the decision making during the sleep mode with PSC of type II to allow the system to wake up at an appropriate stage with certain QoS guarantee by taking the consideration of buffer overflow, delay requirement, and power availability in the system. A novel heuristic algorithm has been proposed to accommodate our target. But different from this current work, the study only focuses on the decision making once the sleep mode has been activated.

In [7], type I and type II were first considered together by conducting a performance study based on the static timeout scheme. Still, this study was not yet ready to solve the issue related to how a mobile station should sleep. Later on, an optimization problem through the MDP approach was formulated in [8] and [9] to solve the issue related to the selection of PSCs using our novel PO solver algorithm. This is the first work in the field of study investigating the optimal choice of PSC. The result shows the validity of the algorithm that helps a mobile station achieves an optimal performance in terms of energy efficiency and delay requirements. To recall our introduction, the mechanism in the work has introduced a frequent switching during the idle mode, which may not be ideal in the short term. More specifically, the randomized decision of system state (normal mode, PSCs of type I, PSCs of type II) in the MDP approach is repeatedly made when the system becomes idle.

Therefore, we aim to extend the concept of the static timeout scheme and MDP approach to form a new joint optimal scheme to address such issue and demonstrate the equivalent optimality of both scheme on average. With this extension, the optimal PSCs selection can be decided in an optimal time instance (optimal timeout value) and the switching frequency can be reduced intuitively. The performance is surprisingly excellent in terms of optimality of energy efficiency. In this paper, we follow our previous rationale [7] to include the PSC of type I and II together in our experiment. Like most of the literatures, type III has no research interest because of its purpose of usage. Thus, we will not consider it in our experiment as well.

III. BACKGROUNDS

In this section, we give a brief review about our previous two schemes, which are the foundation of our comparative study.

A. Static Timeout Scheme

Typically, power managerial algorithms define a control procedure depending on some observations and/or assumptions on the workload. The control procedure is often referred to as policy. An example of a simple policy is the timeout policy, which shuts down components after a fixed inactively time, under the assumption that a component is likely to remain idle if it has been idle for a period of time equal to the timeout value. Because of its simplicity and efficiency, we have adopted this static scheme into our investigation and compare it with our MDP approach.

In the previous work [7], an extensive numerical and performance analysis has been done to model the system as an embedded Markov Chain for PSC Type I and Type II based on a static approach scheme called timeout scheme. This scheme has been recognized to be commonly adopted mechanism for power saving management in networking. The scheme usually works with a basic value called timeout value. This timeout value defines when the system should power down itself and begin the sleep mode. Usually, the value is counted down when the system is in idle, meaning no incoming traffic is detected. When the timeout value expires, then the system will go to sleep until the next wake up period. The details of the Markov Chain analysis are out of the scope of this paper, and can be referred to the original work.

Intuitively, one can design a static timeout scheme based on the traffic demand so that the waiting time during idle mode becomes the most appropriate setting. Yet, this static scheme is incapable in finding the best PSC in coherence with the traffic patterns. In other words, a mobile station may end up choosing a sub-optimal decision that leads to unnecessary waste of energy. Thus, the MDP approach comes into place to attempt for the solution.

B. MDP Approach Scheme

Previously, semi-MDP framework and the stationary controllable Markov model were proposed in [8]. In the paper, it shows the MDP model on the IEEE802.16e sleep mode operation. Based on the MDP definition, it captures the system as a three-state space set $I = \{S_N, S_1, S_{II}\}$. Each state represents the normal mode, sleep mode of type I, and type...
II, respectively. In addition, we define \( R \) as the policy (either randomized or deterministic). In this MDP approach, a MSS chooses an action \( a \in A = \{ s_{-N}, s_{-I}, s_{II} \} \), where each action has an intuitive meaning of “switching to normal mode”, “switching to type I”, and “switching to type II”, respectively. In this model, the MSS makes decision whenever it is idle.

The main goal of the model is to find out the optimal policy \( R^* \) through assigning optimal values among these controllable transitions. Policy \( R \) is written as the solution set of all controllable probabilities, namely, \( \{ x_i(a), \forall i \in I, \forall a \in A \} \), where \( x_i(a) (0 \leq x_i(a) \leq 1) \) is known as the state-action frequencies or distribution. It has the following intuitive interpretation: Given the total number of decisions issued in state \( i \), \( x_i(a) \) is the expected proportion of frequency that command \( a \) is selected. Thus, \( x_i(a) \) satisfied \( \sum_{a \in A} x_i(a) = 1 \) for any given \( i \in I \). In our model, decisions do not occur in sleep mode, which means \( \forall i \in \{ S_I, S_{II} \}, x_i(a) = 0 \). Thus, \( R \) becomes a 3-tuple \( \{ x_{SN}(s_{-N}), x_{SN}(s_{-I}), x_{SN}(s_{II}) \} \). With the definition of our model, we have successfully obtained the steady state probability for all the stages under the policy \( R \) [8]. For the resource-constrained MSS in the runtime environment, a light-weighted algorithm called Policy Optimization (PO) Solving Algorithm (PO Solver) has been proposed. By exploring the PO structure, optimal station-action frequencies can be produced [9].

IV. JOINT OPTIMAL SCHEME FOR THE RUNTIME ENVIRONMENT

Before solving the issue related to how to sleep, a prerequisite is to determine when to sleep. Surely, the static timeout scheme provides an immediate solution about when to sleep. But, the type of PSC needs to be predetermined in advance as the system does not have a mechanism to adaptively choose the types of PSC for sleep mode. On the other hand, the system running our MDP approach makes a decision whenever it is idle. Yet, one problem about this design is to introduce the frequent switching when the normal mode is chosen. In order to leverage the downsides of these two scheme, we propose a novel joint optimal scheme for the runtime environment so that an optimal timeout value can be obtained while the type of PSC is chosen optimally as well.

Indeed, it turns out that a minor modification at the previous approach has led to a new scheme which is equivalent to the MDP approach in terms of energy efficiency. Since we integrate the concept of timeout scheme into the MDP approach, we call our proposed scheme as joint optimal timeout scheme.

Our joint optimal scheme consists of three major components:

1) Optimal Timeout Value
2) Conditional Probability of PSC Selection
3) Traffic Estimation

In Fig.1, it illustrates our proposed scheme as a flowchart, which guides us how the protocol should be implemented in a real-time environments. Simply speaking, the system runs as usual until it becomes idle. Then an optimal timeout value is calculated using Equation 1 based on the result from the PO Solver that gives the \( R^* \). The system will enter to timeout period like the static scheme using this optimal timeout value. At the end if traffic is not detected, the system will choose either type I or type II based on the calculated conditional probability. In fact, our PO Solver requires a \( \lambda \) input for the algorithm. To further enhance the scheme to be a standalone systematic plan of action, we simply make use of an existing traffic estimator to approximate the traffic rate. In the following, we will explain the components in details.

A. Deriving the Optimal Timeout Value

In Fig.1, we see that policy \( R^* \) is first produced from the PO solver and then fed into the Policy Releaser and Timeout modules. To recall in the earlier section of this paper, a mobile station remains in \( S_N \) with probability \( (1 - e^{-\lambda \alpha}) \) under the static timeout scheme [7]. This transition probability can be regarded as equivalent to the transition probability associated with command \( s_{-N} \). In other words, \( 1 - e^{-\lambda \alpha} = x_{SN}(s_{-N}) \). With this equation, we can derive the optimal timeout value \( \alpha^* \) in the following way,

\[
\alpha^* = \frac{1}{\lambda} \ln \frac{1}{1 - x_{SN}(s_{-N})},
\]

which is a function of state action frequency \( x_{SN}(s_{-N}) \) and traffic rate \( \lambda \). Note that if \( x_{SN}(s_{-N}) = 0 \), \( \alpha \) becomes 0.
meaning the switching to sleep mode is immediately followed by the first instance of being idle.

B. Conditional Probability of PSC Selection

Now, this $\alpha^*$ will tell us when the MSS should switch to sleep mode based on the timeout mechanism. The next step is to derive the conditional probability to choose either type I or type II after the system being idle for a period of $\alpha^*$. Since we have already considered the probability of being in the normal mode when we calculate $\alpha^*$, choosing between type I and type II becomes conditioned on going to sleep. Suppose $p_I$ and $p_{II}$ are the conditional probability of choosing type I and type II, respectively. Based on the knowledge of $R^*$, we can find $p_I$ and $p_{II}$ as follows:

$$p_I = \frac{x_{SN}(s_{-I})}{x_{SN}(s_{-I}) + x_{SN}(s_{-II})},$$  \hspace{1cm} (2)

$$p_{II} = \frac{x_{SN}(s_{-II})}{x_{SN}(s_{-I}) + x_{SN}(s_{-II})},$$  \hspace{1cm} (3)

Therefore, the Eqs.(2) and (3) will determine which type of PSCs the MSS should pick after the $\alpha^*$ period of time. In the section V, we will implement this new optimal timeout scheme and compare with the PO randomized method to show the equivalent optimality of both schemes.

C. Traffic Estimator Implementation

The paper [10] presents a traffic rate estimation method of the QoS-enabled Internet, employing a flip-flop filter that measures actual changes in the characteristics of a traffic flow in a timely and accurate manner, while ignoring short term variations or spikes in the traffic flow. Because of the nature of the algorithm, agility and stability of the system can be achieved. For the details of how the estimator works, we can refer to the paper [10]. It is fair enough for this research work to know how to integrate this algorithm into our PO Solver and obtain a $\lambda$. Finally, Fig.1 is the whole architecture of our power saving scheme in IEEE 802.16e, by incorporating the traffic estimator and the MDP module.

V. PERFORMANCE EVALUATION

With the previous two complete models, we want to perform an evaluation based on the running of these two schemes.

A. Simulation Settings

In our comparative study, we have developed a ns-2 version of simulator based on the actual MAC/PHY layer of the IEEE 802.16e to simulate our performance results so as to illustrate and validate the accuracy which is closer to the original standard. In addition, we have made use of the actual mobile WiMAX chipset information [11] to simulate our results again for the accuracy.

Based on the previous study, we setup up a similar topology and investigate the timeout scheme that portrays the expected energy consumption and mean packet delay using this newly developed module.

For other simulation setting for MAC and Physical layer such as DL/UL ratio and Spectrum, we follow the work by [12]. These settings are commonly used in the WiMAX network simulation. In our simulation model, we construct a simple topology that contains one BS and one MS.

B. Simulation Results and Discussions

Fig.2 and Fig.3 show the performance of type I and type II. After the traffic intensity threshold, longer timeout value may prevent the system to be switched to sleep mode easily. This is the case for both type I and type II. Type II seems to be able to adopt higher traffic intensity compared to type I since type II is not adapted to have deeper sleep. When the system goes into sleep mode, it can be switched to normal mode easily so that it is not wasting much energy during the sleeping stage, listening stage, and switching period. Indeed, longer sleeping does not mean no energy consumed. On the other hand, the traffic intensive period requires frequent switching. It seems to be better to have the system to stay in the normal mode.
In Fig 4, it shows the power consumption level when a system runs on the MDP approach with a static choice of single mode for all $\lambda$. To recall from the previous section, $R^* = \{x_{SN}(s_{\pi N}), x_{SA}(s_{\pi I}), x_{SR}(s_{\pi II})\}$. In other words, a system with $R = \{1, 0, 0\}$ will give the result of running on normal mode all the time. For MDP approach with pure type I and II, $R = \{0, 1, 0\}$ and $R = \{0, 0, 1\}$, respectively. This is exactly what happens in Fig.4. Contrarily, if we perform the PO solver to generate the optimal $R^*$, we can see the optimality in the results. It is exactly what we expect since the MDP approach always perform the best in terms of choosing an appropriate system mode based on different $\lambda$. Note that this is an average performance over 1000 simulation runs. Thus, it can confirm that the MDP approach does perform optimally.

In Fig 5, it shows the ultimate result that with the PO solver to come up with the optimal timeout value with sleep mode decision policy. It is clearly that it also performs optimally compared with the pure MDP approach in terms of the energy efficiency. Thus, our proposed joint optimal scheme is the optimal solution for the mobile WiMAX system to know when to sleep and how to sleep with less switching frequency. In addition, we plot the Fig 5 with the 95% confidential interval (CI) calculated to verify to validity of our simulation to be within the range.

In Fig 6(a) and Fig 6(b), we intend to compare our joint optimal timeout scheme, which allows randomized choice of PSCs, with the static timeout scheme, which only allows a preset PSC in advance. Clearly, the optimal timeout value is intelligently chosen based on the traffic demand to achieve the highest efficiency in the power saving. By comparing with the static scheme, we observe that our joint optimal scheme requires no tuning of timeout value and PSC selection and beats all settings of the static scheme. Thus, our proposed methodology can accurately estimate an optimal timeout value for each traffic rate that serves as the key element in our scheme based on our experiments.

C. Performance Impact of Poisson and Non-Poisson Traffic

With the state-action frequency distribution, it tells us the optimal policy that helps the MSS determine when it should choose the different modes. In order to show the energy efficiency, we have experimented this MDP approach scheme using ns-2 to demonstrate the performance of this novel scheme.

In our ns-2 simulation, we will follow all the settings in the previous performance evaluation section to preserve the consistency. The simulation time is 400 seconds. The total numbers of run is 1000. The energy consumption is averaged over these 1000 runs, thus the 95% confidence interval can be obtained. The setting for simulating the voice traffic is based on [13], which uses the GSM 6.10 codec represented as the common on/off model. For the data traffic, we simply generate a file downloading from the BS to the MSS based on Poisson arrival. Throughout our simulation, we follow the downlink traffic only. At the end, the normalized traffic intensity is estimated through the help of the traffic estimator [10].

In Fig 7, we show the mean energy consumption using simulations for both Poisson and non-Poisson traffic. Also, it is interesting to see that the 95% CI for both results are the same. Clearly, our proposed algorithm performs well when adapting to different kinds of traffic. In other words, our MDP model and PO solving algorithm are based on Poisson distribution, and yet it is suitable for non-Poisson traffic. As we can observe from the figure, the performance of the two kinds of traffic is the same when the $\lambda$ is obtained accordingly. This is a
Poisson and non-Poisson investigation can be referred to [9].

significant result which makes our MDP approach applicable to all kinds of traffic nowadays. Partial discussion related to Poisson and non-Poisson investigation can be referred to [9].

VI. CONCLUSION

In this paper, we focused on the comparative study between two proposed schemes, namely the static timeout scheme and MDP approach, related to the sleep mode operation. We presented a brief review of these two schemes and underline their distinctive key features. Afterward, an existing traffic estimation method was implemented in our Policy Optimization (PO) algorithm to provide with an estimated traffic rate so that the algorithm can become self-contained in the runtime environment. With the assistance of PO, we developed a joint scheme with an optimal value of timeout value to show the uniqueness of this algorithm to the design of runtime implementation. All the results were verified with both numerical and simulation results that shows the optimality of our proposal. In addition, our case will not suffer the curse of dimensionality mainly because of the small state space. Therefore, our proposed joint optimal scheme is the best solution with optimal policy as well as the timeout value to allow the MSS to know when to sleep and how to sleep with less switching frequency.

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