A Real-Time Algorithm for Timeslot Assignment in ISM System with DVB-RCS

Ik Sun Lee, Chang Sup Sung, Gwang-Ja Jin, and Ki Seop Han

This paper considers a timeslot assignment problem in an interactive satellite multimedia (ISM) system with digital video broadcast-return channel via satellite (DVB-RCS). The timeslot assignment problem is formulated as a binary integer programming to maximize the overall weighted throughput and is shown to be NP-hard. Thus, three real-time heuristic algorithms including ratio-based, packet-size (PS)-based, and transmission gain (TG)-based are derived, and some computational experiments are made. Considering the results, the ratio-based heuristic algorithm is demonstrated to be the most effective and efficient. We propose adapting the ratio-based heuristic algorithm to the timeslot assignment problem to greatly improve the ISM system utilization.

Keywords: Interactive satellite multimedia, DVB-RCS, MF-TDMA, timeslot scheduling.

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Ik Sun Lee (phone: + 82 42 869 3154, email: lis1007@kaist.ac.kr) and Chang Sup Sung (email: cssung@kaist.ac.kr) are with Department of Industrial Engineering, KAIST, Daejeon, Korea.

Gwang-Ja Jin (email: gjjin@etri.re.kr) is with Telematics & USN Research Division, ETRI, Daejeon, Korea.

Ki Seop Han (email: kshan78@etri.re.kr) is with Radio & Broadcasting Research Division, ETRI, Daejeon.

I. Introduction

An interactive satellite multimedia (ISM) system with digital video broadcast-return channel via satellite (DVB-RCS) has been proposed to provide multimedia services including high-speed Internet services and broadcasting services to subscribers in various high-speed vehicles including buses, cars, high-speed trains (such as KTX in Korea, TGV in France, Shinkansen in Japan, and so on), ships, and airplanes which are distributed over very wide areas [1]-[6]. The ISM system consists of one hub station, a geostationary earth orbit (GEO) satellite, and a number of satellite mobile terminals (SMTs) [3], [4] where each SMT can be considered a user terminal or a terminal group having a number of user PCs.

Recently, the Electronics and Telecommunications Research Institute (ETRI), Korea, has developed an ISM system called *mobile broadband interactive satellite access technology* (MoBISAT). The ISM system based on DVB-RCS uses a TDM scheme for the forward link, but uses a multi-frequency time-division multiple access (MF-TDMA) scheme for the return link [4]. In the return link, however, the available radio resources are very limited, so it is very important to derive an efficient timeslot schedule in a fixed MF-TDMA return link within short time limit. Therefore, the aim of this study is to find a timeslot assignment schedule to maximize the overall throughput of the ISM system.

In order to transmit a packet, it is often necessary to allocate several timeslots. Therefore, this paper considers the situation where transmission gain can be made only when all the timeslots required for a packet transmission are allocated. For example, let the requirement of timeslots for packet k of SMT j be d_k and the transmission gain be w_k. Then, this paper will consider the situation where gain w_k can be made only when d_k

timeslots are allocated for SMT j. Previous studies [7]-[10] have assumed that partial transmission gain can be made by allocating even one timeslot, though not as many timeslots as are required for any packet. In reality, however, packet transmission cannot be completed and hence no gain can be made if the full timeslot requirement is not allocated for any single packet transmission. For this reason, we propose a more practical solution than the algorithm proposed in [8].

The timeslot assignment problem (TAP) is formulated as a binary integer programming (BIP) problem, which will be shown to be NP-hard. Accordingly, three real-time heuristic algorithms including the ratio-based, packet-size (PB)-based, and transmission gain (TG)-based are derived. Computational experiments show that the ratio-based heuristic algorithm is very effective and efficient. Moreover, the ratio-based heuristic algorithm provides solutions 26.5% better than those of the algorithm of [8] within a short time limit.

The rest of this paper is organized as follows. Section II presents the problem description and mathematical formulation. Section III characterizes a solution property, on the basis of which the three real-time heuristic algorithms are derived. Section IV analyzes the performance of the derived real-time algorithms. Finally, in section V we make some concluding remarks.

II. Problem Description and Formulation

Figure 1 illustrates the superframe pattern of the proposed MF-TDMA model. A superframe is defined as a specific time-frequency block $T_{sf} \times W_{sf}$ (μs·MHz) in the time-frequency domain including a group of frames, where each frame, a specific time-frequency block $T_f \times W_f$, consists of common signaling channel (CSC) timeslots ($T_{CSC} \times W_t$), acquisition (ACQ) timeslots ($T_{ACQ} \times W_t$), synchronization (SYNC) timeslots ($T_{SYNC} \times W_t$), and traffic (TRF) timeslots ($T_{trf} \times W_t$). The resources (timeslots) in the MF-TDMA return link, denoted by set S, are defined as available TRF timeslots.

The set of active SMTs and the set of service classes are denoted by R and K, respectively. The number of packets waiting for transmission for service class k of SMT j is denoted by n_{jk}, and (for $j \in R$ and $k \in K$) the required timeslots for each packet are denoted by $d_1^{jk}, d_2^{jk}, \cdots, d_{n_{jk}}^{jk}$. Each service class k of SMT j has a maximum timeslot allocation Q_{jk}, so that, at most, Q_{jk} timeslots can be assigned to service class k of SMT j.

In ISM systems, the resource allocation policy is based on the so-called bandwidth-on-demand (BoD). Any SMT in need of capacity must send capacity request (CR) messages to a scheduler which is a unit of the hub. Since the timeslot assignment in ISM systems is based on BoD, no timeslot can

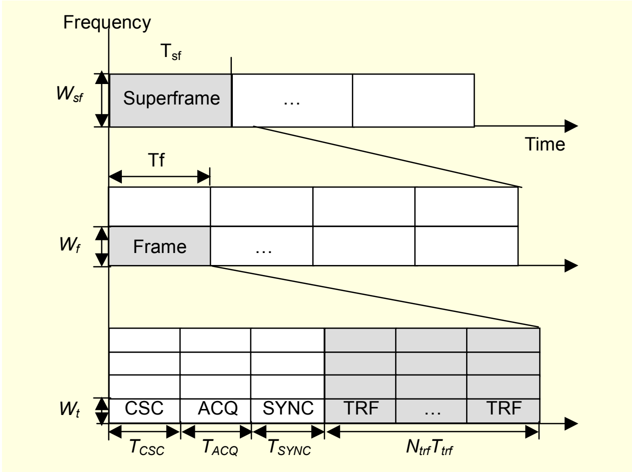

Fig. 1. Example of superframe structure in a return link.

be allocated to any SMT whose SYNC timeslots are at failure, which is critical to quality-of-service (QoS). In order to reduce such QoS degradation caused by SYNC timeslot failure, we consider an allocation policy of assigning the minimal number of TRF timeslots so that CR messages may be transmitted more stably via TRF timeslots, based on the data unit labeling method (DULM) (see [4]). Therefore, we introduce the minimal timeslot requirement, m_j, which must be assigned to an active SMT j. Upon receiving the CR messages, the scheduler generates a terminal burst time plan (TBTP) table and sends it to the SMTs. Upon receiving the TBTP table, each SMT reads the TBTP table to know what timeslots are assigned. This procedure is executed in every superframe.

In the proposed problem, the decision variable $x_m^{jk}(n)$ is a binary integer variable indicating timeslot assignment, where the relation $x_m^{jk}(n) = 1$ denotes that one timeslot is assigned as the n-th timeslot for packet m in association with service class k of SMT j, and $x_m^{jk}(n) = 0$ otherwise. This paper assumes that the relations $x_m^{jk}(n) \geq x_m^{jk}(n-1)$ hold for $\forall j \in R$, $\forall k \in K$, m=1,⋯, n_{jk}, and n=2,⋯, d_m^{jk}, so that timeslots are assigned sequentially to packet m (associated with service class k of SMT j). Therefore, the relation $x_m^{jk}(n) = 1$ denotes that at least n timeslots are assigned to packet m in association with service class k of SMT j. If d_m^{jk} timeslots are assigned to packet m (service class k of SMT j), that is, if the relation $x_m^{jk}(d_m^{jk}) = 1$ holds, then the gain w_m^{jk} will be achieved. The gain value matrix can be dynamically specified according to the QoS conditions of each terminal including packet waiting time and buffer overflow status. Specifically, the value $\sum_{j \in R} \sum_{k \in K} \sum_{m=1}^{n_{jk}} w_m^{jk} x_m^{jk}(d_m^{jk})$ represents the total gain value (throughput) of such a timeslot assignment schedule. This leads to a problem of how to allocate the available resources per superframe regarding the SMTs in order to maximize the total gain value (throughput).

Now, the associated TAP is mathematically formulated as follows:

$$\text{Maximize} \quad \sum_{j\in R}\sum_{k\in K}\sum_{m=1}^{n_{jk}} w_m^{jk} x_m^{jk}\left(d_m^{jk}\right), \tag{1}$$

$$\text{subject to} \quad x_m^{jk}(n) \ge x_m^{jk}(n-1),\ \forall j\in R,\ \forall k\in K,$$

$$m = 1,\cdots, n_{jk} \text{ and } n = 2,\cdots, d_m^{jk}. \tag{2}$$

$$\sum_{m=1}^{n_{jk}}\sum_{n=1}^{d_m^{jk}} x_m^{jk}(n) \le Q_{jk},\quad \forall j\in R \text{ and } \forall k\in K, \tag{3}$$

$$\sum_{j\in R}\sum_{k\in K}\sum_{m=1}^{n_{jk}}\sum_{n=1}^{d_m^{jk}} x_m^{jk}(n) \le |S|, \tag{4}$$

$$\sum_{k\in K}\sum_{m=1}^{n_{jk}}\sum_{n=1}^{d_m^{jk}} x_m^{jk}(n) \ge m_j,\quad \forall j\in R, \tag{5}$$

$$\sum_{m=1}^{n_{jk}}\sum_{n=1}^{d_m^{jk}} x_m^{jk}(n) \ge \min\left\{Q_{jk}, \alpha_{jk}\sum_{m=1}^{n_{jk}} d_m^{jk}\right\},$$

$$\forall j\in R \text{ and } \forall k\in K, \tag{6}$$

$$x_m^{jk}(n) \in \{0, 1\},\ \forall j\in R,\ \forall k\in K,$$

$$m = 1,\cdots, n_{jk}, \text{ and } n = 1, \cdots, d_m^{jk}.$$

The value $\sum_{n=1}^{d_m^{jk}} x_m^{jk}(n)$ represents the number of timeslots allocated to packet m for service class k of SMT j. Constraint (3) signifies that the number of timeslots assigned to class k of SMT j is not greater than the maximum timeslot allocation Q_{jk}. Constraint (4) signifies that the number of timeslots allocated to all SMTs is not greater than the total number of available timeslots $|S|$. Constraint (5) signifies that the number of timeslots allocated to SMT j is not smaller than the minimal timeslot requirement m_j. Constraint (6) signifies that the number of timeslots allocated to service class k of SMT j is not smaller than the value $\min\left\{Q_{jk}, \alpha_{jk}\sum_{m=1}^{n_{jk}} d_m^{jk}\right\}$, where α_{jk} is a threshold value. By using the threshold values α_{jk}, a guaranteed lower bound on the QoS of the respective SMTs can be provided. For example, in a case where the relation, α_{jk} = 0.5, holds, at least 50% of any timeslot requirements must be satisfied for each service class k of SMT j. These threshold values can be specified according to the policies of service providers.

The objective gain function (1) and constraints (3) and (4) form a special type of knapsack problem, so that the TAP can be reduced to a knapsack problem which is known to be NP-hard [11]. This implies that a polynomial (efficient) optimal algorithm is unlikely to exist for the proposed problem. Therefore, we derive three efficient real-time heuristic algorithms in the next section.

III. Solution Algorithms

As characterized above, the proposed problem is an NP-hard knapsack problem, so it is necessary to newly derive the problem-associated real-time heuristic algorithm. First, the problem can be characterized as satisfying the property that any terminal having smaller packet size but larger transmission gain could make a larger contribution in timeslot assignment than any other terminal. In this connection, proposition 1 can be derived.

Proposition 1. Consider any two packets p and q for service class k of SMT j, where the two relations $w_p^{jk} \ge w_q^{jk}$ and $d_p^{jk} \le d_q^{jk}$ hold. Then, packet p has greater transmission priority than packet q.

Based on proposition 1, we derive three real-time heuristic algorithms.

1. Ratio-Based Heuristic

Based on proposition 1, this section proposes the following transmission priority rule: the larger the w_m^{jk}/d_m^{jk} ratio packet, the higher the transmission priority. Based on that priority rule, a two-phase real-time ratio-based heuristic algorithm is derived first.

For the algorithm derivation, the following phase I is derived, which satisfies constraints (5) and (6) in order to allocate the associated minimum requirement of timeslots at each terminal. In step 1 of phase I, all the packets to be transmitted are sequenced in non-increasing w_m^{jk}/d_m^{jk} order, and in steps 2 and 3, their corresponding timeslots are allocated subject to constraints (5) and (6), respectively.

A. Phase I.

Step 1. Sequence all the packets (to be transmitted) in non-increasing ratio w_m^{jk}/d_m^{jk} order for service class k of SMT j as in the order $w_{n_{jk}}^{jk}/d_{n_{jk}}^{jk} \ge \cdots \ge w_1^{jk}/d_1^{jk}$ for each $j \in R$ and $k \in K$.

Step 2. Assign timeslot subject to constraint (6):

```
[Y_j] := 0.
for ( j := 1 ; j ≤ |R| ; j++ ) {
   for ( k := 1 ; k ≤ |K| ; k++ ) {
        X_jk :=  min{ Q_jk , α_jk Σ_{m=1}^{n_jk} d_m^jk , |S| } .
        |S| := |S| – X_jk.
        Y_j := Y_j + X_jk.
        i := n_jk.
        while ( (i ≥ 1) && (X_jk > 0) ) {
                temp := min{d_i^jk , X_jk} .
                X_jk := X_jk – temp.
                d_i^jk :=  d_i^jk – temp.
                if ( d_i^jk == 0), then n_jk := n_jk  –  1.
                i:= i – 1.
        }
        if ( |S| == 0), then terminate the algorithm.
}    }
```

Step 3. Assign timeslot subject to constraint (5):

for (j := 1 ; j ≤ |R| ; j++) {
  $Y_j := m_j - Y_j$.
  while ($Y_j > 0$) {
    if ($\{ k \mid n_{jk} > 0, \text{ for } \forall k\} = \varphi$), then $Y_j := 0$.
    else {
      $\bar{k} := \operatorname{argmax}_{(k)}\{w^{jk}_{n_{jk}} / d^{jk}_{n_{jk}}, \text{ for } n_{jk} > 0\}$.
      temp:= $\min\left\{ d^{j\bar{k}}_{n_{j\bar{k}}}, Y_j, Q_{j\bar{k}}, |S| \right\}$.
      $Y_j := Y_j$ – temp.
      $Q_{j\bar{k}} := Q_{j\bar{k}}$ – temp.
      $d^{j\bar{k}}_{n_{j\bar{k}}} := d^{j\bar{k}}_{n_{j\bar{k}}}$ – temp.
      |S| := |S| – temp.
      if ($d^{j\bar{k}}_{n_{j\bar{k}}} == 0$), then $n_{j\bar{k}} := n_{j\bar{k}} - 1$.
      if ($Q_{j\bar{k}} == 0$), then $n_{j\bar{k}} := 0$.
      if (|S| == 0), then terminate the algorithm.
} } }

After executing phase I, some of the original constraints can be satisfied, so that the proposed original problem can be reduced to the following problem (TAP′), which is concerned with any remaining (not yet satisfied) packets and available timeslots. The problem (TAP′) is expressed as

$$\text{Maximize} \quad \sum_{j\in R}\sum_{k\in K}\sum_{m=1}^{n_{jk}} w_m^{jk} x_m^{jk}\left(d_m^{jk}\right), \tag{7}$$

$$\text{subject to } x_m^{jk}(n) \ge x_m^{jk}(n-1),\ \forall j \in R,\ \forall k \in K,\ m=1,\cdots,n_{jk}, \text{ and } n=2,\cdots,d_m^{jk}, \tag{8}$$

$$\sum_{m=1}^{n_{jk}}\sum_{n=1}^{d_m^{jk}} x_m^{jk}(n) \le Q_{jk},\ \forall j \in R \text{ and } \forall k \in K \tag{9}$$

$$\sum_{j\in R}\sum_{k\in K}\sum_{m=1}^{n_{jk}}\sum_{n=1}^{d_m^{jk}} x_m^{jk}(n) \le |S| \tag{10}$$

$$x_m^{jk}(n) \in \{0, 1\},\ \forall j \in R,\ \forall k \in K,\ m=1,\cdots,n_{jk}, \text{ and } n=1,\cdots, d_m^{jk}.$$

Problem (TAP′) may still have a huge number of binary decision variables, so that it may require huge computation time. Therefore, this paper proposes an efficient approach, introducing a new binary decision variable y_m^{jk} such that the relation y_m^{jk}=1 signifies that d_m^{jk} timeslots are assigned to packet *m* for service class *k* of SMT *j* and y_m^{jk}=0 signifies that no timeslot is assigned to that packet. By using variable y_m^{jk}, the problem (TAP′) can be expressed as in the following mathematical formulation, $(\overline{\text{TAP}})$.

$$\text{Maximize} \quad \sum_{j\in R}\sum_{k\in K}\sum_{m=1}^{n_{jk}} w_m^{jk} y_m^{jk}, \tag{11}$$

$$\text{subject to} \quad \sum_{m=1}^{n_{jk}} d_m^{jk} \cdot y_m^{jk} \le Q_{jk},\ \forall j \in R \text{ and } \forall k \in K, \tag{12}$$

$$\sum_{j\in R}\sum_{k\in K}\sum_{m=1}^{n_{jk}} d_m^{jk} \cdot y_m^{jk} \le |S|, \tag{13}$$

$$y_m^{jk} \in \{0, 1\},\ \forall j \in R,\ \forall k \in K, \text{ and } m=1,\cdots,n_{jk}.$$

Proposition 1 can also be applied to problem $(\overline{\text{TAP}})$, for which phase II will be derived. In step 1 of phase II, a packet which has the maximum w_m^{jk}/d_m^{jk} value is selected first, to which the required timeslots will be assigned if enough timeslots are available for that packet. Otherwise, no assignment will be made to that packet, while another packet will be considered for the available timeslot assignment. This assignment procedure will continue until no available resource or no more packets remain. In step 2, residual assignment will be made with the remaining timeslots to any packet if any timeslots remain after executing step 1.

B. Phase II

Step 1. Assign timeslot:

[y_m^{jk}] : = **0**.
while ($\{(j,k) \mid n_{jk} > 0\} \ne \varphi$, for $\forall$ j, k) {
  $(\bar{j}, \bar{k}) := \operatorname{argmax}_{(j,k)}\{w^{jk}_{n_{jk}} / d^{jk}_{n_{jk}}, \text{ for } n_{jk} > 0\}$.
  temp:= $\min\{Q_{\bar{j}\bar{k}}, |S|\}$.
  if ($d^{\bar{j}\bar{k}}_{n_{\bar{j}\bar{k}}} \le$ temp) {
  $y^{\bar{j}\bar{k}}_{n_{\bar{j}\bar{k}}} := 1$.
  $Q_{\bar{j}\bar{k}} := Q_{\bar{j}\bar{k}} - d^{\bar{j}\bar{k}}_{n_{\bar{j}\bar{k}}}$.
  $|S| := |S| - d^{\bar{j}\bar{k}}_{n_{\bar{j}\bar{k}}}$.
  if ($Q_{\bar{j}\bar{k}} == 0$), then $n_{\bar{j}\bar{k}} := 0$.
  if(|S| == 0), then terminate the algorithm.
 }
 $n_{\bar{j}\bar{k}} := n_{\bar{j}\bar{k}} - 1$.
}

Step 2. Assign residual timeslot:

$B := \{(j, k, m) \mid Q_{jk} > 0\ \ y_m^{jk} = 0, \forall j,k,m\}$.
while ((|S| > 0) && ($B \ne \varphi$)) {
  $(\bar{j}, \bar{k}, \bar{m}) :=$
    $\operatorname{argmax}_{(j,k,m)}\{w_m^{jk}/d_m^{jk}, \text{for } Q_{jk}>0 \text{ and } y_m^{jk}=0, \forall j,k,m\}$.
  temp := $\min\{Q_{\bar{j}\bar{k}}, |S|\}$.
  $d^{\bar{j}\bar{k}}_{\bar{m}} := d^{\bar{j}\bar{k}}_{\bar{m}}$ – temp.
  $Q_{\bar{j}\bar{k}} := Q_{\bar{j}\bar{k}}$ – temp.
  |S| := |S| – temp.
  $B := B - (\bar{j}, \bar{k}, \bar{m})$.
}

Phases I and II are processed together in sequence, called a ratio-based heuristic algorithm, which is in the computational complexity order $O(|R| \cdot |K| \cdot n\log(n))$, where $n = \max_{jk}\{n_{jk}\}$. This complexity order is a polynomial function of the number of the input parameters |*R*|, |*K*|, and *n*, implying an efficient algorithm as verified in section 4. This efficiency could be very beneficial to the proposed timeslot assignment scheduling problem under an interactive satellite communication environment.

2. PS-Based Heuristic

Based on proposition 1, we consider another transmission priority rule: the smaller the size of a packet, the higher its transmission priority. Based on that priority rule, a two-phase real-time PS-based heuristic algorithm is derived as follows.

A. Phase I

Step 1. Sequence all the packets (to be transmitted) in non-decreasing d_m^{jk} order for service class k of SMT j as in the order $d_{n_{jk}}^{jk} \le \cdots \le d_1^{jk}$ for each $j \in R$ and $k \in K$.

Step 2. See step 2 of ratio-based heuristic.

Step 3. Timeslot assignment subject to constraint (5):

```
for ( j := 1 ; j ≤ |R| ; j++ ) {
      Y_j := m_j − Y_j.
      while ( Y_j > 0 ) {
            if ( { k | n_jk > 0, for ∀k } = φ ), then Y_j := 0.
            else {
                  k̄ := argmin_(k) {d^jk_(n_jk) , for n_jk > 0}.
                  temp := min{d^jk̄_(n_jk̄), Y_j, Q_jk̄, |S|}.
                  Y_j := Y_j − temp.
                  Q_jk̄ := Q_jk̄ − temp.
                  d^jk̄_(n_jk̄) := d^jk̄_(n_jk̄) − temp.
                  |S| := |S| − temp.
                  if ( d^jk̄_(n_jk̄) == 0 ), then n_jk̄ := n_jk̄ − 1.
                  if ( Q_jk̄ == 0 ), then n_jk̄ := 0.
                  if ( |S| == 0 ), then terminate the algorithm.
}     }     }
```

B. Phase II

Step 1. Assign timeslot:

```
[ y^jk_m ] := 0.
while ( {(j, k) | n_jk > 0} ≠ φ, for ∀j, k ) {
      (j̄, k̄) := argmin_(j,k) {d^jk_(n_jk) , for n_jk > 0} .
      temp := min{Q_j̄k̄, |S|} .
      if ( d^j̄k̄_(n_j̄k̄) ≤ temp) {
            y^j̄k̄_(n_j̄k̄) := 1.
            Q_j̄k̄ := Q_j̄k̄ − d^j̄k̄_(n_j̄k̄) .
            |S| := |S| − d^j̄k̄_(n_j̄k̄) .
            if ( Q_j̄k̄ == 0 ), then n_j̄k̄ := 0.
            if ( |S| == 0 ), then terminate the algorithm.
      }
      n_j̄k̄ := n_j̄k̄ − 1.
}
```

Step 2. Assign residual timeslot:

```
B := {(j, k, m) | Q_jk > 0 and y^jk_m = 0, ∀j,k,m}.
while ( ( |S| > 0 ) && ( B ≠ φ ) ) {
      (j̄, k̄, m̄) :
            = argmin_(j, k, m) {d^jk_m, for Q_jk > 0 and y^jk_m = 0, ∀j,k,m}.
      temp := min{Q_j̄k̄, |S|} .
      d^j̄k̄_m̄ := d^j̄k̄_m̄ − temp.
      Q_j̄k̄ := Q_j̄k̄ − temp.
      |S| := |S| − temp.
      B := B − (j̄, k̄, m̄).
}
```

3. TG-Based Heuristic

The third transmission priority rule is the following: the larger the transmission gain packet, the higher its transmission priority. Based on that priority rule, a two-phase real-time TG-based heuristic algorithm is derived as follows.

A. Phase I

Step 1. Sequence all the packets (to be transmitted) in non-increasing transmission gain w_m^{jk} order for service class k of SMT j such as in the order $w_{n_{jk}}^{jk} \ge \cdots \ge w_1^{jk}$ for each $j \in R$ and $k \in K$.

Step 2. See step 2 of ratio-based heuristic.

Step 3. Assign timeslot subject to constraint (5):

```
for ( j := 1 ; j ≤ |R| ; j++ ) {
            Y_j := m_j − Y_j.
      while ( Y_j > 0 ) {
            if ( { k | n_jk > 0, for ∀k } = φ ), then Y_j := 0.
            else {
                  k̄ := argmax_(k) {w^jk_(n_jk) , for n_jk > 0}.
                  temp := min{ d^jk̄_(n_jk̄), Y_j, Q_jk̄, |S| } .
                  Y_j := Y_j − temp.
                  Q_jk̄ := Q_jk̄ − temp.
                  d^jk̄_(n_jk̄) := d^jk̄_(n_jk̄) − temp.
                  |S| := |S| − temp.
                  if ( d^jk̄_(n_jk̄) == 0 ), then n_jk̄ := n_jk̄ − 1.
                  if ( Q_jk̄ == 0 ), then n_jk̄ := 0.
                  if ( |S| == 0 ), then terminate the algorithm.
}     }     }
```

B. Phase II

Step 1. Assign timeslots:

$[y_m^{jk}] := \mathbf{0}$.

while ($\{(j,k) \mid n_{jk} > 0\} \neq \varphi$, for $\forall j, k$) {

$(\bar{j}, \bar{k}) := \operatorname{argmax}_{(j,k)} \{ w^{jk}_{n_{jk}}, \text{ for } n_{jk} > 0 \}$.

temp := $\min\{ Q_{\bar{j}\bar{k}}, |S| \}$.

if ($d^{\bar{j}\bar{k}}_{n_{\bar{j}\bar{k}}} \le$ temp) {

$y^{\bar{j}\bar{k}}_{n_{\bar{j}\bar{k}}} := 1$.

$Q_{\bar{j}\bar{k}} := Q_{\bar{j}\bar{k}} - d^{\bar{j}\bar{k}}_{n_{\bar{j}\bar{k}}}$.

$|S| := |S| - d^{\bar{j}\bar{k}}_{n_{\bar{j}\bar{k}}}$.

if ($Q_{\bar{j}\bar{k}} == 0$), then $n_{\bar{j}\bar{k}} := 0$.

if ($|S| == 0$), then terminate the algorithm.

}

$n_{\bar{j}\bar{k}} := n_{\bar{j}\bar{k}} - 1$.

}

Step 2. Assign residual timeslot:

$B := \{ (j, k, m) \mid Q_{jk} > 0 \text{ and } y_m^{jk} = 0, \forall j, k, m \}$.

while (($|S| > 0$) && ($B \neq \varphi$)) {

$(\bar{j}, \bar{k}, \bar{m})$:

$= \operatorname{argmax}_{(j,k,m)} \{ w_m^{jk}, \text{ for } Q_{jk} > 0 \text{ and } y_m^{jk} = 0, \forall j, k, m \}$.

temp := $\min\{ Q_{\bar{j}\bar{k}}, |S| \}$.

$d^{\bar{j}\bar{k}}_{\bar{m}} := d^{\bar{j}\bar{k}}_{\bar{m}} -$ temp.

$Q_{\bar{j}\bar{k}} := Q_{\bar{j}\bar{k}} -$ temp.

$|S| := |S| -$ temp.

$B := B - (\bar{j}, \bar{k}, \bar{m})$.

}

IV. Computational Experiments

Regarding the problem of practical ISM systems, a real-time computationally efficient solution procedure is required. From a practical point of view, it would be useful to find any suboptimal solution which is, however, as close to the global optimal solution as possible.

This section makes extensive experiments to evaluate the efficiency and effectiveness of the three derived heuristic algorithms including the ratio-based, PS-based and TG-based heuristic algorithms. For each given number of SMTs between 10 and 200, 100 problem instances are generated randomly to gather some statistics. The parameters considered in the experiments are shown in Table 1.

In this paper, the three derived heuristic algorithms and the algorithm of [8] are compared in terms of efficiency and effectiveness. The performance comparison results are shown in Fig. 2. In Fig. 2, the gap is defined as GAP $= 100 \times (Sol_{OPT} - Sol_H)/Sol_{OPT}$, where Sol_{OPT} and Sol_H denote the optimal solution value and the heuristic solution value, respectively. If the gap is zero, then the heuristic solution is optimal. In small-sized problem instances, the optimal solution value, Sol_{OPT}, is found for the TAP using the commercial solver CPLEX 7.0; however, this requires a very long computation time. The ratio-based, PS-based, and TG-based heuristic algorithms result in gap values of 2.43%, 11.14%, and 7.23%, respectively, while the algorithm of [8] results in a gap value of 3.31%. Among the three heuristics, the ratio-based heuristic provides better solutions than the algorithm of [8]. Specifically, the ratio-based heuristic reduces the gap by about 26.5% in comparison with the algorithm of [8]. This demonstrates that the ratio-based heuristic algorithm

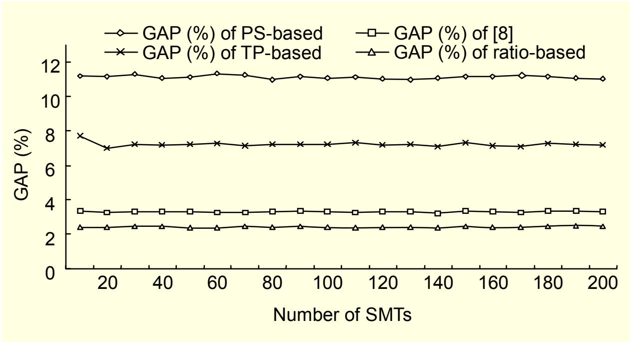

Fig. 2. Performance test results of the three heuristic algorithms and that of [8].

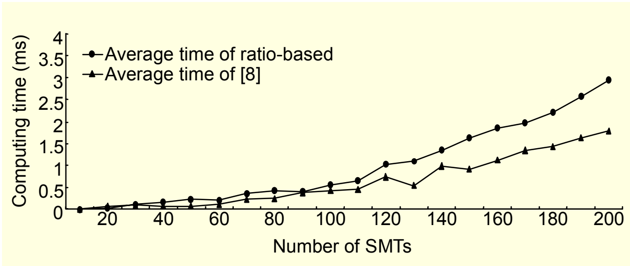

Fig. 3. Computation times of ratio-based heuristic and the algorithm of [8].

Table 1. Parameter values considered in the experiments.

Item	Value	Item	Value	Item	Value
W_{sf}	22.4 MHz	T_{trf}	309 μs	Q_{jk}	~ uniform(30, 100)
W_f	11.2 MHz	N_{trf}	508	w_m^{jk}	~ uniform(1, 100)
W_t	2.8 MHz	m_j	~ uniform(1, 30)	α_{jk}	0.3
T_{sf}	2520832 μs	$\|K\|$	3	d_m^{jk}	~ uniform(1, 50)
T_f	157552 μs	$\|S\|$	65024	n_{jk}	~ uniform(1, 20)

is much more effective than the algorithm of [8].

In using the ratio-based heuristic algorithm, we expect that system performance can be enhanced given any traffic scenario. The proposed ratio-based heuristic algorithm takes only 0.81ms of time on average, as shown in Fig. 3, so it may immediately be applied under a real-time environment. Moreover, the proposed heuristic is as efficient as the algorithm of [8] when the number of SMTs less than 110.

V. Conclusion

In this paper, we derive heuristic algorithms for the timeslot assignment problem for an ISM system. The timeslot assignment problem is expressed as a binary integer programming with the objective of maximizing the overall weighted throughput, which is shown to be NP-hard. Accordingly, three real-time heuristic algorithms including the ratio-based, PS-based, and TG-based heuristic algorithms were derived. Computational experiments showed that the solutions found by the ratio-based heuristic are very close to optimal, with a gap of 2.43%. This gap value implies 26.5% improvement on average in comparison with that of the algorithm of [8]. Moreover, the ratio-based heuristic is very efficient, requiring only 0.81 ms computation time on average. Thus, by applying the derived ratio-based heuristic for timeslot assignment, the associated practical ISM system can be effectively and efficiently utilized and the system performance can be greatly enhanced.

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Ik Sun Lee received the BS degree in industrial engineering from Hanyang University in 1998, and the MS and PhD degrees in industrial engineering from KAIST, in 2000 and 2007, respectively. He joined Samsung Electronics in 2007. His research interests include satellite communication systems, wireless communications systems, supply chain management, and scheduling theory.

Chang Sup Sung is a professor of Industrial Engineering at KAIST in Daejon, Korea. He holds the BS degree in chemical engineering from Hanyang University, and an MS and a PhD in industrial engineering from Iowa State University. His research interests include telecommunication network modeling and evaluation, combinatorial optimization, and network theory.

Gwang-Ja Jin received the BS and MS degrees in electronics engineering from Konkuk University, Seoul, Korea, in 1987 and 1990, respectively. She joined ETRI in 1990 and is now with USN (Ubiquitous Sensor Network) Networking Research Team as a principal member of engineering staff. Her research interests include satellite communication systems, wireless communications systems, reliable routing, and MAC protocols in sensor networks and ad-hoc networks.

Ki Seop Han received his BS and MS degrees in electronics and information engineering from Hankuk University of Foreign Studies, Korea, in 2003 and 2005, respectively. He joined ETRI in 2005 and has been involved in DVB-RCS system development. His current interests include DVB-RCS and radio resource management.