Efficient Resource Allocation for Energy Conservation in Uplink Transmissions of IEEE 802.16j Transparent Relay Networks

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ABSTRACT

By introducing the relay capability, the IEEE 802.16j standard is developed to improve the WiMAX performance. Under the transparent mode, existing studies aim at improving network throughput by increasing the transmission rates of *mobile stations (MSs)*. However, we show that using higher rates will let MSs consume more energy. In the paper, we define an *energy-conserved uplink resource allocation (EURA) problem* in 802.16j networks under the transparent mode, which asks how to arrange the uplink resource to 1) satisfy MSs' requests and 2) minimize their energy consumption. Objective 1 is necessary while objective 2 should be achieved when objective 1 is met. The above bi-objective problem is especially important when the network is non-saturated. The EURA problem is NP-hard and we propose a heuristic with two key designs. First, we exploit relay stations to allow more concurrent uplink transmissions to fully use the frame space. Second, we reduce MSs' transmission powers by adjusting their rates and paths. Simulation results show that our heuristic can save up to 80% of MSs' energy as compared with existing work.

Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design—*wireless communication*

General Terms

Algorithms

Keywords

energy saving, IEEE 802.16j, relay network, resource arrangement, WiMAX

1. INTRODUCTION

The IEEE 802.16 standard is developed to provide broadband wireless access in 4G systems. Its physical layer adopts the OFDMA technique, where a *base station (BS)* can communicate with multiple *mobile stations (MSs)* simultaneously via orthogonal channels. Since the typical PMP (point-to-multi-point) operation [7] could face several problems such as coverage hole and network congestion at the BS, the recent 802.16j extension [8] suggests deploying some *relay stations (RSs)* in a WiMAX network to solve these problems. Two types of RSs are defined in the 802.16j standard. An RS is called *transparent* if it is not aware by MSs. Otherwise, it is *non-transparent*. Transparent RSs help improve network throughput while non-transparent RSs help increase the BS's coverage. Since transparent RSs do not need to arrange resources to MSs, they are easier to implement than the non-transparent ones.

In this paper, we define an *energy-conserved uplink resource allocation (EURA) problem* in an 802.16j network with only transparent RSs (such a network is called a *transparent relay network*). Given the requests of MSs in each frame, the EURA problem asks how to arrange the uplink resource to each MS such that 1) MSs' requests are satisfied and 2) the total energy consumption of MSs is minimized. Note that objective 1 is mandatory while objective 2 should be achieved when the network is running under a non-saturated situation. The resource allocated to each MS is represented by a *burst*, which is the communication time for this MS to transmit data. A burst requires a *modulation and coding scheme (MCS)* to indicate its length. We point out that an MS will consume more energy when it uses a higher level of MCS. Thus, when the network is non-saturated, we can lower down the MCS level of some MSs to save their energy. Besides, the deployment of RSs allows MSs to transmit at a lower power and to exploit spatial reuse to accommodate concurrent uplink transmissions. Thus, it is critical for MSs to select direct or relay *paths* to send their data to the BS.

In the literature, the issue of arranging resources in an 802.16e network has been discussed in [1, 11, 16]. For 802.16j networks, the research efforts in [2, 18, 19] evaluating the 802.16j network capacity. The studies [12, 13, 15] address the RS placement problem to improve network performance. References [3, 10, 4] discuss how to select RSs to relay MSs' data to enhance network capacity. For transparent relay networks, the study [17] leverages channel diversity and spatial reuse to increase network throughput. Reference [20] suggests placing RSs in an irregular manner and reusing

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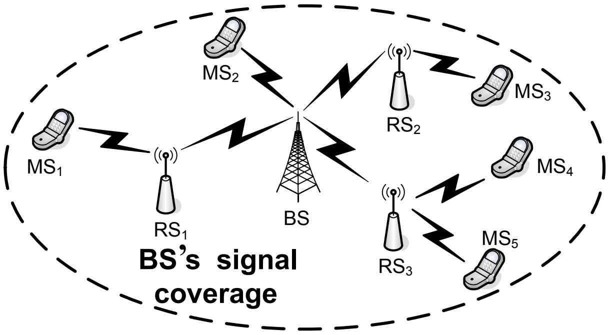

Figure 1: An example of the 802.16j transparent relay network with one BS, 3 RSs, and 5 MSs.

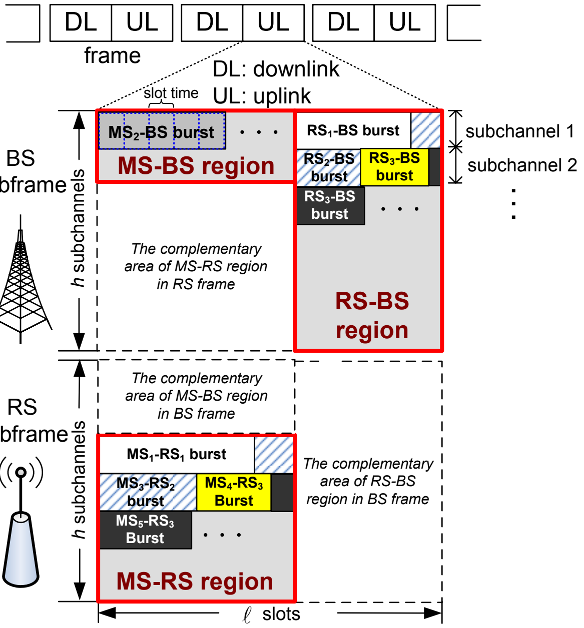

Figure 2: The uplink subframe structures.

the channel to improve network throughput. The work [14] adopts a Markov decision process for admission control and a chance-constrained assignment scheme to place the minimum RSs while maximizing their transmission rates. Reference [5] applies the minimal coloring solution to maximize the downlink capacity while reducing the difference among MSs' data rates. However, the above studies focus on enhancing network capacity but do not consider saving MSs' energy. The work in [21] modifies the multiple-choice knapsack solution to reduce MSs' energy consumption. However, this work does not exploit RSs to help conserve MSs' energy.

It can be observed that existing studies have not well addressed the issue of MSs' energy consumption in 802.16j transparent relay networks. Our EURA heuristic tries to first satisfy MSs' requests and then reduce their energy consumption by selecting proper RSs, MCSs, and transmission powers. In particular, we try to use the minimum frame space to allocate bursts for MSs by assuming that all MSs transmit at the maximum powers (to tolerate the maximal interference) and thus well utilizing spatial reuse. Then, we lower down the transmission powers of some MSs by adjusting their MCSs and paths. To the best of our knowledge, this is the first work that addresses the issue of energy conservation in resource allocation problem of 802.16j transparent relay networks. Simulation results show that our heuristic can save up to 80% of MSs' energy, which verifies its effectiveness.

The rest of this paper is organized as follows. Section 2 gives the system model and formally defines the EURA problem. Section 3 proposes our energy-efficient heuristic. Simulation results are presented in Section 4. Conclusions are drawn in Section 5.

2. PRELIMINARY

In this section, we first introduce the network architecture and frame structure of an 802.16j transparent relay network. Then, we quantify the energy consumption of MSs by considering the physical interference. Finally, we formally define our EURA problem.

2.1 Network Architecture

In an 802.16j transparent relay network, there is one BS supporting multiple MSs. All MSs will roam inside the BS's signal coverage[1]. Besides, there are several RSs inside the BS's coverage to relay data between MSs and the BS. Each MS can send data to the BS either *directly* (i.e., via one hop) or *through an RS* (i.e., via two hops). However, there are no communication links between any two RSs and between any two MSs. Thus, the network will form a two-level tree where the root is the BS and the leaves are the MSs. Fig. 1 shows an example of an 802.16j transparent relay network.

The network resource is divided into *frames*, where a frame is a two-dimensional array over channel and time domains. Each frame is further divided into a *downlink subframe* and an *uplink subframe*. Fig. 2 shows the uplink subframe structures of the BS and RSs. As can be seen, the BS subframe and an RS subframe is *complementary* with each other. The BS subframe is divided into an *MS-BS region* and an *RS-BS region* to allocate bursts for MSs and RSs, respectively. On the other hand, the RS subframe contains an *MS-RS region* to allocate bursts for MSs. Note that all bursts are managed by the BS. We assume that RSs have no buffer in the sense that the data received by an RS from an MS must be delivered to the BS in the same frame. Fig. 2 shows an example. Since an MS$_1$-RS$_1$ burst is allocated in the MS-RS region, there must be an RS$_1$-BS burst allocated in the RS-BS region.

Each burst is a rectangle with a width of one subchannel and a length in several slots. We adopt the mandatory PUSC (partial usage of subchannel) mode, where the qualities of subchannels are treated as common. Thus, there is no channel diversity issue under this mode. Besides, according to the standard, an MS/RS will not change its transmission rate during a burst. Bursts are arranged in a row-wise manner, as shown in Fig. 2. A burst may cross multiple subchannels (e.g., the RS$_2$-BS burst). Since the BS is the only receiver, any two bursts in the MS-BS region and the RS-BS region cannot overlap with each other. On the other hand, since we can exploit spatial reuse to allow concurrent MS-RS communications, the bursts in the MS-RS region could overlap.

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[1] Here, MSs can use QPSK1/2 (i.e., the lowest MCS level) to directly communicate with the BS.

Table 1: The amount of data carried by a slot and the minimum SINR threshold under different MCSs.

level k	MCS	data carried by a slot $D(k)$	minimum SINR threshold $\delta(k)$
1	QPSK 1/2	48 bits	6 dBm
2	QPSK 3/4	72 bits	8.5 dBm
3	16QAM 1/2	96 bits	11.5 dBm
4	16QAM 3/4	144 bits	15 dBm
5	64QAM 2/3	192 bits	19 dBm
6	64QAM 3/4	216 bits	21 dBm

In this paper, we consider the BS as a special RS, say, RS_0. Then, we can divide all MS_i-RS_j bursts into *burst groups*, where the overlapping bursts belong to the same group. Fig. 3 shows an example, where there are three burst groups and bursts $b(\text{MS}_1^2, \text{RS}_1)$ and $b(\text{MS}_4^1, \text{RS}_3)$ belong to the same group g_2.

2.2 Quantification of Energy Consumption

In each frame q, the amount of energy E_i^q that an MS_i will consume when it uses MCS level $\hat{M}_i$ is

$$E_i^q(\hat{M}_i) = T_i^q(\hat{M}_i) \times P_i^q(\hat{M}_i), \tag{1}$$

where $T_i^q(\hat{M}_i)$ and $P_i^q(\hat{M}_i)$ are the communication time (in seconds) and the transmission power (in milliwatts, mWs) of MS_i during frame q, respectively. Suppose that we have n MSs to be served, the total energy consumption of MSs during frame q is

$$E_{\text{total}}^q = \sum_{i=1}^{n} E_i^q(\hat{M}_i) = \sum_{i=1}^{n} T_i^q(\hat{M}_i) \times P_i^q(\hat{M}_i).$$

Since we focus on MSs' energy consumption during *each* frame, we omit the frame index q. Thus, the above equation can be expressed by

$$E_{\text{total}} = \sum_{i=1}^{n} T_i(\hat{M}_i) \times P_i(\hat{M}_i). \tag{2}$$

Each MS_i is allocated with a burst to transmit its uplink data, which consists of multiple *slots* and is associated with an MCS level $\hat{M}_i$. The MCS decides the amount of data (in bits) that each slot can carry, as shown in Table 1. Supposing that MS_i has an uplink request d_i (in bits) in the current frame, the communication time of MS_i is

$$T_i(\hat{M}_i) = t_i(\hat{M}_i) \times \tau = \left\lceil \frac{d_i}{D(\hat{M}_i)} \right\rceil \times \tau, \tag{3}$$

where $t_i(\hat{M}_i)$ is the size of MS_i's burst (in slots), $D(\hat{M}_i)$ is the amount of bits carried by a slot, and τ is the length of a slot (in seconds).

When MS_i sends data to an RS_j using the transmission power P_i and MCS level $\hat{M}_i$, the received signal power $\tilde{P}(i,j)$ at RS_j will be degraded due to path loss:

$$\tilde{P}(i,j) = \frac{G_i \cdot G_j \cdot P_i(\hat{M}_i)}{L(i,j)}, \tag{4}$$

where G_i and G_j are the antenna gains at MS_i and RS_j, respectively, and $L(i,j)$ is the path loss from MS_i to RS_j. Here, we adopt the SUI (Stanford university interim) path loss model [6] to calculate $L(i,j)$, which is recommended by the 802.16j task group. Then, the SINR (in dBm) at RS_j with respect to MS_i's transmission is

Table 2: Energy consumption per bit for different MCSs.

level k	energy consumption per bit (mW/bit)
1	0.082β
2	0.098β
3	0.147β
4	0.219β
5	0.413β
6	0.582β

$$SINR(i,j) = 10 \cdot \log_{10}\left(\frac{\tilde{P}(i,j)}{B \cdot N_o + I(i,j)}\right), \tag{5}$$

where B is the effective channel bandwidth (in Hz), N_o is the thermal noise level, and $I(i,j)$ is the interference caused by other transmitters i' transmitting simultaneously, which is estimated by

$$I(i,j) = \sum_{i' \neq i} \tilde{P}(i',j).$$

MS_i's data can be successfully decoded by RS_j if and only if

$$SINR(i,j) \geq \delta(\hat{M}_i), \tag{6}$$

where $\delta(\hat{M}_i)$ is the minimum SINR threshold under MCS level $\hat{M}_i$. Table 1 lists the minimum SINR threshold of each MCS level. Then, by integrating Eqs. (5) and (6) into Eq. (4), we can calculate the minimum power that MS_i has to use to transmit its data:

$$P_i(\hat{M}_i) \geq \frac{10^{\frac{\delta(\hat{M}_i)}{10}}(B \cdot N_o + I(i,j)) \cdot L(i,j)}{G_i \cdot G_j}. \tag{7}$$

By integrating Eqs. (3) and (7) into Eq. (2), we can calculate the total energy consumption of all MSs.

Although using a lower MCS level will increase the communication time (i.e., the burst size), we show that an MS can save its energy by using a lower MCS level as follows. Recall that the energy cost of MS_i can be written as

$$E_i(\hat{M}_i) = T_i(\hat{M}_i) \times P_i(\hat{M}_i) = \left(\left\lceil \frac{d_i}{D(\hat{M}_i)} \right\rceil \times \tau\right) \times P_i(\hat{M}_i).$$

By ignoring the ceiling function and assuming a fixed interference level of $B \cdot N_o + I(i,j)$, the energy consumption per bit to reach the SINR in Table 1 can be written as

$$E_i = \frac{1}{D(\hat{M}_i)} \times (10^{\frac{\delta(\hat{M}_i)}{10}}\beta),$$

where

$$\beta = \frac{(B \cdot N_o + I(i,j)) \cdot L(i,j)}{G_i \cdot G_j} \times \tau > 0.$$

In Table 2, we do see that the energy consumption per bit decreases as the MCS level decreases.

2.3 The EURA Problem

We are given an 802.16j network with one BS, m RSs, and n MSs, where the distance between any two nodes can be estimated by measuring their received signal strength. An MS_i/RS_j can adjust its transmission power up to a maximum value of $P_i^{\max}/P_j^{\max}$ (per subchannel). We assume that each frame has $\ell \cdot h$ slots. Each MS_i has an uplink request of d_i bits (per frame). The *path* of each MS_i is denoted by $\widehat{p}(\mathrm{MS}_i^k\text{-}\mathrm{RS}_j, \mathrm{RS}_j\text{-BS})$, where k is the MCS level used by MS_i. Note that when $j = 0$, the path will be $\widehat{p}(\mathrm{MS}_i^k, \mathrm{BS})$.

Let $\mathcal{R}$ be the set of all possible paths. Our EURA problem asks how to find a subset of paths $\mathcal{R}_p \subseteq \mathcal{R}$ to serve all MSs' uplink requests (if the frame space allows) and the MCS, burst, and transmission power of each MS such that the total energy consumption E_{total} is minimized.

The EURA problem can be reduced from the *multiple-choice knapsack (MCK) problem* [9], which is known to be NP-complete. Consider the case of no spatial reuse and assume that each MS has only one fixed transmission power. The n MSs can be mapped to n disjointed classes of MCK. The $m + 1$ paths can be mapped to the objects contained in each class. The conserved energy and the burst size of each MS can be mapped to the profit and the weight of each object, respectively. The total frame space can be mapped to the capacity of the knapsack. Thus, if the EURA problem has a solution of maximum energy conservation and thus the MCK problem has a solution of maximum profit selections. This shows that the EURA problem is NP-hard.

3. THE PROPOSED HEURISTIC

Our heuristic consists of two phases. The first phase tries to allocate the minimum resource to satisfy MSs' requests by letting all nodes transmit at their maximum powers. We then exploit spatial reuse to *compactly* arrange their bursts. The second phase saves MSs' energy by lowering down their MCSs and adjusting their paths and burst groups. Then, for each MS_i, $i = 1..n$, our heuristic will return its relay RS_j, burst $b(\mathrm{MS}_i^k, \mathrm{RS}_j)$ with MCS level k, and transmission power P_i.

3.1 Phase 1: Minimize the Usage of Frame Space

Assuming that MSs' energy is not a concern, the objective of phase 1 is to use the minimum frame space to satisfy all MSs' requests. To achieve the objective, this phase will exploit spatial reuse to overlap bursts.

To determine whether spatial reuse can be adopted, we need to calculate the *maximum tolerable interference (MTI)* $\widehat{\mathcal{I}}_{(i,j)}^k$ for correct transmission if MS_i selects RS_j as its relay using MCS level k at its maximum power $P_i^{\max}$, where $i = 1..n$, $j = 0..m$, and $k = 1..6$. Recall that the variable $I(i,j)$ in Eq. (7) indicates the current perceived interference for the transmission from MS_i to RS_j. We should keep $\widehat{\mathcal{I}}_{(i,j)}^k \geq I(i,j)$. Note that using a lower MCS level can tolerate more interference, so we have $\widehat{\mathcal{I}}_{(i,j)}^k < \widehat{\mathcal{I}}_{(i,j)}^{k-1}$. Besides, any MTI of the BS is zero, that is, $\widehat{\mathcal{I}}_{(i,0)}^k = 0$ for $k = 1..6$. For convenience, we calculate all values of $\widehat{\mathcal{I}}_{(i,j)}^k$ and maintain an MTI table using (MS_i, RS_j, k) as its index.

Next, we formulate the amount of frame space needed to allocate burst(s) for MS_i when it selects RS_j as the relay using MCS level k:

$$cost(MS_i, RS_j, k) = \begin{cases} \left\lceil \frac{d_i}{D(k)} \right\rceil, & \text{if } j = 0 \\ F(MS_i, RS_j, k) + \left\lceil \frac{d_i}{D(\hat{M}_j)} \right\rceil, & \text{if } j \neq 0, \end{cases}$$

where $F(MS_i, RS_j, k)$ is the minimum *extra* frame space when we try to overlap burst $b(\mathrm{MS}_i^k, \mathrm{RS}_j)$ with other granted bursts and $\hat{M}_j$ is the best MCS level used by RS_j. Suppose that we have already granted a set of burst groups $\mathcal{G}$. For ease of presentation, we denote g_0 as an *empty* group. Then, the above $F(MS_i, RS_j, k)$ function can be represented by

$$F(MS_i, RS_j, k) = \min_{\forall g_a \in \mathcal{G} \cup \{g_0\}} f_e(MS_i, RS_j, k, g_a), \tag{8}$$

where $f_e(MS_i, RS_j, k, g_a)$ is the extra frame space when we add burst $b(\mathrm{MS}_i^k, \mathrm{RS}_j)$ into group g_a, which can be calculated by the following cases:

- If RS_j already appears in any burst of g_a, we have $f_e(MS_i, RS_j, k, g_a) = \infty$ since RS_j cannot simultaneously receive the packets from two MSs.
- If adding burst $b(\mathrm{MS}_i^k, \mathrm{RS}_j)$ causes the overall interference of *any* burst in g_a to exceed its MTI, we set $f_e(MS_i, RS_j, k, g_a) = \infty$.
- If the total interference from all bursts in g_a exceed the MTI of $b(\mathrm{MS}_i^k, \mathrm{RS}_j)$, we set $f_e(MS_i, RS_j, k, g_a) = \infty$.
- Otherwise, it is safe to add $b(\mathrm{MS}_i^k, \mathrm{RS}_j)$ into g_a. In this case, we have

  $$f_e(MS_i, RS_j, k, g_a) = \max\left\{ \left\lceil \frac{d_i}{D(k)} \right\rceil - size(g_a), 0 \right\},$$

  where $size(g_a)$ is the maximum burst size of g_a:

  $$size(g_a) = \max_{\forall b(MS_x^z, RS_y) \in g_a} \left\lceil \frac{d_x}{D(z)} \right\rceil.$$

Note that when we add burst $b(\mathrm{MS}_i^k, \mathrm{RS}_j)$ into group g_0, we will have $f_e(MS_i, RS_j, k, g_0) = \left\lceil \frac{d_i}{D(k)} \right\rceil$. Fig. 3 gives an example of calculating path costs $cost(MS_i, RS_j, k)$, where it assumes that $n = 5$, $m = 3$, and only two MCS levels are available (i.e., $k = 1, 2$).

Given all possible paths $\mathcal{R}$ and the requests of all MSs $\{d_1, d_2, \cdots, d_n\}$, phase 1 works as follows:

1. Initially, we set each MS as *unsatisfied* and let the set of burst groups $\mathcal{G}$ be empty. The amount of available frame space is set to $S = \ell \cdot h$.
2. Among all unsatisfied MSs, we select the one, say, MS_i that has the minimum value of $cost(MS_i, RS_j, k)$[2]. Suppose that this cost is calculated by adding MS_i's burst into group g_a. If $S < cost(MS_i, RS_j, k)$, we adjust the request of MS_i proportionally to fit into S. We then add burst $b(\mathrm{MS}_i^k, \mathrm{RS}_j)$ into group g_a. Note that if $a = 0$, we create a burst group containing only $b(\mathrm{MS}_i^k, \mathrm{RS}_j)$ and add that group into $\mathcal{G}$. We then deduct S by $cost(MS_i, RS_j, k)$ and set MS_i as *satisfied.*

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[2] If more than one having the minimum costs, we choose the one incurring the least interference to other overlapping bursts of the traget group.

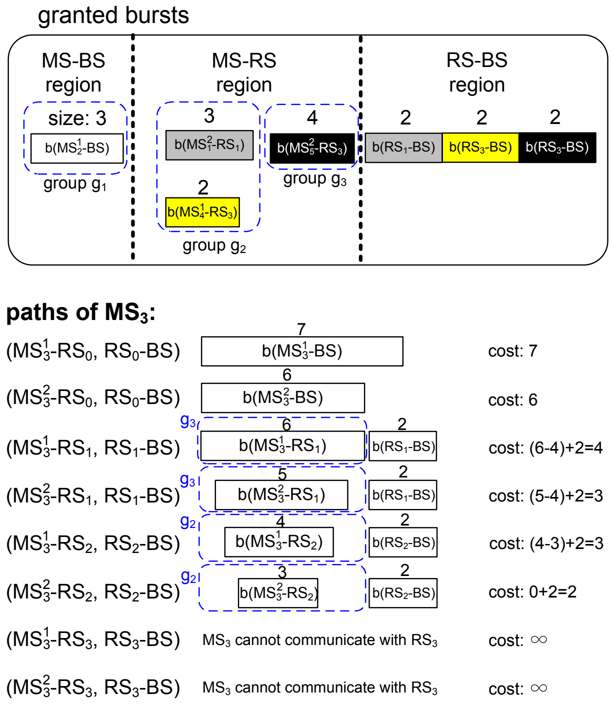

Figure 3: An example of calculating path costs.

3. Repeat step 2 until either $S \leq 0$ or all MSs are satisfied.

3.2 Phase 2: Reduce the Energy Consumption of MSs

Phase 1 targets at reducing the usage of frame space but ignores the energy consumption of MSs. Phase 2 tries to lower down MSs' powers by adjusting their MCSs, paths, and burst groups if there remains frame space. Among all possible combinations of new MCSs, paths, and burst groups, each MS will try to select the one that minimizes its energy consumption while increasing the least cost.

Suppose that an MS$_i$ is allocated with burst(s) of $b(\mathrm{MS}_i^k, \mathrm{RS}_j)$ in burst group g_a after phase 1. We can calculate its energy consumption by Eq. (1):

$$energy(MS_i, RS_j, k, g_a)$$
$$= \left(\left\lceil \frac{d_i}{D(k)} \right\rceil \times \tau \right) \times \frac{10^{\frac{\delta(k)}{10}} (B \cdot N_o + I(i,j)) \cdot L(i,j)}{G_i \cdot G_j}.$$

Note that $I(i,j) = 0$ if burst $b(\mathrm{MS}_i^k, \mathrm{RS}_j)$ is the only member in its burst group since the MS$_i$-RS$_j$ communication will not be interfered by other MSs.

Then, if MS$_i$ changes its MCS level to k', its relay to RS$_{j'}$, and its burst group to $g_{a'}$, we can calculate its new cost by

$$c_{new}(MS_i, RS_{j'}, k', g_{a'})$$
$$= \begin{cases} \infty, & \text{if the remaining space cannot affort the new burst(s)} \\ f_e(MS_i, RS_{j'}, k', g_{a'}) + \lceil \frac{d_i}{D(M_{j'})} \rceil, & \text{otherwise.} \end{cases}$$

Note that MS$_i$ will try all burst groups $g_{a'} \in \mathcal{G} \cup \{g_0\}$ (including its original group) to calculate c_{new}[3]. Then, the new energy consumption of MS$_i$ can be also calculated:

$$energy(MS_i, RS_{j'}, k', g_{a'})$$
$$= \left(\left\lceil \frac{d_i}{D(k')} \right\rceil \times \tau \right) \times \frac{10^{\frac{\delta(k')}{10}} (B \cdot N_o + I(i,j')) \cdot L(i,j')}{G_i \cdot G_{j'}}.$$

Similarly, $I(i,j')$ is zero if the new burst $b(\mathrm{MS}_i^{k'}, \mathrm{RS}_{j'})$ is the only member in its burst group.

Let us define $\Delta_C(MS_i, RS_{j'}, k', g_{a'}) = c_{new}(MS_i, RS_{j'}, k', g_{a'}) - c_{new}(MS_i, RS_j, k, g_a)$ and $\Delta_E(MS_i, RS_{j'}, k', g_{a'}) = energy(MS_i, RS_j, k, g_a) - energy(MS_i, RS_{j'}, k', g_{a'})$. Then, we can calculate the *energy-saving ratio* of MS$_i$ as

$$r_i = \max_{j'=0..m, k'=1..6} \left\{ \frac{\max\{\Delta_E(MS_i, RS_{j'}, k', g_{a'}), 0\}}{\max\{\Delta_C(MS_i, RS_{j'}, k', g_{a'}), 0^+\}} \right\},$$

where 0^+ is a very small positive number. When $r_i = 0$, it means that MS$_i$ cannot change its current path and burst allocation. Note that a negative value of $\Delta_E(MS_i, RS_{j'}, k', g_{a'})$ will make $r_i = 0$, and thus we do not change MS$_i$'s MCS and path since it will consume more energy. Besides, a larger ratio of r_i means that MS$_i$ can change its current path and burst allocation to conserve more energy while increasing less cost. When $\Delta_C(MS_i, RS_{j'}, k', g_{a'}) < 0$, r_i will become very large and thus we may select MS$_i$ to change its MCS and path.

Given the paths and burst allocations in phase 1, phase 2 works as follows:

1. Initially, we set all MSs as *unchecked*.
2. Calculate the energy-saving ratio of each unchecked MS. If MS$_i$ has a ratio of $r_i = 0$, we set MS$_i$ as *checked* since MS$_i$ cannot adjust its path and burst allocation.
3. Among all unchecked MSs, we select the one, say, MS$_i$ that has the maximum ratio. We then change MS$_i$'s path and burst allocation accordingly.
4. Repeat steps 2 and 3 until all MSs are checked.
5. Finally, after we get the allocation results, we lower down each MS's transmission power according to the amount of interference caused by other MSs from the same group. Specifically, for each MS$_i$, $i = 1..n$, we adjust the power as

$$P_i = \frac{10^{\frac{\delta(k)}{10}} (B \cdot N_o + I(i,j)) \cdot L(i,j)}{G_i \cdot G_j},$$

where RS$_j$ and k are the relay and MCS level of MS$_i$, respectively.

4. PERFORMANCE EVALUATION

In this section, we develop a simulator in Java to verify the effectiveness of our heuristic. The system parameters of our simulator are listed in Table 3. We consider four types of traffics defined in the standard: UGS, rtPS, nrtPS, and BE. The uplink request is 960 bits/frame for each MS (in average). The network contains one BS and several RSs and MSs. RSs are uniformly deployed inside the 2/3 coverage

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[3] Here, the cost should be calculated by removing the original burst $b(\mathrm{MS}_i^k, \mathrm{RS}_j)$ and adding the new burst $b(\mathrm{MS}_i^{k'}, \mathrm{RS}_{j'})$. We still use MTI $\widehat{\mathcal{I}}_{(i,j')}^{k'}$ to determine whether or not the new burst $b(\mathrm{MS}_i^{k'}, \mathrm{RS}_{j'})$ can be added into a burst group.

Table 3: The parameters in our simulator.

parameter	value
number of frames	1000
channel bandwidth	10 MHz
FFT size	1024
zone category	PUSC with reuse 1
uplink frame duration	2.5 ms
uplink subframe space	12 × 30
MCS	refer to Table 1
traffics	UGS, rtPS, nrtPS, and BE
request d_i	960 bits/frame in average
path loss model	SUI
antenna hight	BS: 30 m, RS: 10 m, MS: 2 m
thermal noise	-100 dBm
$P_i^{\max}$	1000 mW (milliwatt)

FFT: fast Fourier transform

range of the BS to get the best performance gain [5] and the number of RSs is ranged from 0 to 32. MSs are randomly deployed inside the BS's coverage and the number of MSs is ranged from 10 to 60.

We compare our heuristic against the *minimal-coloring (MC) scheme* [5] and the *modified solution of MCK problem (sMCKP)* [21]. The MC scheme considers spatial reuse while the sMCKP scheme addresses the energy consumption of MSs. Specifically, the MC scheme first selects a path with the minimum transmission time (by using the highest MCS level) for each MS. Then, this scheme assigns one color for those MS-RS communications that can coexist and tries to use the minimum number of colors. In this way, the spatial reuse can be realized. On the other hand, the sMCKP scheme calculates a benefit value for each MS, which is defined by the ratio of the amount of energy reduction to the increase of burst size when the MS changes from its current MCS level to another level. Then, sMCKP iteratively selects one MS with the maximum benefit value and changes its MCS accordingly, until the maximum benefit is zero. However, sMCKP does not exploit RSs to help relay MSs' data.

4.1 Energy Consumption

We first evaluate the total energy consumption of MSs per frame under different number of MSs, as shown in Fig. 4, where the number of RSs is 8. Note that the y-axis is drawn with exponential scales and the network is non-saturated. Clearly, the energy consumption of MSs under all schemes increases when the number of MSs increases. The sMCKP scheme makes MSs consume the most energy because it does not exploit RSs to reduce the transmission powers of MSs. On the other hand, the MC scheme adopts spatial reuse to allow concurrent transmissions but MSs do not change their paths and MCSs. Thus, it will consume more energy compared with our heuristic. From Fig. 4, it can be observed that our heuristic can save up to 80% of MSs' energy compared with the MC scheme.

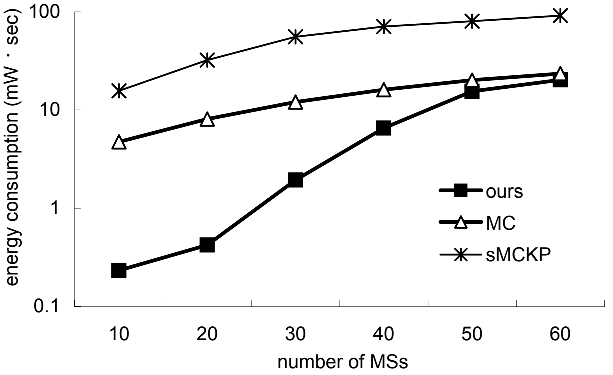

Figure 4: The energy consumption of MSs under different number of MSs, where there are 8 RSs.

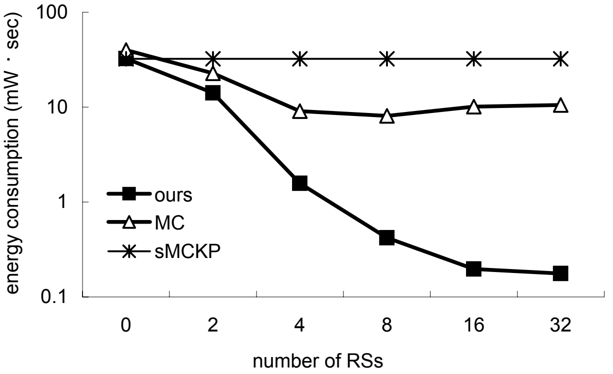

Figure 5: The energy consumption of MSs under different number of RSs, where there are 20 MSs.

We then measure the total energy consumption of MSs under different number of RSs, as shown in Fig. 5. Since the sMCKP scheme does not exploit RSs, its energy consumption will not change. On the other hand, the energy consumption of the MC scheme and our heuristic decreases when the number of RSs increases, because each MS has more choices to select a better RS to save its energy. In addition, it can be observed that when the number of RSs is more than 4, increasing the number of RSs can only reduce a small amount of MSs' energy consumption in our heuristic. The reason is that the number of concurrent transmissions has nearly reached the upper bound when the number of RSs is more than 4. From Fig. 5, our heuristic can save up to 90% of MSs' energy compared with the MC scheme.

4.2 Satisfaction Ratio

Next, we investigate the *satisfaction ratio* of MSs, which is defined by the ratio of the amount of *satisfied* requests to the total amount of requests per frame. When the satisfaction ratio is 1, it means that the scheme can satisfy the requests of all MSs. Fig. 6 shows the satisfaction ratios of all schemes under different number of MSs, where the number of RSs is 32. When the number of MSs is smaller than 40, all schemes can have a satisfaction ratio of 1 because the network is not saturated. The sMCKP scheme has the lowest satisfaction ratio when the number of MSs exceeds 30, because this scheme does not exploit RSs to improve network capacity. By exploiting spatial reuse, both MC scheme and our heuristic have the higher satisfaction ratios. It also is important to note that our heuristic can always have a satisfaction ratio of 1 since it can compactly overlap bursts to satisfy the requests of all MSs.

Fig. 7 shows the satisfaction ratios of all schemes under different number of RSs, where the number of MSs is 60. Again, the satisfaction ratio of the sMCKP scheme is not

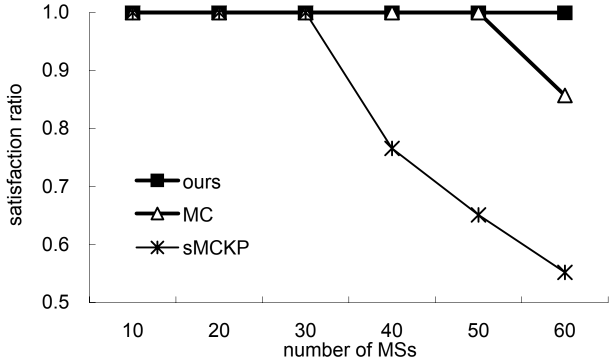

Figure 6: The satisfaction ratio of MSs under different number of MSs, where there are 32 RSs.

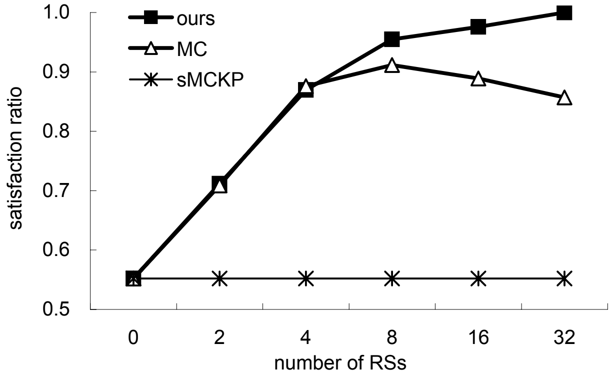

Figure 7: The satisfaction ratio of MSs under different number of RSs, where there are 60 MSs.

affected by the number of RSs because this scheme does not consider the existence of RSs. With the spatial reuse, when the number of RSs is more than 8, increasing the number of RSs will decrease the satisfaction ratio of the MC scheme. The reason is that the MC scheme makes all MSs transmit at their highest MCS levels. In this case, more interference may be arisen when there are more RSs. On the other hand, when the number of RSs is 32, our heuristic can have a satisfaction ratio of 1 because there are sufficient RSs to fully exploit spatial reuse to satisfy the requests of all MSs.

5. CONCLUSIONS

In this paper, we have addressed the issue of energy conservation in uplink resource allocation problem of an 802.16j transparent relay network. We point out that using a higher MCS level may harm an MS in terms of its energy consumption. We have proposed an energy-efficient heuristic with two phases. The first phase tries to use the minimum frame space to satisfy all MSs' requests while the second phase lowers down the transmission powers of MSs by changing their MCSs, paths, and burst groups. Simulation results have verified the effectiveness of our heuristic, where our heuristic can save more energy of MSs while increasing their satisfaction ratios, as compared with the MC and sMCKP schemes.

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