Comparative Analysis of Sleep Mode Control Algorithms for Contemporary Metropolitan Area Wireless Networks

Alexey Anisimov[1], Sergey Andreev[2], Olga Galinina[3], and Andrey Turlikov[4]

H&NM Motorola Software Organization[1], RUSSIA
alexey.anisimov@motorola.com
Tampere University of Technology[2] (TUT), FINLAND
sergey.andreev@tut.fi
Speech Technology Center[3], RUSSIA
olga.galinina@gmail.com
State University of Aerospace Instrumentation[4] (SUAI), RUSSIA
turlikov@vu.spb.ru

Abstract. Recently, broadband wireless networks, such as IEEE 802.16 [1] and LTE, receive more and more attention from the researchers. Increasing the energy efficiency of the end clients in these systems is an important research task and the evaluation of the energy efficient mechanisms remains an open problem. In this paper we consider the sleep mode control algorithm of the novel metropolitan area networking standard, known as IEEE 802.16m. Also we introduce an alternative enhanced algorithm that contains the features described by the previous standard versions. We compare the sleep mode performance under the control of both standard and proposed algorithms for different arrival flow types and QoS restrictions. A relation between the parameters of the proposed algorithm and the standard IEEE 802.16m algorithm is also established.

Keywords: IEEE 802.16, wireless network, energy efficiency, sleep mode.

1 Introduction and Background

Nowadays wireless networks receive increasing research attention due to the growing number of such networks and their clients. One of the core advantages provided by the wireless technology is the mobility of the end clients. However, mobile clients have limited battery power. For that reason, contemporary wireless networks impose additional restrictions on the energy efficiency of their clients. In this paper we conduct a comparative analysis between the various modifications of the sleep mode control algorithms for IEEE 802.16 standard designed specifically to increase the energy efficiency of the end clients.

IEEE 802.16 standard defines a high speed wireless access system with support for various multimedia services. The standard contains specifications of

Media Access Control layer (MAC) and of Physical layer (PHY). There are several possible realizations of the PHY layer. However, the most popular one is Orthogonal Frequency Division Multiple Access (OFDMA) [2].

Originally, IEEE 802.16 [3] has been designed for fixed Subscriber Stations (SSs), but the most recent IEEE 802.16-2009 standard [1] has support for mobile clients (Mobile Stations, MSs). Therefore, power saving is one of the constitutive issues and increasing client energy efficiency is an important objective.

There are several proposals to make sleep mode operation more flexible and more effective [4], [5]. These proposals can be included into the future IEEE 802.16m standard [6], which is currently being processed for standardization. The most part of existing research papers considers sleep mode defined by IEEE 802.16-2009 standard. Zhang and Fujise [7] provide an analytical model to calculate the power consumption during the sleep mode. The model takes into account both types of traffic: downlink and uplink. However, the model estimates power consumption during a sleep period only (without awake periods) and packet delay is not taken into account. In [8] the authors consider the average power consumption and the average delay under the sleep mode operation (including awake period). Moreover some information is provided about sleep mode parameters influence on the average delay and on the average power consumption.

Another research direction is summarized in [9]. The authors provide full analysis of the sleep mode operation for the efficient power saving mechanism and delay-guaranteed services. They use the M/GI/1/K queueing system with multiple vacations. Moreover, optimal parameters for sleep mode operation are presented. However, this analysis considers the sleep mode operation of IEEE 802.16-2009 standard. In [10] sleep mode operation proposed by Samsung for IEEE 802.16m is analyzed. There only power consumption is considered without any delay analysis. One more option to increase client energy efficiency is scheduling mechanism improvement. It is considered in [11].

The rest of the paper is organized as follows. In Section 2 we detail the sleep mode operation as described by various versions of IEEE 802.16 standard, including the proposed algorithm. Section 3 introduces the simulation methodology we follow to assess the performance of the sleep mode control algorithms. The obtained simulation results are presented in Section 4. Finally, Section 5 concludes the paper.

2 Sleep Mode Description

The most recent version of IEEE 802.16 standard [1] defines two energy efficient operation modes, namely, sleep mode and idle mode. Idle mode is used by the client's MS in between data transmission sessions. By contrast, sleep mode is used during a data transmission session. In the idle mode an MS closes the network connection, which should be re-established to proceed with data transmission and/or reception. In what follows we concentrate on the sleep mode, whereas the idle mode is considered in [12].

The main property of the sleep mode operation is that an MS alternates listening and sleep periods with predefined durations. During a sleep period the MS temporarily switches off its radio interface and, consequently, reduces own energy consumption. The set of parameters for the sleep mode control algorithm is termed a Power Saving Class (PSC). According to the standard there are three types of PSC. PSC of type I defines the sleep mode with the variable sleep window. This type of PSC is recommended for Best-Effort (BE) and Non-Real-Time Variable Rate (NRT-VR) connections and it specifies the following parameters:

- Listening window size, L.
- Initial sleep window size, S_1.
- Maximum sleep window size, S_{max}.

PSC of type II defines sleep mode operation with the constant sleep window size and is recommended for Unsolicited Grant Service (UGS) and Real-Time Variable Rate (RT-VR) connections. As such, the only parameters of this type of PSC are:

- Listening window size, L.
- Sleep window size, S.

PSC of type III specifies a single sleep period after which an MS resumes its normal active operation.

An example operation of the sleep mode for IEEE 802.16-2009 is given in Fig. 1. In order to initiate the sleep mode an MS sends a request to the Base Station (BS). In its response the BS specifies the time instant starting from which the MS may enter the sleep mode. During the listening periods the BS notifies the MS about the buffered data, if any, destined to this MS. If the BS outgoing buffer is empty, the MS may continue with the next sleep period. Therefore, for the PSC of type I the following sleep window size is given by:

$$S_i = \min(2 \cdot S_{i-1}, S_{max}), \tag{1}$$

where S_{i-1} is the size of the previous sleep window and S_{max} is the size of the maximum sleep window.

When BS notifies the MS about the buffered data, the MS exits the sleep mode and the downlink data transmission starts. In case of PSC of class II data transmission may take place during the listening period without explicit termination of the sleep mode by an MS. As such, the MS exits the sleep mode when the listening period duration is insufficient to transmit all the pending data packets.

Today the novel version of the standard IEEE 802.16m is nearly being completed. It will incorporate several important extensions and amendments, including the advanced sleep mode control. An example operation of the modified sleep mode control algorithm is presented in Fig. 2. The operation time is broken into the sleep cycles. Each cycle comprises a listening period and a sleep period with the exception of the first cycle, which contains only a sleep period. Denote the

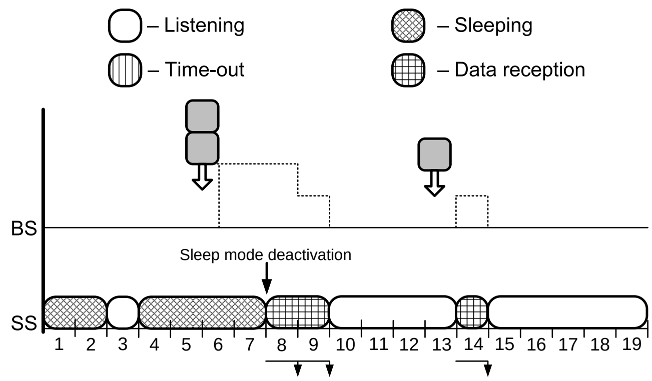

Fig. 1. IEEE 802.16-2009 sleep mode operation example.

duration of the i-th sleep cycle by C_i and the durations of listening and sleep periods by L_i and S_i, respectively. For PSC of type I the duration of the sleep cycle is variable. The duration of the following sleep cycle is calculated exactly as in the legacy IEEE 802.16-2009 standard.

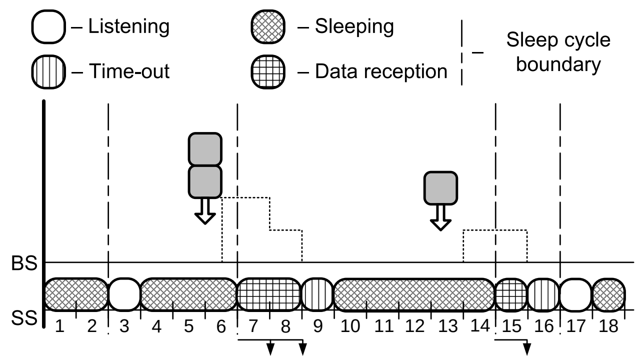

Fig. 2. IEEE 802.16m sleep mode operation example.

One major improvement in the sleep mode operation of IEEE 802.16m is that the data transmission may occur without explicit termination of the sleep mode regardless of the PSC type. Therefore, the duration of the listening period increases either until all the pending packets are transmitted to the particular MS, or until the sleep cycle ends. In case of PSC of type I the duration of the sleep cycle is reset to its initial value of C_1. The MS enters the sleep mode either when BS notifies it that the outgoing packet buffer is empty, or after a time-out value T expires after the last data packet transmission.

Below we propose and evaluate an alternative sleep mode control algorithm as a possible candidate for consideration by IEEE 802.16m standard. This algorithm is a combination of those defined by IEEE 802.16-2009 and IEEE 802.16m versions of the standard. An example operation of the proposed algorithm is shown in Fig. 3. On the one hand, the main difference between the new algorithm and the legacy one of IEEE 802.16-2009 is that an MS does not terminate the sleep mode during the reception of data packets. On the other hand, the difference from the IEEE 802.16m sleep mode control is that there is no explicit division into the sleep cycles.

According to the IEEE 802.16m sleep mode control algorithm an MS always knows when the following sleep cycle starts. In the proposed algorithm the start time of the next sleep cycle is unknown. This is explained by the fact that for the IEEE 802.16m algorithm the data transmission time is included into the overall sleep cycle duration, whereas in the proposed algorithm the respective time is not included.

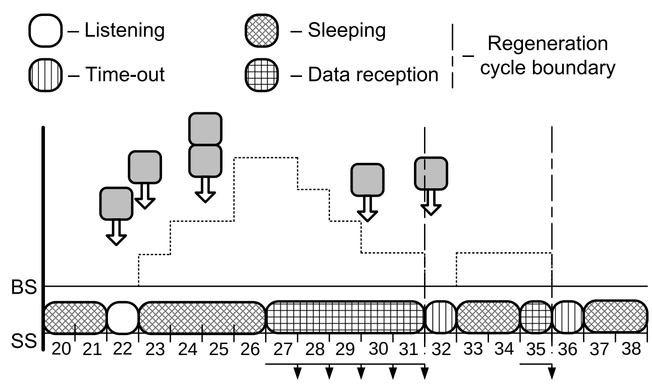

Fig. 3. Proposed IEEE 802.16 sleep mode operation example.

Clearly, the sleep mode operation not only decreases the power consumption of an MS, but also increases the data packet transmission delay. Therefore, one should account for both performance metrics, when analyzing the efficiency of the sleep mode operation.

Several metrics may be used to assess the energy efficient performance of the system. Below we consider two main options. Firstly, we account for the number of bits that may be received successfully by spending one Joule of energy. This value is measured in bits per Joule [13]. Additionally, we consider the reverse value, that is, the number of Joules to receive a bit reliably. Secondly, we account for the energy efficiency coefficient [14]. This coefficient shows, which part of total operation time an MS resided in the sleep state and may be calculated as follows:

$$\eta = \lim_{t \to \infty} \frac{T_S}{T_S + T_A}, \tag{2}$$

where η is the energy efficiency coefficient, T_S is the amount of time the MS spent in the sleep state and T_A is the amount of time it spent in the active state.

In order to simplify the subsequent derivations below we concentrate on the energy efficiency coefficient for the system energy efficiency evaluation. However, the considered model may be easily extended to allow for the consideration of the actual energy efficiency value. To perform this, it is sufficient to account for the packet length value.

Considering the QoS requirements predefined for a particular data flow, one may formulate several optimization problems. We consider a practical optimization task that accounts only for the restriction on the mean packet delay:

Maximize

$$f_\eta(S_1, S_{max}, L, T)$$

under the restriction

$$f_D(S_1, S_{max}, L, T) \leq D_{max},$$

where D_{max} is the mean packet delay.

However, some data flows are also sensitive to the packet delay variation (jitter) at the receiver side. As such, the above optimization task could be extended to account for the explicit restriction on the jitter value.

There are also several alternative optimization task formulations. For instance, instead of the mean packet delay the maximum delay value could be subject to a restriction, or the probability of the event that the delay exceeds some threshold value.

One may establish the maximum energy efficiency coefficient as:

$$\eta_{max} = 1 - \rho, \tag{3}$$

where ρ is the system load, that is the stationary proportion of time during which the server is busy.

3 Simulation Methodology and Analysis

In this section we detail the system model used for the development of the IEEE 802.16m MAC simulator. The model is based on the following assumptions.

Assumption 1. Data transmission between the BS and a single MS is considered.

Assumption 2. The BS has an outgoing data packet buffer of infinite size.

Assumption 3. Only the downlink data flow is accounted for (from the BS to the MS).

Assumption 4. Data packets are served by the BS in the order of their arrival.

Assumption 5. The transmission time of a data packet takes exactly one frame.

Assumption 6. The model accounts for two power consumption levels. Active state consumes the power P_A and sleep state consumes the power P_S.

Below we discuss the assumptions of the simulation methodology. In practice the operation of an MS influences the work of the other MSs. However, this influence is dependent mostly on BS scheduling algorithms. Accounting for the fact that the scheduling algorithm is out of scope of the standard, there are numerous proposals of such an algorithm in the research literature, such as [15], [16] and [17].

All these algorithms are based on the particular set of input parameters. In order to reduce the number of parameters in the developed simulation model it was decided to focus on the system with one BS and one MS. The service discipline is FIFO and the transmission time of a packet equals to a frame duration for the sake of simplicity.

Accounting for the Assumption 5 we rewrite expression (3) as:

$$\eta \leq \eta_{max} = 1 - \lambda, \tag{4}$$

where λ is the mean arrival rate measured in data packets per frame.

Below we introduce a technique to numerically evaluate the mean packet delay and energy efficiency coefficient for the proposed sleep mode control algorithm. This technique uses the regenerative approach from [18]. A regeneration cycle begins when time-out starts, conditioning on the fact that there was no data transmission during this time-out. A cycle ends when BS buffer empties. As such, there is at least one data packet transmission per regeneration cycle. For more details the reader is referred to our previous work [19].

3.1 Mean packet delay analysis

The value of the mean packet delay may be established by the following expression:

$$E[W] = \frac{\lambda \cdot E[X^2]}{2 \cdot (1-\rho)} + \frac{E[T^2]}{2 \cdot E[T]} + W_t, \tag{5}$$

where λ is mean arrival rate, $E[X]$ is the service time, ρ is the system load, $E[T]$ is the estimated time interval between two consecutive data packet transmissions, which are separated by at least one sleep period and $E[T^2]$ is its second moment. W_t is the transmission delay of a packet.

The values of $E[T]$ and $E[T^2]$ may be obtained as follows:

$$E[T] = \sum_{i=1}^{\infty} \Pi_0^{t_{i-1}} \cdot (1 - \Pi_0^{L+S_i}) \cdot t_i, \text{ and}$$
$$E[T^2] = \sum_{i=1}^{\infty} \Pi_0^{t_{i-1}} \cdot (1 - \Pi_0^{L+S_i}) \cdot t_i^2, \tag{6}$$

where t_i stand for the possible duration of a regeneration cycle, that is $t_0 = 0$, $t_1 = L + S_1$, $t_2 = t_1 + L + S_2$, etc. Here $\Pi_0^{t_i}$ is probability that there are no packet arrivals during t_i. In the case of Poisson arrivals it equals to:

$$\Pi_0^{t_i} = e^{-t_i \cdot \lambda}. \tag{7}$$

3.2 Energy efficiency coefficient analysis

The value of the energy efficiency coefficient may be established by the following expression:

$$\eta = \frac{T_S}{T_S + T_A} = (1 + \frac{T_A}{T_S})^{-1} = (1 + \frac{E[m] + \sum_{i=1}^{\infty} i \cdot \Pi_0^{t_{i-1}} \cdot (1 - \Pi_0^{L+S_i})}{\sum_{i=1}^{\infty} S_i \cdot \Pi_0^{t_{i-1}} \cdot (1 - \Pi_0^{L+S_i})})^{-1}, \tag{8}$$

where $E[m]$ is the mean number of packets transmitted per regeneration cycle.

4 Simulation Results

Poisson arrival flow. Consider Poisson arrival flow as an example. Fig. 4 shows the dependence of the energy efficiency coefficient on the mean data packet delay restriction for two sleep mode control algorithms. We notice that the two algorithms demonstrate nearly the same values of the energy efficiency coefficient. We, therefore, conclude that the analysis from our previous work [19] may be applied for both sleep mode control algorithms. However, for the case of the IEEE 802.16m algorithm it is not straightforward to obtain the optimal parameters.

Below we introduce a simple expression to derive the optimal parameters of the IEEE 802.16m algorithm as a function of the optimal parameters of the proposed algorithm:

$$C = \left\lceil \sum_{i=0}^{\infty} (S_e + 1) \cdot \lambda^{i+1} \right\rceil, \tag{9}$$

where S_e is the optimal duration of the sleep period for the proposed algorithm obtained as shown in [19] and C is the optimal duration of the sleep cycle for the IEEE 802.16m algorithm.

HTTP arrival flow. In order to compare the considered versions of the sleep mode control algorithms for different traffic arrival flows, we implemented the HTTP flow model from [20].

Fig. 5 demonstrates the dependence of the energy efficiency coefficient on the mean data packet delay restriction for HTTP arrival flow. As we can see, the proposed sleep mode control algorithm outperforms the standard IEEE 802.16m algorithm. However, increasing the mean delay restriction we notice the convergence between the two algorithms. We note that HTTP belongs to the BE QoS

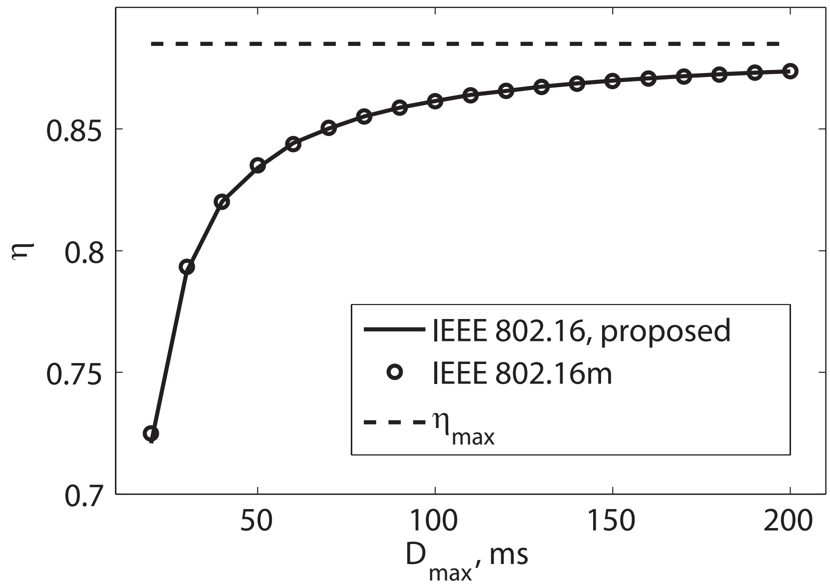

Fig. 4. Energy efficiency coefficient for Poisson arrival flow.

class, which imposes no limitations on the QoS parameters. Therefore, sleep period durations (and, consequently, the delay) may be considerably high. At the same time, the traffic of this QoS class uses the residual bandwidth after scheduling all the other higher-priority QoS classes. Consequently, if MS takes too long sleep periods, the amount of the unused residual bandwidth grows and, as such, system spectral efficiency drops. As a consequence, the economical attractiveness of the system decreases.

By contrast, the proposed algorithm allows for the increase in the energy efficiency coefficient of end clients and at the same time accounts for the service provider interests.

VoIP arrival flow. This flow type imposes a restriction not only on the data packet delay, but also on the jitter value. Accounting for the jitter restriction, the sleep mode control algorithm of IEEE 802.16m standard provides higher energy efficiency coefficient than the proposed algorithm.

5 Conclusions

In this paper we proposed a novel sleep mode control algorithm that is a combination of the algorithms proposed in IEEE 802.16-2009 and in IEEE 802.16m standards. Also we introduced a technique to evaluate the energy efficiency of the sleep mode operation accounting for the QoS restrictions. Additionally, we compared the two considered control algorithms for different traffic arrival flow

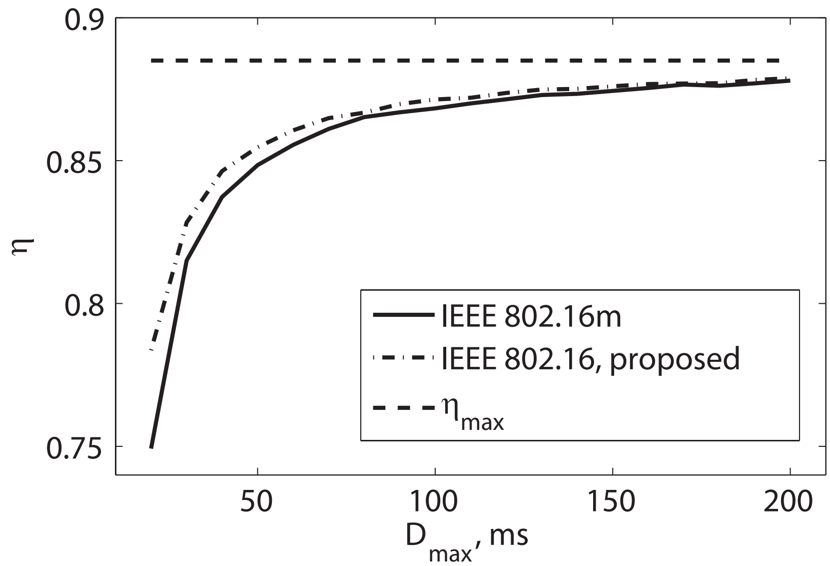

Fig. 5. Energy efficiency coefficient for HTTP arrival flow.

types. We established that for the case of Poisson arrival flow the performance of the two algorithms is approximately the same. Therefore, the method to numerically analyze the performance of the sleep mode described in our previous work [19] may also be applied for the evaluation of the energy efficiency and the mean packet delay for the novel IEEE 802.16m standard. Moreover, a simple relationship between the optimal parameters of the proposed and IEEE 802.16m sleep mode control algorithms was established.

Further, we conducted the comparative analysis of the two considered sleep mode control algorithms for the case of the bursty traffic. As follows from our results, for the case of HTTP traffic the proposed algorithm demonstrates the higher value of the energy efficiency coefficient. In particular, the highest gain of the proposed algorithm is noticed for the sufficiently small values of the mean packet delay restriction. Increasing the value of the mean delay restriction, the energy efficiency coefficients of the two algorithms converge and, in the end, become equal. We also note that HTTP traffic generally belongs to the best effort QoS service class and, as such, has no explicit QoS parameters. At the same time, the use of the high sleep mode durations leads to the decrease in the system spectral efficiency, which contradicts the service provider interests. Therefore, the proposed algorithm accounts for the interests of the end clients (in particular, the reduction in their power consumption and the increase in their operation time), as well as for the interests of the service providers (in particular, preserving the high value of the spectral efficiency).

We also established that the use of the proposed algorithm for the VoIP arrival flow type is impractical, since IEEE 802.16m sleep mode control algorithm demonstrates higher energy efficiency coefficient for this case. We remind that this is due to the fact that VoIP traffic has strong restriction on the jitter value.

Summarizing, we conclude that the proposed sleep mode control algorithm may be used for the bursty traffic without explicit restriction on the jitter value, or when this restriction is rather flexible.

Acknowledgments

This work is supported by the Russian Foundation for Basic Research (projects # 10-08-01071-a and # 08-08-00403-a), as well as by the Branch of Nano- and Information Technologies of Russian Academy of Sciences (project 2.3)

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