Analysis of The Energy Efficiency of Wireless Communication When Receiving A Data Stream

Nafisa Inoyatovna Juraeva¹, Alisher Fayzulla ugli Khayrullaev², Javlon Hoshim ugli Hamraev³

¹Head of Department of Telecommunications Engineering, Karshi branch of Tashkent University of Information Technologies named after Muhammad al-Khwarizmi, Uzbekistan
²Assistant of Department of Telecommunications Engineering, Karshi branch of Tashkent University of Information Technologies named after Muhammad al-Khwarizmi, Uzbekistan
³Assistant of Department of Telecommunications Engineering, Karshi branch of Tashkent University of Information Technologies named after Muhammad al-Khwarizmi, Uzbekistan

Address: Karshi city, Beshkent highway 3 km, Republic of Uzbekistan
E-mail: ¹nafisa0878@mail.ru, https://orcid.org/0000-0001-7459-003X
²alisher.kayrullayev@mail.ru, ³everest_neutral@bk.ru

Abstract. In this article, the tasks of energy efficient operation of a mobile station in wireless communication system were considered. At the same time, the main attention was paid to the consideration of ensuring energy efficient data delivery to the mobile station while meeting the transmission delay requirements. In particular, the operation of a standard power saving mode control algorithm in an IEEE 802.16m network was investigated. Issues related to the functioning of this algorithm when receiving data streams with variable intensity were studied. To conduct such a study, a model of a data transmission system was developed and a universal characteristic was introduced for comparing various control algorithms for the energy saving mode - the energy efficiency coefficient. In addition, an optimization problem was formulated for choosing the parameters of the energy saving mode.

After analyzing the existing control algorithm for the energy saving mode, an effective control algorithm was proposed, the use of which makes it possible to achieve a gain in the energy efficiency coefficient of up to 20% when receiving a data stream with variable intensity.

Key words: energy efficient, IEEE 802.16m, data transmission system, control algorithm, random access memory (RAM), stream receiving case, regeneration cycle, standby mode control algorithm.

Introduction

As wireless data, networks cover more and more areas and the number of their users’ increases, the complexity of their design and implementation increases significantly. First of all, this is due to the mobility of user devices, which requires fundamentally new approaches to issues, the development and operation of modern communication systems. LTE and IEEE 802.16 hold the leading positions in the field of protocols of regional (metropolitan) data transmission networks [1, 2].

Since mobile user devices have a limited power supply, reducing the power consumption of
mobile devices is one of the fundamental research tasks in the implementation of existing and development of new versions of protocols.

The article discusses the most modern protocol for the operation of the IEEE 802.16m wireless data transmission system, developed for mobile user devices and taking into account the peculiarities of their wireless interaction: The urgent problem of energy efficient data transmission control is solved taking into account the timely delivery of data to the user device.

Data transmission is a means of transmitting digital or analog data over a communication medium to one or more devices. It allows the transmission and communication of devices in different environments: point-to-point, point-to-multipoint, or multipoint-to-multipoint.

Data transmission can either be analog or digital, but is mostly earmarked for sending and receiving digital data. As such, data transmission is also referred to as digital transmission or digital communications.

It works when a device aims to transmit a data object or file to one or multiple recipient devices. The digital data comes from the source device in the form of digital bit streams. These data streams are positioned over a communication medium for transmission to the destination device [3, 4, 5]. An outward signal can either be baseband or pass band. Aside from external communication, data transmission may be done internally, between different parts of the same device. The sending of data to a processor from the random access memory (RAM) or hard disk is a form of data transmission.

As the world becomes increasingly digitalised, data centres and data transmission networks are emerging as an important source of energy demand, each accounting for about 1% of global electricity demand. Despite exponential growth in demand for these services, huge strides in energy efficiency have helped to limit electricity demand growth. Sustained efforts by the ICT industry to improve energy efficiency, as well as government policies to promote best practices, will be critical to keep energy demand in check over the coming decades.

**Materials And Methods**

Various aspects of data transmission management are presented in the works of famous domestic and foreign authors (B.S.Tsybakov, V.M. Vishnevsky, A.I. Lyakhov, L. Kleinrok, F. Tobaga, K. Blondia, A.V. Anisimov) ... Recently, a large number of works have appeared on algorithms for energy efficient data transmission control. Despite this, a number of questions remain open. These include taking into account the dynamic nature of the input stream; requirements for the quality of user service, features of the wireless communication channel and other factors. In addition, in a number of works, the disadvantages of common algorithms for energy-efficient data transmission control are noted, but the ways to improve these algorithms are not fully investigated.
The purpose of this article is to reduce the energy consumption of mobile devices by improving existing and developing new algorithms for managing data transmission. The main provisions of the thesis are formulated mainly on the example of the modern protocol of the regional (urban) network IEEE 802.16m. Nevertheless, most of the results obtained can be used in other centralized communication networks, such as Long-term evolution (LTE) [6].

In accordance with the purpose of the article, the following specific tasks were set.

1. To develop models of a data transmission system for studies of typical energy saving modes used in data transmission to a mobile station, and algorithms for controlling these modes.
2. Investigate the most common modes of saving energy of a mobile station when transmitting data from a base station and control algorithms for these modes.
3. Develop ways to select the optimal parameters for typical options for energy conservation.
4. Propose and analyze an effective algorithm for managing the energy saving mode.
5. Develop system models to study the average latency and energy conservation mechanisms when transmitting data from a mobile station.

The paper considers the process of data transmission both from the base station (BS) to the mobile station (MS) and in the opposite direction, from the MS to the BS. Further, in the article for the sake of brevity, where this will not cause ambiguity, when considering the process of transferring data from BS to MS, the term data reception will be used, and for the opposite direction - data transmission. Taking into account modern approaches to organizing data transmission over a wireless communication channel, it should be noted that the amount of energy consumed by the MS for transmitting and receiving data is comparable. It should also be noted that the amount of received MS data is significantly greater than the amount of data transmitted. Based on these facts, the work focuses on the consideration of energy conservation mechanisms when receiving data by a mobile station. As such a mechanism, the so-called sleep mode is considered, which is described in modern standards for mobile data transmission networks and is based on the principle of periodic listening to a radio channel. Figure 2 shows an example of standby operation. As you can see from the figure, the entire operation time is divided into intervals, which are called waiting cycles.

Figure 2. Example of standby operation
The energy efficiency ratio shows how much of the time the MS is in a standby state, that is, the larger the value of this ratio, the more MS energy is saved.

Results
To conduct such a research, a model of the data transmission system is specified in the article. A feature of this model is that it considers the interaction of only one MS with the aircraft. Also, the fact that two levels of energy consumption are taken into account. A high level corresponds to the MS being in an active state, and a low level to a standby state.

IEEE 802.16 technology provides quality of service (QoS) for various types of user data streams. In particular, the main QoS parameter is the data transmission delay. In the work, the delay in the transmission of a data packet is defined as the time interval from the moment this packet arrives in the buffer on the BS to the moment when its transmission over the radio channel ends. Using the standby mode in the process of transmitting data from the BS to the MS, on the one hand, reduces the power consumption of the MS, and on the other hand, increases the data transmission delay. Accordingly, the choice of the sleep mode parameters must be carried out to provide the required value of the data transmission delay [7, 8, 9].

The work introduces the functions \( f_n(S_0, S_{\text{max}}, L, T, \lambda) \) and \( f_D(S_0, S_{\text{max}}, L, T, \lambda) \), which describe the dependence of the energy efficiency coefficient and the average delay on the parameters of the standby mode. Where \( S_0 \) is the duration of the initial waiting interval; \( S_{\text{max}} \) is the duration of the final (maximum possible) waiting interval; \( L \) is the duration of the listening interval; \( T \) is the duration of the timeout period during which the MS continues listening to the radio channel, if data was received in the previous frame; \( A \) is the average intensity of the received data stream.

In this paper, the following optimization problem is formulated and solved.

Maximize \( f_n(S_0, S_{\text{max}}, L, T, \lambda) \) with restriction \( f_D(S_0, S_{\text{max}}, L, T, \lambda) \leq D_{\text{max}} \), where \( D_{\text{max}} \) is the maximum allowable average delay. The energy efficiency factor using the IEEE 802.16m standard control algorithm is calculated using the following formula

\[
\eta_{\text{Im}} = \frac{\sum_{i=1}^{C-1}(C-1)\pi^{i}(0,R)}{\sum_{i=1}^{C-1}(C-1)\pi^{i}(0,R)+\sum_{i=1}^{C-1}i\pi^{i}(0,R)+\sum_{i=0}^{C-1}i\pi^{i}(j,R)}
\]  

(1)

Thus, the functions necessary for solving the optimization problem can be easily calculated both for the case of receiving a Poisson flow, and for stream receiving case a DSRC flow (flow with variable intensity).

In addition to the method for analyzing the sleep mode of the IEEE 802.16m standard, the paper proposes a method for finding the suboptimal sleep cycle duration for the case of receiving a DBMAP data stream. Since finding the optimal duration of the waiting cycle (at which the requirements for QoS are met and the maximum energy efficiency is observed) is a complex and resource-intensive task, the paper describes an alternative algorithm for choosing the duration of the waiting cycle. This algorithm is based on the use of upper bounds for the function of the average latency versus the sleep cycle duration \( f_D(C) \) when receiving a data stream with a variable rate [10, 11, 12].

In the region of low intensities (up to 0.2 packets / frame), the function of the average delay observed when receiving a DSRC stream is used as an upper estimate. In the region of higher intensities, such an estimate ceases to be the upper one; therefore, the function of the average delay observed when receiving a Poisson stream with the intensity \( \lambda_{\text{ON}} \) is used as an upper estimate. The use of the estimates described above allows you to choose such a value of the sleep cycle duration at which the compliance with the data transfer delay requirements is guaranteed and the loss in energy efficiency ratio will be less than 2.5% (compared to the optimal sleep cycle duration).

The article introduces a new control algorithm standby mode, which takes into account largely such a property of modern data streams as uneven packet arrival in time. In what follows, the proposed standby mode control algorithm will be called modified, and the IEEE 802.16m standard control algorithm will be called standard.
The main differences between the modified control algorithm and the standard algorithm are that in this case there is no clear division into waiting cycles. An example of the operation of the modified standby mode control algorithm is shown in Figure 3.

![Figure 3. An example of the operation of the modified standby mode control algorithm](image)

The paper investigates a modified standby mode control algorithm using the model of the data transmission system introduced in the second section. Within this study, the functioning of the data transmission system is considered as a regenerative process. A feature of regenerative processes is their property to constantly return to a certain point of regeneration, from which the further development of the process does not depend on its behavior in the past and is determined by the same probabilistic law. The points of regeneration for the system under consideration are the times when the buffer on the BS becomes empty. The time interval between two adjacent regeneration points is called the regeneration cycle. Note that in one regeneration cycle, one data packet is received as minimum. To calculate the average data transmission delay and the energy efficiency factor, it is sufficient to consider the operation of the data transmission system during one regeneration cycle.

As a result of the study, expressions were obtained for calculating the average delay of data packet transmission and the energy efficiency factor for the case of using a modified standby mode control algorithm (see formulas (2) and (3)).

**Discussion**

The energy efficiency coefficient of the modified standby control algorithm is calculated by the formula

$$\eta_m = \left(1 + \frac{E[G] + \sum_{i=1}^{\infty} i^* A_0^{i-1} (1-A_0^{L+S_i})}{\sum_{i=1}^{\infty} S_i A_0^{i-1} (1-A_0^{L+S_i})}\right)^{-1}$$

(2)

where $E$ is the mathematical expectation of the number of received data packets during the regeneration cycle; $L$ is the duration of the listening interval; $S_i$ is the duration of the $i$-th waiting interval in the regeneration cycle; $A_0$ is the probability that no data packets will arrive in $i$ frames.

The mathematical expectation of the data packet transmission delay under the conditions of using the modified sleep mode of control algorithm is calculated as

$$E[D] = \frac{\lambda E[X^2]}{2(1-\lambda)} + \frac{E[X]^2}{2E[\ell]} = D_t$$

(3)
where \( \lambda \) is the intensity of the received flow; \( E[X^2] \) - the second moment of service of one data packet; \( E[I] \) and \( E[I^2] \) - the first and second moments of the time interval between two subsequent data reception periods, respectively; \( D_k \) (is the data packet transmission time. Note that formula (3) is a generalization of the Pollachek-Khinchin formula for the \( M/D/1 \) system with breaks [12, 13].

The paper also compares the modified standby control algorithm with the standard algorithm in cases of receiving different data streams. When receiving a Poisson input stream, both algorithms demonstrate the same values of the energy efficiency factor with the same constraint on the average data transfer delay. However, in the case of receiving a data stream with a variable rate (for example, HTTP), when using the modified sleep mode control algorithm, a higher energy efficiency ratio is observed than when using the standard algorithm.

The analysis introduces the designation of the random variable \( M^f_{i,j} \) - equal to the number of packets that arrived at the \( i^{th} \) MS in the \( j^{th} \) group per frame with the number \( f \). It is assumed that these values are independent for different frames and have the same distribution. The result of the analysis is an expression for calculating the average data transfer delay:

\[
d_{i,j} = \frac{N_{T_f}}{2(P-E[M_{ij}])T_f} + \frac{E[M_{ij}^2]-E^2[M_{ij}]-E[M_{ij}][N]}{2E[M_{ij}][P-E[M_{ij}][N_T]}}
\]

where \( d_{i,j} \) is the average transmission delay of the \( i^{th} \) MC in the \( j^{th} \) group; \( N \) is the total number of MCs in the system; \( T_f \) - frame duration; \( P \) - number of MCs in one group; \( W_{i,j} \) - time of transmission of one data packet from the \( i^{th} \) MC in the \( j^{th} \) group.

As such methods, algorithms for controlling the transmission power of a mobile station and special algorithms for the scheduler at the BS are considered. These algorithms are currently being implemented as two independent, separate blocks. However, recently now there are new variants of BS operation, in which the coordinated functioning of these two nodes is assumed. In the article, a comparison of the characteristics of the system observed when using one and the other approaches are made.

The characteristics of the system observed in the study of such algorithms strongly depend on the conditions in which the MS are located, therefore, a fairly simple model of the data transmission system is introduced in the article, in which the main attention is paid to the physical layer. Within the framework of this model, the functioning of several neighboring BSs and a set of MSs is considered, each of which is assigned to a particular BS. One of the features of this model is that the data transmission system is considered under saturation conditions, that is, any MS in the system at any time has data to transmit. This approach makes it possible to identify the maximum possible gain in terms of system efficiency.

The proposed model of the data transmission system takes into account the main recommendations of the international research communities and is quite simple, which is expressed in a small number of model parameters. The main parameters of the model include the radius of the cell and the number of MCs in one sector. The values of the remaining parameters were selected in accordance with the recommendations of various research communities. Moreover, the results obtained using the proposed model are quite close to the results of more complex known models.

With the help of the proposed model, special algorithms were investigated for controlling the mobility of MS transmission and the work of the scheduler on the BS. Two mechanisms are considered as such algorithms, one of which maximizes the sum of the energy efficiency of all MS from the system, the other maximizes the product of energy efficiency. In what follows, the first
algorithm will be called arithmetic mean, and the second - geometric mean. For comparison, as the most common set of algorithms, the transmission power control mechanism of the MS, which provides the required signal-to-noise ratio when receiving at the BS. In what follows, this set of algorithms will be called basic.

Compared to the basic set of algorithms, both the arithmetic mean and geometric mean algorithms allow achieving a higher level of system energy efficiency. However, this win is achieved because the resource for data transmission is more often allocated to those MSs that are in conditions that are more different (closer to the BS). The most unfair resource allocation is observed when using the arithmetic mean algorithm [13, 14, 15]. While the geometric mean algorithm demonstrates the most reasonable compromise between the inequity of resource allocation and the energy efficiency of the system.

Conclusions

When obtaining the main results of the work, general methods of system analysis, methods of probability theory, the theory of random processes, in particular, regenerative and Markov processes, the theory of queuing systems, numerical methods of linear algebra, as well as methods of simulation were used.

The scientific novelty of this article is as follows.

1. A model of a data transmission system for analyzing energy saving modes and control algorithms for these modes has been built, which makes it easy to compare different modes and control algorithms for these modes.

2. A method for analyzing the energy saving mode of a mobile station when transmitting data from a base station has been developed, taking into account the change in the intensity of the input data stream over time.

3. An optimization problem is formulated for choosing the parameters of the energy saving mode when transmitting data from a base station and methods for solving it for flows with constant intensity are proposed. An algorithm for selecting nod optimal parameters of the power saving mode of a mobile station when transmitting a data stream with variable intensity from a base station is also formulated.

4. An algorithm for controlling the energy saving mode is proposed, which allows achieving higher energy efficiency indicators when transmitting a data stream with variable intensity to a mobile station.

Acknowledgements

The results obtained in this article allow reducing the amount of energy consumed by the mobile station during data transmission from the base station, which, in turn, leads to an extension of the operating time of the mobile station without additional recharging of the batteries [15, 16].

The low computational complexity of the proposed algorithm for finding nod optimal parameters of the energy saving mode allows organizing its operation on the side of the mobile station and, thereby, avoiding an increase in the load on the base station. At the same time, this algorithm takes into account one of the main advantages of modern data transmission technologies, namely, compliance with the quality of service parameters. In addition, the use of the proposed algorithm to search for nod optimal parameters of the energy saving mode will make it possible to choose the parameter values that are close enough to the optimal ones, for the calculation of which more algorithms that are complex are required. Note that the implementation of the proposed algorithm does not require changes in existing standards, so it can be used in the development of software for mobile.
stations in the IEEE 802.16 network. In addition, this algorithm can be applied with minor changes in LTE technology.

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