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Energy Efficient Integrated Scheduling of Unicast and Multicast Traffic in 802.16e WMANs

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***Abstract*— In this paper we address a new problem that has not been addressed in the past: how to improve energy efficiency for both unicast and multicast services without violating QoS requirements of mobile stations in 802.16e wireless networks. We propose a Scheduling Set Based Integrated Scheduling (SSBIS) algorithm to solve the problem. SSBIS partitions all the mobile stations into multicast Scheduling Sets and a unicast Scheduling Set on the principle of minimizing mobile stations' energy consumptions by making use of the multicast transmission scheme and it adopts different scheduling policies based on the attributes of the Scheduling Sets to improve energy efficiency of the whole system. Numerical results show that SSBIS can result in a significant overall energy saving while at the same time guaranteeing the minimum data rates of mobile stations.**

I. Introduction

Energy efficiency is a very important issue for battery-powered mobile computing devices and it becomes one of the primary objectives in such system design. The IEEE 802.16e [1] defines Sleep Mode to reduce the power consumption of Mobile Stations (MSs). There are two states of MS in Sleep Mode: the awake state and the sleep state. When there is no data traffic between the Base Station (BS) and the Mobile Station, MS can enter the sleep state where energy consumption is minimized.

There have been some papers to study the mechanisms and algorithms of the sleep mode in IEEE 802.16e. Authors in [2] analyze the sleep mode operation quantitatively in order to give the guidance of selecting parameter values such as sleep durations and so on. In [3], a scheduling algorithm for unicast traffic is proposed which schedules packets of each MS in the burst mode and puts those uninvolved MSs into the sleep state as much as possible to save their energy. Ref. [4] defines the concept of "multicast super-frame" and proposes a transmission scheme of multicast data which allows the hosts not to be active all of the time in order to save energy. A basic idea of energy efficient scheduling algorithms involves bursty transmissions because bursty transmissions are preferred to minimize total energy consumption [3] [5] [6]. Moreover, because services supported by IEEE 802.16e have QoS requirements and the sleep opearation of MSs should not violate their service qualities, the main idea of a bursty transmission policy is to transmit packets for MS continually as long as possible without violating other MSs' service qualities.

However, the focus of existing algorithms is to improve energy efficiency for unicast or multicast service separately (we classify this type of algorithms as Separated Scheduling), instead of considering unicast and multicast services at the same time (classified as Integrated Scheduling). In fact, with the popularization of multimedia services, multicast and unicast services are more and more likely to coexist in one MS. If multicast services are used, it is not enough to design bursty scheduling algorithms for MSs without considering the transmission characteristics of multicast services. This can be demonstrated in the following simple example as depicted in Figure 1. MS1, MS2 and MS3 intend to receive data of one multicast service. In Figure 1(a), unicast data and multicast data are scheduled separately, so MS1, MS2 and MS3 should wake up twice to receive multicast data and unicast data respectively. If the scheduler can make its decision based on the transmission characteristics of multicast and unicast traffic, it will try to schedule the unicast data for MS1, MS2 and MS3 adjacent to the multicast data transmission period, as shown in Figure 1(b). Therefore, MS1, MS2, MS3 only need to wake up once to receive all the data, which results in energy saving.

There are two main reasons for the demand of Integrated Scheduling. Firstly, all the MSs receiving the same multicast service must be awake during the multicast data transmission periods, so if the scheduler can make use of the adjacent intervals of multicast data transmission periods to transmit unicast data for MSs, it will achieve higher energy efficiency, as shown in Figure 1. Secondly, multicast traffic imposes bounds on bursty scheduling of unicast data, so the previous proposed bursty scheduling algorithms are not feasible in this situation. However, to our best knowledge there is at present little research reported on energy efficient Integrated Scheduling in the field of Broadband Wireless Communication.

In this paper, we propose a Scheduling Set Based Integrated Scheduling (SSBIS) algorithm. SSBIS partitions all the MSs into multicast and unicast Scheduling Sets in advance. All the unicast data of MSs in the multicast Scheduling Sets are transmitted in the adjacent intervals of their multicast data transmission periods and the data of MSs in the unicast Scheduling Set are transmitted in the burst mode to achieve the longest sleep durations. SSBIS improves energy efficiency of MSs by making the best use of a multicast transmission scheme and bursty scheduling.

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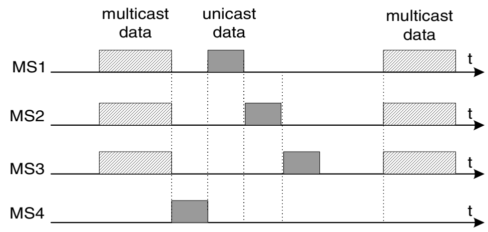

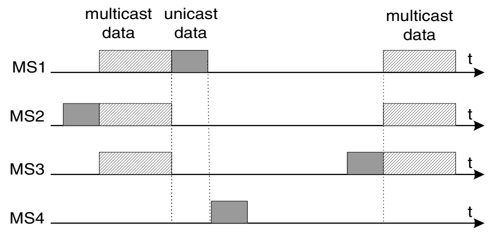

Fig. 1. Scheduling Samples for unicast and multicast traffic

II. System Model

In this paper, the centrally controlled IEEE 802.16e wireless network with a central BS and multiple MSs is considered. We only use the downlink scenario as a case study. The time on the downlink channel is divided into fixed size frames and the bandwidth is calculated in time slots. Since it has been proven in [7] that the minimum data rate is a sufficient parameter to guarantee MSs' service quality, we apply the minimum data rate as the only QoS requirement of MS in this paper. For simplicity, we assume that the achievable data rate of each time slot is fixed for all the MSs and use c to represent it.

The multicast transmission model in [4] is used in this paper. There are G logical broadcast channels and every G consecutive frames constitute a single "multicast super-frame" [4]. The static model of [4] is used as the transmission scheme of multicast services, which decides the association between each multicast service and a logical channel in advance. In this paper, multicast service #1 occupies logical broadcast channel #1, multicast service #2 occupies logical broadcast channel #2 and so on. The size of logical broadcast channel #j is fixed. We divide the MSs into broadcast groups based on the services MSs intend to receive. For example, MSs of broadcast group 1 intend to receive data of service #1. We assume that a MS belongs to no more than one broadcast group.

We first present some notations used in this paper. M is the number of MSs in the cell and i represents the index of MSs, $i \in (1, 2, \ldots, M)$; G is the number of broadcast groups in the cell and j represents the index of broadcast groups, $j \in (1, 2, \ldots, G)$; P_{aw} stands for the average energy consumed in each time slot by each MS in the awake state; P_{tn} stands for the average energy consumed when MS turns from the sleep state to the awake state, and the energy consumed when MS turns from the awake state to the sleep state is very small, so assumed negligible [8]; n_i is the number of state transitions of MS i from the sleep state to the awake state to receive unicast data; d_i is the number of time slots allocated for MS i in an allocation cycle; r_i represents the data rate of MS i after an allocation cycle; R_i^{min} represents the minimum data rate that MS i should receive to guarantee its service quality.

In this paper, we assume that no energy is consumed during the sleep period of MS. So the energy consumed by one MS is decided by the duration when the MS stays in the awake state and the number of state transitions from the sleep state to the awake state. The MS in a broadcast group need be awake not only when receiving unicast data but also in the corresponding logical broadcast channels. The total energy consumed by MS i during period T, denoted as P_i, can be expressed as follows:

$$P_i = \begin{cases} PM_j + D_i P_{aw} + (m_j + n_i) P_{tn}; & i \in BG_j \\ D_i P_{aw} + n_i P_{tn}; & \text{otherwise} \end{cases} \quad (1)$$

where BG_j = $\{i$: MS i belongs to broadcast group $j\}$, PM_j is the total energy consumption for receiving multicast service #j and m_j is the number of state transitions for receiving the service, namely, the number of logical broadcast channel j. PM_j and m_j is fixed because the transmission scheme of multicast data is decided in advance. D_i is the total number of time slots that MS i stays in the awake state excluding the time slots to receive multicast data. T is long enough.

The goal of the scheduling algorithm is to minimize the average energy consumed by all MSs during period T while at the same time guaranteeing the QoS requirements of MSs in terms of minimum data rates. This can be formulated as:

$$\begin{aligned} & min \ \frac{1}{M} \sum_{i=1}^{M} P_i \\ & s.t. \ \ r_i \geq R_i^{min}; \ i = (1, 2, \ldots, M) \end{aligned} \quad (2)$$

To obtain the optimal result, the scheduling algorithm should consider the characteristics of both multicast traffic and unicast traffic. We will discuss the problem and present our scheduling algorithm to obtain the optimal solution of the programming problem (2) in the next section.

III. Integrated Scheduling Algorithm

A. Adjacent Interval and Scheduling Set

Ref. [3] defines the idle state as the time when a MS stays in the awake state without receiving packets and it realizes that the time spent in the idle state is a waste of energy. Therefore, we need to avoid the time spent in the idle state. The most optimal case is that MSs are always busy receiving data in the awake state, otherwise they are in the sleep state. However, because energy is consumed when MS turns from the sleep state to the awake state, if the time spent in the idle state is short enough, the energy consumed by a state transition will be more than that consumed in the idle state and it is unnecessary for MS to enter the sleep state. Therefore, the condition of entering the sleep state is that the energy consumed in a potential idle state is more than that consumed by a state transition, which can be expressed as follows:

$$E_{idle} \cdot t > P_{tn} \Longrightarrow t > \frac{P_{tn}}{E_{idle}} \quad (3)$$

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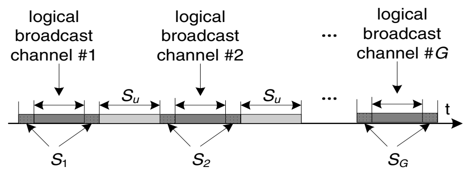

Fig. 2. S_u and S_j

where E_{idle} stands for the average power consumption of each time slot in the idle state and t is the potential duration of the idle state. We define T_{tn} as the idle duration threshold of MS: $T_{tn} = P_{tn}/E_{idle}$. Hence, if the potential time spent in the idle state is longer than T_{tn}, the MS needs to enter the sleep state.

Based on T_{tn}, We define the Adjacent Interval S_j of logical broadcast channel #j as: $S_j = (t_s - T_{tn}, t_s) \cup (t_e, t_e + T_{tn})$, where t_s is the start time of the logical broadcast channel #j in one multicast super-frame and t_e is the stop time.

We assume that $i \in BG_j$ and t_i represents the start time of unicast data transmission for MS i in an allocation cycle. If $t_i \in S_j$, MS i will receive unicast data without entering the sleep state after (or before) receiving multicast data because the potential duration of the idle state between t_i and t_e (or t_s) is shorter than T_{tn}. $n_i = 0$ if every start time of unicast data transmission for MS i is in S_j. In Expression (1), PM_j and m_j are fixed, so P_i is only decided by n_i and D_i. If $n_i = 0$, D_i can reach its minimum value with appropriate scheduling policies. Therefore, P_i is minimum with $n_i = 0$.

Based on the above analysis, it can be seen that the integrated scheduling scheme should make as many MSs of broadcast groups satisfy the condition $n_i = 0$ as possible in order to reduce the overall energy consumption. The MSs not satisfying this condition will be scheduled with the MSs which do not belong to any broadcast groups. Hence, we propose a Scheduling Set Based Integrated Scheduling (SSBIS) algorithm to allocate time slots for different types of MSs. A Scheduling Set is defined as follows:

Scheduling Set: A Scheduling Set includes several MSs which will be scheduled together in a group of time slots with the same policy. One MS must be in one and only one Scheduling Set. There are two types of Scheduling Set, multicast and unicast Scheduling Sets.

The SSBIS algorithm partitions all the MSs into one unicast Scheduling Set C_u and G multicast Scheduling Sets C_j ($j = 1, 2, \ldots, G$). The multicast Scheduling Set C_j consists of the MSs which belong to broadcast group j and can be scheduled in the adjacent interval S_j. All the MSs which are not included in any multicast Scheduling Set belong to the unicast Scheduling Set C_u. The unicast data of MSs in C_j will be scheduled in the adjacent interval S_j and the unicast data of MSs in C_u will be scheduled in other time slots except S_j and logical broadcast channel #j ($j = 1, 2, \ldots, G$), defined as S_u in this paper. S_u and S_j are illustrated by Figure 2.

Based on the above analysis, the SSBIS algorithm can be divided into two parts: (a) decide which MSs should be included in each Scheduling Set; (b) design the scheduling policies for different types of Scheduling Sets. We concentrate upon the method to solve (a) and (b) in the next subsections.

B. Scheduling Sets Partition

According to the definition of multicast Scheduling Set C_j, the principle of C_j generation is to select as many MSs which can be scheduled in S_j to satisfy the condition $n_i = 0$ as possible from broadcast group j. We present a method to generate C_j based on this principle. Assuming that SL_i represents the longest sleep duration of MS i after an allocation cycle, we can calculate SL_i based on the commonly used sliding window mechanism as:

$$(1 - \frac{SL_i}{L_{sw}})r_i = R_i^{min} \Rightarrow SL_i = L_{sw}(1 - \frac{R_i^{min}}{r_i}) \quad (4)$$

where L_{sw} is the size of the sliding window. We define T_j as the cycle period of logical broadcast channel #j. $SL_i \geq T_j$ is a necessary condition of $n_i = 0$. The reason is that MS i should wake up not only in the broadcast channel but also some time during the cycle period of logical broadcast channel #j to guarantee the service quality when $SL_i < T_j$. Hence, r_i reaches its minimum value when $SL_i = T_j$ to satisfy the necessary condition of $n_i = 0$ based on (4).

Moreover, r_i can be expressed by the number of slots that should be allocated for MS i, i.e., d_i as follows:

$$\begin{aligned} &\frac{R_i^{min}(L_{sw} - d_i)}{L_{sw}} + \frac{c \cdot d_i}{L_{sw}} = r_i \\ &\Rightarrow d_i = \frac{(r_i - R_i^{min}) \cdot L_{sw}}{c}; \quad (c \gg R_i^{min}) \end{aligned} \quad (5)$$

we can obtain the minimum value of d_i when r_i is minimum:

$$min\ d_i = \frac{R_i^{min} \cdot T_j \cdot L_{sw}}{(L_{sw} - T_j) \cdot c} \quad (6)$$

We rank d_i of all the MSs of broadcast group j in the ascending order and get the set $A = \{d^1, d^2, \ldots, d^{M'}\}$, where M' is the number of MSs in broadcast group j. Let $K_j = max\{k : \sum_{i=1}^{k} d^i \leq 2T_{tn}\}$. K_j is the maximum number of MSs which can be scheduled in S_j to ensure that their sleep durations are equal to T_j. Next, we will prove that K_j is the maximum number of MSs whose energy consumptions reach minimum values in broadcast group j.

Proof: Assume that K' MSs can finish receiving unicast data in S_j and $K' > K_j$. Because $K_j = max\{k : \sum_{i=1}^{k} d^i \leq 2T_{tn}\}$, there is at least one MS (assuming that its index is k) of K' MSs whose d_k is less than $(R_k^{min} \cdot T_j \cdot L_{sw})/((L_{sw} - T_j) \cdot c)$, i.e., $SL_k < T_j$ and MS k must wake up some time during the cycle periods of logical broadcast channel #j. Hence, $n_k \neq 0$. The energy consumption of MS k does not reach the minimum. Therefore, K_j is the maximum number of MSs whose energy consumptions reach minimum values in broadcast group j. ■

We arrive at the partition method of Scheduling Sets based on the above discussion. For every broadcast group j, calculate d_i of all MSs in it according to (6) and sort MSs in the ascending order of d_i. The first K_j MSs will make up C_j. After all the multicast Scheduling Sets are generated,

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the remaining MSs which do not belong to any multicast Scheduling Sets make up the unicast Scheduling Set C_u.

Since the number of time slots allocated for every MS in C_j are decided when C_j is generated, we put emphasis on the design of the scheduling policy for unicast Scheduling Set in the following subsection.

C. Longest Sleep Duration Based (LSDB) scheduling

The main idea of LSDB is to implement bursty transmissions for MSs in C_u to make the total sleep durations longest under the constraint of the multicast transmission scheme. t_i^{awake} is used to represent the time when MS i must be allocated time slots to guarantee its service quality and the LSDB scheduling algorithm records this time for each MS of C_u. Based on t_i^{awake}, we can decide whether MS i needs to be scheduled in the current S_u to guarantee its minimum data rate. Assume that MS i $(i = 1, \ldots, K)$ of C_u needs to be scheduled, the target of the scheduling algorithm is to allocate slots for K MSs in the current S_u to minimize the total energy consumption of these K MSs. The target will be achieved when the total sleep duration of these K MSs is longest after they finish receiving data. Therefore, the scheduling problem can be formulated as follows:

$$max\sum_{i=1}^{K} SL_i \Rightarrow max\sum_{i=1}^{K} L_{sw}\left(1-\frac{R_i^{min}}{r_i}\right) \tag{7a}$$

$$s.t. \ \sum_{i=1}^{K} d_i = T_c \tag{7b}$$

$$SL_i \geq L_{min} \Rightarrow r_i \geq \frac{R_i^{min}\cdot L_{sw}}{L_{sw}-L_{min}} \quad (i = 1, 2, \ldots, K) \tag{7c}$$

where T_c is the size of current S_u, L_{min} is the sum of the size of S_j and the size of logical broadcast channel #j successive to the current S_u. Because the time slots in S_j and logical broadcast channel #j can not be allocated for MS i, the sleep duration of MS i must be longer than L_{min} in order to guarantee the MS's service quality, which is the interpretation of Constraint (7c). Objective function (7a) is the total sleep duration of MS i $(i = 1, 2, \ldots, K)$ as a result of the current allocation cycle. Constraint (7b) ensures that the number of time slots allocated for these K MSs in this allocation cycle equals to the size of S_u and can be expressed as $\sum_{i=1}^{K} r_i = e$ based on (5) where $e = (T_c \cdot c)/L_{sw} + \sum_{i=1}^{K} R_i^{min}$. The equivalent objective function of (7a) is:

$$min\ f(r) = \sum_{i=1}^{K} \frac{R_i^{min}}{r_i} \tag{7a$'$}$$

It can be proven easily that the optimizaiton problem (7) is convex with object function (7a′), which can be efficiently solved using the interior point method [9] to obtain the optimal result r^*. Then d_i $(i = 1, 2, \ldots, K)$ is calculated according to (5) with the optimal result r^*.

Based on the discussion above, we present the steps of LSDB in one S_u as follows (T_u is the start time of S_u; h_i is the number of allocated time slots for MS i and n is the number of MSs for which the allocations have been finished):

Step 1: Select MSs which need to be scheduled in the current S_u from C_u and assume that MS i $(i = 1, 2, \ldots, K)$ is selected. $n = 0$, $h_i = 0$ $(i = 1, 2, \ldots, K)$.

Step 2: Solve the optimization problem (7) and obtain the optimal result r^*. Calculate d_i $(i = 1, 2, \ldots, K)$ according to (5) with r^* and round them to integer values under the Constraints (7b) and (7c).

Step 3: Select MS j whose t_j^{awake} is minimum at present.

Step 4: If $h_j \geq d_j$, update t_j^{awake} and put MS j into the sleep state, then go to Step 7; otherwise go to Step 5.

Step 5: If there is $t_i^{awake} (i \neq j)$ earlier than T_u, allocate the current time slot for MS i and set $h_i = h_i + 1$, $T_u = T_u + 1$, update t_i^{awake}, then go to Step 4; otherwise go to step 6.

Step 6: Allocate the current time slot for MS j and set $h_j = h_j + 1$, $T_u = T_u + 1$, then go to Step 4 for the next time slot allocation.

Step 7: $n = n + 1$. If $n > K$, this scheduling cycle is finished and the algorithm stops; otherwise go to Step 3.

D. Overall Algorithm

Based on the Scheduling Sets and LSDB, we conclude the overall SSBIS algorithm as follows: 1) At the start of scheduling, partition all the MSs into multicast Scheduling Set C_j $(j = 1, 2, \ldots, G)$ or unicast Scheduling Set C_u and decide the scheduling scheme A_j for C_j. The scheduling scheme A_j is to allocate continuous time slots of S_j for every MS in C_j and the number of allocated time slots is calculated according to (6). 2) For every allocation cycle (an allocation cycle is a set of contiguous time slots which includes one S_u, one logical broadcast channel and its Adjacent Interval), if $t \in S_u$, allocate time slots for MSs of C_u following the LSDB scheduling algorithm. If $t \in S_j$, use the scheduling scheme A_j, otherwise, schedule multicast data of broadcast group j. t represents the current time of scheduling.

IV. Simulation Results

In this section, we study the performance of the SSBIS algorithm by simulation. Our simulation is based on the implementation of IEEE 802.16e and includes a single cell with one BS and a varying number of MSs. We assume that every broadcast group includes four MSs in the simulation. In this paper, we are concerned with multicast services and unicast data services which have prescribed minimum data rates requirements as defined in 802.16e. The unicast traffic is generated as Poission process in BS.

We use AEE defined in [3] to measure the energy efficiency, where AEE is the ratio of energy used to transmit data to overall energy consumed. According to [8], we assume that the average power consumptions in the idle state, the awake state and the state transition are equal and each state transition will cost 2 time slots unit of energy. Figure 3 shows the AEE as a function of the number of MSs. There are two broadcast groups in the system. We compare the AEE of SSBIS with that of LVBF [3]. We can see that SSBIS significantly outperforms

LVBF. There are two main reasons for this. Firstly, SSBIS makes use of adjacent intervals of logical broadcast channels to reduce the number of state transitions whereas LVBF does not consider the transmission characteristics of multicast services, so the number of state transitions of SSBIS is less than that of LVBF. The second reason is that SSBIS reduces the overall idle state time more than LVBF by maximizing the total sleep durations and putting MSs into the sleep state when the potential idle state time reaches a threshold whereas there are always some MSs in the idle state for a long time in LVBF.

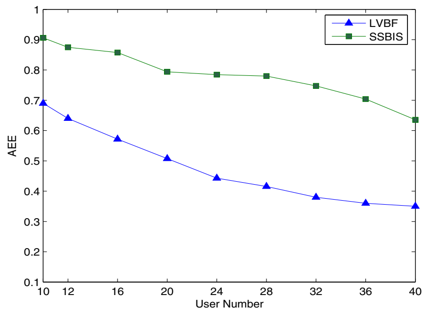

Fig. 3. AEE vs. Number of MSs

Figure 4 shows the AEE of SSBIS in two scenarios which have different numbers of broadcast groups. Scenario 1 has two broadcast groups and scenario 2 has four broadcast groups. We can see that AEE in scenario 1 is always lower than that in scenario 2 with the same number of MSs. The reason is that more MSs can be scheduled in the adjacent intervals of logical broadcast channels to achieve minimum energy consumptions when there are more broadcast groups in the system.

Figure 5 shows the average data rate received by different MSs when the system load is increasing. We choose three MSs with different minimum data rates requirements as a study case. The minimum data rates requirements of all other MSs are 10kbps. As indicated in Figure 5, when the number of MSs increases, the data rates of these three MSs decrease, but they are always higher than the minimum data rates prescribed. The reason is that SSBIS will check whether there are MSs whose QoS requirements are not satisfied every time slot and allocate time slots for them as soon as possible. Moreover,

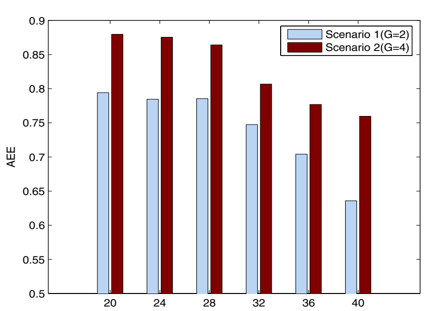

Fig. 4. AEE of SSBIS vs. Number of MSs

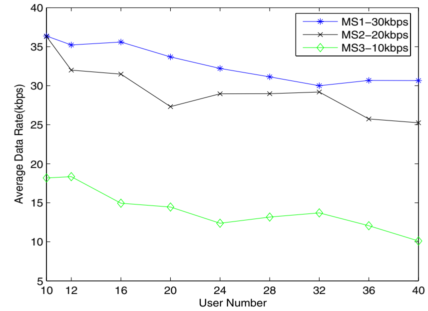

Fig. 5. Average Data Rate vs. Number of MSs

it can been seen that when the system load is low, the data rates of these three MSs are not significantly higher than their minimum data rates. It is because that SSBIS will not serve the MS until its data rate decreases to the minimum data rate, even though the scheduler is idle.

V. Conclusion

In this paper we addressed a new problem: how to improve energy efficiency for both unicast and multicast services without violating QoS requirements of MSs. We proposed a Scheduling Set Based Integrated Scheduling (SSBIS) algorithm to solve this problem. The SSBIS algorithm partitions all the MSs into different types of Scheduling Sets and adopts different scheduling policies based on the attributes of Scheduling Sets to improve energy efficiency of the whole system in which multicast traffic and unicast traffic coexists. Numerical results show that SSBIS can result in a significant overall energy saving while at the same time guaranteeing the minimum data rates of MSs.

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