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Jinglin Shi
Chinese Academy of Sciences

Gengfa Fang
Chinese Academy of Sciences

Yi Sun
Chinese Academy of Sciences, sunyi@ict.ac.cn

Jihua Zhou
Chinese Academy of Sciences, jhzhou@ict.ac.cn

Zhongcheng Li
Chinese Academy of Sciences

See next page for additional authors

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Abstract

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Keywords

Improving, mobile, station, energy, efficiency, IEEE, 802, 16e, WMAN, burst, scheduling

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Authors

Jinglin Shi, Gengfa Fang, Yi Sun, Jihua Zhou, Zhongcheng Li, and Eryk Dutkiewicz

Improving Mobile Station Energy Efficiency in IEEE 802.16e WMAN by Burst Scheduling

Jinglin Shi, Gengfa Fang, Yi Sun, Jihua Zhou, Zhongcheng Li
Institute of Computing Technology
Chinese Academy of Sciences, Beijing, China
{gengfa.fang, sunyi, jhzhou, sjl, zcli}@ict.ac.cn

Eryk Dutkiewicz
Wireless Technologies Laboratory
University of Wollongong, Wollongong, Australia
eryk@uow.edu.au

Abstract— **In this paper, we tackle the packet scheduling problem in IEEE 802.16e Wireless Metropolitan Area Network (WMAN), where the Sleep Mode is applied to save energy of Mobile Stations (MSs). Our objective is to design an energy efficient scheduling policy which works closely with the Sleep Mode mechanism so as to maximize battery lifetime in MSs. To the best of our knowledge no power saving scheduling algorithms based on Sleep Mode defined in IEEE 802.16e have been proposed so far in the literature. We propose a Longest Virtual Burst First (LVBF) scheduling algorithm which schedules packets of MSs in a virtual burst mode where there is one primary MS and multiple secondary MSs sharing the wireless link resource. LVBF prolongs MSs' lifetime by reducing the average time when MSs stay in the idle state and the number of state transitions between the awake and sleep states. Simulation results show that, in comparison with the round robin scheduling scheme, LVBF can produce significant overall energy saving, while guaranteeing the QoS requirements of MSs in terms of their minimum data rates.**

I. Introduction

Recently, IEEE 802.16 has been standardized to provide a fixed solution for the next generation broadband wireless access networks. IEEE 802.16e [1] provides enhancements to IEEE 802.16 to support mobility of Mobile Stations (MSs) at vehicular speed. Like any other mobile cell systems, energy efficiency of MSs in IEEE 802.16e is a key factor for its application because most of the mobile stations are powered by an energy-limited battery. According to studies [2][3], the main part of the energy consumption of a mobile station is due to its Wireless Network Interface (WNI). Recent studies [4] also show that the battery performance improvement rate in terms of energy per unit size or weight is fairly slow. These accentuate the need for efficient energy management of WNI of MSs.

Sleep Mode has been defined in IEEE 802.16e in order to minimize energy consumption of MSs. When Sleep Mode is enabled, each Sleep Mode supported MS has two states: the awake state and the sleep state. At any time, MSs stay in either the awake state or the sleep state. MSs save energy by turning off their WNI during the sleep state. Before going into the sleep state, a MS should send a MOB-SLP-REQ message to the serving BS and the BS should respond with a MOB-SLP-RES message, which may include parameters of Sleep Mode, such as the initial-sleep window, the final-sleep window base, the listening window and the start frame number for the first sleep window. After receiving the approved response message, MS starts a sleep cycle based on the content of the MOB-SLP-RES message. Each sleep cycle is divided into multiple sleep intervals. Each sleep interval is made up of a sleep window and a listening window as shown in Figure 1. Each next sleep window is twice the size of the previous one but not greater than the specified final value. The listening window is of fixed size. MS wakes up during each listening window to check whether there are packets destined to it. If there are packets to the MS, then it wakes up, otherwise it goes into another sleep interval. The above process continues until eventually the MS wakes up.

Although Sleep Mode defined in IEEE 802.16e can theoretically save MS' energy by putting their WNI into sleep mode, performance of Sleep Mode in terms of energy saving is affected by the following factors. Firstly, services supported by IEEE 802.16e have QoS requirements, such as the minimum rate data services which indicates that MSs cannot be put to sleep for a long time without violating their QoS requirements. Secondly, it takes some extra time and energy to transit from the awake state to the sleep-state and vice versa. The inter-state transition delay indicates that a MS cannot be put to sleep if the time interval between the successive packet transmissions is not long enough. The extra energy during the inter-state transition indicates that we must reduce the number of state transitions between the awake state and sleep state in order to improve energy efficiency. Performance of Sleep Mode in terms of energy efficiency can be optimized by a properly designed scheduling algorithm.

Energy efficiency for battery supplied wireless devices has been studied extensively. In [5], several types of energy efficient mechanisms were designed by trading off energy and other costs associated with the overhead. In [6] and [7], an energy efficient scheduler is proposed with the help of PSM defined in IEEE 802.11. Although it's also an AP centric case, the power management mode is not the same as the Sleep Mode in IEEE 802.16e, so the scheduler is not applicable to IEEE 802.16e. Reference [8] presents a deadline-based priority bulk scheduling (PBS) scheme for streaming applications, however, the problem of scheduling data services is still left to be solved.

In this paper, we propose an energy efficient Longest Virtual Burst First (LVBF) scheduling algorithm. LVBF works in the

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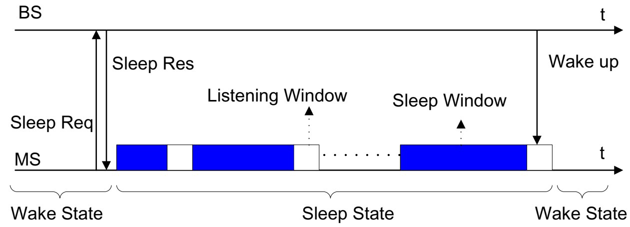

Fig. 1: Sleep Mode in IEEE 802.16e

virtual burst mode during which there are one primary MS and multiple secondary MSs. The primary MS has a higher priority over other secondary MSs in resource allocation, so that almost all the packets of the primary MS almost transmitted in the burst mode. As a result of burst transmission, MSs' lifetime is prolonged for the average time in the idle state and the number of state transitions is reduced. Numerical results are obtained to verify the properties of LVBF.

The rest of the paper is organized as follows. In Section II, system model is introduced and the energy efficient scheduling problem is formulated. In Section III, our Longest Virtual Burst First scheduling policy is presented. Simulation results are given in Section IV which is followed by our conclusions in Section V.

II. System Model

In this paper, we consider the centrally controlled IEEE 802.16e wireless network where there is a single base station (BS) and multiple MSs. TDMA is used in the physical layer where bandwidth is calculated in time slots. The uplink and downlink traffic is separated in the TDD mode and we only use the downlink scenario as a case study where packets are transmitted from BS to MSs. BS maintains a buffer for each MS where packets destined to the MS are buffered and wait to be scheduled under the control of the scheduler in BS. For simplicity, we assume in this paper that the data rate is fixed for all the MSs, although Adaptive Modulation and Coding (AMC) scheme is also supported by IEEE 802.16e and will be considered in future work. We also assume that BS and MSs are well synchronized which allows MSs to go into the sleep state and come back to the awake state precisely when needed. Although different QoS parameters have been defined for various types of services in IEEE 802.16e, such as the maximum latency and tolerated jitter for UGS services, the minimum reserved traffic rate and maximum sustained traffic rate for rtPS and nrtPS an BE services [1], all of them can be mapped into the minimum data rate requirements of MSs. As a result, we apply the minimum data rate as the only QoS requirement of each MS and it has been proven by [9] that the minimum data rate is a sufficient parameter to guarantee MSs' service quality. Next we list some notation used in the rest of this paper and then formulate the energy conserving scheduling problem in the Sleep Mode enabled IEEE 802.16e wireless network.

- M The number of MSs included in one cell system.
- i Index of users in the cell. $i \in (1,2,...,M)$.
- n The index of time slot. $n \in (1,2,...)$.
- r_i^n Data rate in bits per second that MS i has been allocated by time slot n.
- R_i^{min} Minimum data rate in bits per second that user i should receive in order to guarantee its service quality.
- s_i^n State indication of MS i in time slot n. s_i^n is equal to 1 if MS i stays in awake-state in time slot n, and s_i^n equals to 0 if MS i stays in sleep-state in time slot n.
- P_{aw} The average energy consumed in each time slot by each MS in the awake state. In this paper, we assume that no energy is consumed during the sleep state.
- P_{tn} The average energy consumed when MS turns from the awake state to the sleep state or from the sleep state to the awake state.

Because we assume that the time duration and energy consumed in the listening window is very small and negligible, the energy consumed by MS i is decided by the duration when it stays in the awake state and the number of state transitions between the sleep state and the awake state. The overall energy consumed by M MSs by time slot n is:

$$\sum_{i=1}^{M}\sum_{n=1}^{n} s_i^n P_{aw} + \sum_{i=1}^{M} T_i^n P_{tn}. \tag{1}$$

where T_i^n is the number of state transition of MS i by time slot n. Then the goal of the scheduling algorithm is to minimize the average energy consumed by all the MSs, while at the same time guaranteeing the QoS requirements of MSs in terms of their minimum data rates. This can be formulated as:

$$\min \lim_{n\to\infty} \frac{1}{M}\frac{1}{n}(\sum_{i=1}^{M}\sum_{n=1}^{n} s_i^n P_{aw} + \sum_{i=1}^{M} T_i^n P_{tn} \tag{2a}$$

$$s.t.\ r_i^n \geq R_i^{min};\ i = (1,2,...,M). \tag{2b}$$

Obviously, the most optimal result is that there is only one MS in the awake state exchanging packets with BS during any time slot and all the packets belonging to one MS are transmitted successively in order to minimize the overall energy consumed. Unfortunately this may break other MSs' QoS requirements in terms of their minimum data rates. This makes it necessary to design an energy efficient scheduling policy, which well coordinates the sleep mode defined in IEEE 802.16e, so as to improve energy efficiency without violating the QoS requirements of MSs.

III. Longest Virtual Burst First scheduling

In this section, we analyze the energy consumption of MSs and provide some Scheduling Rules, which help to design the energy efficient scheduling scheme. Then our Longest Virtual Burst First scheduling (LVBF) algorithm is proposed based on the analysis and the Scheduling Rules.

A. Energy Consumption Analysis

The total energy consumed by each MS consists of two parts: energy consumed in the awake state and energy consumed for the state transitions as expressed in (1). In this subsection, we aim to compute the average energy consumptions of each MS and to learn some general Scheduling Rules which will guide the design of our energy efficient scheduling algorithm.

The time of a MS is divided into the awake-state duration and the sleep-state duration as shown in Figure 1. For a given K packets of a MS, the scheduler should schedule them in a way that the time spent in the awake state and the number of inter-state transitions is minimized. We define the idle state as the time when a MS stays in the awake state without receiving packets from BS. When a MS stays in the awake state, it is either receiving packets from BS or staying in the idle state. As described above, the energy spent in the idle state is almost the same as that spent while receiving packets from BS. So it is obvious that the time spent in the idle state is a waste of energy for MS. An intuitive solution to this problem is to allocate as much time to the awake state MS as possible so that the awake-state MS is always busy receiving packets from BS. Based on the above discussion, we propose the first Scheduling Rule as:

SR 1: Once a MS transits into the awake state, the scheduler must allocate as many time slots to it as possible in order to make efficient use of the awake-state MSs' energy.

The second cause of the idle state is that a packet from BS to MS was dropped because of transmission errors in the fading wireless channel. To avoid the transmission error, the scheduler may try to transmit packets of MSs whose channel quality is in a good state. Taking this into consideration, we present the second Scheduling Rule as:

SR 2: The scheduler must choose relatively better channel quality MS for each time slot, so that the energy loss due to transmission errors is minimized.

Once MSs enter into the sleep state, it is the BS that wakes up the sleep state MSs by transmitting packets to them under the control of a scheduling policy. One important question to answer is when should sleeping MSs be woken up? When a sleeping MS transits from the sleep state to the awake state, it will join the scheduling process, so that other awake-state MSs are more unlikely to receive resources. This is adverse to SR 1. On the other hand, frequent inter-state transitions may increase the extra energy consumption. Taking the above into account, we make sleeping MSs sleep for as long as possible. We then propose the third Scheduling Rule as follows:

SR3: When a MS stays in the sleep state, it should not be interrupted until it must awaken in order to guarantee its QoS requirement.

The above scheduling rule makes the scheduler working in a none-conversing mode which means the scheduler may not serve the MS until it finishes the longest sleep cycle, even though the scheduler is idle. Based on the above discussion and the proposed energy efficient Scheduling Rules, we propose our LVBF scheduling policy in the following subsection.

B. Longest Virtual Burst First scheduling (LVBF)

The main idea of our LVBF scheduling policy is to transmit packets of each MS in burst mode and put those uninvolved MSs into the sleep state as much as possible so as to save the energy of MSs. We first present the following definitions.

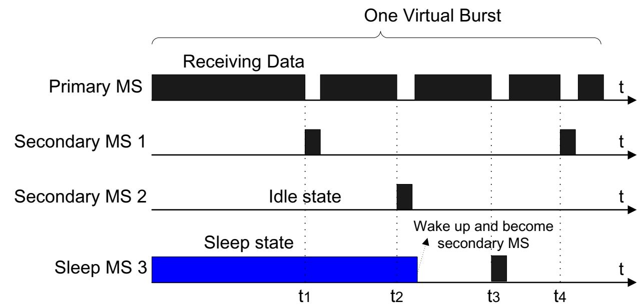

Fig. 2: Example of Virtual Burst Scheduling

Virtual Burst: a virtual burst is a period of time (time slots in this paper) where there are one primary MS and multiple secondary MSs sharing the time slot resources under the control of the scheduling policy.

Primary MS: a primary MS is the one which is selected as the virtual burst owner by the scheduler at the start of each virtual burst transmission. There is only one primary MS during each burst transmission and it is chosen from the awake state MSs. Ideally, the primary MS will occupy almost all the bandwidth resources during the corresponding burst.

Secondary MS: all the other awake state MSs except the primary MS are called secondary. A secondary MS will be allocated as few resources as possible - just enough to guarantee its minimum rate requirements.

Based on the definitions above, our Longest Virtual Burst First (LVBF) works as follows. There are three types of MSs: the sleep state MS, the primary MS and the secondary MS. Both primary and secondary MSs belong to the awake state MSs. MS i starts the sleep mode request process once its received data rate is larger than its predefined maximum data rate, i.e., $r_i^n > R_i^{max}$. We assume that R_i^{max} is large enough, so that the sleep duration is much longer than twice of the state transition delay. LVBF works in the virtual burst mode. During each virtual burst, there are only one primary MS and multiple secondary MSs sharing time slots under the control of LVBF. As shown in Figure 2, primary MS occupies the majority of the resource and secondary MS 1, MS 2 and MS 3 are only served at time t_1, t_2, t_3 and t_4 accordingly. At the start of each virtual burst, LVBF chooses one of the awake-state MSs as the primary MS and the remaining awake-state MSs as secondary MSs. If a sleep-state MS transits from the sleep state to the awake state during the burst, it will also be served as a secondary MS and join the scheduling process. The main idea of LVBF is to allocate almost all the bandwidth (time slots in this paper) in a burst to the primary MS and allocate just enough bandwidth to secondary MSs to guarantee their minimum data rate requirements. That is the reason why we call it a virtual burst. During each virtual burst, secondary MSs may not be likely to enter into the sleep state as they are only served at a slow rate, so the event of $r_i^n > R_i^{max}$ may not happen for secondary MSs.

There are several questions to answer for LVBF according to the scheduling process above: Question 1: How to choose the primary MS from the awake state MSs? Question 2: How long should each virtual burst be? Question 3: When should BS wake up sleeping MSs? Question 4: How to allocate bandwidth between primary MS and secondary MSs? Next we answer these questions one by one.

We define the set of awake-state MSs at the beginning of each burst as A_{aw}. We will let sleep-state MSs stay in the sleep state, which is in accordance with SR 3. So we only choose the primary MS from current awake-state MSs. We use *j* as the index of awake-state MSs at the beginning of each burst and we have $j \in A_{aw}$. The goal of choosing a primary MS is to transit it into the burst mode in the upcoming virtual burst so that it can go into sleep as soon as possible. The main idea is to choose an awake-state MS as the primary MS that has the shortest time to meet the condition of $r_i^n > R_i^{max}$. Based on the discuss ion above, we solve Question 1 by applying the following policy to choose MS j^* as the primary MS at the starting of each virtual burst:

$$j^* = \underset{j \in A_{aw}}{arg} \; min(R_j^{max} - r_j^n). \tag{3}$$

In order to answer Question 2, we first define Idle Rate ξ as follows:

Definition 1: Idle Rate is the rate of the idle time slots to the total time slots for the primary MS.

ξ indicates the degree to which the primary MS occupies the bandwidth resource in terms of time slots, i.e., a low ξ results in the primary MS being allocated more resources per time unit, while high results in fewer resources being allocated to the primary MS per time unit. ξ is an increasing function of the number of secondary MSs during each virtual burst. ξ increases when the number of secondary MSs is increasing as each secondary MS must be allocated the minimum data rate in order to guarantee its service quality. ξ can be calculated as:

$$\xi = \frac{\sum_{i \in A_{sec}} R_i^{min}}{C} \tag{4}$$

where A_{sec} is the set of secondary MSs and C is the total channel capacity in bits per second. We define the event of ending each virtual burst as:

$$\xi > \varepsilon. \tag{5}$$

where ε is a system parameter, which trades off average delay and energy efficiency. When the event of $\xi > \varepsilon$ happens, it indicates the end of the current virtual burst and the primary MS i^* goes into the sleep state with the sleep duration request $d_{i^*}^n$. According to our Scheduling Rule 3, $d_{i^*}^n$ should be as large as possible, can be calculated based on the sliding window mechanism. We have:

$$\begin{aligned}(1 - \frac{d_{i^*}^n}{L_{sw}}) r_{i^*}^n = R_{i^*}^{min} \\ \Rightarrow d_{i^*}^n = L_{sw}(1 - \frac{R_{i^*}^{min}}{r_{i^*}^n}).\end{aligned} \tag{6}$$

where L_{sw} is the size of the sliding window. According to SR 3, we try to keep the sleep-state MSs sleeping for as long as possible, so we invoke the sleep-state MS *i* when the following event happens:

$$r_i^n \le R_i^{min}. \tag{7}$$

During the burst bandwidth allocation process, time slots are shared among the primary MS and the secondary MSs. In order to achieve burst transmission, time slots are allocated to the primary MS explicitly except in situations where the secondary MSs must be served in order to guarantee their minimum data rates. This allocation scheme can be expressed as:

$$A = \begin{cases} \underset{i}{arg} \; min \; \dfrac{r_i^n - R_i^{min}}{R_i^{min}}; & if \; S_{wk} \; is \; empty \\ \qquad i^* \quad ; & otherwise. \end{cases} \tag{8}$$

where $S_{wk} = \{i : \; MS \; i \; is \; secondary \; MS \; and \; r_i < R_i^{min}\}$ and *A* is the scheduling result. Based on the discussion above, we propose the LVBF scheduling policy works as follows:

Step 1: Start a burst by choosing the primary MS according to (3) and the remaining awake-state MSs work as secondary MSs.

Step 2: Do the scheduling for the current time slot among the primary and secondary MSs according to (8).

Step 3: Update MSs' perceived data rate for all the users base on the scheduling result in Step 2.

Step 4: If the current primary MS goes into the sleep state invoked by the MS, start a new virtual burst and go to Step 1, otherwise, go to Step 5.

Step 5: If the event of ending each virtual burst in (5) happens, start a new virtual burst and go to Step 1, otherwise, go to Step 2 for the next scheduling cycle.

IV. SIMULATION RESULTS

In this section, we study performance of our LVBF energy efficient scheduling algorithm by simulation. We consider a single cell with one Base Station and a varying number of Mobile Stations. Because there are no comparable algorithms designed for the Sleep Mode in IEEE 802.16e at this moment, we compare the performance of LVBF with that of the Round Robin (RR) algorithm. In this paper, we concern data services, who have prescribed minimum data rates requirements ad defined in IEEE 802.16. The fading channel is represented by a nine-state Markov chain[11]. Each channel between an MS and the BS corresponds to a Markov Chain Process, which monitors the current channel state of the channel. Channels between MSi (i = 1, 2, 3, .., N) and the BS have the same Markov Chain parameters, i.e. the same transmission probability matrix in the Markov chain. All the channels are iid, i.e. they have the same Markov transmission probability matrix and are independent of each other.

We use the average energy efficiency and minimum data rate as the performance measures. The simulations are set as follows. We generate the traffic in BS as a Poisson process with rate (packets per second) and each packet is fixed in size and can be transmitted in one time slot. The minimum data rate requirements are predefined when MSs enter the network. We define the average energy efficiency (AEE) as:

$$AEE = \frac{Energy\ used\ to\ transmit\ packets}{Overall\ all\ energy\ consumed}.$$

We use the number of slots to measure the energy consumption and we assume that each state transition will cost 100 time slots unit of energy [5]. The overall energy consumed is decided by the time that the MS stays in the awake state and the number of state transitions.

Figure 3 shows the AEE as a function of the number of MSs. We can see that LVBF outperforms the RR in terms of energy saving especially when the number of MSs is low. The reason is that when the system load is low, each MS can transmit their packets in a long dense burst. Dense bursts make sure that during each burst transmission the number of secondary MSs is small, so that the overall idle state time slots are decreased. A relatively long burst reduces the number of state transitions between the sleep state and the awake state, so that energy consumed for the state transitions is minimized. When the number of MSs increases, AEE decreases as the number of secondary MSs increases during each burst. The primary MS cannot transmit its packets in a dense burst way asit must sacrifice some of the time slots in order to guarantee other secondary MSs' minimum data rates. This dramatically increases the energy consumption for the idle state time and state transitions.

Figure 4 shows the minimum data rate guarantee with different MSs when the system load is increasing. We choose three MSs with different minimum data rates requirement as a case study. MS1 has a 24kbps minimum data rate requirement, MS2 has16kbps and MS3 has 8kbps. We increase the system load by admitting more MSs with the 10kbps minimum data rate. We can see that when the number of MSs increases, the date rates of MS1, MS2 and MS3 decrease to the minimum data rate prescribed.

V. Conclusion

In this paper we have tackled the problem of reducing power consumption of mobile stations in IEEE 802.16e wireless network using a Sleep Mode aware scheduling approach. We proposed a Longest Virtual Burst First (LVBF) scheduling algorithm. The main idea of our LVBF scheduling policy is to transmit packets of each MS in a burst mode and put those uninvolved MSs into the sleep state so as to save the energy of MSs. We further divided the awake-state MSs into primary and secondary categories. At the start of each burst transmission, LVBF first selects one MS as the primary MS and serve the remaining MSs as secondary. LVBF allocates almost all the bandwidth in a burst to the primary MS and allocate just enough bandwidth to the secondary MSs to guarantee their minimum data rate requirements. LVBF prolongs MSs' lifetime by reducing the average time when MSs stay in the awake state and the number of state transitions between the awake state and the sleep state. Simulation results show that, in comparison with the round robin scheduling scheme, the proposed scheduling algorithm can result in a significant overall energy saving and can guarantee the QoS requirements of MSs in terms of their minimum rates.

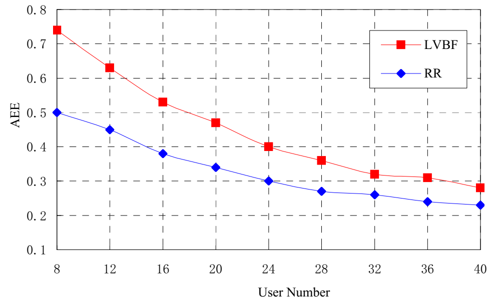

Fig. 3: Average Energy Efficiency vs System Payload

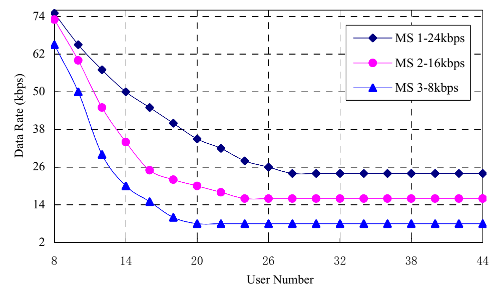

Fig. 4: Minimum Data rates Guarantee for users

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