

A Real-Time Algorithm for Timeslot Assignment in Multirate Return Channels of Interactive Satellite Multimedia Networks

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Abstract—Since the digital video broadcast-return channel via satellite (DVB-RCS) standard was released in 2000, developing an interactive satellite multimedia (ISM) network has become a hot issue. In order to provide high-speed multimedia services using a DVB-RCS system, it is important to efficiently and dynamically assign the timeslots to a number of terminals according to their various demands. Also, it is imperative to improve the degradation of link quality due to rain-fade attenuation in *Ka*-band satellite communications. As a result, multirate superframe structures should be implemented for a relatively low data rate at the cost of stable connection to terminals in rain-fade regions and a relatively high data rate to terminals in clear-sky regions. Timeslot scheduling in this environment is studied in this paper. We mathematically formulate the timeslot assignment problem as a nonlinear integer programming problem and develop an efficient real-time solution algorithm. Extensive simulation results show that our algorithm successfully finds a feasible solution with optimality gap less than 0.05% within about 5 ms at Pentium III PC. We believe that our algorithm can be utilized as a guideline in developing real-time timeslot assignment algorithms for ISM networks.

Index Terms—Digital video broadcast-return channel via satellite (DVB-RCS), interactive, multimedia, rain-fade attenuation, satellite, timeslot scheduling.

I. INTRODUCTION

AN interactive satellite multimedia (ISM) network, such as digital video broadcast-return channel via satellite (DVB-RCS) network, will provide high-speed multimedia service, including Internet service to subscribers distributed over a very wide area. A DVB-RCS network is a geostationary earth orbit (GEO) satellite interactive network, which consists of a hub, a GEO satellite, and a number of RCS terminals (RCSTs), providing multimedia services [1]–[3]. Implementation of a DVB-RCS system has become one of the interesting issues. Worldwide companies and industries are developing broadband ISM systems, and its commercial availability and technical feasibility have been announced recently [3]–[5].

To accommodate increasing network access demand at the lowest possible cost, it is imperative to maximize the utilization

of radio resources. In the return link of DVB-RCS networks (RCST to hub via satellite), since there is neither a broadcasting effect as in the forward link nor high reuse efficiency as in the present and emerging cellular systems, it is an important focus of investigation to achieve high capacity with limited available radio resources [6].

In optimizing a radio resource allocation problem, one of imperative requirements to consider is that the system should provide a stable service using flexible multirate transmission according to radio link conditions. In GEO satellite communications, rain-fade attenuation may give rise to a critical degradation of radio link quality [7], [8]. In cases of rain-fade attenuation, the link quality is improved by using more stable coding rates and symbol rates. Using different coding rates and symbol rates for subscribers in rain-fade regions and those in ordinary (clear-sky) regions requires two different channels: rain-fade channels (channels for rain-fade attenuation) and ordinary channels. Since rain-fade subscribers can hardly communicate through ordinary channels, they should use rain-fade channels only. Since, however, ordinary subscribers may communicate through rain-fade channels, they may use both channels.

As a result, it is necessary to solve a resource allocation problem with heterogeneous resources and heterogeneous subscribers in order to achieve a high utilization of radio resources, while providing a stable link quality. We formulate this resource allocation problem as a nonlinear integer programming problem [9]–[13], and develop an efficient real-time heuristic solution algorithm. Performance analysis and extensive simulation results show that our algorithm has excellent computational efficiency and successfully finds timeslot schedules with optimality gap within 0.05%.

Since the DVB-RCS standard [1] was released in 2000, several resource allocation algorithms have been discussed [14], [15]. In [14], homogeneous frame structures are considered in timeslot assignment problems for DVB-RCS systems. However, heterogeneous frame structures and the resulting multirate channels are not considered. An overview of capacity scheduling in a multichannel satellite environment is provided [15]. However, that paper only discusses some strategies and scheduling-level algorithms are not developed. We believe that this paper is a milestone for the newly proposed DVB-RCS system by the European Telecommunications Standards Institute (ETSI) and our algorithm can be utilized as a guideline for optimal timeslot scheduling in practical environments with heterogeneous frame structures and satellite terminals.

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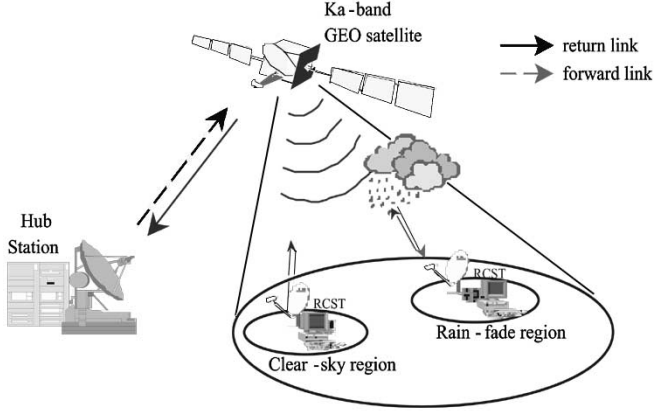


Fig. 1. Reference system model of ISM networks.

The rest of this paper is organized as follows. In Section II, we present our return link model with multirate frame structures. We mathematically formulate the timeslot assignment problem in Section III and propose solution algorithms in Section IV. We analyze the performance of the proposed algorithm in Section V. Finally, we conclude our work in Section VI.

II. RETURN LINK MODEL

We consider an ISM network with one earth station (hub), a GEO satellite, and a number of RCSTs as shown in Fig. 1. The ETSI's DVB-RCS standard [1] calls for a return link (RCST to hub via satellite) using a multifrequency time-division multiple-access (MF-TDMA) scheme. RCSTs are divided into clear-sky RCSTs (RCSTs in clear-sky region) and rain-fade RCSTs (RCSTs in rain-fade region).¹ In DVB-RCS systems, the resource allocation policy is based on so-called bandwidth-on-demand (BoD). In Fig. 1, RCSTs in need of capacity send capacity request (CR) messages to a scheduler which is a unit of the hub. Upon receiving the CR messages, the scheduler generates a terminal burst time plan (TBTP) table and sends it to RCSTs. Upon receiving the TBTP table, each RCST reads the TBTP table to know what timeslots are assigned. This procedure is executed every superframe.

Fig. 2 shows an example of a superframe pattern in our MF-TDMA model. We consider an MF-TDMA model, where a superframe, which is defined as a specific time-frequency block $T_{sf} \times W_{sf}$ ($\mu s \cdot MHz$) in time-frequency domain, includes a group of frames. The time-frequency block $T_{sf} \times W_{sf}$ is divided into four second-level time-frequency blocks $T_{sf} \times W_f$'s. This second-level block $T_{sf} \times W_f$ is used to generate clear-sky frames (clear-sky timeslots) or rain-fade frames (rain-fade timeslots). If the second-level block $T_{sf} \times W_f^c$ is used to generate clear-sky frames,² it is divided into n_f^c clear-sky frames, where a clear-sky frame is defined as a specific time-frequency block $T_f^c \times W_f^c$. A clear-sky frame consists of several carrier blocks $T_f^c \times W_t^c$ [$(W_f^c/W_t^c) = 1$ in Fig. 2], and each car-

¹The hub measures the signal-to-interference ratio (SIR) received from each RCST through the return link and determines whether each RCST is faded or not.

²We consider a practical case of $W_f^r = W_f^c (=W_f)$ so that each of (W_{sf}/W_f) time-frequency blocks of size $T_{sf} \times W_f$ may be dynamically used for either rain-fade frames or clear-sky frames.

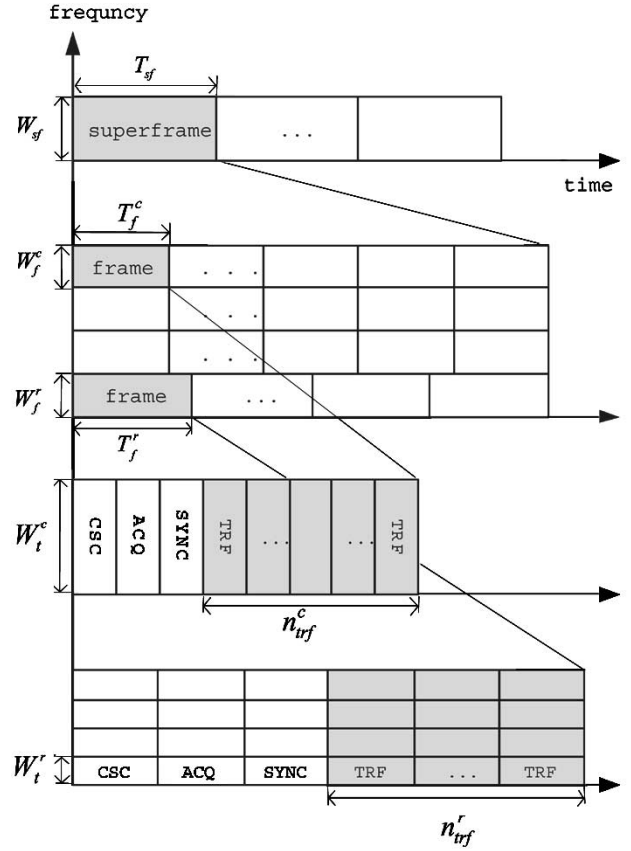


Fig. 2. Superframe structure with multirate frames in MF-TDMA.

rier block consists of one common signaling channel (CSC) timeslot, one acquisition (ACQ) timeslot, one synchronization (SYNC) timeslots, and n_{trf}^c traffic (TRF) timeslots. If the second-level block $T_{sf} \times W_f^r$ is used to generate rain-fade frames, it is divided into four n_f^r rain-fade frames, where a rain-fade frame is defined as a specific time-frequency block $T_f^r \times W_f^r$. A rain-fade frame consists of several carrier blocks $T_f^r \times W_t^r$ [$(W_f^r/W_t^r) = 4$ in Fig. 2], and each carrier block consists of one CSC timeslot, one ACQ timeslot, one SYNC timeslots, and n_{trf}^r TRF timeslots. Clear-sky RCST can use clear-sky timeslots or rain-fade timeslots, and rain-fade RCST should use only rain-fade timeslots.

III. TIMESLOT ASSIGNMENT PROBLEM

A. Mathematical Formulation

In this section, we mathematically formulate the optimal timeslot assignment problem (TAP) with two types of RCSTs and multiple data and delay classes, under the assumption that the set of clear-sky timeslots and the set of rain-fade timeslots are given. The objective of the problem TAP is to minimize the overall weighted penalty defined by

$$\sum_{j \in R} \sum_{k \in C_1} \sum_{l \in C_2} w_j^{kl} \cdot \max \left(0, d_j^{kl} - \sum_{i \in S} x_{ij}^{kl} \right)$$

where the decision variable x_{ij}^{kl} is a binary integer variable indicating timeslot assignment, where $x_{ij}^{kl} = 1$ represents that TRF timeslot i is assigned to service class (k, l) of RCST j and

TABLE I
SYSTEM PARAMETERS ON RADIO RESOURCE ALLOCATION

Parameter	Description
R	set of active RCSTs ($R = R_c \cup R_r$)
R_c	set of active clear-sky RCSTs
R_r	set of active rain-fade RCSTs
C_1	set of data classes
C_2	set of delay classes
S	set of TRF timeslots ($S = S_c \cup S_r$)
S_c	set of clear-sky TRF timeslots
S_r	set of rain-fade TRF timeslots
F_c^t	set of t th clear-sky TRF timeslots generated by each clear-sky time-frequency block $T_{sf} \times W_t^c$ ($t = 1, \dots, N_c$)
F_r^t	set of t th rain-fade TRF timeslots generated by each rain-fade time-frequency block $T_{sf} \times W_t^r$ ($t = 1, \dots, N_r$)
B_c	number of second-level time-frequency blocks $T_{sf} \times W_f$'s used to generate clear-sky frames
B_r	number of second-level time-frequency blocks $T_{sf} \times W_f$'s used to generate rain-fade frames
N_c	number of clear-sky TRF timeslots generated by a clear-sky time-frequency block $T_{sf} \times W_t^c$
N_r	number of rain-fade TRF timeslots generated by a rain-fade time-frequency block $T_{sf} \times W_t^r$
\bar{N}_c	number of total clear-sky TRF timeslots
\bar{N}_r	number of total rain-fade TRF timeslots
d_j^{kl}	number of TRF timeslots requested by service class (k, l) of RCST j where $k \in C_1$ and $l \in C_2$
n_{irf}^c	number of TRF timeslots per clear-sky carrier during a frame, i.e., $T_f^c \times W_f^c$
n_{irf}^r	number of TRF timeslots per rain-fade carrier during a frame, i.e., $T_f^r \times W_f^r$
<i>Design Parameters</i>	
w_j^{kl}	weighting value for service class (k, l) of RCST j
Q_j	maximum capacity that can be assigned to RCST j ($Q_j \leq \min\{N_c, N_r\}$)
α_j^{kl}	threshold value denoting the minimal requirement on the fraction of assigned capacity out of requested capacity
m_j	minimum number of timeslots that must be assigned to RCST j for the purpose of improving signaling message failure

$x_{ij}^{kl} = 0$, otherwise. The value $\sum_{i \in S} x_{ij}^{kl}$ represents the number of timeslots allocated to service class (k, l) of RCST j and, thus, the value $(d_j^{kl} - \sum_{i \in S} x_{ij}^{kl})$ represents the number of timeslots which is not satisfied by the timeslot assignment. (See Table I for system parameters on radio resource allocation.)

In practical services, subscribers (RCSTs) may be classified into several classes according to their capacity requirements and their contribution to the revenue, and their traffic may be classified into several classes according to the respective characteristics such as quality-of-service (QoS) requirements. These different contribution/penalty factors should be incorporated into the objective function, which are widely used in economic modeling for resource allocation [12]. In this paper, the weighting value w_j^{kl} used in the objective reflects the QoS of each RCST and service class case. This value may be determined by various factors such as the grade of RCSTs (e.g., 2-, 1-, and 0.5-Mb/s subscribers) and the average waiting time. In this paper, we give priority to rain-fade RCSTs over clear-sky RCSTs for rain-fade timeslots and, thus, the weighting value of rain-fade RCST is assumed to be much larger than that of clear-sky RCST. We also give priority to data class over delay class and, thus, the weighting value of a higher data class is assumed to be larger than that of a lower data class regardless of their delay classes.

Now, the problem TAP is mathematically formulated as follows:

$$(TAP) \quad \text{Min} \quad \sum_{j \in R} \sum_{k \in C_1} \sum_{l \in C_2} w_j^{kl} \cdot \left(d_j^{kl} - \sum_{i \in S} x_{ij}^{kl} \right) \quad (1)$$

$$\text{s.t.} \quad \sum_{i \in S} x_{ij}^{kl} \leq d_j^{kl}, \quad \forall j \in R, \quad k \in C_1, \quad l \in C_2 \quad (2)$$

$$\sum_{j \in R} \sum_{k \in C_1} \sum_{l \in C_2} x_{ij}^{kl} \leq 1, \quad \forall i \in S \quad (3)$$

$$\sum_{i \in S} \sum_{k \in C_1} \sum_{l \in C_2} x_{ij}^{kl} \leq Q_j, \quad \forall j \in R \quad (4)$$

$$z_j \sum_{i \in S_c} \sum_{k \in C_1} \sum_{l \in C_2} x_{ij}^{kl} + (1 - z_j) \sum_{i \in S_r} \sum_{k \in C_1} \sum_{l \in C_2} x_{ij}^{kl} = 0, \quad \forall j \in R \quad (5)$$

$$\sum_{i \in F_c^t} \sum_{k \in C_1} \sum_{l \in C_2} x_{ij}^{kl} \leq 1, \quad \forall j \in R, \quad t = 1, \dots, N_c \quad (6)$$

$$\sum_{i \in F_r^t} \sum_{k \in C_1} \sum_{l \in C_2} x_{ij}^{kl} \leq 1, \quad \forall j \in R, \quad t = 1, \dots, N_r \quad (7)$$

$$\sum_{i \in S} x_{ij}^{kl} \geq \alpha_j^{kl} d_j^{kl}, \quad \forall j \in R, \quad k \in C_1, \quad l \in C_2 \quad (8)$$

$$\sum_{i \in S} \sum_{k \in C_1} \sum_{l \in C_2} x_{ij}^{kl} \geq m_j, \quad \forall j \in R \quad (9)$$

$$z_j = 1, \quad \forall j \in R_r \quad (10)$$

$$z_j = 0 \text{ or } 1, \quad \forall j \in R_c \quad (11)$$

$$x_{ij}^{kl} = 0 \text{ or } 1, \quad \forall i \in S, \quad j \in R, \quad k \in C_1, \quad l \in C_2 \quad (12)$$

where the decision variable z_j is a binary integer variable, where $z_j = 1$ represents that rain-fade timeslots are allocated to RCST j and $z_j = 0$ represents that clear-sky timeslots are allocated to RCST j .

Constraint (3) means that the number of timeslots allocated to service class (k, l) of RCST j should not be greater than the requested amount d_j^{kl} . Constraint (3) means that each timeslot should not be assigned to more than one RCST and service class case. Constraint (4) means that the number of timeslots allocated to RCST j should not be greater than the maximum capacity Q_j . Constraint (5) means that a RCST should not use clear-sky timeslots and rain-fade timeslots together. Constraints (6) and (7) mean that timeslots assigned to a RCST should not use same time domain. Constraint (8) means that the number of timeslots allocated to service class (k, l) of RCST j should satisfy the minimal requirement $\alpha_j^{kl} d_j^{kl}$. Introducing a threshold sequence $\{\alpha_j^{kl}\}$, we can provide a *guaranteed lower bound* of the QoS of the respective RCSTs. The threshold value $\alpha_j^{kl} = 0.5$ means that at least 50% of the demand d_j^{kl} must be assigned to class (k, l) of RCST j . This value will be specified according to service providers' policies.

An RCST should be assigned exactly one SYNC timeslot every superframe to maintain *fine_sync* [1]. A SYNC timeslot contains the satellite access control (SAC) field composed of signaling information added by the RCST for the purpose of requesting capacity on the session, or other additional medium access control (MAC) information. SYNC timeslots may be failed because of rain-fade attenuation and so on. In cases that a SYNC timeslot with CR message is failed, then the RCST cannot be assigned TRF timeslots at its request. Since the timeslot assignment in DVB-RCS is based on BoD, SYNC timeslot failure is critical to QoS. In order to reduce the

QoS degradation caused by SYNC timeslot failure, we assign the minimal number of TRF timeslots so that CR messages may be transmitted more stably via TRF timeslots.³ In our mathematical formulation for timeslot assignment, thus, we introduce the minimal requirement m_j for the purpose of improving signaling message failure. Constraint (9) means that the number of timeslots assigned to RCST j is greater than or equal to the minimal requirement m_j . Constraint (10) means that a rain-fade RCST should use only rain-fade timeslots.

The problem TAP is a nonlinear binary integer programming problem which is NP-complete. To deal with the problem TAP more conveniently, we employ a problem reduction technique [10], where TAP is reduced to the problem of determining the number of timeslots allocated to service class (k, l) of RCST j as follows:

(RTAP)

$$\begin{aligned}
& \text{Min} \quad \sum_{j \in R} \sum_{k \in C_1} \sum_{l \in C_2} w_j^{kl} \cdot (d_j^{kl} - y_j^{kl}) \\
& \text{s.t.} \quad y_j^{kl} \leq d_j^{kl}, \quad \forall j \in R, \quad k \in C_1, \quad l \in C_2 \\
& \quad \sum_{k \in C_1} \sum_{l \in C_2} y_j^{kl} \leq Q_j, \quad \forall j \in R \\
& \quad \sum_{j \in R} (1 - z_j) \sum_{k \in C_1} \sum_{l \in C_2} y_j^{kl} \leq \bar{N}_c \\
& \quad \sum_{j \in R} z_j \sum_{k \in C_1} \sum_{l \in C_2} y_j^{kl} \leq \bar{N}_r \\
& \quad y_j^{kl} \geq \alpha_j^{kl} d_j^{kl}, \quad \forall j \in R, \quad k \in C_1, \quad l \in C_2 \\
& \quad \sum_{k \in C_1} \sum_{l \in C_2} y_j^{kl} \geq m_j, \quad \forall j \in R \\
& \quad z_j = 1, \quad \forall j \in R_r \\
& \quad z_j = 0 \text{ or } 1, \quad \forall j \in R_c \\
& \quad \forall y_j^{kl}: \text{nonnegative integer}
\end{aligned}$$

where the decision variable y_j^{kl} denotes the number of timeslots allocated to service class (k, l) of RCST j . The problem RTAP is equivalent to the problem TAP because we can easily obtain timeslot scheduling satisfying constraints of the problem TAP when the number of timeslots allocated to RCSTs are determined.

B. Capacity Request Category and Mapping

The ETSI's DVB-RCS standard [1] recommended five categories of CR: continuous rate assignment (CRA), rate-based dynamic capacity (RBDC), volume base dynamic capacity (VBDC), absolute volume-based dynamic capacity (AVBDC), and free capacity assignment (FCA). RCSTs use the CRA type

³CR message may be transmitted via TRF timeslots. This method is called data unit labeling method (DULM) [1].

if they need constant rates. If a specific number of timeslots are assigned to an RCST according to CRA, then this amount is continuously assigned to that RCST every superframe until that RCST sends the *assignment release* message. The RBDC type is used for the same purpose of the CRA type but the continuous assignment is automatically expired if the time (in superframes) is out. The VBDC and AVBDC types are used for volume capacity request, where VBDC is for cumulative request and AVBDC is for the initial request or initialization of the previous requests. In FCA, free capacity may be assigned as a bonus opportunity of transmission of any traffic. Especially, FCA should not be mapped to any traffic category, since availability is highly variable [2]. Capacity assigned in this category is intended as bonus capacity, which can be used to reduce delays on any traffic which can tolerate delay jitter.

When an RCST sends a CR message, it uses the 2 byte SAC request subfield which consists of 1-bit *scaling factor*, 3-bit *capacity request type*, 4-bit *channel ID*, and 8-bit *CR value* [1]. For example, suppose that capacity demand vector for service class (k, l) of RCST j is $(d_j^{k,1}, \dots, d_j^{k,|C_2|}) = (0, \dots, 0)$ at superframe n , and suppose that this RCST sends its SAC request subfield with *scaling factor* 1 (denoting factor 16), *capacity request type* 000 (denoting VBDC type), and *CR value* 10. Then, at next superframe, we have the equation at the bottom of the page, where *payload size* is 53 (ATM cell) or 188 (MPEG2-TS packet) bytes according to encapsulation mode defined at log-on, and *capacity per TRF timeslot* is the amount of information (in bytes) per TRF timeslot [1]. According to the DVB-RCS guideline [2], free TRF timeslots can be additionally assigned to log-on RCSTs to improve delays. This strategy is most commonly implemented by assigning timeslots on a round-robin basis to a group of RCSTs [16]. The respective FCA amounts should be determined considering fairness and their average delay measurements. Even though FCA is advantageous to improve the end-to-end delay of one satellite hop (up and down), it may be impractical to assign sufficient free timeslots to all RCSTs in a system with large subscriber communities.

IV. SOLUTION PROCEDURE

In this section, we suggest a three-phase solution procedure for timeslot assignment. The first phase determines the set of clear-sky TRF timeslots S_c , and the set of rain-fade TRF timeslots S_r . The sets S_c and S_r may be updated according to the sets R_c and R_r , and the demand matrix $\{d_j^{kl}\}$. The second and third phases solve the problem TAP with S_c and S_r obtained in Phase 1. The second phase determines the number of timeslots allocated to each RCST and service class case. First, the number of timeslots allocated to rain-fade RCSTs

$$d_j^{k,l} = \begin{cases} \frac{(\text{payload size}) \times (\text{scaling factor}) \times (\text{CR value})}{(\text{capacity per TRF timeslot})}, & l = 1 \\ d_j^{k,l-1} - y_j^{k,l-1}, & l = 2, \dots, |C_2| - 1 \\ \sum_{n=|C_2|}^{|C_2|} (d_j^{k,n} - y_j^{k,n}), & l = |C_2| \end{cases}$$

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Step 1 (Initialization)
   $r = \bar{N}_c$ .
   $R_c^* = \emptyset$ .
   $R^t = R_c$ .
Step 2 (Iteration)
  WHILE ( $r > 0$  and  $R^t = \emptyset$ ) {
     $j^* = \arg \max_j \{m'_j, j \in R^t\}$ .
     $R^t = R^t - \{j^*\}$ .
    IF ( $r - m'_{j^*} \geq 0$ ), THEN {
       $r = r - m'_{j^*}$ .
       $R_c^* = R_c^* + \{j^*\}$ .
    }
  }

```

Fig. 3. Procedure KPA.

are determined, and then the number of timeslots allocated to clear-sky RCSTs are determined. The third phase determines the schedule of timeslots allocated to each RCST.

A. Phase 1: Timeslot Set Determination

In this phase, we determine the sets S_c and S_r . These sets are determined by the number of second-level time-frequency blocks $T_{sf} \times W_f$'s used to generate clear-sky frames, B_c , and the number of second-level time-frequency blocks $T_{sf} \times W_f$'s used to generate rain-fade frames, B_r . Suppose that an extreme case that all frames are used for clear-sky channels when all RCSTs are rain-faded. In this case, no RCST can be served and no RCST can be logged on although there are available channels until this rain-fade condition disappears. To avoid this abnormal case in operating a system, it is preferred to have at least one rain-fade channel. Then, we obtain that $(B_c, B_r) \in \{((W_{sf}/W_f) - x, x) : x = 1, \dots, (W_{sf}/W_f)\}$.

The optimal value pair (B_c^*, B_r^*) is determined using three criteria: the total number of TRF timeslots, minimal requirement, and fairness between clear-sky RCSTs and rain-fade RCSTs. Our objective is to find the optimal value pair (B_c^*, B_r^*) , which maximizes the total number of TRF timeslots satisfying the minimal requirement condition and the fairness condition.

The minimal requirement condition is as follows:

$$\sum_{j \in R_c^*} m'_j \leq \bar{N}_c \left(= N_c \cdot B_c \cdot \frac{W_f^c}{W_t^c} \right)$$

$$\sum_{j \in R_r} m'_j + \sum_{j \in R_c - R_c^*} m'_j \leq \bar{N}_r \left(= N_r \cdot B_r \cdot \frac{W_f^r}{W_t^r} \right)$$

where $m'_j = \max\{m_j, \sum_{k \in C_1} \sum_{l \in C_2} \alpha_j^{kl} d_j^{kl}\}$, and the set R_c^* is the set of RCST j 's such that $v_j^* = 1$ in the optimal solution of the following problem KP: $\max\{\sum_{j \in R_c} m'_j v_j \mid \sum_{j \in R_c} m'_j v_j \leq \bar{N}_c, v_j = 0 \text{ or } 1, \forall j \in R_c\}$. This knapsack problem KP is NP-complete and, thus, it is very difficult to obtain an optimal solution. An efficient heuristic algorithm is obtained by the following heuristic procedure KPA (Fig. 3).

The fairness condition is that the ratio of average service quality of rain-fade RCSTs to that of clear-sky RCSTs is greater

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Compute  $D_r$  and  $D_c$ 
Let  $b = \frac{W_f^r}{W_t^r}$ 
IF ( $D_r = 0$  &&  $D_c = 0$ ), Return  $(B_c, B_r) = (b - \lfloor b/2 \rfloor, \lfloor b/2 \rfloor)$ 
IF ( $D_r = 0$  &&  $D_c \neq 0$ ), Return  $(B_c, B_r) = (b - 1, 1)$ 
IF ( $D_r \neq 0$  &&  $D_c = 0$ ), Return  $(B_c, B_r) = (0, b)$ 
FOR ( $B_r = 1; B_r \leq b; B_r++$ ) {
   $B_c = b - B_r$ 
   $\bar{N}_r = \frac{W_f^r}{W_t^r} \cdot N_r \cdot B_r$  and  $\bar{N}_c = \frac{W_f^c}{W_t^c} \cdot N_c \cdot B_c$ 
  Procedure KPA
  IF ( $D_r < \bar{N}_r - \sum_{j \in R_c - R_c^*} m'_j$ ),  $Y_r = D_r$ 
  ELSE,  $Y_r = \bar{N}_r - \sum_{j \in R_c - R_c^*} m'_j$ 
  IF ( $D_c < \bar{N}_c + \bar{N}_r - \sum_{j \in R_r} y_j$ ),  $Y_c = D_c$ 
  ELSE,  $Y_c = \bar{N}_c + \bar{N}_r - Y_r$ 
  IF ( $\sum_{j \in R_c} m'_j \leq \bar{N}_c, \sum_{j \in R - R_c^*} m'_j \leq \bar{N}_r, \frac{Y_r/D_r}{Y_c/D_c} \geq FR_0$ ), Return  $(B_c, B_r)$ .
}

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Fig. 4. Procedure TSD.

than or equal to a given threshold value FR_0 . We label this ratio as assigned amount to demand ratio, ADR, defined as

$$ADR \equiv \min \left\{ \text{average} \left(\frac{\text{no. of assigned timeslots}}{\text{no. of requested timeslots}} \right), 1 \right\}.$$

Then, ADR of rain-fade RCSTs and ADR of clear-sky RCSTs, respectively, are given by

$$ADR_r = \frac{\sum_{j \in R_r} \sum_{k \in C_1} \sum_{l \in C_2} \frac{y_j^{kl}}{d_j^{kl}} \cdot I_{(d_j^{kl} \neq 0)}}{\sum_{j \in R_r} \sum_{k \in C_1} \sum_{l \in C_2} I_{(d_j^{kl} \neq 0)}}$$

$$ADR_c = \frac{\sum_{j \in R_c} \sum_{k \in C_1} \sum_{l \in C_2} \frac{y_j^{kl}}{d_j^{kl}} \cdot I_{(d_j^{kl} \neq 0)}}{\sum_{j \in R_c} \sum_{k \in C_1} \sum_{l \in C_2} I_{(d_j^{kl} \neq 0)}}$$

where $I_{(\cdot)}$ is an indicating variable denoting 1 if the expression is true and 0, otherwise. With ADR, fairness ratio FR between rain-fade RCSTs and clear-sky RCSTs is defined as

$$FR = \frac{ADR_r}{ADR_c}.$$

This fairness ratio, FR, is used to determine (B_c^*, B_r^*) . However, it is necessary to find an optimal solution $\{y_j^{kl}\}$ for computing ADR_r and ADR_c . In order to improve real-time solution efficiency, we revise the original ADR as

$$ADR'_r = \frac{Y_r}{D_r}$$

$$ADR'_c = \frac{Y_c}{D_c}$$

where $D_r = \sum_{j \in R_r} \sum_{k \in C_1} \sum_{l \in C_2} d_j^{kl}$ and $D_c = \sum_{j \in R_c} \sum_{k \in C_1} \sum_{l \in C_2} d_j^{kl}$ denote the total numbers of timeslots requested by rain-fade RCSTs and clear-sky RCSTs, respectively, and $Y_r = \sum_{j \in R_r} \sum_{k \in C_1} \sum_{l \in C_2} y_j^{kl}$ and $Y_c = \sum_{j \in R_c} \sum_{k \in C_1} \sum_{l \in C_2} y_j^{kl}$ denote the total numbers of timeslots allocated to rain-fade RCSTs and clear-sky RCSTs, respectively. The values ADR'_r and ADR'_c are simply computed, since the values Y_r and Y_c are computed as $\min\{\sum_{j \in R_r} d_j, \bar{N}_r - \sum_{j \in R_c - R_c^*} m'_j\}$ and $\min\{\sum_{j \in R_c} d_j, \bar{N}_c + \bar{N}_r - \sum_{j \in R_r} y_j\}$, respectively.

In general, as B_r increases, the total number of TRF timeslots decreases and the fairness ratio increases. Thus, the smallest B_r (and, thus, $B_c = (W_{sf}/W_f) - B_r$) satisfying the minimal

requirement condition and the fairness condition is the optimal value.

B. Phase 2: Timeslot Amount Determination

In this phase, we try to solve the problem RTAP in order to determine the optimal timeslot amount for each RCST and service class case. However, the problem RTAP is a nonlinear integer programming problem and, thus, there is no polynomial time algorithm for solving that problem. Thus, we decompose the problem RTAP into two subproblems RTAP_r and RTAP_c, under the assumption that we give priority to rain-fade RCSTs over clear-sky RCSTs for rain-fade timeslots and, thus, the weighting factor of rain-fade RCSTs is much greater than that of clear-sky RCSTs

$$\begin{aligned}
 & \text{(RTAP}_r\text{)} \\
 & \text{Min} \quad \sum_{j \in R_r} \sum_{k \in C_1} \sum_{l \in C_2} w_j^{kl} \cdot (d_j^{kl} - y_j^{kl}) \\
 & \text{s.t.} \quad y_j^{kl} \leq d_j^{kl}, \quad \forall j \in R_r, \quad k \in C_1, \quad l \in C_2 \\
 & \quad \sum_{k \in C_1} \sum_{l \in C_2} y_j^{kl} \leq Q_j, \quad \forall j \in R_r \\
 & \quad \sum_{j \in R_r} \sum_{k \in C_1} \sum_{l \in C_2} y_j^{kl} \leq \bar{N}_r - \sum_{j \in R_c - R_c^*} m'_j \\
 & \quad y_j^{kl} \geq \alpha_j^{kl} d_j^{kl}, \quad \forall j \in R_r, \quad k \in C_1, \quad l \in C_2 \\
 & \quad \sum_{k \in C_1} \sum_{l \in C_2} y_j^{kl} \geq m_j, \quad \forall j \in R_r \\
 & \quad \forall y_j^{kl}: \text{nonnegative integer.}
 \end{aligned}$$

$$\begin{aligned}
 & \text{(RTAP}_c\text{)} \\
 & \text{Min} \quad \sum_{j \in R_c} \sum_{k \in C_1} \sum_{l \in C_2} w_j^{kl} \cdot (d_j^{kl} - y_j^{kl}) \\
 & \text{s.t.} \quad y_j^{kl} \leq d_j^{kl}, \quad \forall j \in R_c, \quad k \in C_1, \quad l \in C_2 \\
 & \quad \sum_{k \in C_1} \sum_{l \in C_2} y_j^{kl} \leq Q_j, \quad \forall j \in R_c \\
 & \quad \sum_{j \in R_c} \sum_{k \in C_1} \sum_{l \in C_2} y_j^{kl} \leq \bar{N}'_r + \bar{N}_c \\
 & \quad y_j^{kl} \geq \alpha_j^{kl} d_j^{kl}, \quad \forall j \in R_c, \quad k \in C_1, \quad l \in C_2 \\
 & \quad \sum_{k \in C_1} \sum_{l \in C_2} y_j^{kl} \geq m_j, \quad \forall j \in R_c \\
 & \quad \forall y_j^{kl}: \text{nonnegative integer}
 \end{aligned}$$

where \bar{N}'_r denotes the number of rain-fade timeslots not allocated to rain-fade RCSTs, which is obtained from the optimal solution of the subproblem RTAP_r.

The first subproblem RTAP_r considers only rain-fade RCSTs, and the second subproblem RTAP_c considers only clear-sky RCSTs. In the second subproblem RTAP_c, we relax the constraint that a clear-sky RCST should not use clear-sky timeslots and rain-fade timeslots together. Thus, the optimal solutions of the subproblems RTAP_c and RTAP_r may not satisfy the constraints of RTAP. Then, the sum of the objective values at those solutions becomes a lower bound of RTAP.

The subproblems RTAP_r and RTAP_c are sequentially solved by the procedures TAD_r and TAD_c. Under the assumptions about $\{w_j^{kl}\}$ given in Section III, for the

```

Step 1. (Allocate minimal requirement)
r = N_r - sum_{j in R_c - R_c^*} m'_j. Initialize Q_j.
FOR (forall j in R_r) {
  y_j^{kl} = ceil(alpha_j^{kl} d_j^{kl}).
  r = r - y_j^{kl}.
  Q_j = Q_j - y_j^{kl}.
}
FOR (forall j in R_r) {
  m_j = m_j - sum_{k in C_1} sum_{l in C_2} y_j^{kl}.
  IF (m_j > 0), THEN {
    FOR (k = |C_1|; k >= 1; k--) {
      FOR (l = |C_2|; l >= 1; l--) {
        m_bar = min(m_j, d_j^{kl} - y_j^{kl}).
        y_j^{kl} = y_j^{kl} + m_bar.
        m_j = m_j - m_bar.
        Q_j = Q_j - m_bar.
        r = r - m_bar.
        IF (m_j <= 0), THEN exit. /* for k */
      }
    }
  }
}
}

Step 2. (Allocate residual timeslots)
FOR (k = |C_1|; k >= 1; k--) {
  FOR (l = |C_2|; l >= 1; l--) {
    FOR (forall j in R_r) { /* order is randomly determined */
      m_bar = min(r, d_j^{kl} - y_j^{kl}, Q_j).
      y_j^{kl} = y_j^{kl} + m_bar. Q_j = Q_j - m_bar.
      r = r - m_bar.
      IF (r <= 0), THEN terminate.
      IF (Q_j <= 0), THEN exit. /* for j */
    }
  }
}
}

```

Fig. 5. Procedure TAD_r.

Set $r = \bar{N}_c + \bar{N}'_r$ and substitute R_c for R_r in Procedure TAD_r.

Fig. 6. Procedure TAD_c.

sake of convenience, we set $w_j^{kl} = M + (k - 1) \cdot |C_2| + l$ for $j \in R_r$ and $w_j^{kl} = (k - 1) \cdot |C_2| + l$ for $j \in R_c$, where M is a big number.⁴ Note that the lowest data class has index 1 and the highest data class has index $|C_1|$. In general cases, a sorting procedure for $\{w_j^{kl}\}$ is necessary, which is very simple. The procedures TAD_r and TAD_c obtain optimal solutions of the subproblems RTAP_r and RTAP_c, respectively, by the Proposition 1.

Proposition 1: The procedures TAD_r (Fig. 5) and TAD_c (Fig. 6) obtain optimal solutions of the subproblems RTAP_r and RTAP_c, respectively.

Proof: Convergence of Procedure TAD_r⁵

- *Feasibility:* The procedure TAD_r always finds a feasible solution. First, in Step 1, each RCST is allocated a certain number of timeslots required to satisfy the minimal

⁴ M should be greater than $|C_1| \cdot |C_2|$. Refer to [9] for the *Big-M* method.

⁵Proof of the convergence of TAD_c is similar.

```

Step 1. (Allocate clear-sky timeslots) /* rain-fade timeslots are allocated like in Procedure TADr */
rc = 0. yj = ∑k∈C1 ∑l∈C2 yjkl. Rt = Rc. Rc0 = ∅. Initialize Qj.
WHILE (Rt ≠ ∅){
  j* = arg maxj{yj, j ∈ Rt}. Rt = Rt - {j*}.
  If rc + yj* ≤ Nc, THEN { rc = rc + yj*. Rc0 = Rc0 + {j*}. }
}
If rc = Nc, then terminate. /* current solution is an optimal solution */
Step 2. (Find a feasible solution)
r'c = Nc - rc. j* = arg minj{yj - r'c, j ∈ Rc - Rc0}.
IF (∑j∈Rc0 m'j + m'j* ≤ Nc), THEN set Rc0 = Rc0 + {j*} and go to Step 2.1,
ELSE IF (∑j∈Rc-Rc0 m'j ≤ N'r), THEN go to Step 2.2,
ELSE, go to Step 2.3.
Step 2.1.
FOR (p = 0, k = 1; k ≤ |C1|; k++){
  FOR (l = 1; l ≤ |C2|; l++){
    Rt = Rc0.
    WHILE (Rt ≠ ∅){
      j* = arg maxj{yj, j ∈ Rt}. Rt = Rt - {j*}.
      WHILE (yj*kl > αj*kl dj*kl) and (yj* > m'j*){
        yj*kl = yj*kl - 1. yj* = yj* - 1. p = p + 1. IF (p ≥ r'c), THEN exit. /* for k */
      }
    }
  }
}
FOR (p = 0, k = |C1|; k ≥ 1; k--){
  FOR (l = |C2|; l ≥ 1; l--){
    Rt = Rc - Rc0.
    WHILE (Rt ≠ ∅){
      j* = arg minj{yj, j ∈ Rt}. Rt = Rt - {j*}.
      WHILE (yj*kl < Qj) and (yj*kl < dj*kl){
        yj*kl = yj*kl + 1. yj* = yj* + 1. p = p + 1. IF (p ≥ r'c), THEN exit. /* for k */
      }
    }
  }
}
}
Step 2.2.
Substitute Rt = Rc - Rc0 for Rt = Rc0 in Step 2.1.
Substitute Rt = Rc0 for Rt = Rc - Rc0 in Step 2.1.
Step 2.3
Set r = N'r and Rc0 = Rc*, and substitute Rc - Rc0 for Rr in Procedure TADr.
Set r = Nc and Rc0 = Rc*, and substitute Rc0 for Rr in Procedure TADr.

```

Fig. 7. Procedure ETAD.

requirement. Note that the numbers of clear-sky timeslots and rain-fade timeslots are determined considering the minimal requirement in Phase 1. Next, in Step 2, y_j^{kl} is increased exactly depending upon the number of remaining available timeslots.

- *Optimality*: Let us relax the integer constraint on decision variables y_j^{kl} 's. Then, RTAP_r is relaxed to a linear programming (LP) problem [9]. If an optimal solution of this LP-relaxed problem is integral, then it is an optimal solution of the original problem RTAP_r. Since the solution obtained by the procedure TAD_r is always integral and is an optimal solution of this LP-relaxed problem, it is an optimal solution of the original problem RTAP_r. First, we can know intuitively that the solution obtained by the procedure TAD_r is integral. Next, the procedure TAD_r converges to the global optimum, since the allocation of the available resources is done by a highest-penalty-first-assigned manner, which is a subprocedure of the simplex method [9], [14]. This completes the proof. ■

If $\bar{N}'_r = 0$, or $\bar{N}'_r > 0$ and $\sum_{j \in R_c} \sum_{k \in C_1} \sum_{l \in C_2} \bar{y}_j^{kl} \leq \bar{N}_c$, where \bar{y}_j^{kl} is an optimal solution of the subproblem RTAP_c,

the optimal solutions of the subproblems RTAP_r and RTAP_c consequently become an optimal solution of RTAP by the Proposition 2.

Proposition 2: If $\bar{N}'_r = 0$, or $\bar{N}'_r > 0$ and $\sum_{j \in R_c} \sum_{k \in C_1} \sum_{l \in C_2} \bar{y}_j^{kl} \leq \bar{N}_c$, where \bar{y}_j^{kl} is an optimal solution of the subproblem RTAP_c, the optimal solutions of the subproblems RTAP_r and RTAP_c consequently become an optimal solution of RTAP.

Proof: If $\bar{N}'_r = 0$, or $\bar{N}'_r > 0$ and $\sum_{j \in R_c} \sum_{k \in C_1} \sum_{l \in C_2} \bar{y}_j^{kl} \leq \bar{N}_c$, then $z_j^* = 1, j \in R_r$ and $z_j^* = 0, j \in R_c$. Thus, the optimal solutions of the subproblems RTAP_r and RTAP_c become a feasible solution of RTAP. Finally, since the sum of the objective values at the optimal solutions of the subproblems RTAP_r and RTAP_c is a lower bound of RTAP, the optimal solutions of the subproblems RTAP_r and RTAP_c consequently become an optimal solution of RTAP. ■

If the optimality condition of Proposition 2 is not satisfied, the procedure ETAD is performed (Fig. 7). ETAD finds an optimal solution or a feasible solution from the optimal solutions of the subproblems RTAP_c and RTAP_r. In the procedure, we define R_c^0 by the set of clear-sky RCSTs which are allocated clear-sky

```

Step 0 (Initialization)
  x = 0
Step 1 (Timeslot Scheduling in Rain-Fade Channels)
  i := 0 // i: slot counter
  FOR(∀j ∈ R - R_c^0) {
    FOR(k = 1; k ≤ |C_1|; k++) {
      FOR(l = 1; l ≤ |C_2|; l++) {
        FOR(; y_j^{kl} ≥ 0; y_j^{kl}--) {
          x_{ij}^{kl} = 1, i++.
        }
      }
    }
  }
Step 2 (Timeslot Scheduling in Clear-Sky Channels)
  i = 0
  FOR(∀j ∈ R_c^0) {
    FOR(k = 1; k ≤ |C_1|; k++) {
      FOR(l = 1; l ≤ |C_2|; l++) {
        FOR(; y_j^{kl} ≥ 0; y_j^{kl}--) {
          x_{ij}^{kl} = 1, i++.
        }
      }
    }
  }

```

Fig. 8. Procedure TS.

timeslots and, thus, $R_c - R_c^0$ is the set of clear-sky RCSTs which are allocated rain-fade timeslots. In Step 1, if $r_c = \bar{N}_c$, then the current solution $\{y_j^{kl}\}$ is an optimal solution, which results from the optimal solutions of the subproblems RTAP_c and RTAP_r. If $r_c < \bar{N}_c$, then Step 2 is performed and a feasible solution is found by adjusting $\{y_j^{kl}\}$. Fortunately, the feasible solution found in Step 2 may be an optimal solution.

C. Phase 3: Timeslot Scheduling (TS)

In this section, we propose a simple and efficient algorithm to assign timeslots to each RCST according to the timeslot amount determined in Phase 2. In a superframe, TRF timeslots are numbered from 0 (lowest frequency, first in time) to $|S| - 1$ (highest frequency, last in time), ordered in time then in frequency. Then, the TBTP table is built up iteratively by the procedure TS shown in Fig. 8.

V. PERFORMANCE ANALYSIS

We analyze the computational complexity and optimality gap of the proposed algorithm. Since the DVB-RCS standard is released in 2000, many system-specific resource allocation algorithms are necessary for field application but no algorithm for this system on the rain-fade attenuation issue is found. Thus, instead of comparing these two performance measures, e.g., efficiency and optimality, with other algorithm, we study the computational complexity and extensively simulate for more than 10 000 superframes.

A. Computational Complexity

Our algorithm has the following computational complexities.

- Phase 1: TSD has $O(|R_c|^2)$.

TABLE II
TRAFFIC PARAMETERS

k	Data class	Bandwidth requirement (kbps)	Average arrival rate (per hour)	Average holding time (s)
1	E-mail	5-20	10	3
2	Web	9.6	360	0.1
3	Video chatting	128-256	1	90
4	FTP	384	5	30
5	Streaming video	1024	1	300
Delay class		Meaning		
l	$l = 1, 2, 3, 4$	delayed for $l - 1$ superframes		
	$l = 5$	delayed for $l' - 1$ superframes, $\forall l' \geq l$		

- Phase 2:
 - TAD_r has $O(|R_r| \cdot |C_1| \cdot |C_2|)$;
 - TAD_c has $O(|R_c| \cdot |C_1| \cdot |C_2|)$;
 - ETAD has $\max\{O(|R_c|^2), O(|R_r| \cdot |C_1| \cdot |C_2|)\}$.
- Phase 3: TS has $O(|S|)$.

In a practical system, $|R_r|$, $|R_c|$, $|C_1|$, and $|C_2|$ are much less than $|S|$. For example, we have $|R_c| \approx 128$ and $|S| \approx 65\,000$ in an optimally designed superframe pattern [6], and $|C_1|$ is less than the average $|R_c|$ because there are not so many classes. This complexity analysis implies that our algorithm has a linear function of computational complexity on $|S|$. It is expected that this efficiency is very beneficial to the capacity request and assignment function in interactive satellite communications.

B. Simulation Model

In order to use an algorithm in practical systems, it should have real-time solution procedure (i.e., computational efficiency). With this, however, it is imperative to find a suboptimal solution as close to the global optimal solution as possible. Our algorithm is a real-time heuristic algorithm. It finds the optimal solution in some cases but it finds a suboptimal solution in other cases. Thus, we simulate extensive problems for more than 10 000 superframes to analyze the solution quality achieved with our algorithm. In our simulation, we have three target measures: *ADR*, *optimality gap*, and *computation time*. Remind that *duality gap* of an optimization problem [10], [11] means the normalized distance between the optimal objective value of the primal problem and the optimal objective value of the dual problem. When the dual problem is easier to solve than the primal problem, we generally attack the dual problem as an efficient heuristic alternative (refer to the Lagrangian relaxation algorithm) [10], [11]. However, it is not always guaranteed to find a feasible optimal solution of the primal problem if the primal problem is nonlinear. In this case, the measure gap shows how far the distance (between the true optimal solution and the current solution best ever found) is. In this paper, we introduce *optimality gap*, which means the normalized distance between the objective value at a feasible solution obtained by our heuristic algorithm and the objective value at the optimal solution.

In Tables II and III, simulation parameters are summarized. We consider five data classes in a return channel of 22.4 MHz: streaming video, FTP traffic, video chatting, web browsing, and e-mail. Also, we consider five delay classes according to the delayed transmission time (in superframes), where delay class l

TABLE III
RCST AND RETURN LINK PARAMETERS

Parameter	Value	Parameter	Value
T_f^r	304.776ms	N_r	1240 ($= n_{trf}^r \cdot n_f^r$)
T_f^c	190.485ms	N_c	15520 ($= n_{trf}^c \cdot n_f^c$)
W_{sf}	22.4MHz	R	{1, 2, ..., 240}
W_f	5.6MHz ($= W_f^r = W_f^c$)	R_r	{1, 2, ..., 90}
W_f^r	0.7MHz	R_c	{91, ..., 240}
W_f^c	5.6MHz	C_1	{1, 2, ..., 5}
n_f^r	5	C_2	{1, 2, ..., 5}
n_f^c	8	$ S $	$B_c \cdot N_c + B_r \cdot N_r$
n_{trf}^c	1940	B_c	0, 1, 2, or 3
n_{trf}^r	248	B_r	4 - B_c
T_{sf}	1523.880ms	FR_0	1.0 (fairness ratio)
α_j^{kl}	$k \times l, j \in R_r$ $\begin{bmatrix} 0.6 & 0.6 & 0.6 & 0.6 & 0.7 \\ 0.6 & 0.6 & 0.6 & 0.6 & 0.7 \\ 0.6 & 0.6 & 0.6 & 0.6 & 0.7 \\ 0.4 & 0.4 & 0.4 & 0.4 & 0.5 \\ 0.4 & 0.4 & 0.4 & 0.4 & 0.5 \end{bmatrix}$	$k \times l, j \in R_c$ $\begin{bmatrix} 0.5 & 0.5 & 0.5 & 0.5 & 0.6 \\ 0.5 & 0.5 & 0.5 & 0.5 & 0.6 \\ 0.5 & 0.5 & 0.5 & 0.5 & 0.6 \\ 0.3 & 0.3 & 0.3 & 0.3 & 0.4 \\ 0.3 & 0.3 & 0.3 & 0.3 & 0.4 \end{bmatrix}$	

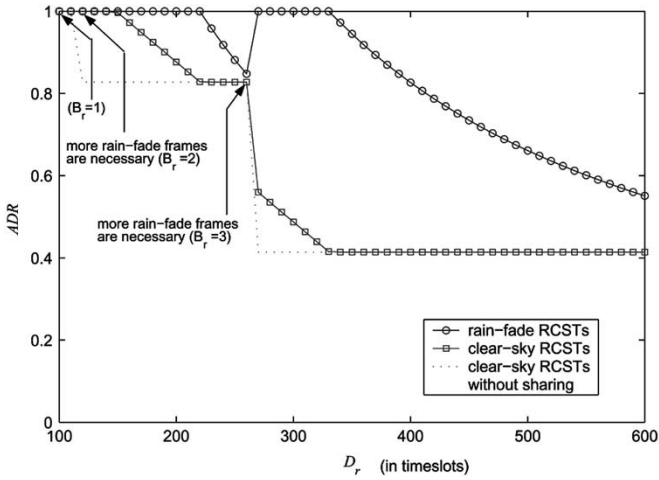


Fig. 9. ADR versus average demand of rain-fade RCSTs (D_r): $D_c = 250$ (in timeslots).

means that a certain burst is delayed for $l-1$ superframe (for $l = 1, 2, 3, 4$) and delay class 5 means that a certain burst is delayed for at least four superframes. Demand of service class $(k, 1)$ of RCST j is randomly generated from a uniform distribution with a randomly chosen period specified in Table II. Demand of service class (k, l) for $l \geq 2$ is computed by $d_j^{k,l} = d_j^{k,l-1} - y_j^{k,l-1}$ (for $l = 2, 3, 4$), and $d_j^{k,5} = \sum_{l=4}^5 (d_j^{k,l} - y_j^{k,l})$.

C. Simulation Results and Discussions

Fig. 9 shows the ADR as the average demand of rain-fade RCSTs increases given that the average demand of clear-sky RCSTs D_c is 250 (in timeslots). It is observed that the number of rain-fade channels B_r increases as the average demand of rain-fade RCSTs increases. In Fig. 9, we have several intervals [100, 120), [120, 150), [150, 230), [230, 270), [270, 340), and [340, 600], which are labeled as A, B, C, D, E, and F, respectively. In interval A, rain-fade RCSTs are assigned 100% of the demand at $B_r = 1$. In interval (B \cup C \cup D), B_r should be 2 to meet the fairness condition with $FR_0 = 1$. In interval (A \cup B \cup C), a certain number of rain-fade timeslots are assigned to clear-sky RCSTs. However, the number of rain-fade timeslots are not available for clear-sky RCSTs in interval D.

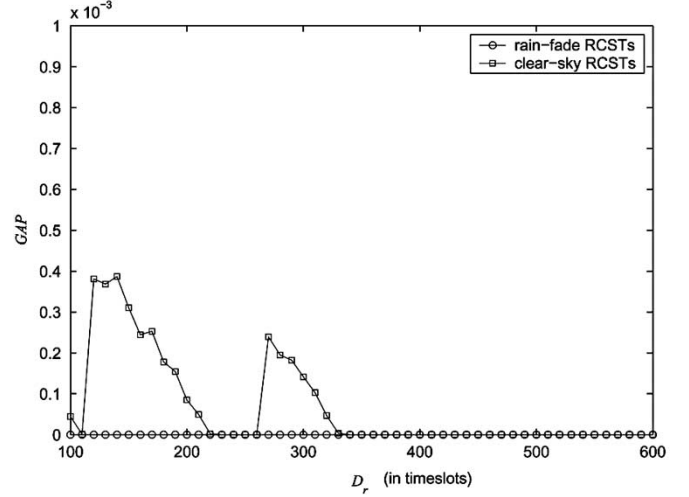


Fig. 10. Optimality gap: $D_c = 250$ (in timeslots).

Thus, ADR_r is 100%, whereas ADR_c decrease in interval C, and ADR_r decreases, whereas ADR_c does not decrease in interval D. Although ADR_c is less than 100% at $D_r = 260$, B_r should be increased by one at $D_r = 270$ because the fairness condition should be satisfied, i.e., $FR \geq FR_0$. In interval (E \cup F), B_r should be 3 to meet the fairness condition with $FR_0 = 1$. Similar features as shown in interval (C \cup D) are also observed in interval (E \cup F). The dotted line in Fig. 9 shows ADR_c when residual rain-fade timeslots are not shared by clear-sky RCSTs. As shown in the figure, ADR_c is improved by sharing of residual rain-fade timeslots when the demand of rain-fade RCSTs is not overflowed (saturated). In Fig. 10, GAP is plotted with the same test set used in Fig. 9, where GAP is usually defined as the relative difference between the optimal objective value A and the objective value at the heuristic solution B as

$$GAP = \frac{B - A}{A}.$$

If GAP is zero, then the heuristic solution is optimal. The maximum value of GAP is less than 0.0004 (0.04%), which shows good performance of our algorithm.

Fig. 11 shows the relation between ADR and D_c given that $D_r = 250$ (in timeslots). It is observed that the number of clear-sky channels B_c increases as D_c increases. In Fig. 11, we have several intervals [100, 160), [160, 235), [235, 715), and [715, 850], which are labeled as A, B, C, and D, respectively. In interval (A \cup B), a certain number of rain-fade timeslots are available for clear-sky RCSTs because the residual rain-fade timeslots are shared by clear-sky RCSTs, which are overflowed (saturated). ADR_r and ADR_c are 100% in interval A, whereas ADR_c decrease in interval B because of demand overflow of clear-sky RCSTs (D_c is greater than the number of available timeslots). By procedure TSD (Fig. 4), we obtain that $B_c = 2$ in interval C and $B_c = 3$ in interval D. Similar features as observed in interval B are also observed in interval C and in interval D, respectively. The dotted line in Fig. 11 shows ADR_c when residual rain-fade timeslots are not shared by clear-sky RCSTs. It is also observed that ADR_c is improved by sharing of residual rain-fade timeslots when the demand of rain-fade

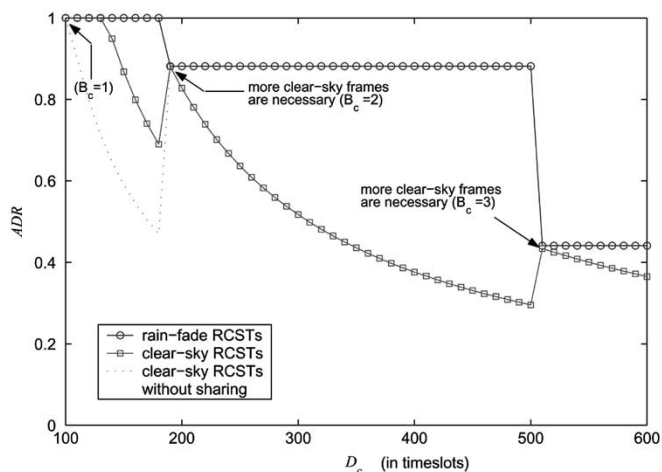


Fig. 11. ADR versus average demand of clear-sky RCSTs (D_c): $D_r = 250$ (in timeslots).

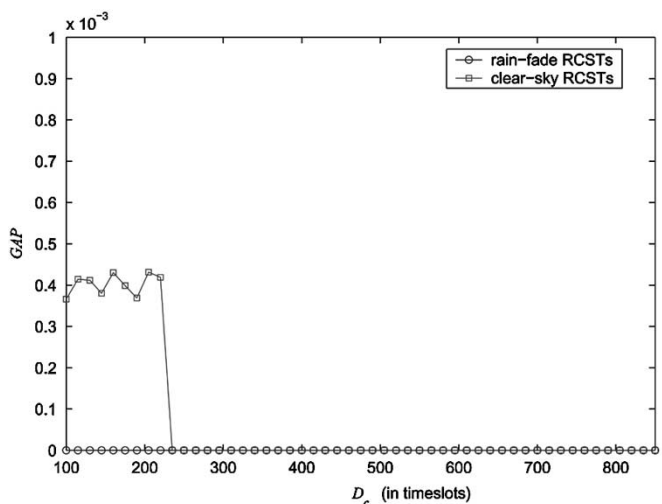


Fig. 12. Optimality gap: $D_r = 250$ (in timeslots).

RCSTs is not overflowed(saturated). In Fig. 12, GAP is plotted with the same test set used in Fig. 11. The maximum value of GAP is less than 0.0005 (0.05%), which shows good performance of our algorithm. Fig. 13 shows extensive measurements of computation time of our algorithm with Pentium III 1.0 GHz machine. Three kinds of cases are considered in our simulation. In the first case, rain-fade channels are not saturated. This means that the number of rain-fade timeslots is greater than the demand of rain-fade RCSTs, where the residual amount can be assigned to clear-sky RCSTs. In the second case, rain-fade channels are always saturated and, thus, there is no residual rain-fade timeslot available for clear-sky RCSTs. In the first case (no saturation of rain-fade channels), additional scheduling is necessary to assign the residual rain-fade timeslots to clear-sky RCSTs. As a result, the computation time is slightly greater than that in the second case. The third case emulates a general environment, where rain-fade channels are sometimes saturated and sometimes not. After timeslot scheduling, the result of schedule is transformed into a TBTP table [1] and the TBTP table is packetized as transport stream packets, and then the hub broadcasts

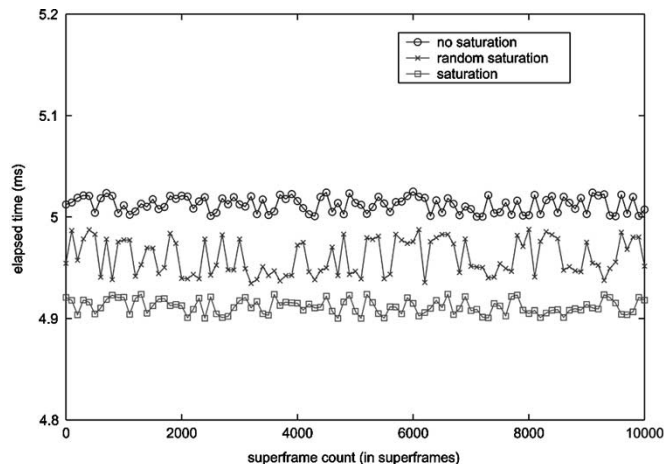


Fig. 13. Computation time for 10000 superframes: no saturation, random saturation, and saturation of rain-fade channels.

these packets to RCSTs via a satellite. Scheduling time of about 5 ms is short enough to complete this TBTP table generation and transmission procedure within a certain period of time shorter than the designed superframe duration, e.g., thousands of milliseconds. As shown in the figure, our heuristic algorithm has an excellent computational efficiency.

VI. CONCLUSION

In ISM systems, such as a DVB-RCS system, it is imperative to provide multirate services in order to guarantee various QoS levels with limited valuable radio resources. Since *Ka*-band link quality is usually affected by rain-fade attenuation, providing multirate services is even more important to efficiently classify and manage the terminals suffering from rain-fade attenuation.

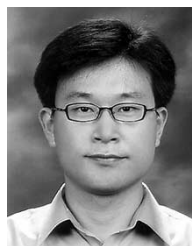
We have focused on developing an efficient real-time algorithm for timeslot assignment in an ISM network with multirate superframe patterns. We mathematically formulated this timeslot assignment problem as a nonlinear integer programming problem to minimize the overall weighted penalty (maximize the weighted throughput). In order to improve real-time computational efficiency, we developed an efficient heuristic algorithm for an NP-complete problem. We analyzed the computational complexity and performed extensive simulation. Extensive simulation results showed that solutions found by our heuristic algorithm are very close to the global optimal solutions with the gap between the heuristic solution and the optimal solution in within 0.05%. Thanks to these solution efficiency and excellent solution quality, we believe that the proposed real-time heuristic algorithm can be used for performance improvement in practical systems.

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