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Efficient and reliable slice allocation for multi-services in DVB-T2 networks

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Abstract: Digital television terrestrial broadcasting (DTTB) networks can help to alleviate the congestion problem in cellular networks by delivering rich contents to a large number of clients simultaneously. In particular, recently, there is a strong interest of extending current DTTB systems to support multimedia broadcasting services. The lack of return channel and long transmission time interval however impose great challenge to the resource allocation for this application in DTTB networks. The reliable resource allocation is studied for multi-services with data delivery delay constraints in the second generation digital video broadcasting terrestrial (DVB-T2) system. To solve this challenging problem, the data cells of a T2-frame are divided into data slices which are indexed by binary numbers. These data slices are organised in a binary tree, and each node in the tree is associated with a certain number of non-adjacent data slices. Then a node can be allocated to a service by using the predefined policies. Based on this scheme, this study proposes a heuristic algorithm to allocate resources to multi-services. Simulation results validate the effectiveness of the proposed algorithm and demonstrate its advantage over the current resource allocation scheme in DVB-T2 networks.

1 Introduction

With the ever-increasing popularity of smartphones and tablets, there is an explosion of mobile traffic. By the end of 2015, the global mobile data traffic has reached 3.7 EB (exabytes) per month, among which more than half is video traffic [1]. Such large amount of traffic is causing congestion and dissatisfaction among clients in cellular networks, especially at peak times and urban areas. Digital television terrestrial broadcasting (DTTB) networks, however, can help to alleviate such problems by delivering rich contents to a large number of users. Therefore, there is a strong interest in extending current DTTB systems to support multimedia broadcasting services. Nowadays, there exist four DTTB standards: integrated service digital broadcasting-terrestrial (ISDB-T) [2], advanced television system committee (ATSC) [3], digital video broadcasting terrestrial (DVB-T) [4] and digital television terrestrial multimedia broadcasting (DTMB) [5]. To better support multi-services, for example, ISDB-Tmm was launched in 2013 to support both high-quality real-time broadcasting and storage-based broadcasting [6], while ASTC published the mobile digital TV (DTV) standard to supplement mobile services for DTTB systems [7]. European telecommunications Standards Institute (ETSI) published its first version (V1.1.1) of the second generation DVB-T (DVB-T2) in September 2009, and have launched three new versions since: V1.2.1 in October 2010, V1.3.1 in November 2011 and V1.4.1 in July 2015 [8]. One of the significant features of DVB-T2 is the proposal of physical layer pipes (PLPs) to support the compatible transmission of both mobile and fixed services. The works [9, 10] compare technique employed and achievable performance between DVB-T and DVB-T2. Specifically, the study [9] introduces key modules in DVB-T2 systems and present the achievable performance in laboratory and field trials, while the study [10] compares the structures of transmitter in the two standards and presents the simulation results, which demonstrate that DVB-T2 outperforms DVB-T in several scenarios, since the former employs an advanced error correction scheme and offers more configuration options. Similar to PLP, the concept of physical sub-channel (PSC) has been proposed for DTMB-advanced (DTMB-A) systems [11]. Unlike the traditional method whereby all services adopt the same coding and modulation mode and are delivered by multiplexing the time slots, each service is coded and modulated according to its own requirements and is separately mapped to orthogonal frequency-division multiplexing (OFDM) sub-carriers by using PLPs or PSCs in these DTTB systems. Although the state-of-the-art work has solved how to support multi-service transmission in these systems, how to efficiently allocate resources between multi-services remains an open and challenging problem.

Recently, there have been several works investigating resource allocation for multi-services in DTTB systems. Hao *et al.* [12] proposed an algorithm to select appropriate sizes for fixed and mobile services, respectively, in order to achieve the maximum transmission capacity under mobile environment. A power allocation scheme in multiple input, multiple output associated DTTB systems was proposed in [13]. Jin *et al.* [14] proposed two multi-service transmission schemes based on embedded constellation and bit division multiplexing. However, the quality-of-service, such as delay constraint, is not included in these works. Unlike these existing works, we focus on how to map multiple services onto T2-frames of DVB-T2 networks.

Allocating resources to multi-services in DTTB networks, such as DVB-T2 and DTMB-A, is challenging due to no return channel and long transmission time interval. Without uplink communication from the receivers to the transmitter, the scheduler has no knowledge of channel information and thus cannot select sub-carriers with high channel gain to allocate to a service. Therefore, channel quality information based resource allocation algorithms [15–19] cannot be applied to these broadcasting systems. Furthermore, the transmission time interval of DTTB systems is usually very long, whereas the channel condition may change rapidly. Taking DVB-T2 networks as an example, once a resource allocation is decided, it will last for at least as long as a T2-frame and can only be changed at the beginning of the next T2-frame. However, the duration of a T2-frame may last 250 ms, much longer than the channel coherent time, and it is impossible to predict the channel condition over the duration of a T2-frame. Even if the scheduler knows the channel information at the beginning of a T2-frame and allocates services with sub-carriers of good

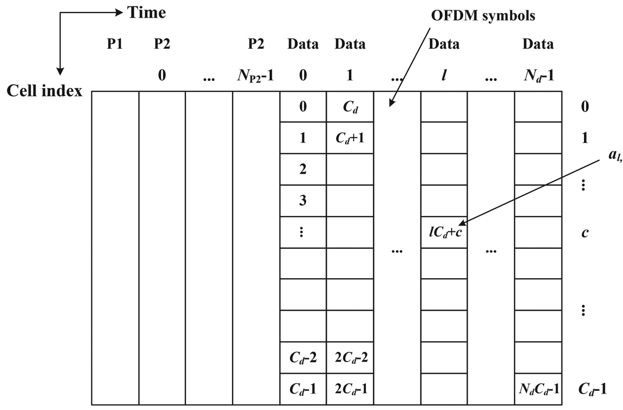


Fig. 1 *T2-frame structure*

performance accordingly, it cannot be ensured that these sub-carriers will still satisfy the services' requirements, such as packet loss rate and bit error rate, at the end of this frame. Therefore, it is difficult to provide reliable resource allocation. Another problem caused by the long transmission time interval is that the allocated resources may not meet the services' delay constraints. Some services, such as emergency notification and mobile services, are associated with strict delay constraints and they should be delivered as soon as possible. However, there is no scheme available in current DTTB systems which considers and guarantees services' data delivery delay constraints. The scheduler may actually allocate to a service with sub-carriers later than its delay constraint in the frame.

This paper proposes a new resource allocation scheme for multi-services in DVB-T2 systems. Without channel information, it is inadvisable to allocate a service with resources contiguous in time and frequency. Consequently, the basic idea of the proposed scheme is to allocate each service with scattered time and frequency resources within its delay constraint, so as to achieve diversity capability against time or frequency selective fading. In the proposed scheme, data cells in a T2-frame are divided into data slices where each data slice is composed with an equal number of data cells. These data slices are then encoded into binary numbers and organised in a binary tree. Each node in the tree corresponds to several non-adjacent slices, and each service is allocated with a tree node that satisfies its data rate and delay constraints. Our main contributions are summarised as follows.

- The current resource allocation scheme in DVB-T2 systems is analysed, and our novel resource allocation problem is formulated.
- The diversity in resource allocation is considered, and a heuristic algorithm is proposed to allocate slices for different services using a binary tree.
- Simulation studies are carried to evaluate the proposed scheme and several benchmark algorithms, and the results obtained validate the effectiveness of our proposed scheme in terms of allocation efficiency and symbol error rate (SER).

Table 1 Notation summary

Notation	Explanation
L_{F}	number of symbols in a T2-frame
N_{P2}	number of P2 symbols in a T2-frame
N_d	number of data symbols in a T2-frame
C_d	number of OFDM cells in a data symbol
N_c	number of OFDM cells in an FEC block
N_b	number of FEC blocks contained in an IF
N_{ss}	number of sub-slices for one PLP within the T2-frame
P_{I}	number of T2-frames an IF is mapped to
K	number of OFDM cells in a data slice
N_{S}	number of data slices in a T2-frame
T_{F}	duration of a T2-frame
T_{P}	duration of a P1 symbol
T_{S}	duration of a P2 symbol or a data symbol
I_{C}	sub-slice interval
I_{S}	data slice interval

The rest of this paper is organised as follows. Section 2 introduces the DVB-T2 system and its frame structure, while Section 3 analyses the current resource allocation scheme and shows that it may perform poorly. The proposed resource allocation problem is formulated in Section 4, and a heuristic algorithm is proposed to solve it in Section 5. Section 6 conducts the evaluation and discusses the results, while Section 7 concludes the paper. The notations and their physical meanings are summarised in Table 1, which are used throughout this paper.

2 System overview

There are three kinds of PLPs, common PLP, data PLP type 1 and data PLP type 2. In this paper, only data PLP type 2 is studied for the reason to be given shortly. Since each data PLP carries one service, the terminologies 'PLP' and 'service' are interchangeably used to refer to a service throughout the paper.

In DVB-T2 networks, time interleavers (TIs) operate at PLP level whose inputs are forward error correction (FEC) blocks of the PLPs. Each FEC block contains a certain number of data cells. During the process of time interleaving, the FEC blocks of each PLP are grouped into interleaving frames (IFs), which are then mapped to one or more T2-frames. Each IF is also divided into one or more TI-blocks, where a TI-block corresponds to one usage of TI memory. The TI is a row–column block interleaver and interleaves cells over one TI-block. Although there are different TI modes, this paper focuses on the scenario that each IF contains one TI-block and is mapped to one T2-frame.

When mapping to a T2-frame, the IF may be used as a whole or split into multiple sub-slices, which is decided by the type of PLP. For a type 1 PLP, the IF is mapped to a single contiguous range of cell addresses. For a type 2 PLP, the IF is divided into several sub-slices where each sub-slice contains an equal number of data cells, and each sub-slice is mapped to a contiguous range of cell addresses but the cell addresses between different sub-slices are non-adjacent. In this way, the system can provide certain diversity capability to enhance reliability. For this reason, this study focuses on how to allocate resources for type 2 PLPs.

There are L_{F} symbols in a T2-frame depicted in Fig. 1, which is composed of 1 P1 symbol, N_{P_2} P2 symbols and N_d data symbols. P1 and P2 symbols carry signalling information and data symbols carry PLPs. Although P2 symbols can carry PLPs in their free capacity, the case of allocating PLPs with data cells only in data symbols is considered in this paper for analysis simplicity. The information of each PLP is carried in P2 symbols and a receiver can locate its desired service accordingly. Each data symbol is composed of C_d OFDM data cells and a data cell is the minimum resource element that can be allocated to a PLP. Denote $a_{l,c}$ as the address of a data cell, where l $(l = 0, 1, \ldots, N_d - 1)$ is the index number of the data symbol and c $(c = 0, 1, \ldots, C_d - 1)$ is the index number of the cell in the data symbol. The data cell can also be indicated using a one-dimensional addressing scheme which defines an increasing order of the data cells. The relation between the two addressing schemes is: $a_{l,c} = a(n)$ if and only if $n = C_d \cdot l + c$. Using the one-dimensional addressing scheme, the two-dimensional resource allocation problem is transferred to a one-dimensional problem.

Due to large signalling overhead, it is not reasonable to specify the cell addresses mapped to every sub-slice of a PLP, especially when the number of sub-slices is large. The DVB-T2 system sets an equal address interval between cells allocated to any two adjacent sub-slices of the same PLP, which is denoted as I_{C} and is represented as the number of cells from the start of one sub-slice to

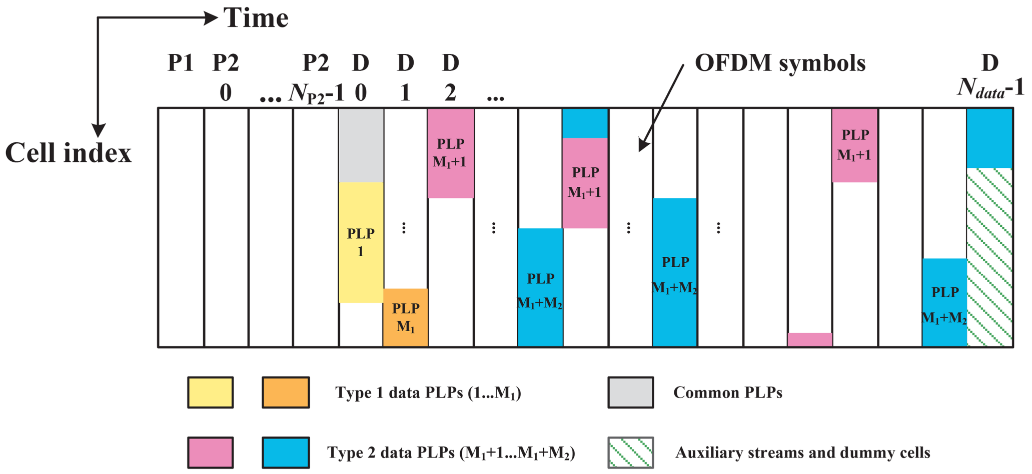


Fig. 2 *Current resource allocation patterns in DVB-T2 system*

the start of the next sub-slice. Let N_b, N_{ss} and N_c denote the number of FEC blocks contained in the IF, the number of sub-slices for each PLP within the T2-frame and the number of data cells in an FEC block, respectively. Denote P_I as the number of T2-frames to which an IF is mapped. In this paper, $P_I = 1$. Then the addresses of the first (sub_slice_start(i)) and last (sub_slice_end(i)) cells for the sub-slice i ($i = 0, 1, \ldots, N_{ss} - 1$) of a PLP can be obtained from

$$\text{sub\_slice\_start}(i) = \text{PLP\_START} + i \cdot I_C \tag{1}$$

and

$$\text{sub\_slice\_end}(i) = \text{sub\_slice\_start}(i) + \frac{N_b \cdot N_c}{N_{ss} \cdot P_I} - 1, \tag{2}$$

where PLP_START is the start position of the associated PLP within the current T2-frame.

3 Analysis of current resource allocation scheme

This section first presents the current resource allocation scheme in DVB-T2 networks and then analyses its performance, in terms of transmission delay.

3.1 Current resource allocation scheme

The current resource allocation scheme in DVB-T2 systems is depicted in Fig. 2. The common PLPs are transmitted at the beginning of the T2-frame after the signalling cells. Then type 1 PLPs are transmitted after the common PLPs and type 2 PLPs are transmitted after type 1 PLPs. Every type 2 PLP is split into the same number of sub-slices in a T2-frame. When mapping IFs of type 2 PLPs to a T2-frame, the scheduler first allocates the first sub-slices of every PLPs one by one and then the second sub-slices of the PLPs in the same order and so on. This process is repeated until all the sub-slices are mapped. Although this resource allocation scheme can provide certain diversity against time or frequency selective fading, it may not be able to meet services' delay constraints satisfactorily.

3.2 Analysis of transmission delay

Since transmission delay is mainly caused by time interleaving, this section analyses the transmission delay caused by time interleaving in the current resource allocation scheme for DVB-T2 systems. The principle of the TI dictates that when a receiver receives the cells of a PLP, it does not decode them immediately but caches them in its time de-interleaver's memory until it has received all the cells of a TI-block. Consequently, the transmission delay of a sub-slice in an IF is not decided by the position of the data cells this sub-slice is mapped to in the T2-frame, but is decided by the position of the data cells which the last sub-slice of the same IF is mapped to.

Assume that there are M PLPs and all these PLPs are of type 2. The number of data cells allocated to a sub-slice of PLP i is $L_c(i) = ((N_b(i) \cdot N_c(i))/(N_{ss} \cdot P_I))$, $i = 1, 2, \ldots, M$. Therefore, the last cell allocated to the last sub-slice of PLP i is $a(n_i)$, where $n_i = (N_{ss} - 1)\sum_{j=1}^{M} L_c(j) + \sum_{j=1}^{i} L_c(j) - 1$. Suppose that the transmission time is T_P for a P1 symbol and T_S for any other symbol. Then the delay of PLP i is given as

$$d(i) = T_\text{P} + T_\text{S} \cdot \left(N_\text{P2} + \left\lceil \frac{n_i + 1}{C_d} \right\rceil\right), \tag{3}$$

where $\lceil \bullet \rceil$ denotes the integer ceiling operator.

The above analysis demonstrates that the delay of a PLP is not only related to the amount of data in the PLP itself, but also related to the amounts of data in other PLPs. After all the data cells have been allocated in a T2-frame, the shortest service delay d_min satisfies

$$\begin{aligned} d_\text{min} &> T_\text{P} + N_\text{P2} \cdot T_\text{S} + \frac{N_{ss} - 1}{N_{ss}}(L_\text{F} - 1 - N_\text{P2}) \cdot T_\text{S} \\ &\geq T_\text{P} + N_\text{P2} \cdot T_\text{S} + \frac{1}{2}(L_\text{F} - 1 - N_\text{P2}) \cdot T_\text{S} \\ &> \frac{1}{2}T_\text{F}, \end{aligned} \tag{4}$$

where T_F is the duration of a T2-frame. Since T_F can be as long as 250 ms, d_min obtained above is definitely much larger than the strict delay constraints of the delay-sensitive services, such as emergency notification and mobile services, which must be delivered as soon as possible. Although these delay-critical services can be delivered as type 1 PLPs by allocating contiguous data cells at the beginning of data symbols in order to meet the services' delay requirements, the system is much more unreliable as it cannot provide diversity to transmission fading. The main contribution of this paper is to propose a novel resource allocation scheme that not only meets services' data rate requirements and delay constraints, but also provides diversity capability.

4 Modelling and problem formulation

In current DVB-T2 systems, every type 2 PLP contains an equal number of sub-slices, and the data cells in a sub-slice may be different for different PLPs. Differing from the current scheme, *data slice* is defined in this paper. In the proposed scheme, each data slice contains an equal number of data cells, and different PLPs are mapped to different number of data slices according to their data rate requirements. Specifically, as illustrated in Fig. 3, every K data cells are grouped together to form a data slice,

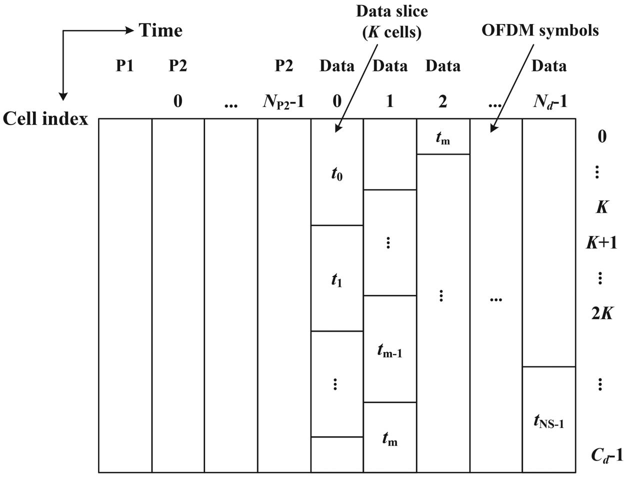


Fig. 3 *Proposed data slices in a T2-frame*

denoted as t. The available number of data slices in the T2-frame is therefore $N_S = \lfloor C_d N_d / K \rfloor$, where $\lfloor \bullet \rfloor$ denotes the integer floor operator. Using one-dimensional addressing scheme, the addresses of the data slices can be obtained as a sequence of numbers in an ascending order.

Denote $\mathcal{I}$ as the set of PLPs. Each $i \in \mathcal{I}$ is associated with a weight W_i, a required data slice number S_i and a delay constraint D_i. Generally, the smaller D_i is, the larger W_i is. Let T_i be the address of the data slice no later than which PLP i should be mapped to in order to satisfy D_i. Then the relation between T_i and D_i is given as

$$T_i = \left\lfloor \frac{(D_i - T_P - N_{P2}T_S)C_d}{T_S K} \right\rfloor - 1. \tag{5}$$

Therefore, T_i can also be used to define the delay constraint of service i.

Denote $t_{\text{end}}(i)$ as the last data slice allocated to PLP i and $f(\cdot)$ as the utility function, which is defined by

$$f(i) = \begin{cases} W_i, & t_{\text{end}}(i) \le T_i, \\ 0, & t_{\text{end}}(i) > T_i. \end{cases} \tag{6}$$

The problem of resource allocation for multi-services in DVB-T2 systems can be defined as follows:

$$\max \sum_{i \in \mathcal{I}} f(i) S_i x^i_{t_{\text{end}}}, \tag{7}$$

$$\text{s.t.} \quad \sum_{t=0}^{T_i} y^i_t - S_i x^i_{t_{\text{end}}} \ge 0, \quad \forall i, \tag{8}$$

$$\sum_{i \in \mathcal{I}} y^i_t \le 1, \quad \forall t, \tag{9}$$

$$x^i_{t_{\text{end}}} \in \{0, 1\}, \tag{10}$$

$$y^i_t \in \{0, 1\}, \tag{11}$$

where the binary variable $x^i_{t_{\text{end}}} = 1$ if and only if $0 < t_{\text{end}}(i) \le T_i$, otherwise $x^i_{t_{\text{end}}} = 0$; while the binary variable $y^i_t = 1$ if and only if PLP i is allocated with data slice t, otherwise $y^i_t = 0$. In this resource allocation problem, the objective is to broadcast as many weighted PLPs as possible in the T2-frame, and the constraint (8) represents that when PLP i is successfully delivered, there are at least S_i data slices carrying the data of PLP i before its deadline, while the constraint (9) represents that at most one PLP is broadcast at any given data slice.

The above problem can be transformed into a knapsack problem [20] which is solvable, and a solution is given by the addresses of data slices that each PLP is mapped to. However, in the above formulation, data slices that a PLP is mapped to are independent. Since the addresses of all the data slices must be indicated in the signalling symbols so that a receiver can locate its desired data, this may introduce excessive signalling costs to the system. In order to reduce this signalling expenditure, the intervals between all the pairs of two consecutive data slices of PLP i are set to the same, denoted as $I_S(i)$. Without loss of generality, $I_S(i)$ is set to a power of 2. Let $t_{\text{start}}(i)$ be the address of the first data slice that PLP i is mapped to. Then the address of the jth data slice that PLP i is mapped to is given by $t_j(i) = t_{\text{start}}(i) + (j-1)I_S(i)$. Therefore, the above resource allocation problem can alternatively be rewritten as

$$\max \sum_{i \in \mathcal{I}} f(i) S_i x^i_{t_{\text{end}}}, \tag{12}$$

$$\text{s.t.} \quad \sum_{t_{\text{start}}(i)=0}^{T_i} \sum_{m=0}^{\infty} y^i_{t_{\text{start}}(i) + mI_S(i)} - S_i x^i_{t_{\text{end}}} \ge 0, \quad \forall i, \tag{13}$$

$$t_{\text{start}}(i) + mI_S(i) \le T_i, \quad \forall i, \tag{14}$$

$$I_S(i) = 2^n, \quad n \in \mathbb{Z}^+, \tag{15}$$

$$x^i_{t_{\text{end}}} \in \{0, 1\}, \tag{16}$$

$$y^i_{t_{\text{start}}(i) + mI_S(i)} \in \{0, 1\}. \tag{17}$$

5 Proposed slice allocation algorithm

This section proposes a solution of data slice allocation among PLPs for the resource allocation problem defined in (12)–(17). Since the wireless environment is unknown and changing, a PLP should be allocated with data slices scattered in the T2-frame in order to combat the effects of time or frequency selective fading. Specifically, the addresses of the data slices are first transformed into binary numbers and organised in a tree structure, such that each node in the tree corresponds to one or several non-adjacent data slices. Then a heuristic algorithm is utilised to allocate tree nodes to each PLP. The details of this slice allocation tree (SAT) and this heuristic slice allocation algorithm are now explained.

5.1 Slice allocation tree

The slice allocation can be carried out with the aid of a complete binary tree T_{ree} whose height is L, where $L = \lceil \log_2 N_S \rceil$, and each tree node is associated with one or several data slices. Such a tree is referred to as a *slice allocation tree*. The root of T_{ree} is in level 0, its leaves are in level 1 and so on. Every tree node is described using a structure

$$[str = \{Parent, Left, Right, Level, Label, AvaNum, Content, State\}]$$

, where *Parent* denotes the parent node, *Left* and *Right* are the left and right children, respectively, while *Level* shows which level the node is in and $Level = l$ represents that the interval of data slices that the node corresponds to is 2^l. Additionally, *Label* is the unique identity for a node and is assigned in the following way. For a node in level l, the assigned label consists of l digits where the last $l-1$ are the same as of the node's parent, while the first digit is set to 0 for a left child and to 1 for a right child, as illustrated in Fig. 4. Let r be the label of node n in the tree, and $d(r)$ be the decimal value of r. Then, node n is associated with data slices $t_{\text{start}} = d(r)$ and $I_S = 2^l$. For example, node n_1 in Fig. 4 is associated with data slices $t_{\text{start}}(1) = 0$ and $I_S(1) = 2$, while node n_2 is associated with data

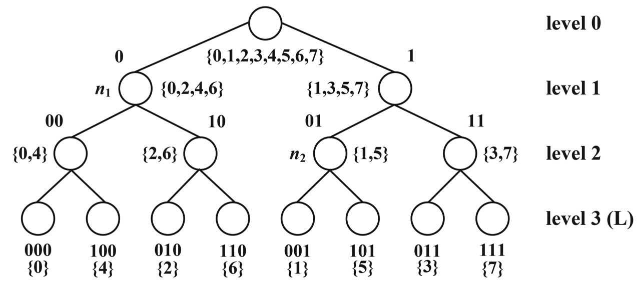


Fig. 4 *Illustration of SAT*

slices $t_{\text{start}}(2) = 1$ and $I_S(2) = 4$. Furthermore, *Content* is an array which contains all the data slices that the nodes correspond to in an ascending order, and the length of *Content* is *AvaNum*. For a node n with level l, if $n \cdot Content(i+1) - n \cdot Content(i) = 2^l$ for each $i = 1, 2, \ldots, n \cdot AvaNum - 1$, $n \cdot State = 1$; otherwise $n \cdot State = 0$.

5.2 Slice allocation for one PLP

SAT is used to allocate data slices to each PLP. When mapping a PLP to a tree node, the data slices contained in this tree node are allocated to this PLP. For a PLP, a feasible tree node is defined as follows.

Definition 1: Assume that PLP i is associated with weight W_i, slice requirement S_i and deadline T_i. Given a SAT T_{ree}, node $n \in T_{\text{ree}}$ is feasible for PLP i if it satisfies:

(i) $n \cdot State = 1$;
(ii) $n\,.\,AvaNum \geq S_i$;
(iii) $n \cdot Content(1 + S_i - 1) \leq T_i$;
(iv) $n \cdot Left \cdot AvaNum < S_i$;
(v) $n \cdot Right \cdot AvaNum < S_i$.

In the above definition, constraint (i) represents that there is an equal interval between any two adjacent data slices in the node's *Content*, constraints (ii) and (iii) ensure that the slice and delay requirements are met, while constraints (iv) and (v) indicate that the number of the residual data slices in node n after allocating the required data slices to PLP i is the smallest among all the nodes who satisfy the requirements of the PLP and contain the data slices in the node.

There may be more than one feasible node in the SAT. However, one PLP can be mapped to one and only one node in the tree. The following criteria are used to select a node from all the feasible ones.

Definition 2: Consider two feasible nodes n_1 and n_2. The following rules indicate which of these two is better than the other from the broadcasting transmitter's perspective:

(i) if $n_1 \cdot AvaNum < (>) n_2 \cdot AvaNum$, then n_1 (n_2) is better;
(ii) when $n_1 \cdot AvaNum = n_2 \cdot AvaNum$, if $n_1 \cdot Level > (<) n_2 \cdot Level$, then n_1 (n_2) is better;
(iii) when $n_1 \cdot Level = n_2 \cdot Level$ and $n_1 \cdot AvaNum = n_2 \cdot AvaNum$, if $n_1 \cdot Content(1) < (>) n_2 \cdot Content(1)$, then n_1 (n_2) is better.

Algorithm 1 listed in Fig. 5 shows how to map a PLP to data slices using a SAT. This algorithm first searches for all the feasible nodes in T_{ree} using the preorder tree walk algorithm [21]. Since *AvaNum* of a node is the sum of all *AvaNum*s at its child nodes, if *AvaNum* is smaller than the required number, its child nodes definitely cannot satisfy the requirements and thus there is no need to search them. All the feasible nodes are stored in *Candidate*. The algorithm then selects the best node from *Candidate* according to the criteria defined in Definition 2. $flag = 1$ indicates that the PLP can be successfully mapped to the T2-frame; otherwise $flag = 0$. Next, the algorithm maps the PLP to data slices. Since the available number of data slices contained in a node may be larger than the requirement, the algorithm maps the PLP to data slices with the S_i smallest addresses, as described in lines 7–9. Finally, the algorithm clears the already allocated data slices and renews the state of the nodes in the tree (lines 14–23). T_{ree} is then used to allocate data slices to other PLPs.

Fig. 6 depicts an example of such allocation. For simplicity, a decimal number is used to indicate each tree node, which is marked on the node. Available data slices are indicated beside each node. Suppose that PLP i is associated with $S_i = 3$ and $T_i = 13$. Algorithm 1 first searches the tree and obtains $Candidate = \{2, 6, 7\}$, as shown in Fig. 6*a*. Next, it selects node 7 and maps PLP i to data slice set $\Gamma_i = \{3, 7, 11\}$. The residual of the tree after mapping is shown in Fig. 6*b*.

For PLP i associated with S_i and T_i, there is no need to search for the nodes whose level is larger than $L_i = \lfloor \log_2(T_i/S_i) \rfloor$. Therefore, the computational complexity of searching for feasible nodes is on the order of $O(2^{L_i + 1} - 1) = O(2T_i/S_i)$. Assuming that there are C_i nodes in *Candidate*, then the complexity of selecting a node in line 5 is $O(C_i)$. Each time removing an already allocated data slice, it needs to renew the states of L nodes, where L is the level of the tree. Hence, the complexity of renewing the states of the nodes is $O((2^L - 1 - L)S_i) = O((N_S - 1 - \log_2 N_S)S_i)$ $= O(N_S S_i)$. Consequently, the computational complexity of Algorithm 1 is on the order of $O((2T_i/S_i) + C_i + N_S S_i)$ $= O((2T_i/S_i) + N_S S_i)$.

5.3 Heuristic algorithm for slice allocation

The proposed heuristic algorithm of data slice allocation for multiple PLPs is presented in Algorithm 2 given in Fig. 7, which consists of two steps. The PLPs are first put into a queue, and then they are mapped to the T2-frame one by one using Algorithm 1.

To avoid overlapping, a data slice can be allocated to one and only one PLP. Therefore, if a data slice has been allocated to a PLP, it cannot be allocated to others behind this PLP in the waiting queue. The following criteria are used to decide the priority of each PLP.

Definition 3: The following rules indicate which of any two PLPs has a higher priority:

(i) the PLP with a stricter delay constraint (T) has a higher priority;
(ii) if the two PLPs have the same delay constraint, then the one with a higher weight (W) has a higher priority;
(iii) if the two PLPs have the same delay constraint and weight, the one requiring more data slices (S) to map to has a higher priority.

The computational complexity of arranging M PLPs in a sequence, as described in line 4 of Algorithm 2, is on the order of $O(M \log_2 M)$. Taking into account the complexity of Algorithm 1, it can easily be seen that the computational complexity of Algorithm 2 is on the order of $O(M \log_2 M + N_S \sum S_i + 2 \sum (T_i/S_i)) = O(N_S^2)$.

Remark 1: The DVB-T2 can be deployed in the single frequency network (SFN) and the multiple frequency network (MFN). The influence of these two networks on the architecture of broadcasting system mainly lies in the design of cyclic prefix, channel estimation and interference management between cells. It should be noticed that all these technical aspects belong to physical layer. The slice allocation problem studied in this paper, however, belongs to transport layer, and the parameters of physical layer have been fixed. Therefore, the proposed slice allocation algorithm is applicable in both SFN and MFN.

6 Performance evaluation

The effectiveness of the proposed heuristic algorithm, denoted as HA, was evaluated in a simulation study. A T2-frame structure

Algorithm 1

```
Input $T_{ree}$, $S_i$, $T_i$;
Set $Candidate = \emptyset$, $\Gamma_i = \emptyset$, $flag = 0$;
Search for all feasible nodes and obtain $Candidate$;
if $Candidate \neq \emptyset$ then
    Select $n_C \in Candidate$ according to Definition 2;
    $flag = 1$;
    for $t = 1 : S_i$ do
        $\Gamma_i \leftarrow \Gamma_i \cup \{n_C \cdot Content(t)\}$;
    end for
end if
for $\gamma \in \Gamma_i$ do
    Compute $b(\gamma)$, the binary value of $\gamma$ in $L$ digits;
    Let $n$ be the node whose label is $b(\gamma)$;
    while $n \neq root$ do
        $n \cdot AvaNum = n \cdot AvaNum - 1$;
        $n \cdot Content \leftarrow n \cdot Content \backslash \{\gamma\}$;
        if $n \cdot Content(i+1) - n \cdot Content(i) = 2^{n \cdot Level}, \forall i = 1, 2, \cdots, n \cdot AvaNum - 1$ then
            $n \cdot State = 1$;
        else
            $n \cdot State = 0$;
        end if
        $n \leftarrow n \cdot Parent$;
    end while
end for
Output $\{\Gamma_i, flag\}$.
```

Fig. 5 *Algorithm 1: slice allocation for one PLP*

consisting of 100 data symbols was adopted. The fast Fourier transform size of each data symbol was set to 4096, and every data symbol contained 3084 data cells. Furthermore, every 100 data cells formed a data slice, and thus the number of available data slices in the T2-frame was $N_S = \lfloor C_d N_d / K \rfloor = \lfloor (3084 \cdot 100)/100 \rfloor = 3084$. The delay constraint of each PLP was uniformly generated in the interval range of 1–100 data symbols. The weight of each PLP was inversely proportional to its deadline, with the slope of 30. The required data slices of each PLP were randomly generated. When choosing a PLP to map, the number of the required data slices for the chosen PLP should be no larger than half of the data slices already contained in the T2-frame before the PLP's deadline [Let the deadline for PLP i be T_i, and there are N_i data slices in the T2-frame before T_i. Furthermore, let S_i be the number of required data slices for PLP i. If $S_i > N_i/2$, the data slices allocated to PLP i will be contiguous, which should be avoided.]. All the simulation investigations were conducted using a customarily implemented application in MATLAB. Specifically, the simulation of modulation and the associated signal processing were implemented using MATLAB functions. Frame builder function was customarily created with the parameters defined in the DVB-T2 standard, where we specifically adopted pilot pattern 1 (PP1). The channel environment was also modelled with the parameters given in the standard.

The allocation efficiency of the proposed HA was evaluated using the following benchmark algorithms.

- Random algorithm (RA): PLPs are put in a random sequence, and Algorithm 1 is used to allocate data slices to each PLP.
- Best-order algorithm (BoA): All the legitimate PLP sequences are searched, and the sequence achieving the maximum value of the total utility is chosen as the best-order one. Then Algorithm 1 is used to allocate data slices. Obviously, this scheme is optimal in terms of allocation efficiency, but it suffers from the drawback of exponentially increasing complexity.
- DVB-T2 algorithm [8] (DVB-T2): PLPs are put in a random sequence. For a PLP i, if the sum of the required data slices for PLP i plus the already allocated data slices does not exceed the system capacity, this PLP is mapped to the T2-frame using the current resource allocation scheme. In this scheme, N_{ss} was set to 10 and 400, respectively.

Remark 2: As analysed in Section 5.3, the computational complexity of the proposed HA is on the order of $O(N_S^2)$. Since there is no need to rearrange the PLPs, the complexity of the RA is on the order of $O(N_S \sum S_i + 2\sum (T_i/S_i)) = O(N_S^2)$. Similarly, the BoA has the computational complexity on the order of $O(M!(N_S \sum S_i + 2\sum (T_i/S_i))) = O(M!N_S^2)$. As for the DVB-T2

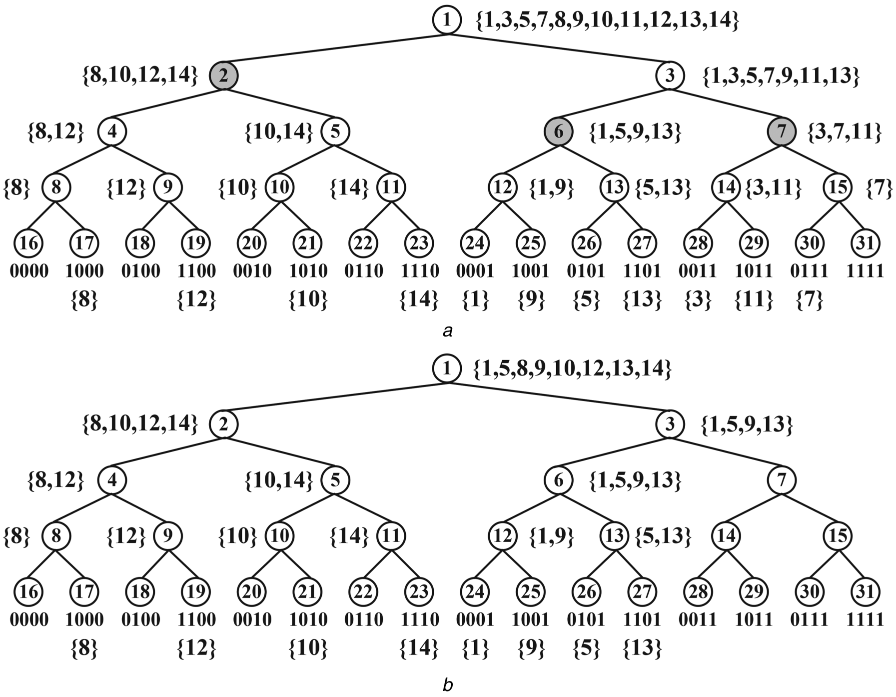


Fig. 6 *Example of Algorithm 1 (Fig. 5)*
(a) Before slice allocation, ***(b)*** After slice allocation

Algorithm 2

```
Input $\mathcal{I}$, $N_S$;
Set $\mathcal{R} = \emptyset$;
Construct a binary tree $T_{ree}$, where $L = \lceil \log_2(N_S) \rceil$;
Put PLPs in a sequence $Q$ according to Definition 3;
for $q \in Q$ do
    Map $q$ to $T_{ree}$ using Algorithm 1 and obtain $\Gamma_q$;
    $\mathcal{R} \leftarrow \mathcal{R} \cup \Gamma_q$;
end for
Output allocation solution $\mathcal{R}$.
```

Fig. 7 *Algorithm 2: heuristic algorithm for slice allocation*

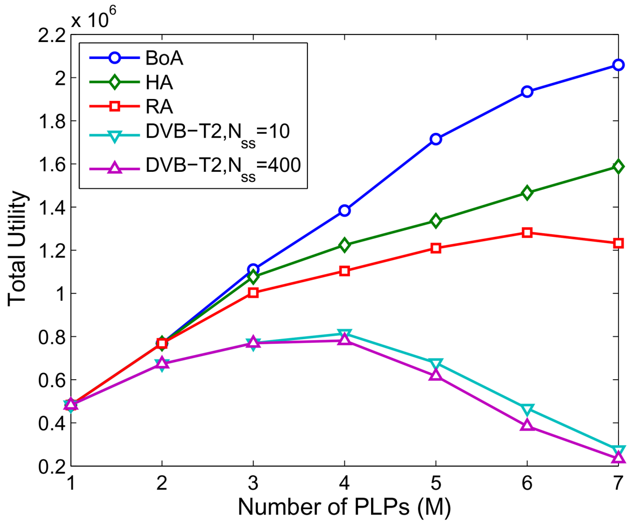


Fig. 8 *Total utility comparison of four different schemes*

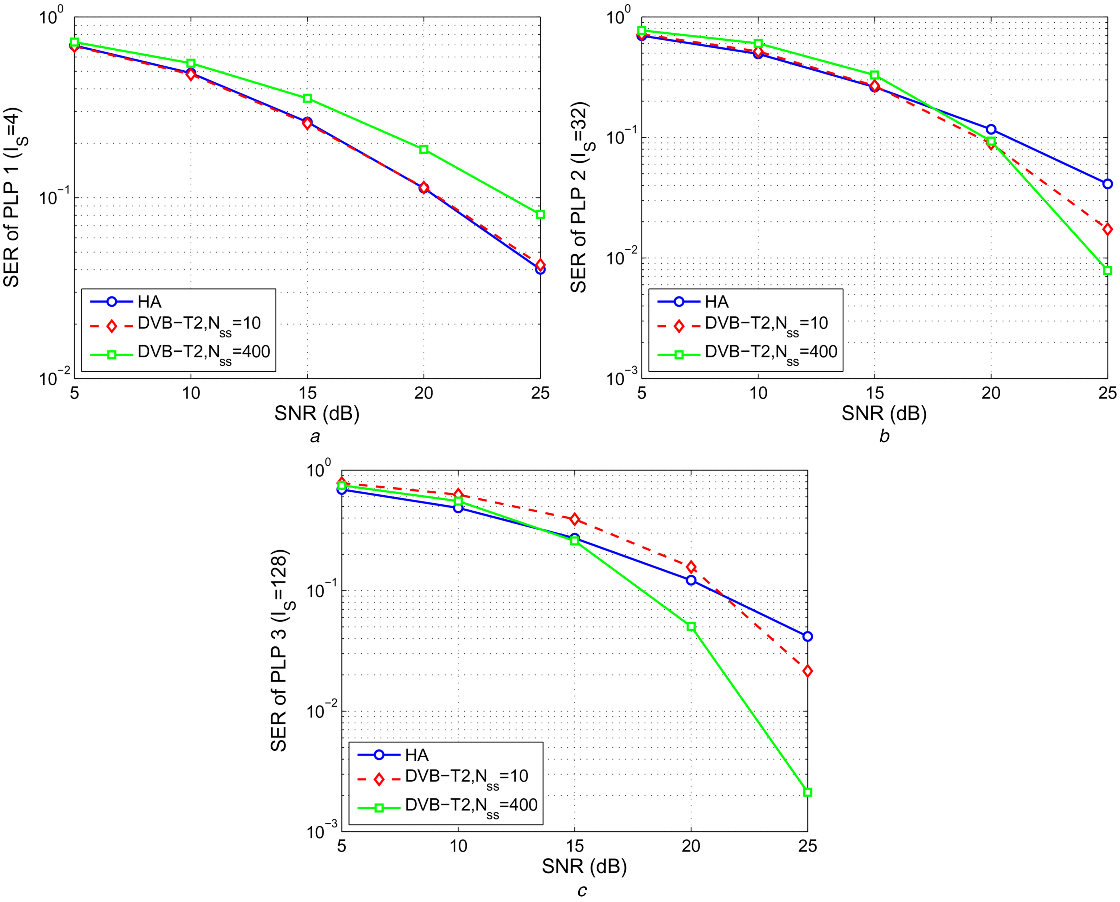
algorithm, the complexity of deciding how many PLPs can be delivered in a T2-frame is on the order of $O(M)$, while the complexity of mapping these PLPs onto the frame is on the order of $O(MN_{ss})$. Therefore, the computational complexity of the DVB-T2 algorithm is on the order of $O(M + MN_{ss}) = O(MN_{ss})$.

The performance of each algorithm was evaluated using the following two metrics:

- *Allocation efficiency*: Measured as the total utility, which is given by $\sum_{i\in\mathcal{I}} f(i)S_i x^i_{t_{\text{end}}}$ in (12). The larger the total utility is, the more efficient an algorithm is.
- *SER*: Defined as the ratio of the error symbols over the total symbols, which measures the reliability of an algorithm. The smaller the SER is, the more reliable an algorithm is.

The total utility obtained by each algorithm is depicted in Fig. 8. As expected, the BoA attains the highest total utility, but it has a much higher computational complexity than the other three schemes. It can be seen from Fig. 8 that the proposed HA outperforms the RA by about 7.3–28.9% for $M \geq 3$. Also for $M \geq 3$, the HA's total utility is lower than the optimal BoA by about 3.1–24.2%. This indicates that the HA can attain more than 75% of the optimal total utility value at a much reduced computational complexity, in comparison to the BoA. From Fig. 8, it can be observed that the Algorithm 1 based schemes (RA, HA and BoA) all perform much better than the DVB-T2 scheme, especially for large M. Even the RA, which puts the PLPs in a random sequence, achieves 14.1–425.9% higher total utility than the DVB-T2 scheme when M increases from 2 to 7. This is because the current DVB-T2 scheme only considers how to obtain diversity capability, but does not include service delay into consideration. Observe from Fig. 8 that for $M \geq 4$, the allocation efficiency of the DVB-T2 decreases as M increases. Also the total utility achieved by the DVB-T2 scheme with $N_{ss} = 10$ is larger or equal to that of the DVB-T2 scheme with $N_{ss} = 400$. This confirms the analysis given in (3), which reveals that for the current DVB-T2 scheme, the delay of a service increases with the increase of N_{ss} and M. More specifically, for the current DVB-T2 scheme, when the data traffic is low, there are enough data cells for all the PLPs before their delay deadlines, and this ensures the increase of the total utility achieved with the increase of PLPs. However when the data traffic is heavy, further increasing the data amount leads to more and more PLPs whose delay constraints cannot be met, which results in a decrease in the total utility achieved.

As discussed in Section 3, the diversity capability is an important consideration in the design of the current resource allocation scheme for DVB-T2 systems, and the DVB-T2 scheme



a

b

c

Fig. 9 *SER performance comparison of the HA and the DVB-T2 with $N_{ss} = 10$ and $N_{ss} = 400$ for three different PLPs*
(a) SER of PLP 1, ***(b)*** SER of PLP 2, ***(c)*** SER of PLP 3

is a reliable scheme. Therefore, the performance of the proposed HA was compared with that of the DVB-T2 scheme, in terms of SER under a static multipath channel environment. More specifically, the simulations were conducted using the Rayleigh channel model with twenty paths (RL20) [22]. Three PLPs with different data slice intervals were adopted, specifically, $I_S(1) = 4$, $I_S(2) = 32$ and $I_S(3) = 128$. Fig. 9 illustrates the SERs of the three different PLPs as functions of the channel's signal-to-noise ratio (SNR), obtained by the proposed HA and the DVB-T2 with $N_{ss} = 10$ and $N_{ss} = 400$. Generally, the SERs achieved by the two algorithms are similar in the SNR range of 5–15 dB, but the performance of the two algorithms are clearly different for SNR > 15 dB. More specifically, for PLP 1, the SERs of the HA and the DVB-T2 with $N_{ss} = 10$ are almost identical and are lower than that of the DVB-T2 with $N_{ss} = 400$. However, for PLP 2, the DVB-T2 with $N_{ss} = 400$ attains the lowest SER given SNR ≥ 20 dB, while for PLP 3, it attains the lowest SER given SNR ≥ 15 dB. The results of Fig. 9 demonstrate that the proposed HA has a compatible reliability to the current DVB-T2 design.

Fig. 10*a* further depicts the SERs achieved by the HA for PLPs 1, 2 and 3 in a single plot, while Fig. 10*b* shows the SERs achieved by the DVB-T2 with $N_{ss} = 400$ for these three PLPs in one plot. It can be seen that the HA attains the same SER for all the three PLPs, but the DVB-T2 with $N_{ss} = 400$ achieves different SERs for different PLPs. This demonstrates that the HA can achieve a similar SER independent of the services' resource requirements, while the DVB-T2 is incapable of doing so. This is because in the proposed HA design, each data slice contains an equal number of data cells. By contrast, for the current DVB-T2 design, there are fewer data cells in the sub-slices for the services with smaller resource requirements.

7 Conclusions

This paper has focused on efficient and reliable resource allocation for multi-services with data rate and delay constraints in DVB-T2 networks. By grouping data cells of a T2-frame into a number of data slices, a heuristic algorithm has been proposed to allocate the data slices to each service using a tree structure. Simulation results demonstrate that the proposed algorithm is more efficient than the current resource allocation scheme in satisfying services' requirements. Like the current resource allocation scheme in DVB-T2 networks, the proposed scheme is reliable and is capable of offering diversity. Moreover, unlike the current resource allocation scheme which attains different SERs for different services, the proposed algorithm achieves a similar SER for the services with different requirements. Compared with the optimal resource allocation algorithm whose complexity may become prohibitively high, it has been observed that the proposed heuristic algorithm achieves 75% of the optimal total allocation utility value, while only imposing a dramatically lower complexity.

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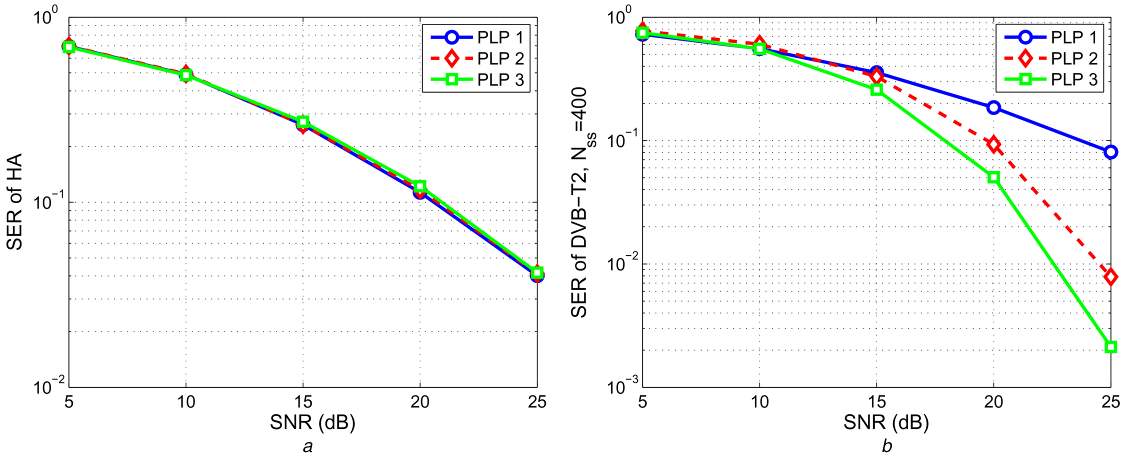

Fig. 10 *SERs achieved by the HA and the DVB-T2 with* $N_{ss} = 400$*, respectively, for PLPs 1, 2 and 3*

(a) SER of HA, ***(b)*** SER of DVB-T2

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