Backward compatible multi-service transmission over the DTMB system

Huangping Jin, Kewu Peng, Senior Member, IEEE and Jian Song, Senior Member, IEEE

Abstract—In this paper, a backward compatible multi-service transmission scheme over the digital television terrestrial multimedia broadcasting (DTMB) system is proposed, which is based on embedded constellation and bit division multiplexing. With the proposed scheme, simultaneous transmission of original services and multiple augmented services can be supported in the DTMB system in a backward compatible manner. No additional RF spectrum is required and no additional complexity is introduced to the legacy DTMB receivers. Two schemes over the DTMB system are proposed towards two different requirements, which are maintaining the transmission rate of original services and maintaining the reception SNR-threshold of original services, respectively. Average mutual information analysis and bit error ratio simulations are performed. In both schemes, the increment in the throughput of the DTMB system can be over 7.6 Mbps in typical mode.

Index Terms—DTMB, Backward compatibility, Multi-service transmission.

I. INTRODUCTION

With the emerging enormous number of handheld terminals, diversified multimedia contents are increasingly demanded in the last decade. However, the available frequency spectrum for the digital terrestrial television broadcasting (DTTB) network is limited. Therefore, it is significantly important to design a power and bandwidth efficient multi-service transmission scheme for the DTTB networks. To achieve a smooth transition, backward compatible multi-service transmission scheme is preferred for the existing DTTB network with large volume of users.

Many literatures [1]-[4] have been devoted to backward compatible data transmission over the DTTB network. In [1], hierarchical modulation was firstly proposed to upgrade digital broadcast system, but no practical scheme was provided and only one kind of additional data was considered. A novel augmented data transmission (ADT) scheme was recently proposed for the ATSC terrestrial DTV system in [3], which can offer an additional data rate up to a few Mbps for receivers under favorable reception conditions with negligible impact to the legacy ATSC receivers. The ADT scheme described in [3] was also based on hierarchical modulation. However, DTV signal cancellation should be performed at the receiver and the practical performance of the ADT scheme may be limited by the accuracy of channel estimation and is far away from the Shannon limit. For the DTMB system, a backward compatible multi-service transmission scheme was proposed in [5]. But the scheme proposed in [5] is devoted to provide augmented services with lower reception SNR-threshold than the original services with the legacy DTMB receivers. Original services and augmented services are transmitted in a time division multiplexing (TDM) way, which decreases the transmission rate of original services. Furthermore, augmented services are doubly encoded to guarantee the backward compatibility and performance, which leads to significantly degradation in the throughput of the DTMB system.

In this paper, based on our previous work in [6], a novel backward compatible multi-service transmission scheme over the DTMB system is proposed, which is based on the techniques of embedded constellation [7] and bit division multiplexing (BDM) [8]. With the proposed scheme, simultaneous transmission of original services and multiple augmented services can be supported, in which the reception SNR-thresholds of augmented services are higher than those of original services. Two schemes towards two different requirements are provided, which are referred to as Scheme 1 and Scheme 2 in this paper. With Scheme 1, the transmission rate of original services is maintained while the performance (reception SNR threshold) of original services degrades due to signal embedding. With Scheme 2, the performance of original services is maintained while the transmission rate of original services decreases due to the lower order constellation employed for original services. In both schemes, the users under favorable reception conditions can demodulate original services and augmented services simultaneously. Furthermore, the performance of augmented services can be capacity-approaching with the aid of advanced coded modulation techniques.

The remainder of this paper is organized as follows: in Section II, the existing DTMB system is described briefly as well as BDM and the technique of embedded constellation. Then the mechanism of the proposed backward compatible multi-service transmission scheme over the DTMB system is introduced. Two potential schemes towards two requirements over the DTMB system, including the average mutual information (AMI) analysis and bit error ratio (BER) simulations of original services and augmented services, are presented in Section III. In Section IV, the design of constellation mapping of the transmitted symbol and the algorithm employed at the receiver are discussed to optimize the performance of augmented services. Finally, conclusions are drawn in Section V.

For the sake of clarity, several nouns in this paper are
specified here. Users under favorable reception conditions are referred to as outstanding users. Original receivers in the traditional DTMB system are referred to as legacy receivers, as shown in Fig. 1(b), while the receivers newly designed in this paper to obtain original services and augmented services simultaneously are referred to as advanced receivers, as shown in Fig. 6.

II. BACKWARD COMPATIBLE MULTI-SERVICE TRANSMISSION OVER THE DTMB SYSTEM

A. Overview of the DTMB system

The transmitter and receiver structure of the DTMB system are presented in Fig. 1. At the transmitter, as shown in Fig. 1(a), the input MPEG-2 bit stream is scrambled with an m-sequence of $2^{15} - 1$ bit long. Then the bit stream is encoded by forward error correction code, which consists of a BCH (762, 752) outer code and a low-density parity-check (LDPC) inner code. And then, the coded bit stream is mapped to M-QAM symbols and interleaved by convolutional symbol interleaver. 36 transmission parameters signaling (TPS) symbols are added for transmitting the information about encoding and modulation, before constructing the signal frame by combining the frame body and the pseudo random noise (PN) sequence with the length of 420, 595 and 945 symbols. In the following, the baseband processing and the up-converting are carried out. In the DTMB system, 8 MHz is assigned to transmit the radio frequency (RF) signals at a symbol rate of 7.56 mega symbols per second (Msps).

At the receiver, as shown in Fig. 1(b), with the channel state information (CSI) obtained via channel estimation, the signal received can be equalized and then processed by the inverse operation corresponding to the transmitter.

The transmission rate of certain service in the DTMB system can be calculated:

$$R_{bit} = \frac{N_{service}}{N_{info} + N_{TPS} + N_{PN}} \times m \times r_{code} \times R_{sym}$$

where $R_{bit}$ denotes the bit rate of the given service in DTMB. $R_{sym}$ denotes the symbol rate in DTMB and $R_{sym} = 7.56 \text{Msps}$. $m$ denotes the number of bits within each symbol assigned to the transmission of the given service. $r_{code}$ denotes code rate employed for the given service. $N_{info}$ and $N_{service}$ denote the length of symbols used to transmit the information of all the services and the given service, respectively. $N_{info}$ is set to 3744 in DTMB. $N_{TPS}$ denotes the length of TPS symbols and $N_{TPS}$ is set to 36 in DTMB. $N_{PN}$ denotes the length of PN sequence and is chosen from $\{420, 595, 945\}$.

B. Overview of Embedded constellation

In the context of multi-resolution broadcasting of high-definition television (HDTV), embedded constellation was proposed in [7] to create a stepwise graceful degradation for HDTV reception.

An example of non-uniform 16-QAM generated by embedding 4-QAM into a 4-QAM constellation is presented in
Fig. 2, in which the minimum Euclidian distances between the constellation points in original 4-QAM and embedded 4-QAM are $d_1$ and $d_2$ respectively. Simply, the technique of embedded constellation is to replace each constellation point in original constellation with an embedded constellation. The constellation obtained via the technique of embedded constellation is called expanded constellation in this paper. Actually, the technique of embedded constellation is also referred as hierarchical modulation in many literatures [1]-[4].

C. Overview of BDM

BDM was proposed in [8] to provide a power and bandwidth efficient multi-service transmission in broadcast channel. From the perspective of channel resource allocation, BDM is a strategy of channel resource allocation across multiple symbols at the bit level essentially. When BDM is employed for the transmission of multiple services, bits carried by every $N$ symbols are separated into multiple parts arbitrarily and each part makes up a sub-channel. Each service is transmitted via each sub-channel.

An example of channel resource allocation by BDM for two-service transmission is illustrated in Fig. 3, where the bit with lower index has the higher error protection level. It is shown that 30 bits in the slash shadow within every 12 symbols are allocated for service 1 and the rest bits for service 2, i.e., the actual channel is divided into two sub-channels at the bit level and two services are transmitted via individual sub-channels.

$$x_t = \sqrt{P}x_o + \sqrt{\alpha P}x_e$$

(2)

where $x_o$ is the constellation point chosen from the original constellation in DTMB and $x_e$ is the constellation point chosen from the embedded constellation. $P$ is the power of the transmitted symbol in the traditional DTMB system. $\alpha$ is the proportion of the power assigned to the embedded constellation to the power of the original constellation in DTMB. It can be shown from (2) that the power of the transmitted symbol increases slightly, but it is not the prerequisite of the proposed scheme. Actually, the power of the transmitted symbol can be normalized, which will be discussed in Section III-A.

At the modulation block, the original constellation mapping is maintained and only the labeling of the embedded constellation can be configured. Simply to say, the coded bits from original services are mapped into original constellation to obtain $x_o$. Then the coded bits from multiple augmented services are mapped into the embedded constellation and choosing constellation point from the embedded constellation may be dependent or independent on the value of $x_o$, obtained, which is reflected by the labeling of the expanded constellation. For example, assume that both the original constellation mapping and the embedded constellation mapping are 16-Gray-QAM. Labeling of the expanded constellation can merely be the superposition of 16-Gray-QAM and 16-Gray-QAM, in which case the value of $x_e$ is independent on the value of $x_o$. However, labeling of the expanded constellation may also be designed as Gray mapping, in which case the value of $x_e$ is dependent on the value of $x_o$. The design of labeling of the expanded constellation and the corresponding algorithm employed at the receiver will be discussed extensively in Section-IV.

D. Mechanism of the proposed scheme

To provide backward compatible multi-service transmission over the DTMB system, we propose to expand the original constellation in DTMB to a constellation of higher order by using the technique of embedded constellation. Original services can be transmitted by the original constellation in DTMB, while multiple augmented services can be carried by the embedded constellation in a bit division multiplexing way, i.e., bits carried by embedded constellation within every $N$ symbols can be divided into multiple sub-channels and each augmented service is transmitted via each sub-channel.

At the transmitter, original services and multiple augmented services are separately encoded by individual channel codes. Then their outputs are combined to select a constellation point in the expanded constellation. With the technique of embedded constellation to provide the simultaneous transmission of multiple augmented services as well as original services, the transmitted symbol can be described as:

Assume that both the original constellation and the embedded constellation are 16-QAM, an example of channel resource allocation within the expanded constellation by the proposed scheme is presented in Fig. 4, where the bit (represented by rectangular) with lower index has the higher error protection level. Bits carried by original constellation are in whole colored shadow and other bits are those carried by embedded constellation. It is shown that two augmented services are transmitted by the embedded constellation in a BDM way. Those 27 bits in the slash shadow within every 12 symbols are allocated for the transmission of one augmented service and the rest bits in embedded constellation are allocated for the other augmented service.
At the receiver, on one hand, legacy receivers can demodulate the signal received as before to recover original services, considering transmitted symbols being chosen from original constellation while being interfered by embedded constellation, which means the proposed scheme is backward compatible with the traditional DTMB system and newly-designed receiver is unnecessary for legacy receivers. However, embedded constellation, which is considered as noise/interference in the synchronization, channel estimation, and demapping process of original services, would inevitably degrade the performance of original services with legacy receivers. On the other hand, outstanding users are required to update their receivers and demodulate the received signal based on the expanded constellation to obtain augmented services and original services simultaneously.

The block diagram of the transmitter of the DTMB system with the proposed scheme is presented in Fig. 5. A reference structure of receiver with single stage decoding (SSD) [9] and independent demapping employed at the receiver for the outstanding users is depicted in Fig. 6. In both Fig. 5 and Fig. 6, besides the modules defined in the traditional DTMB system and the additional modules in white colored shadow to deal with augmented services, the module of "Mapping and Interleaving" and "De-Interleaving and De-Mapping" should also be modified with original constellation changed to expanded constellation. For augmented services, advanced coded modulation techniques such as advanced channel code and the technique of bit mapping [10] can be employed to achieve a capacity-approaching performance. It should be pointed out that the bit interleaving in Fig. 5 is performed at bit level, which is different from the convolutional interleaving in the traditional DTMB system performed at the symbol level.

### III. TWO POTENTIAL SCHEMES

In this section, two potential backward compatible multi-service transmission schemes over the DTMB system towards two requirements will be presented to give an insight into the mechanism of the proposed scheme, and are referred to as Scheme 1 and Scheme 2.

Only two augmented services will be considered for simplicity, although three or more augmented services can be supported by the proposed scheme. For FEC encoding/decoding, BCH is not included in both schemes and only the LDPC code is considered for simplicity. Bit interleaving is not performed in both schemes, while it will be designed to improve the performance of augmented services in our future work. Furthermore, perfect synchronization and channel estimation are assumed in this paper.

With Scheme 1, the transmission rate of original services is maintained while the performance (reception SNR-threshold) of original services degrades due to signal embedding. With Scheme 2, the performance of original services is maintained while the transmission rate of original services decreases due to the lower order constellation employed for original services.

Typical modulation mode and code rate in the DTMB system for applications with high spectrum efficiency are uniform 64-Gray-QAM and 3/5 respectively, which are assumed to be employed in the transmission of original services.

#### A. Parameters for Scheme 1 and Scheme 2

Assume that $d_1$ and $d_2$ are the minimum Euclidian distances between the constellation points in original constellation and embedded constellation respectively, embedded ratio can be defined as in (3). It should be noted that the BER performances of both original services and augmented services vary with the ratio $\lambda$.

$$\lambda = \frac{d_1}{d_2}$$  \hspace{1cm} (3)

Assume that the power of the original constellation is $P_o$ and the power of the embedded constellation is $P_e$, it is easy to conclude:

$$P_o \propto d_1^2$$  \hspace{1cm} (4)

$$P_e \propto d_2^2$$  \hspace{1cm} (5)
Then we can obtain:

\[ \alpha = \frac{P_t}{P_o} \propto \frac{d_2^2}{d_1^2} = \frac{1}{\lambda} \quad (6) \]

According to AMI analysis results, we know that the larger the value of \( \lambda \), i.e., the smaller the power allocated to the embedded constellation, the better the performance of original services and the worse the performance of augmented services. Therefore, the trade-off should be made between the performance of original services and that of augmented services. The value of \( \lambda \) as well as code rates of original services and augmented services should be configured appropriately to obtain the expected performance and transmission rates of original services and augmented services.

As shown in (2), with the proposed scheme, the power assigned to the original constellation is same as the power of the transmitted symbol in traditional DTMB system and the power of the transmitted symbol increases. However, for the convenience in comparing the performance of original services with legacy receivers with and without the proposed scheme, the signal to noise ratio (SNR) used in the following AMI analysis and BER simulation is computed by:

\[ SNR = 10 \times \log \left( \frac{P}{\sigma^2} \right) \quad (7) \]

where \( P \) is the power of the transmitted symbol in the traditional DTMB system and \( \sigma^2 \) is the noise variance at the receiver. Actually, in the DTMB system with the proposed scheme, SNR will be larger than that in (7).

As described before, the power of the transmitted symbol increases, but it is not the prerequisite of the proposed scheme. In the Scheme 1 and Scheme 2, \( \lambda \) will be assumed to \( 2\sqrt{2} \) and 4.26 respectively, which will lead to 0.6% and 5.76% increment in the power of the transmitted symbol. Actually, the power of the transmitted symbol can be normalized and the transmitted symbol is described as:

\[ x_t = \sqrt{\frac{P}{1+\alpha}} x_o + \sqrt{\frac{\alpha}{1+\alpha}} P x_e \quad (8) \]

However, if the power of the transmitted symbol is normalized, the equivalent power assigned to the original constellation in the proposed scheme is smaller than that in the traditional DTMB system, which would further degrade the performance of original services in Scheme 1 and require the readjustment of \( \lambda \) to maintain the performance of original services in Scheme 2.

1) Scheme 1: To maintain the transmission rate of original services, constellation mapping of 64-Gray-QAM and code rate of 3/5 are still employed for original services. To provide the transmission of two augmented services, we propose to expand the constellation from uniform 64-QAM to non-uniform 256-QAM via the technique of embedded constellation, i.e., replacing each constellation point in 64-QAM with a 4-QAM constellation. Although the value of \( \lambda \) may be application dependent, \( \lambda = 2\sqrt{2} \) is assumed in the example of this scheme.

At the transmitter, labeling of non-uniform 256-QAM is set as Gray mapping. For original services, original LDPC code in DTMB and code rate of 3/5 are employed, and then the coded bits are mapped into original 64-Gray-QAM. For the two augmented services, information bits are separately encoded by individual LDPC codes, which are specified in DVB-T2 [11] with code rates of 1/2 and 2/3 for individual augmented services. Then the coded bits of two augmented services are mapped into embedded 4-QAM. The mapping rule is depicted in Fig. 7(a), in which bits in the slash shadow are allocated to transmit augmented service 2 and the others to augmented service 1. At the receiver, the advanced receiver depicted in Fig. 6 is employed, i.e., SSD and independent demapping are employed.

2) Scheme 2: The embedded constellation will inevitably degrade the performance of original services. It is well known that, for the same rate, the lower constellation order is, the better performance of the system is. To maintain the performance of original services with legacy receivers, we propose to change the modulation mode employed for original services, i.e., constellation mapping of 64-Gray-QAM are replaced by 16-Gray-QAM for the transmission of original services, which is informed to legacy receivers by the TPS signaling of the modulation mode. To provide the transmission of two augmented services, we propose to expand the constellation from uniform 16-QAM to non-uniform 256-QAM by replacing each constellation point in 16-QAM with a 16-QAM constellation. The performance of original services can be maintained by adjusting the ratio of \( \lambda \) and \( \lambda = 4.26 \) is assumed in the example of this scheme.

At the transmitter, labeling of non-uniform 256-QAM is set as Gray mapping. For original services, original LDPC code and code rate of 3/5 are employed, and then the coded bits are mapped into original 16-Gray-QAM. For the two augmented services, information bits are separately encoded by individual LDPC codes, which are specified in DVB-T2 with code rates of 1/2 and 2/3 for individual augmented services. Then the coded bits of two augmented services are mapped into embedded 16-QAM. The mapping rule is depicted in Fig. 7(b), in which bits in the slash shadow are allocated to transmit augmented service 2 and the others to augmented service 1. At the receiver, the advanced receiver depicted in Fig. 6 is employed, i.e., SSD and independent demapping are employed.
B. AMI analysis

With independent demapping employed at the receiver, the AMI between each bit and the channel output $Y$ can be calculated by [12]:

$$I(b_i; Y) = 1 - \text{E}_{b,y} \left[ \log_2 \frac{\sum_{x \in \chi_i^b} p(y|x)}{\sum_{x \in \chi_i^b} p(y|x)} \right]$$  \hspace{1cm} (9)

where $b_i$ denotes the $i$-th bit carried by an AMI constellation symbol, $I(,:)$ and $p(,:)$ denote AMI function and conditional probability respectively, $\text{E}_{b,y} [ \cdot ]$ is the expectation respect to the distribution $b$ and $y$, and $\chi_i^b$ denotes the constellation subset with the $i$-th bit being $b$ where $b \in \{0, 1\}$.

In the traditional DTMB system, all of the 6 bits carried by each 64-Gray-QAM symbol are used for the transmission of original services. With independent demapping employed at the receiver as depicted in Fig. 1(b), the capacity of original services can be calculated by:

$$C_{\text{orig}} = \sum_{i=0}^{5} I(b_i; Y)$$  \hspace{1cm} (10)

where $b_i$ denotes the $i$-th bit carried by a 64-Gray-QAM symbol in DTMB and $I(b_i; Y)$ is calculated by (9).

1) Scheme 1: In the DTMB system with the Scheme 1, 8 bits are carried by each non-uniform 256-QAM symbol. 6 of them are used for transmission of original services and 2 of them are for the transmission of augmented services.

For the outstanding users with advanced receivers in Fig. 6, in which SSD and independent demapping are employed at the receiver, the capacities of original services, augmented service 1 and augmented service 2 can be calculated by:

$$C_o = \sum_{i=0}^{5} I(b_i; Y)$$  \hspace{1cm} (11)

$$C_o^1 = I(b_o; Y)$$  \hspace{1cm} (12)

$$C_o^2 = I(b_o; Y)$$  \hspace{1cm} (13)

where $b_i$ denotes the $i$-th bit carried by a non-uniform 256-QAM symbol and $I(b_i; Y)$ is calculated by (9).

For legacy receivers, the embedded 4-QAM signal is considered as noise/interference during the demapping process of received signal, which leads to performance degradation. With non-optimal demapping algorithm in legacy receivers, it can be predicted that the reception SNR-thresholds of original services with legacy receivers are higher than those with advanced receivers. Actually, the capacity of the original services with legacy receivers can be calculated by:

$$C_o' = \sum_{i=0}^{5} I'(b_i; Y)$$  \hspace{1cm} (14)

where $b_i$ denotes the $i$-th bit carried by a 64-Gray-QAM symbol and $I'(b_i; Y)$ is calculated by (15) with $p = 1$ under AWGN channel, $\rho \sim CN(0, 1)$ under Rayleigh channel and $N \sim CN(0, \sigma^2)$. (14) is proved in Appendix.

According to (10)-(11) and (14), the capacities of original services with and without the Scheme 1 under AWGN and Rayleigh channels respectively with the code rate of original services being 3/5. The reception SNR-thresholds of original services with advanced receivers are 0.03/0.07 dB lower than those with legacy receivers. The difference is due to the non-optimal demapping algorithm of the original services in legacy receivers.

![Fig. 8. Capacities of original services with and without Scheme 1 under AWGN channel.](image8)

![Fig. 9. Capacities of original services with and without Scheme 1 under Rayleigh channel.](image9)

![Fig. 10. Capacities of augmented services with Scheme 1 under AWGN and Rayleigh channels.](image10)
According to (12)-(13), the capacities of augmented services in Scheme 1 under AWGN and Rayleigh channels are calculated and presented in Fig. 10. It shown form Fig. 10 that the capacities of two augmented services are the same, because the 2 bits carried by the embedded constellation have the same error protection level. The reception SNR-thresholds of two augmented services are 22.45/24.21 dB and 24.56/27.25 dB under AWGN and Rayleigh channels respectively with code rates of two augmented services being 1/2 and 2/3.

For the outstanding users with advanced receivers, two augmented services can be obtained. Therefore, the throughput of the system increases by 7/6 bits/symbol, which means additional rate of 7.86 Mbps in DTMB with length of PN sequence being 420 according to (1). To demonstrate the Scheme 1 in a visual way, the sketch map of coverage performances of the DTMB system with/without Scheme 1 are presented in Fig. 11.

2) Scheme 2: In the DTMB system with the Scheme 2, 8 bits are carried by each non-uniform 256-QAM symbol. 4 of them are used for the transmission of original services and 4 of them are for the transmission of augmented services. The capacity of original services with the legacy receivers with/without the proposed scheme as well as the capacities of two augmented services can be analyzed in the same way employed in Scheme 1.

The capacities of original services in the DTMB system with and without Scheme 2 under AWGN and Rayleigh channels are calculated and presented in Fig. 12 and Fig. 13 respectively. For legacy receivers, the reception SNR-thresholds of original services with Scheme 2 (16QAM and rate 3/5) are 2.67/1.48 dB lower than that (64QAM and rate 3/5) in traditional DTMB system, which means the performance of original services with legacy receivers is maintained. However, with the lower constellation order, one thirds of the transmission rate of original services is decreased. The reception SNR-thresholds of original services with legacy receivers are 0.42/1.0 dB higher than those with advanced receivers, which is also because of the non-optimal demapping algorithm of the original services in legacy receivers.

The capacities of augmented services in Scheme 2 under AWGN and Rayleigh channels are calculated and presented in Fig. 10. The reception SNR-thresholds of two augmented services are 14.97/17.35 dB and 21.7/24.55 dB under AWGN and Rayleigh channels respectively with code rates of two augmented services being 1/2 and 2/3.

For the outstanding users with advanced receivers, two augmented services can be obtained. Therefore, the throughput of the system increases by 17/15 bits/symbol, which means additional rate of 7.64 Mbps in DTMB with length of PN sequence being 420 according to (1). To demonstrate the
Scheme 2 in a visual way, the sketch map of coverage performances of the DTMB system with/without Scheme 2 are presented in Fig. 15.

C. Simulation results

The BER simulations of original services and augmented services in the DTMB system with and without Scheme 1 and Scheme 2 under AWGN and Rayleigh channels are performed, and the results are presented in Fig. 16, Fig. 17, Fig. 18 and Fig. 19 respectively.

As shown in Fig. 16 and 17, in the DTMB system with Scheme 1, the performance degradation of original services with legacy receivers is only 0.85/1.25 dB at a BER of $10^{-5}$ under AWGN and Rayleigh channels respectively. The reception SNR-thresholds of original services with legacy receivers are 0.16/0.31 dB higher than those with advanced receivers, which is in correspondence with the AMI analysis results in Section III-B.

For the outstanding users with advanced receivers, two augmented services can be obtained. The reception SNR-thresholds of two augmented services are 23.13/25.09 dB and 25.27/28.32 dB under AWGN and Rayleigh channels respectively with code rates of augmented services being 1/2 and 2/3. It is also shown that the performances of the augmented services are only 0.68/0.88 dB and 0.71/1.07 dB away from the Shannon limit under AWGN and Rayleigh channels respectively with the advanced LDPC code specified in DVB-T2.

As shown in Fig. 18 and 19, in the DTMB system with Scheme 2, for legacy receivers, the reception SNR thresholds of original services are 1.07/0.05 dB lower than those in traditional DTMB system at a BER of $10^{-5}$ under AWGN and Rayleigh channels respectively, which means the per-
formances of original services are maintained. The reception SNR-thresholds of original services with legacy receivers are 1.36/1.78 dB higher than those with advanced receivers, which is in correspondence with the AMI analysis results in Section III-B.

For the outstanding users with advanced receivers, two augmented services can be obtained. The reception SNR-thresholds of two augmented services are 15.88/18.41 dB and 22.41/25.59 dB under AWGN and Rayleigh channels respectively with code rates of augmented services being 1/2 and 2/3. It is also shown that the performances of the augmented services are only 0.91/1.06 dB away from the Shannon limit under AWGN and Rayleigh channels respectively with the advanced LDPC code specified in DVB-T2.

IV. DESIGN OF RECEPTION ALGORITHM AND LABELING OF THE EXPANDED CONSTELLATION

For original services, original constellation mapping is maintained and only the ratio of $\lambda$ can be adjusted to obtain the demanded practical performance. However, for augmented services, labeling of the expanded constellation and the algorithm employed in the process of demapping at the receiver can be configured to optimize the practical performance. In the proposed Scheme 1 and Scheme 2 in Section III, SSD and independent demapping are employed at the receiver, and labeling of non-uniform 256-QAM is set as Gray mapping. In this Section, the reason for those will be presented and only one augmented service is considered for simplicity.

A. Single Stage Decoding

The labeling of the expanded constellation is set as Gray mapping in Scheme 1 and Scheme 2. Actually, the labeling of the expanded constellation may also be superposition of 64-Gray-QAM and 4-Gray-QAM and superposition of 16-Gray-QAM and 16-Gray-QAM in Scheme 1 and 2 respectively.

To demonstrate the superiority of Gray mapping over non-Gray mapping with SSD and independent demapping employed, the capacities of augmented service with two labelings described above are calculated and presented in Fig. 20. Only AWGN channel and Scheme 1 are considered for simplicity. As shown in Fig. 20, with the code rate being 2/3, the reception SNR-threshold of augmented service with labeling of the expanded constellation being Gray mapping is lower than that being superposition of 64-Gray-QAM and 4-Gray-QAM, which indicates a better performance in the practical system. The comparison in BER performances of augmented service with two labelings employed will be conducted in Section IV-C.

B. Multi-stage Decoding

When SSD and independent demapping are employed, the demapping and decoding of original services and augmented services are independent from each other. Actually, at the receiver, the obtained soft information about original services can be fed back to the demapper as the a priori information, which can assist the demapping and decoding of augmented services. In that case, the demapping and decoding process of augmented services can be modeled as the structure depicted in Fig. 21, which is called multi-stage decoding (MSD) in previous literature [9]. However, compared with SSD, MSD adds additional complexity to the advanced receivers for receiving augmented services.

When MSD is performed at the receiver, as shown in Fig. 21, the capacities of augmented service can be increased and
calculated by:

\[ C = \sum_{i=k}^{M} I(b_i, Y | b_0 \sim b_{k-1}) \]  

(16)

where \( M \) is the number of the bits carried by the expanded constellation, among which \( k \) is the number of the bits assigned for the transmission of original services, e.g., \( k = 6 \) in Scheme 1 and \( k = 4 \) in Scheme 2.

The capacities of augmented service with SSD or MSD employed are calculated and presented in Fig. 22. Only AWGN channel and Scheme 1 are considered for simplicity. The labeling of the expanded constellation is Gray mapping. It is shown that with code rate of the augmented service being 2/3, negligible improvement can be made by MSD if labeling of non-uniform 256-QAM is Gray mapping.

Actually, as shown in (16), the maximum capacity of augmented services with MSD employed can be achieved when the labeling of constellation subset given the value of \( 0-th \sim (k-1)-th \) bit carried by the expanded constellation is Gray mapping. It indicates that the optimal labeling of the expanded constellation may not be Gray mapping.

The labeling of the expanded constellation may be Gray mapping or the superposition of Gray mapping original constellation and Gray mapping embedded constellation. However, the labeling of constellation subset given the value of \( 0-th \sim (k-1)-th \) bit carried by the expanded constellation is Gray mapping in both labelings, which means capacities of augmented service with two labelings are equal. Therefore, it can be predicted that the reception SNR-thresholds of the augmented service with MSD employed are same with the two labelings employed.

C. Simulation results

The BER simulation of augmented service with all the options in Table 1 is performed and the simulation results are presented in Fig. 23 and 24. Code rate of the augmented service is set to 2/3. The reception SNR-thresholds of augmented service at a BER of \( 10^{-5} \) can be obtained and are also presented in Table 3.

\[
\begin{array}{|c|c|c|c|}
\hline
\text{Channel} & \text{Parameters} & \text{Scheme 1} & \text{Scheme 2} \\
\hline
\text{AWGN} & \text{SSD, Gray mapping} & 25.28 & 21.21 \\
\text{AWGN} & \text{SSD, non-Gray mapping} & 25.40 & 21.89 \\
\text{AWGN} & \text{MSD, Gray mapping} & 25.28 & 21.21 \\
\text{AWGN} & \text{MSD, non-Gray mapping} & 25.28 & 21.21 \\
\text{Rayleigh} & \text{SSD, Gray mapping} & 28.33 & 24.23 \\
\text{Rayleigh} & \text{SSD, non-Gray mapping} & 28.70 & 25.12 \\
\text{Rayleigh} & \text{MSD, Gray mapping} & 28.25 & 24.12 \\
\text{Rayleigh} & \text{MSD, non-Gray mapping} & 28.25 & 24.12 \\
\hline
\end{array}
\]

It is shown from Table 3 that with SSD and independent demapping employed, the reception SNR-thresholds of augmented service with labeling of the expanded constellation being Gray mapping are 0.12/0.37 dB lower than those being superposition of 64-Gray-QAM and 4-Gray-QAM on the AWGN and Rayleigh channels respectively and 0.68/0.89 dB in Scheme 2. So Gray mapping is preferred for the expanded constellation in the practical system.

With labeling of the expanded constellation being Gray mapping, reception SNR-thresholds of augmented service with MSD employed are 0/0.07 dB lower than those with SSD on the AWGN and Rayleigh channels respectively in Scheme 1. The improvements by MSD are only 0/0.11 dB in Scheme 2. The simulation results indicate little improvement can be made by MSD if labeling of non-uniform 256-QAM is Gray mapping, which is corresponding to the results obtained by AMI analysis in Section IV-B. Therefore, MSD is not preferred for its negligible improvement in performance and higher complexity, compared with SSD and labeling of the expanded constellation being Gray mapping. It is also shown in Table 3 that the reception SNR-thresholds of the augmented service are equal when MSD is performed for either Gray or non-Gray expanded constellation, as predicted in section IV-B.
V. Conclusion

In this paper, a backward compatible multi-service transmission scheme over DTMB system is proposed based on embedded constellation and bit division multiplexing. With the proposed scheme, the simultaneous transmission of original services and multiple augmented services can be supported, in which the reception SNR-thresholds of augmented services are higher than those of original services.

Two potential schemes over the DTMB system named Scheme 1 and Scheme 2 are proposed towards different requirements considerations only two augmented services for simplicity. With Scheme 1, the transmission rate of original services is maintained while the performance of original services degrades for the embedded signal. With Scheme 2, the performance of original services is maintained while the transmission rate of original services decreases for the lower order of constellation employed for original services. In both schemes, the receivers under favorable reception conditions can demodulate the augmented services, and the increment in the total throughout of the DTMB system is over 7.6 Mbps. The AMI analysis and BER simulation of original services and augmented services with/without the proposed schemes are conducted and the results obtained can help give an insight into the mechanism of the proposed backward compatible multi-service transmission scheme. The design of reception algorithm and labeling of the expanded constellation are also discussed in this paper to optimize the performance of augmented services.

It should be noted that in principle the proposed backward compatible multi-service transmission scheme might also be employed in the other DTTB systems, in which high order of modulation can be supported, such as DVB-T2.

Appendix

With the technique of embedded constellation to support the simultaneous transmission of original services and augmented services, the transmitted symbol can be described as:

\[ x_i = \sqrt{P}x_0 + \sqrt{\alpha P}x_e \]  

where \( x_0 \in \chi_o \) and \( x_e \in \chi_e \).

At the receiver, the received symbol can be described as:

\[ y = \rho (\sqrt{P}x_0 + \sqrt{\alpha P}x_e) + N \]  

\[ = \rho \sqrt{P}x_0 + \rho \sqrt{\alpha P}x_e + N \]  

(18)

where \( \rho \) is the channel gain with \( E(\rho^2)=1 \) and \( N \sim CN(0,\sigma^2) \), \( \rho \equiv 1 \) under AWGN channel and \( \rho \sim CN(0,1) \) under Rayleigh channel.

For legacy receivers, the embedded constellation signal is considered as noise during the demapping process of received signal and

\[ y = \rho \sqrt{P}x_0 + N' \]  

(19)

where \( N' = \rho \sqrt{\alpha P}x_e + N \).

It should be noted that \( N' \) is not Gaussian distributed, which is the superposition of a variable with uniform distributed and a variable with Gaussian distributed. The achievable rate of original services for legacy receivers in the DTMB system with the proposed scheme is assumed to be:

\[ y = f(SNR) \]  

(20)

According to the equivalent transmission model in (19), we can obtain:

\[ y = f(SNR) = \psi_{x_0}(P, N') = \psi_{x_0}(P, \rho \sqrt{\alpha P}x_e + N) \]  

(21)

where \( \psi_{x_0} \) is the achievable rate of the original services when the input in chosen from \( x_0 \), \( P \) is the power of the transmitted symbol, and \( N' \) is the noise.

So the capacity of original services can be calculated by:

\[ C = f(SNR) = \sum_{i=0}^{m-1} \mathbf{I}(b_i; Y) \]  

(22)

where \( b_i \) denotes the \( i \)-th bit carried by each original constellation symbol, \( m \) is the number of the bits carried by the original constellation and \( \mathbf{I}(b_i; Y) \) is calculated by (23).

References

\[ I (b_i; Y) = H (b_i) - H (b_i|Y) = 1 - E_{b_i,Y} \left[ \log_2 \frac{1}{p(b_i|Y)} \right] \]
\[ = 1 - E_{b_i,Y} \left[ \log_2 \frac{\sum_{x'} \exp \left( -C_{o,i} \|x'\|^2 \right)}{\sum_{x''} \exp \left( -C_{o,i} \|x''\|^2 \right)} \right] \]
\[ = 1 - \frac{1}{2^{\|X\| \times |X_o|}} \sum_{x_o} \sum_{x_e} \sum_{b} E_{N} \left[ \log_2 \frac{\sum_{x'} \exp \left( -C_{o,i} \|x'\|^2 \right)}{\sum_{x''} \exp \left( -C_{o,i} \|x''\|^2 \right)} \right] \]