Capacity Scheduling for Heterogeneous Mobile Terminals in Broadband Satellite Interactive Networks

Ki-Dong Lee and Ho-Kyom Kim

ABSTRACT—We develop a simple exact solution method for return link capacity allocation scheduling in a satellite interactive network using a hybrid code-division multiple access / time-division multiple access (CDMA/TDMA) scheme.

Keywords—Scheduling, capacity, throughput, satellite, CDMA, TDMA.

I. Introduction

The digital video broadcasting (DVB) return channel via satellite (RCS) network is an interactive network for geostationary Earth orbit satellites, providing multimedia communication and broadcasting services [1]-[3]. It consists of one Earth station (hub), a geostationary Earth orbit satellite, and a number of immobile terminals. In the future, however, it will be essential that communication and broadcasting services be provided for mobile satellite interactive terminals (SITs) during their movement. Using the system architecture of the DVB-RCS standard [1], it is not possible to efficiently utilize the radio resources for mobile terminals because of their frequent synchronization failures and high bit-error rates caused by high terminal mobility, e.g., in cases of mobile speeds of more than hundreds of miles per hour.

As an alternative, we consider a mobility-supported interactive satellite system using hybrid CDMA/TDMA return channels over a Ku-band. Such mobility-supported services using Inmarsat can be found. However, these are narrow band communication services whereas our system using Ku-band channels is a broadband service (40 Mbps in the forward link, 384 kbps/user in the return link) [4]. Several scheduling algorithms for DVB-RCS are found in the literature [5]-[7]. However, these algorithms are based on multi-frequency time-division multiple access, where we divide the total available radio resources into time-frequency slots. Since the radio resources are divided into code frequency time (CFT) slots in the proposed system model, we need to figure out an enhanced problem with more constraints for CFT slot scheduling in this hybrid CDMA/TDMA scheme. The additional constraints usually make the solution procedure more complex than those shown in [5] and [6].

We mathematically formulate the CFT slot assignment

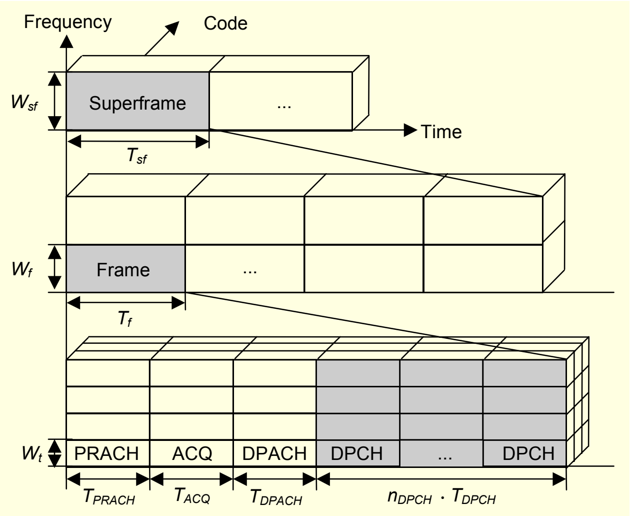


Fig. 1. A superframe pattern in a hybrid CDMA/TDMA return link.

Manuscript received Oct. 15, 2003; revised Apr. 7, 2004.

Ki-Dong Lee (phone: +82 42 860 5225, email: kdlee@etri.re.kr) and Ho-Kyom Kim (email: hokykim@etri.re.kr) are with Digital Broadcasting Research Division, ETRI, Daejeon, Korea.

problem (SAP) as a binary integer programming (BIP) problem. The penalty weight sequence used in the formulation can be dynamically specified according to the quality-of-service condition of each satellite terminal, such as delayed service time, buffer overflow status, and so on. In order to solve the BIP problem with computational efficiency, we use a problem reduction and decomposition technique [8]. As a result, the BIP problem is decomposed into two sub-problems: where the optimal assignment amount vector is determined in the first phase and a terminal burst time-code plan is determined in the second phase. Performance analysis shows that the proposed method provides both solution efficiency and optimality.

II. Mathematical Formulation

1. Return Link Model

We consider a hybrid CDMA/TDMA model [4], where a superframe, which is defined as a specific time-frequency block $T_{sf}\times W_{sf}$ (μs·MHz) in the time-frequency domain, includes a group of frames, and each frame, a specific time-frequency block $T_f\times W_f$, consists of physical random access channel (PRACH) slots ($T_{PRACH}\times W_t$), acquisition (ACQ) slots ($T_{ACQ}\times W_t$), dedicated physical acquisition channel (DPACH) slots ($T_{DPACH}\times W_t$), and dedicated physical channel (DPCH) slots ($T_{DPCH}\times W_t$). The resources in the CDMA/TDMA return link, denoted by set S, are defined as available DPCH slots.

2. Input Parameters and Control Variables

The scheduler periodically requires updated information such as the set of active SITs (denoted by set R where the number of elements is limited by $R_{\max}$) and the capacity demands of active SITs during T_{sf} (denoted by matrix $\mathbf{D}=[D_k]$). A four dimensional array, $\mathbf{x}=[x^l_{ijk}]$, denotes the slot assignment: x^l_{ijk} equals one if code j during slot (l, i) is assigned to SIT k; otherwise, x^l_{ijk} equals zero. Slot (l,i) is characterized by the frequency-time block, where l and i denote the channel index and the time index, respectively. x^l_{ijk}'s are binary control variables of (SAP).

3. Problem Formulation

Our objective is to maximize the return link throughput for each superframe. Each SIT $k\in R$ has a capacity upper bound, Q_k $(\le n|S|)$. Because the following objective function shown in (1) denotes the weighted number of timeslots which do not satisfy the SITs (called penalty in this letter), the maximization problem of the throughput can be formulated as a minimization problem of the total penalty. The main concern of this study is how to allocate the available resources per each superframe to the SITs in order to minimize the total penalty.

(SAP)

$$\text{Minimize}\quad g(\mathbf{x})=\sum_{k\in R}a_k\left(D_k-\sum_{l\in F}\sum_{i\in S}\sum_{j\in C}x^l_{ijk}\right) \tag{1}$$

subject to constraints

$$\sum_{l\in F}\sum_{i\in S}\sum_{j\in C}x^l_{ijk}\le \min(Q_k,D_k),\ k\in R \tag{2}$$

$$\sum_{l\in F}\sum_{i\in S}\sum_{j\in C}x^l_{ijk}\ge \min(m_k,\alpha_k D_k),\ k\in R \tag{3}$$

$$\sum_{l\in F}\sum_{j\in C}\sum_{k\in R}x^l_{ijk}\le 1,\ i\in S \tag{4}$$

$$x^{l_1}_{ijk}+x^{l_2}_{ijk}\le n,\ l_1\ne l_2\in F \tag{5}$$

$$\forall x^l_{ijk}\in\{0,1\}$$

where a_k is a given threshold value denoting the minimal requirement on a fraction of the assigned capacity out of the requested capacity. For example, consider a case where a_k = 0.5. In this situation, at least 50% of the demand, D_k, must be assigned to SIT k. These threshold values can be specified according to each service provider's quality-of-service policies.

In (1), the objective function of (SAP) indicates a weighted penalty, where the respective penalty increases by factor a_k proportional to $\sum_{l\in F}\sum_{i\in S}\sum_{j\in C}x^l_{ijk}$ if the assignment amount is less than the requested amount, D_k. Constraint (2) implies that the number of DPCH slots assigned to SIT k is not greater than the maximum capacity, Q_k, or the requested amount, D_k. Each SIT k must be assigned a certain amount of capacity greater than or equal to the minimum capacity. Constraint (3) denotes a requirement that a given fraction of the demand should be assigned for each SIT. Constraint (4) shows that no DPCH slot can be assigned to more than one SIT. Constraint (5) indicates that no SIT can use more than n CFT slot(s) at the same epoch. If the demodulator does not have a segmentation-and-reassembly function over the multi-frequency channels, then we must solve (SAP) given n=1. With the solution algorithm for the case of n=1, we can simply generalize the algorithm with any positive integer value n.

III. Capacity Allocation Procedure

We employ a problem decomposition technique in order to reduce the computational burden to the packet scheduler. (SAP) is divided into two sub-problems: the optimal amount of resources allocated to each SIT is determined by solving the first sub-problem, and a CFT slot allocation schedule is made using the solution of the second sub-problem.

We reduce problem (SAP) to the following sub-problem (SAP1) under the assumption that that problem is feasible. In this sub-problem, y_k denotes the amount of capacity for allocation to SIT k excluding the minimal amount, min (m_k, $\alpha_k D_k$).

(SAP1)

$$\text{Minimize} \qquad g(y)=\sum_{k\in R} a_k\left(D_k-y_k\right) \qquad (6)$$

subject to constraints

$$y_k \le \min\left(Q_k, D_k\right), k \in R \qquad (7)$$

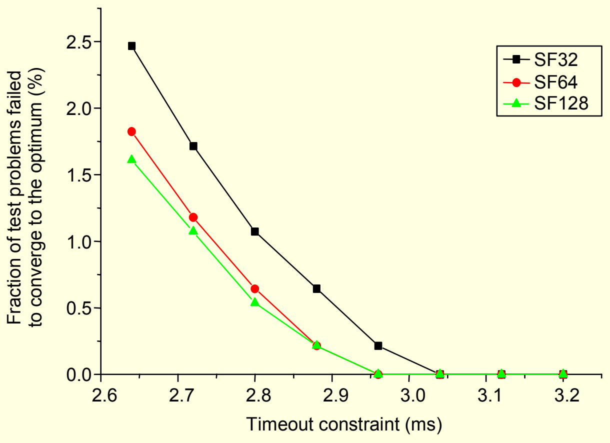
$$\forall y_k\text{: non-negative integers.}$$

If a feasible optimal solution of (SAP1) exists, then this solution can be simply transformed into a feasible solution of (SAP). Under the condition that $Q_k \le n|S|$ and $|S||F||C| \ge \sum_{k\in R} \min\left(m_k, \alpha_k D_k\right)$, a feasible optimal solution exists. The trivial feasible optimal solution of this problem is given by $y_k = \min\left(Q_k, D_k\right), k \in R$. With the optimized amount of capacity for allocation to each SIT, we now need to determine which CFT slot(s) should be assigned to each SIT. This problem is simply and exactly solved using the following procedure.

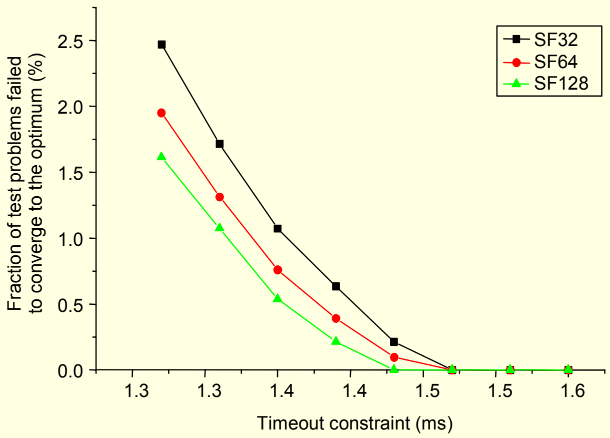
```
$Slot\_count = 0$;
$z_k = y_k + min(m_k, \alpha_k D_k), \forall k \in R$;
FOR ($x = 0, k = 1$;  $k <= |R|$;  $k{+}{+}$) {
    FOR ($i = 0$;  $i < z_k$;  $i{+}{+}$) {
        $x_{i+Slot\_counter, j_k} = 1$,  $Slot\_count \mathrel{+}= z_k$;
    }
}
```

IV. Results and Discussions

We extensively simulated the proposed method for three different cases: spreading factors 32, 64, and 128, in order to evaluate the computational efficiency and solution quality. We consider a superframe pattern with a 2.9 MHz bandwidth and durations of 2.635 and 1.276 seconds. The number of SITs is randomly generated from a discrete uniform distribution with parameters (1, 1536). We take a_k=1 and α_k=0.3. D_k is randomly chosen from discrete uniform distributions with parameters (m_k, 61), (m_k, 32), and (m_k, 16) for spreading factors 32, 64, and 128, respectively, where m_k is chosen to be 0. We take 1,365 test problems using 1 hour for each spreading factor value.



(a) Superframe duration=2.635 s



(b) Superframe duration=1.276 s

Fig. 2. The fraction of test problems failed to reach the optimum before timeout constraint.

Table 1. Computation time (in ms) for capacity scheduling.

Spreading factor	Superframe duration	Min	Avg	Max
32	2.635 s	2.190	2.549	3.180
	1.276 s	1.110	1.310	1.550
64	2.635 s	1.880	2.401	3.010
	1.276 s	1.020	1.209	1.520
128	2.635 s	1.790	2.352	2.980
	1.276 s	0.980	1.191	1.480

Figure 2 shows the fraction of test problems where the method stopped at a suboptimum level because of scheduling time expiration. Compared to the superframe duration, the proposed method shows an excellent efficiency. Table 1 shows the statistics of the computing times where we measured the computing time of the same problem 1,000 times and took the average as a sufficient statistic (e.g., 2.190 ms is estimated without loss of generality from 2190 ms/1000).

V. Concluding Remarks

We developed an efficient method of optimal resource allocation scheduling for mobile terminals in an interactive satellite multimedia network in order to maximize the system throughput. We mathematically formulated the slot-code assignment problem as a binary integer programming problem and employed a problem decomposition technique to improve computational efficiency. Extensive simulation results showed that the proposed method finds the optimal solution for capacity allocation within 3.180 ms at most for a superframe duration of about 2.6 s. Because of a fast convergence speed to the global optimum, we believe that the proposed optimization approach can be used for throughput performance improvement in practical interactive satellite multimedia networks.

References

[1] *Digital Video Broadcasting (DVB); Interaction Channel for Satellite Distribution Systems*, ETSI EN 301 790 (V1.2.2), 2000.

[2] J. Neale, R. Green, and J. Landovskis, “Interactive Channel for Multimedia Satellite Networks,” *IEEE Com. Mag.*, Mar. 2001.

[3] T. Le-Ngoc, V. Leung, P. Takats, and P. Garland, “Interactive Multimedia Satellite Access Communications,” *IEEE Com. Mag.*, July 2003.

[4] K.-D. Lee et al., “Optimal Capacity Assignment in Interactive Satellite Return Channels for Mobile Multimedia Services,” *Proc. IEEE VTC Fall 2003*, Florida, 2003.

[5] K.-D. Lee, H.-J. Lee, Y.-H. Cho, and D.G. Oh, “Throughput-Maximizing Slot Scheduling for Interactive Satellite Multiclass Services,” *IEEE Commun. Lett.*, vol. 7, no. 6, June 2003.

[6] K.-D. Lee, Y.-H. Cho, H.-J. Lee, and D.-G. Oh “Improving Efficiency of Timeslot Assignment for Non-realtime Data in a DVB-RCS Return Link: Modeling and Algorithm,” *ETRI J.*, vol. 25, no. 4, Aug. 2003, pp. 211-218.

[7] A. Iuoras, “Advanced Scheduling Techniques,” *Proc. 8th Ka-Band Util. Conf.*, Italy, Sept. 2002, pp. 397-406.

[8] K. Murty, *Linear and Combinatorial Programming*, Wiley, 1976.