A Study on LDM-BST-OFDM Transmission for the Next-Generation Terrestrial Broadcasting

Hiroto Yamamoto, *Member, IEEE*, Akira Nakamura, *Member, IEEE*, and Makoto Itami, *Member, IEEE*

***Abstract*—In this paper, the scheme that combines LDM (Layered Division Multiplexing) with the FDM (Frequency Division Multiplexing) scheme based on BST-OFDM (Band Segmented Transmission - Orthogonal Frequency Division Multiplexing) is proposed for the next-generation DTTB (Digital Terrestrial Television Broadcasting). The proposed LDM-BST-OFDM scheme provides a more effective frequency utilization of the stream for fixed reception. The performance of the proposed scheme is evaluated by computer simulations where the effectiveness of proposed scheme for fixed reception is shown. Although LDM-BST-OFDM improves the performance, dedicated receivers that can demodulate symbols multiplexed by LDM are required. In this paper, LDM-BST-OFDM using punctured LDPC code is proposed, which can decode the stream for fixed reception even if symbols multiplexed by LDM are not demodulated. The reception characteristics of the proposed scheme are evaluated by computer simulations.**

***Index Terms*—BST-OFDM, FDM, LDM, UHDTV, LDM-BST-OFDM, punctured LDPC codes.**

I. Introduction

RECENTLY, next-generation DTTB (Digital Terrestrial Television Broadcasting) for UHDTV (Ultra-High Definition Television) is being researched and developed in the world [1], [2]. The most advanced terrestrial broadcasting systems such as DVB-T2 (Digital Video Broadcasting - Terrestrial 2) and ATSC3.0 (Advanced Television Systems Committee 3.0) support 4K [3], [4]. In Japan, 8K commercial satellite broadcasting service started in December 2018 [5]. In addition, the 8K terrestrial broadcasting system is being researched and developed.

In the next-generation DTTB for UHDTV, the scheme that inherits and extends the current BST-OFDM (Band Segmented Transmission - Orthogonal Frequency Division Multiplexing) in ISDB-T (Integrated Service Digital Television Broadcasting-Terrestrial) is proposed [6]. BST-OFDM is considered as one of the good candidates that realize advanced and flexible broadcasting service for mobile and fixed receptions. However, it is not always possible to achieve the optimal band utilization using the BST-OFDM scheme with fixed size segments. As in the case of the current ISDB-T one segment service, the required CNR (Carrier to Noise Ratio) has to be sufficiently larger than the full segment service around the fringe of the service area of full segment service for HDTV reception. As the result, the area that the one segment service can be received is usually very wider than that of the full segment service. Although the margins for mobile reception, indoor reception and so on are added against one segment service design, excessive signal power is sometimes assigned to the one segment service. Therefore, channel allocation based on the unit segment cannot always achieve optimal frequency band utilization due to the single segment size. In the preliminary specification of the next-generation DTTB for UHDTV, a narrower segment as compared to ISDB-T is used by increasing the number of segments and more efficient and flexible frequency utilization is realized [7], [8]. However, limitation due to the fixed size segment still exists.

In ATSC3.0, the non-orthogonal multiplexing scheme which is called LDM (Layered Division Multiplexing) has been adopted [4], [9]. The non-orthogonal scheme is widely known as NOMA (Non-Orthogonal Multiple Access) in the cellular multiple access schemes [10], [11]. LDM increases the transmission capacity and improves the power efficiency of mobile reception. In this paper, LDM-BST-OFDM that combines LDM to the BST-OFDM is proposed [12], [13]. In the proposed scheme, transmitted symbols for mobile and fixed reception are LDM multiplexed in the segments for partial reception band. By combining the LDM scheme with the preliminary DTTB scheme for UHDTV, a better spectral efficiency can be achieved, leading to an improved UHDTV transmission. The basic performance of the proposed scheme is first evaluated by computer simulations, where the effectiveness of the proposed scheme for UHDTV fixed reception is shown.

LDM-BST-OFDM scheme is effective to improve transmission characteristics. However, dedicated receivers that can demodulate symbols multiplexed by LDM are required. Thus LDM-BST-OFDM using punctured LDPC code is proposed in this paper [14]. The proposed transmission scheme can decode the stream for fixed reception even if symbols multiplexed by LDM are not demodulated. At first, the coded transmitted symbols for the fixed reception after LDPC coding are generated. After that, the generated symbols are punctured. In addition, the removed symbols by puncturing are multiplexed by LDM in the segments for mobile reception. By using the punctured LDPC code, it is possible to decode symbols even with receivers that do not support LDM. On the other hand, in

Manuscript received February 28, 2019; revised June 2, 2019; accepted June 23, 2019. Date of publication August 15, 2019; date of current version June 5, 2020. *(Corresponding author: Hiroto Yamamoto.)*

The authors are with the Department of Applied Electronics, Tokyo University of Science, Tokyo 125-8585, Japan (e-mail: tama@itamilab.te.noda.tus.ac.jp; nakamura@te.noda.tus.ac.jp; itami@te.noda.tus.ac.jp).

Color versions of one or more of the figures in this article are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TBC.2019.2932340

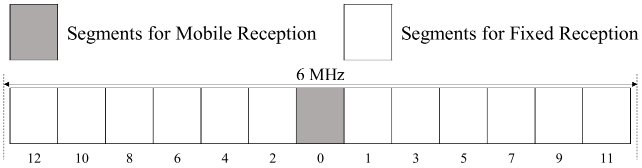

Fig. 1. Example of typical use of the segments in the Japanese current terrestrial broadcasting system.

the receiver for fixed reception that is capable of demodulating symbols multiplexed by LDM, the reception characteristics can be improved.

The proposed system that performs per symbol puncturing is easy to implement. However, there is a problem that burst error occurs. Therefore, we propose the transmission scheme that performs per bit puncturing. Since this scheme punctures bit data before symbol modulation, the modulation scheme can be flexibly selected. In this paper, the reception characteristics of the proposed scheme under the multipath environment are evaluated by computer simulations.

II. Preliminary Specification of the Next-Generation Terrestrial UHDTV Transmission Scheme

In the preliminary specification of the next-generation DTTB scheme for UHDTV is proposed in the papers [7], [8], the 6MHz transmission band is uniformly divided into 36 segments, and 35 segments or 33 segments among then are actually used for data transmission. The number of segments is increased as compared to current ISDB-T standard in order to realize more flexible frequency utilization and it is possible to transmit maximum 3 PLP (Physical Layer Pipe) streams by combining segments. In the preliminary specification, the central 9 segments can be used for partial reception and the stream for mobile reception is transmitted using the 1∼9 segments out of the central 9 segments. When the number of the segments used by the stream for mobile reception is smaller than 9, the remaining segments are used for transmission of other streams such as the part of the stream for UHDTV fixed reception. When the partial reception mode is used, the frequency interleave is independently applied to the central 9 segments and other segments and it is possible for the mobile receiver to receive the stream for mobile reception by only demodulating the central 9 segments. On the other hand, the UHDTV fixed receiver demodulates whole 35 or 33 segments. The detailed specifications for segment allocation and frequency interleaving are shown in the papers [7], [8].

The example of typical use of the segments in the Japanese current terrestrial broadcasting system is shown in Fig. 1. In Fig. 1, the central 1 segment is used for transmission of the stream for mobile reception and the remaining 12 segments are used for transmission of the stream for fixed reception. In contrast, the example of typical use of the segments in the preliminary specification is shown in Fig. 2. In Fig. 2, the central 9 segments are used for transmission of the stream

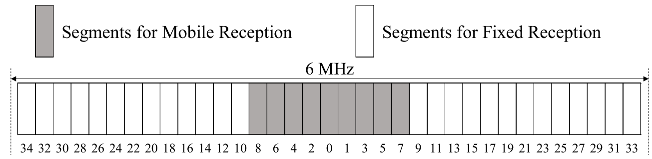

Fig. 2. Example of typical use of the segments in the preliminary specification of the next-generation terrestrial broadcasting system.

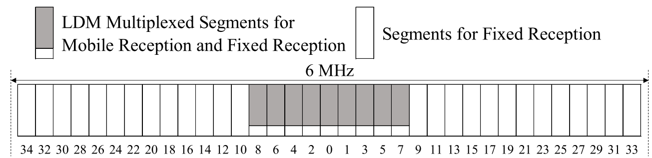

Fig. 3. Example of typical use of the segments in LDM-BST-OFDM.

for mobile reception and the remaining 26 segments are used for transmission of the stream for UHDTV fixed reception. The transmission of 2K stream is assumed in the central 9 segments for partial reception.

III. LDM-BST-OFDM Scheme

A. System Model

As described in the previous section, BST-OFDM scheme is not always possible to utilize the assigned frequency band shared by multiple streams optimally because it uses the fixed size segments depending on the applications. The aim of this paper is to increase frequency utilization and improve performances of UHDTV fixed reception by applying the LDM scheme to the central segments for partial reception. The structure of the segments of the proposed scheme is shown in Fig. 3. In the proposed scheme, based on the preliminary specification of the next-generation DTTB scheme for UHDTV described in the previous section, the part of the stream for UHDTV transmission is multiplexed to the segments that transmit the stream for mobile reception by using LDM. In the example shown in Fig. 3, data symbols of the stream for mobile reception and the stream for UHDTV fixed reception are multiplexed by LDM in the central 9 segments for partial reception and the data symbols of fixed reception are also transmitted in the remaining 26 segments. In this case, the data symbols of the stream for mobile reception are assigned to the LDM upper layer and the data symbols of stream for UHDTV fixed reception are assigned to LDM lower layer. As the result, total 35 segments are used to transmit the stream for UHDTV fixed reception and increase of transmission rate or improvement of required CNR is expected in the transmission of the stream for UHDTV fixed reception. In this case, the CNR in the receiver against the LDM multiplexed 9 segments of the stream for UHDTV fixed reception is usually much lower than that of the other 26 segments. In order to improve this problem, the data symbols in the stream for UHDTV fixed reception are interleaved over the whole 35 segments before allocating to the physical segments to achieve diversity effect so that error correction by the BICM (Bit-Interleaved Coded Modulation) decoder is effectively performed.

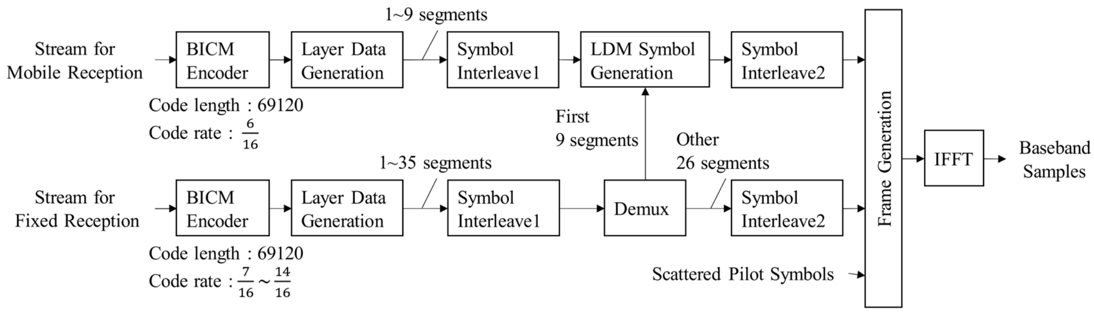

Fig. 4. The structure of the proposed transmitter in LDM-BST-OFDM scheme.

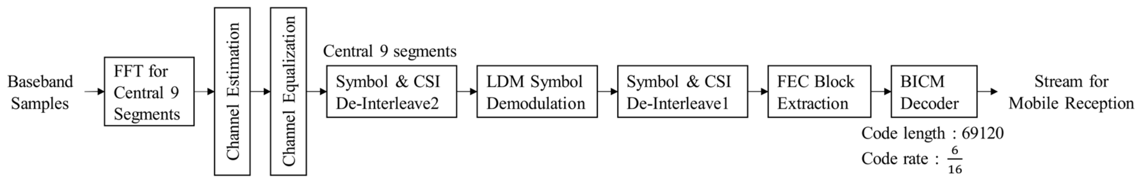

Fig. 5. The structure of the mobile receiver in LDM-BST-OFDM scheme.

The data symbols transmitted in the segments for partial reception, $d_{LDM}(n)$, that are modulated by LDM are shown as,

$$d_{LDM}(n) = \sqrt{1-\alpha}\, d_M(n) + \sqrt{\alpha}\, d_F(n), \tag{1}$$

where, n denotes the sub-carrier index. α denotes the average LDM power ratio that is the average power of the lower layer symbols in the LDM symbols. $d_M(n)$ and $d_F(n)$ denote transmitted symbols for mobile reception and fixed reception in n-th sub-carrier. These transmitted symbols are modulated by NU-QAM (Non-Uniform - Quadrature Amplitude Modulation) that is generated after BCH coding, LDPC coding and bit interleaving. In this paper, the average power of $d_{LDM}(n)$, $d_M(n)$ and $d_F(n)$ is assumed to be 1.0. The received symbols, $r_{LDM}(n)$, are shown as,

$$\begin{aligned} r_{LDM}(n) &= H(n) d_{LDM}(n) + z(n) \\ &= H(n)\{\sqrt{1-\alpha}\, d_M(n) + \sqrt{\alpha}\, d_F(n)\} + z(n) \\ &= H(n)\sqrt{1-\alpha}\, d_M(n) + H(n)\sqrt{\alpha}\, d_F(n) + z(n), \end{aligned} \tag{2}$$

where, $z(n)$ and $H(n)$ denote additive Gaussian noise and the transfer function of the n-th sub-carrier signal, respectively [15]. If the receiver can demodulate LDM symbols, transmitted symbols, $d_M(n)$, for the mobile reception can be demodulated by,

$$\begin{aligned} \frac{r_{LDM}(n)}{H(n)\sqrt{1-\alpha}} &= d_M(n) + \frac{\sqrt{\alpha}}{\sqrt{1-\alpha}} d_F(n) + \frac{z(n)}{H(n)\sqrt{1-\alpha}} \\ &\approx d_M(n) + \frac{\sqrt{\alpha}}{\sqrt{1-\alpha}} + \frac{z(n)}{H(n)\sqrt{1-\alpha}}. \end{aligned} \tag{3}$$

After the demodulation of symbols for mobile reception, transmitted bit data can be obtained by decoding of coded symbols. Obtained transmitted bit data is used for generation of replica symbols. Replica symbols, $d'_M(n)$, are generated by re-coding and re-modulating obtained bit data. In the demodulation of the symbols for fixed reception, demodulated symbols, $d_F(n)$, can be obtained by,

$$\frac{r_{LDM}(n)}{H(n)\sqrt{\alpha}} - \frac{\sqrt{1-\alpha}}{\sqrt{\alpha}} d'_M(n) = d_F(n) + \frac{z(n)}{H(n)\sqrt{\alpha}}. \tag{4}$$

After the demodulation of the symbols for fixed reception, demodulated symbols, $d_F(n)$, are decoded and transmitted bit data for fixed reception can be obtained.

In Fig. 4, the detailed structure of the proposed LDM combined BST-OFDM transmitter is shown. Before generating LDM symbols, the data symbols of the stream for mobile reception (LDM upper layer) are generated in the same manner as the preliminary specification of the Japanese next-generation DTTB scheme for UHDTV. In this paper, the BICM encoder is used to generate NU-QAM symbols. The generated data symbols in each stream are first interleaved over the corresponding number of segments ("Symbol Interleave1"). In the stream for fixed reception, the output after "Symbol Interleave1" is de-multiplexed to generate 9 segments of symbols that is transmitted in the central 9 segments and the symbols that are transmitted in the remaining 26 (or 24) segments. Then, LDM symbols are generated using 9 segments from stream for fixed reception after de-multiplexing and 1∼9 segments from stream for mobile reception. The symbols in the 1∼9 segments in the stream for mobile reception are combined with the symbols in the first 1∼9 segments from the stream for fixed reception using (1) to generated 1∼9 segments that consist of LDM symbols. After generating LDM symbols, the data symbols in the central 9 segments are interleaved again ("Symbol Interleave2"). After interleaving, central 9 segments and remaining segments are combined to generate the OFDM frame and mapped in the frequency domain using IFFT.

In Fig. 5, the structure of the mobile receiver that receives the stream for mobile reception is shown. This receiver is equivalent to the receiver in the conventional band segmented scheme without LDM. In this case, simple implementation is possible because the mobile receiver should only demodulate the central 9 segments without considering the

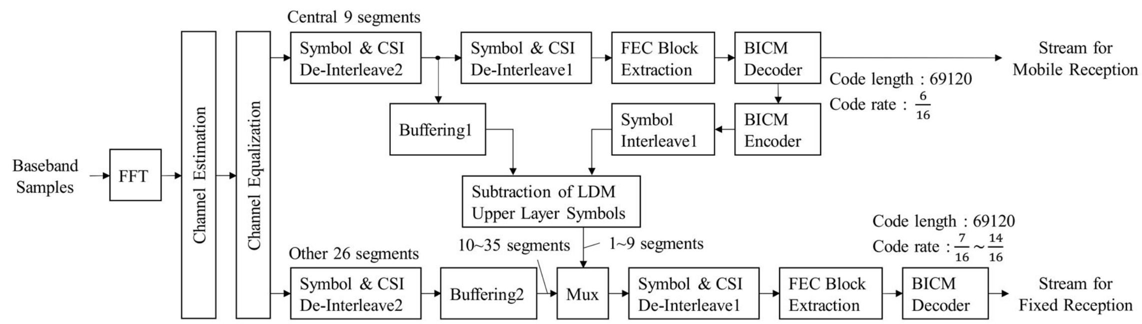

Fig. 6. The structure of the UHDTV fixed receiver in LDM-BST-OFDM scheme.

TABLE I
SIMULATION PARAMETERS

Number of Carriers per Segment		864
Scattered Pilot Pattern		12×2
Number of Data Carriers per Segment		792
Number of Segments		35
Number of Carriers		30241=864×35+1
LDM Power Ratio, α		0.05, 0.10
Modulation and Coding Parameters of the Stream for Mobile Reception	Number of Segments	9
	LDPC Code Length	69120
	LDPC Code Rate	6/16
	Number of Iterations	50
	Symbol Modulation Scheme	Non-Uniform 64QAM
Modulation and Coding Parameters of the Stream for Fixed Reception	Number of Segments	26, 35
	LDPC Code Length	69120
	LDPC Code Rate	7/16 $\sim$ 10/16
	Number of Iterations	50
	Symbol Modulation Scheme	Non-Uniform 4096QAM

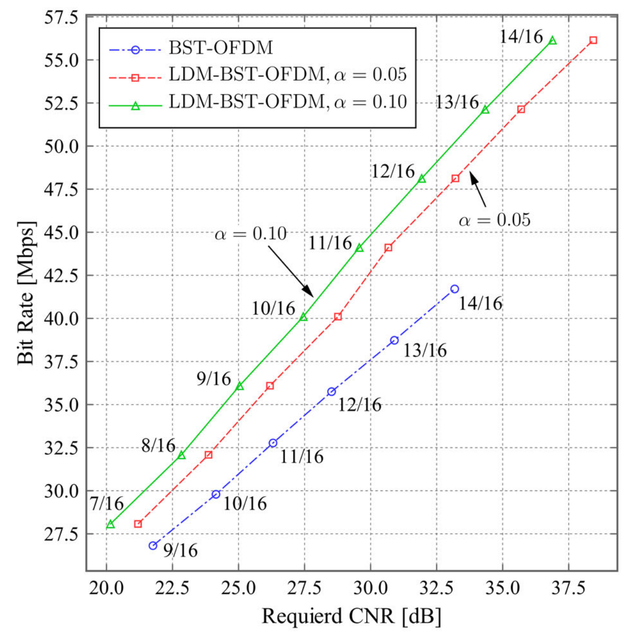

Fig. 7. Comparison of the achieved bit rates against the required CNR at 10^{-6} bit error rate in the stream for fixed reception.

multiplexed symbols from stream for fixed reception. In Fig. 6, the structure of the receiver for UHDTV fixed reception is shown. In this case, the stream for mobile reception is first decoded and the stream for fixed reception is decoded using the decoded data of the stream for mobile reception. Decoding of the stream for mobile reception is performed in the same manner as the mobile receiver case in Fig. 5 and BICM encoding is re-applied against the decoded data of the stream for mobile reception to generate the replica symbols of stream for mobile reception (LDM upper layer symbols). Until the replica symbols are generated, LDM symbols are buffered in "Buffering1". The generated replica symbols are subtracted from the received LDM symbols to generate the symbols of the stream for fixed reception (LDM lower layer symbols). The generated symbols are then multiplexed with the other non-LDM symbols which are buffered in "Buffering2" and de-interleaving is performed over whole segments wise. Finally, the BICM decoder is applied to the de-interleaved symbols to decode the data of stream for fixed reception.

B. Computer Simulations

In this paper, the performance of the proposed scheme under the AWGN channel is evaluated by computer simulations. In the simulations, the parameters shown in TABLE I are assumed. In this paper, it is assumed that the average powers of all data carriers are equivalent to 1.0 and the average powers of scattered pilot symbols are equivalent to 4/3. In this case, layouts of the scattered pilot symbols are equivalent in stream for mobile and fixed reception to perform precise channel estimation against LDM symbols. The maximum number of iterations in LDPC decoding in the receiver is assumed to be 50 in this paper.

Fig. 7 shows the comparison of the conventional BST-OFDM scheme in the preliminary specification of the Japanese next-generation DTTB scheme for UHDTV and the proposed LDM combined scheme using 35 segments. In Fig. 7, the achieved bit rate in the stream for UHDTV fixed reception against the required CNR at 10^{-6} BER (Bit Error Rate) is evaluated changing the coding rate of LDPC in BICM. In the conventional BST-OFDM scheme, the stream for mobile and fixed reception are transmitted using 9 segments and 26 segments without performing LDM. In the proposed LDM-BST-OFDM scheme, in addition to the 26 segments by FDM, the 9 segments are also LDM multiplexed for fixed reception and equivalently 35 segments are used to transmit the

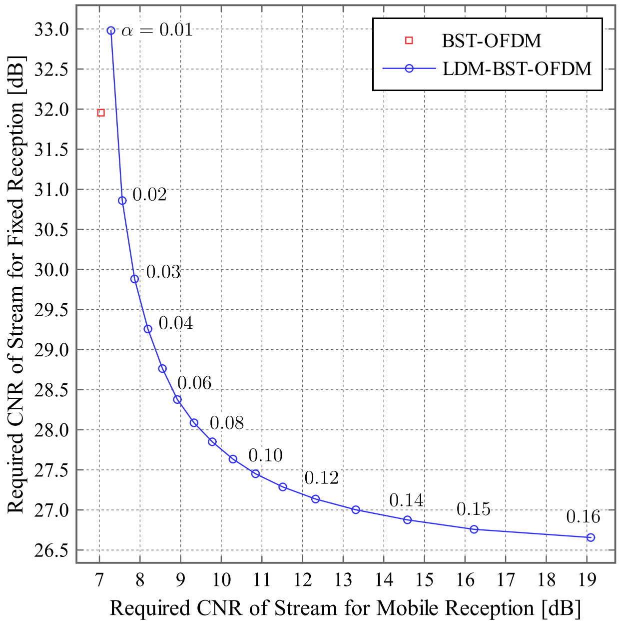

Fig. 8. Required CNR of stream for mobile and fixed reception if the LDM power ratio, α, is changed in the range of 0.02 to 0.16.

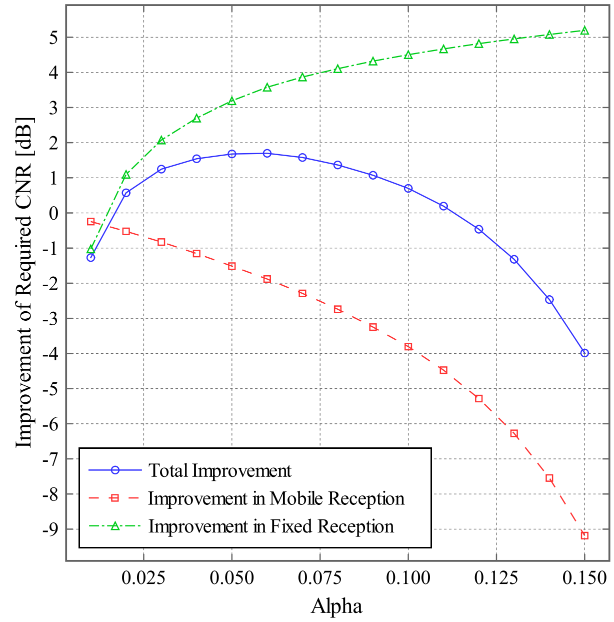

Fig. 9. Improvement of required CNR in mobile and fixed reception if the LDM power ratio, α, is changed.

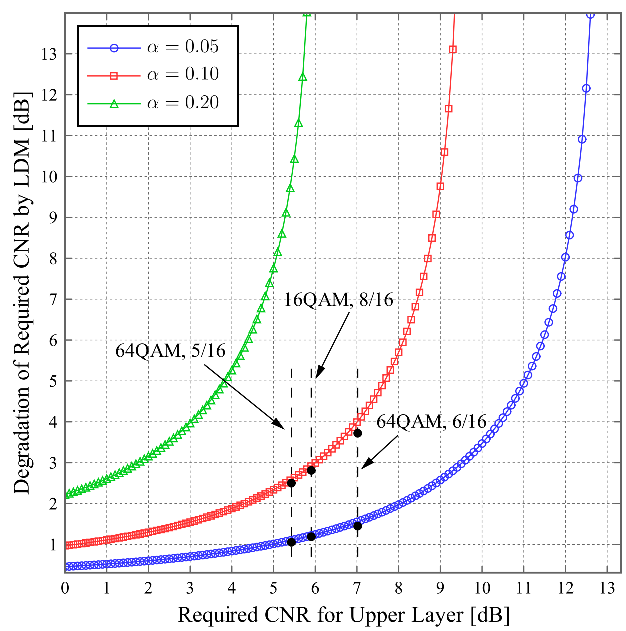

Fig. 10. Degradation of the required CNR of the stream for mobile reception by LDM-BST-OFDM against the required CNR in BST-OFDM.

stream for fixed reception as shown in TABLE I. As shown in the result in Fig. 7, the proposed LDM-BST-OFDM scheme can achieve better performance as compared to the conventional BST-OFDM scheme in $\alpha = 0.05$ and $\alpha = 0.10$ cases. Although, in the case of the simple BST-OFDM scheme, maximum bit rate limited to below 42.5Mbps even if the highest coding rate is used, the proposed LDM-BST-OFDM scheme can achieve maximum bit rate over 55Mbps. This is considered to very advantageous in case of 8K transmission that requires high quality. If the required CNR is limited to the maximum value of the BST-OFDM case, more than almost 6 and 9Mbps faster bit rate can be achieved in $\alpha = 0.05$ and $\alpha = 0.10$, respectively. Under the point of view of improving required CNR, it is possible to improve CNR by approximately 3dB for $\alpha = 0.05$ and 4.5dB for $\alpha = 0.10$.

Fig. 8 shows the required CNR if the LDM power ratio, α, is changed in the range of 0.02 to 0.16. In this simulation, the bit rates of stream for mobile and fixed reception are 3Mbps and 40Mbps, respectively. The higher the power ratio, α, is, the better the characteristics of stream for fixed reception is improved. Fig. 9 shows the improvement of required CNR in mobile and fixed reception as compared to the BST-OFDM scheme if the LDM power ratio, α, is changed. From Fig. 9, total improvement of required CNR (improvement in mobile reception + improvement in fixed reception) is maximum 1.7dB if $\alpha = 0.06$.

As mentioned in the above discussion, by performing LDM in the central 9 segments for partial reception, it is possible to improve performance of the stream for UHDTV fixed reception. However, the performance of the stream for mobile reception degrades by the addition of the symbols of the stream for fixed reception and degradation of the required CNR of the stream for mobile reception is evaluated. If it is assumed that the required CNR under the specific modulation and coding parameters is denoted by CNR_0[dB], the theoretical degradation of the required CNR assuming the influence of the LDM lower layer symbol as Gaussian noise, ΔCNR, is expressed by the following formula.

$$\Delta CNR = -10\log_{10}\left(1 - \alpha - \alpha 10^{\frac{CNR_0}{10}}\right)[\text{dB}] \qquad (5)$$

Fig. 10 shows the degradation of the required CNR by LDM-BST-OFDM against the required CNR in the BST-OFDM case for the several modulation and coding parameters. The solid curves denote the theoretical degradation of the required CNR changing the value of α. In this

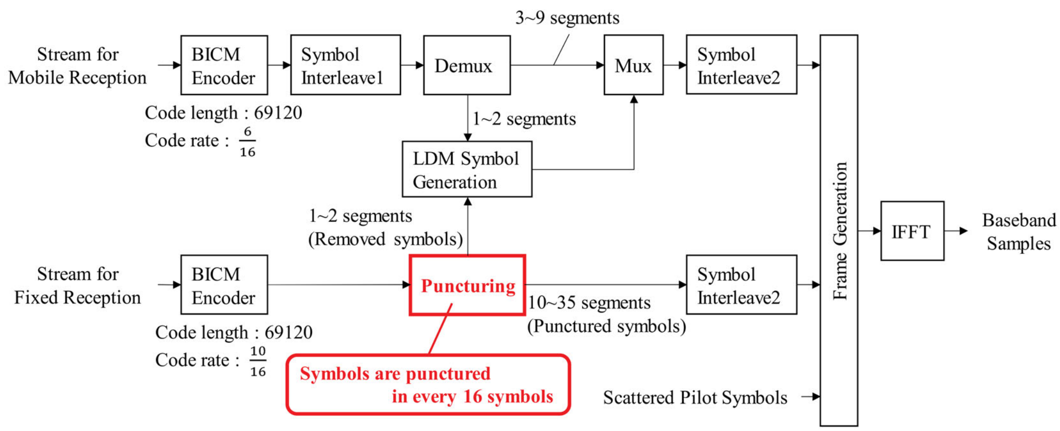

Fig. 11. The structure of the proposed transmitter in the symbol puncturing scheme.

figure, degradations of CNR of 64QAM-5/16, 16QAM-8/16 and 64QAM-6/16 cases obtained by simulations are plotted by the solid circle symbols. As shown in Fig. 10, in the case of $\alpha = 0.05$, the values obtained by simulations well agree to the theoretical values. In the case of $\alpha = 0.10$, degradations obtained by the simulations are larger than theoretical values. The reason of this degradation is considered that the influence of the LDM lower symbols is not modeled by Gaussian noise. As for the larger value of α, the degradation increases rapidly and it becomes impossible to perform LDM. In this case, for $\alpha = 0.20$, it is impossible to perform LDM against 16QAM-8/16 and 64QAM-6/16 cases. Therefore, if appropriate value of α is used, the degradation in the stream for mobile reception (LDM upper layer stream) is made small. In the case of 64QAM-6/16, degradation of the CNR in the stream for mobile reception and improvement of the CNR in stream for fixed reception are shown in TABLE II. As shown in TABLE II, by sacrificing 1.5dB of the CNR in the stream for mobile reception, the transmission rate of the stream for UHDTV fixed reception can be improved by maximum 3.0dB approximately. If 3.7dB of degradation in the stream for mobile reception is acceptable, maximum 4.5dB improvement of the required CNR is possible. As shown in these results, if slight degradation of the required CNR in the stream for mobile reception, the proposed LDM-BST-OFDM scheme is expected to be able to achieve more efficient transmission in the stream for UHDTV fixed reception.

TABLE II
REQUIRED CNR FOR THE STREAM FOR MOBILE RECEPTION AND THE IMPROVEMENT OF THE CNR IN THE STREAM FOR FIXED RECEPTION

		Required CNR in Mobile Reception (64QAM-6/16)	Improvement of the Required CNR in Fixed Reception
BST-OFDM		7.0dB	-
LDM-BST-OFDM	$\alpha = 0.05$	8.5dB (1.5dB degradation)	3.0dB
	$\alpha = 0.10$	10.7dB (3.7dB degradation)	4.5dB

IV. LDM-BST-OFDM SCHEME THAT PUNCTURES SYMBOLS AFTER BICM

A. System Model

Although LDM-BST-OFDM scheme improves performance as shown in Section III, dedicated receivers that can demodulate symbols multiplexed by LDM are required. Therefore, LDM-BST-OFDM using punctured LDPC code is proposed in this section. In the proposed scheme, fixed receivers can decode the stream for fixed reception even if symbols multiplexed by LDM are not demodulated.

Fig. 11 shows the block diagram of the transmitter in the proposed symbol puncturing scheme. In the proposed scheme, the transmitted symbols for the fixed reception are modulated by BICM and modulated symbols are punctured in every 16 symbols as shown in Fig. 12. Then, removed symbols by puncturing are multiplexed by LDM and transmitted in LDM lower layer of the partial reception band. On the other hand, symbols for the mobile reception are transmitted in LDM upper layer. Fig. 13 shows the block diagrams of the fixed receiver in the proposed symbol puncturing scheme. Symbols multiplexed by LDM are processed differently depending on the capability of the fixed receiver. The fixed receiver that does not support LDM demodulation cannot demodulate symbols for fixed reception in LDM lower layer. In the receiver, removed symbols by puncturing that are multiplexed by LDM are zeroed and used for demodulation. On the other hand, the receiver that supports LDM demodulation can demodulate removed symbols by puncturing in LDM lower layer. In the receiver, the symbols before puncturing are restored and decoded. Therefore, it is possible to improve reception characteristics of the stream for fixed reception.

If the coded symbols are punctured in every 16 symbols, the removed symbols by puncturing are multiplexed by LDM within only about 2 segments of the partial reception band. Thus, it is possible to increase LDM sub-carriers up to 9 segments by transmitting each removed symbols over multiple sub-carriers. In this paper, the number of LDM sub-carriers that transmit each removed symbols by puncturing is changed in the range of 1 to 4 as shown in Fig. 14. In Fig. 14, duplicates of removed symbols by puncturing are made (copy)

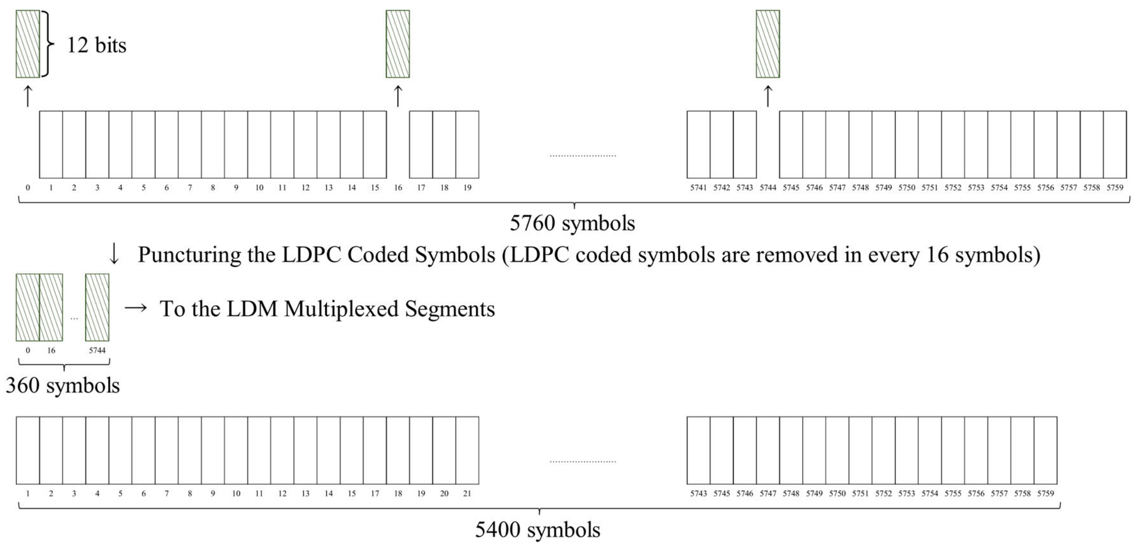

Fig. 12. Schematic diagram of symbol puncturing at transmitter in the symbol puncturing scheme.

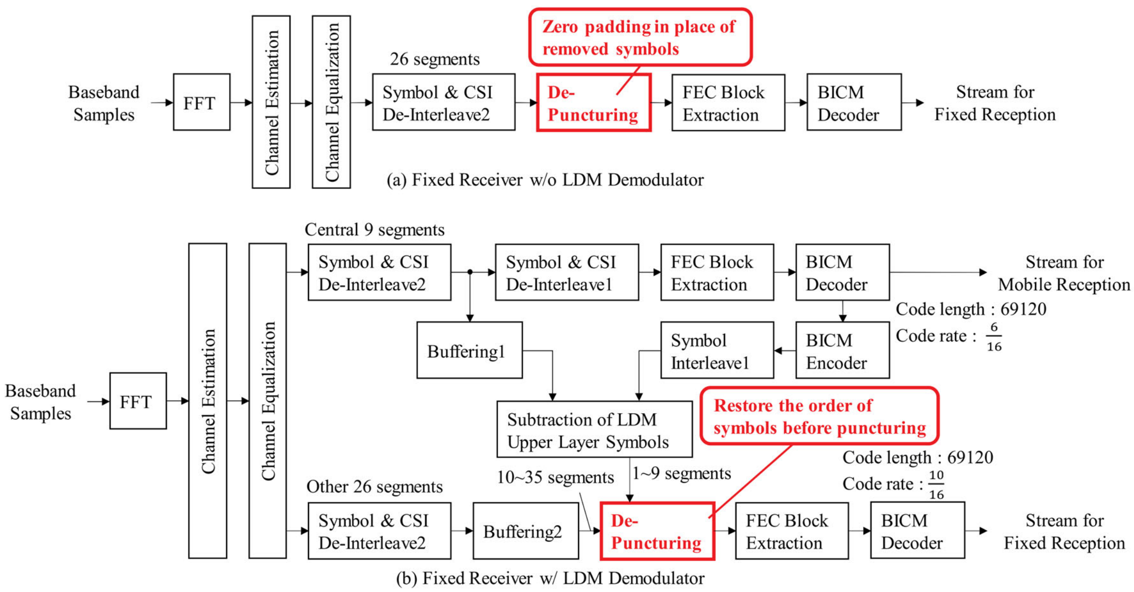

Fig. 13. The structure of the fixed receiver in the proposed symbol puncturing scheme.

and maximum 4 sets are transmitted using LDM lower layer. Transmitted lower LDM symbols are demodulated by MRC (Maximum Ratio Combining) to improve the reception characteristics of the stream for fixed reception. In MRC, the output, $r'_{LDM}(n)$, is obtained by multiplying appropriate weights, $w_i(n)$ as,

$$r'_{LDM}(n) = \sum_{i=0}^{I-1} w_i(n) \left\{ \frac{r_{LDM,i}(n)}{\sqrt{\alpha}} - \frac{\sqrt{1-\alpha} H_i(n) d'_{M,i}(n)}{\sqrt{\alpha}} \right\}, \quad (6)$$

where n and i denote the sub-carrier index and the number of the sets of LDM sub-carriers, respectively. Using this output, the reception characteristic can be improved.

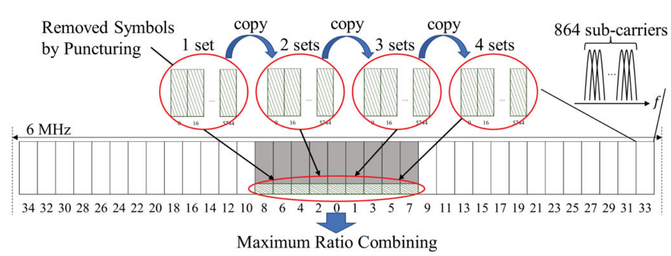

Fig. 14. MRC of the proposed symbol puncturing scheme.

B. Computer Simulations

In this section, the characteristics of the proposed symbol puncturing scheme under the multipath environment is evaluated by computer simulations. TABLE III shows simulation parameters that are used in this section. TABLE IV shows the multipath model which is shown in the paper [15]. In

TABLE III
SIMULATION PARAMETERS

Number of Carriers per Segment		864
Scattered Pilot Pattern		12×2
Number of Segments		35
Number of Carriers		30241=864×35+1
Carrier Interval, f_0		125/648 kHz
Carrier Frequency, f_c		557.142857 MHz
LDM Power Ratio, α		0.02∼0.20
Intervals of Retrieved Symbols		16
Modulation and Coding Parameters of the Stream for Mobile Reception	Number of Segments	9
	LDPC Code Length	69120
	LDPC Code Rate	6/16
	Number of Iterations	50
	Symbol Modulation Scheme	Non-Uniform 64QAM
Modulation and Coding Parameters of the Stream for Fixed Reception	Number of Segments	26
	LDPC Code Length	64800 69120
	LDPC Code Rate	10/15 10/16
	Number of Iterations	50
	Symbol Modulation Scheme	Non-Uniform 4096QAM

TABLE IV
PARAMETERS OF MULTIPATH MODEL

Path Index	DUR[dB]	Delay Time[μs]
1	0.00	0.000
2	13.45	0.235
3	14.24	9.981
4	18.67	8.871
5	18.83	0.458

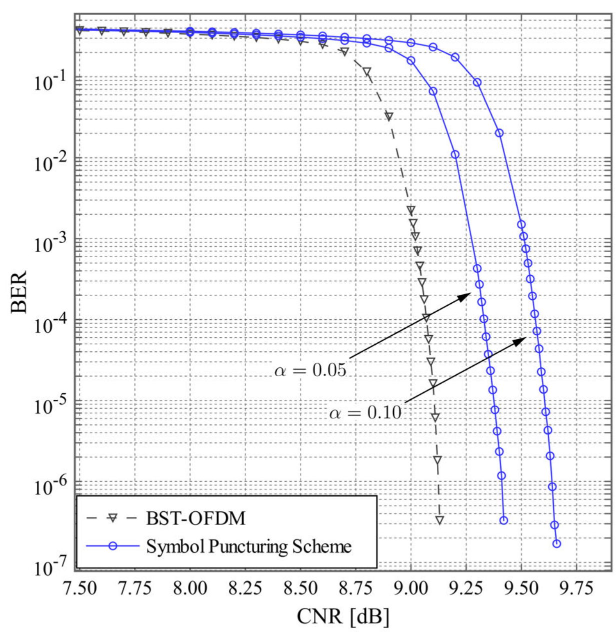

Fig. 15. BER characteristics of the stream for mobile reception in the symbol puncturing scheme under the multipath environment.

this simulation, BICM encoder and decoder based on LDPC code whose length and rate are 69120 and $\gamma/16$ respectively are used in the proposed puncturing scheme. Also, the conventional BST-OFDM scheme uses LDPC code whose length and rate are 64800 and $\gamma/15$, respectively. If the proposed scheme punctures LDPC coded symbols in every 16 symbols, symbol rate of the proposed puncturing scheme becomes the

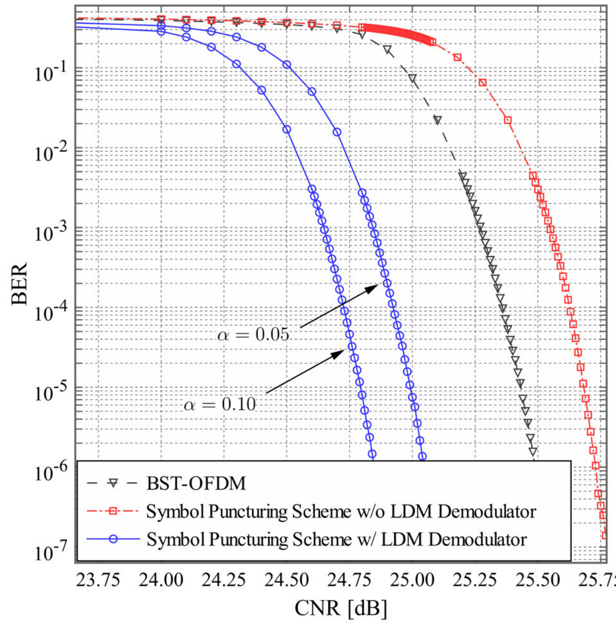

Fig. 16. BER characteristics of the stream for fixed reception in the symbol puncturing scheme under the multipath environment.

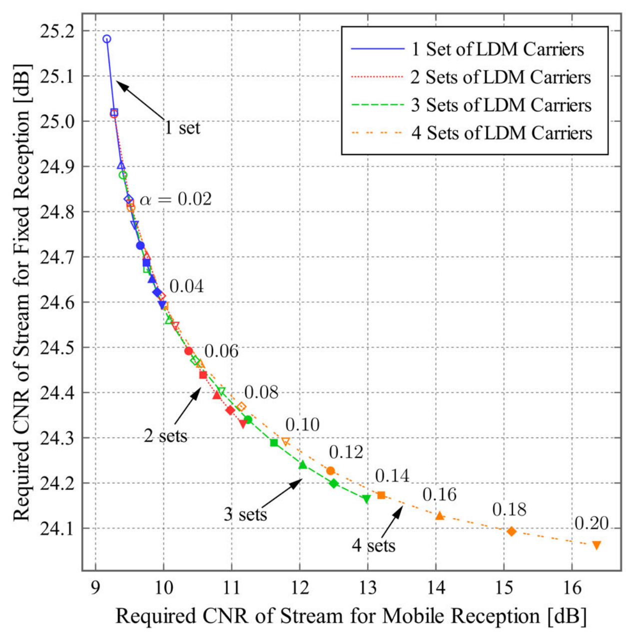

Fig. 17. Required CNR of stream for mobile and fixed Reception under the multipath environment.

same symbol rate of the conventional BST-OFDM scheme as,

$$69120 - \frac{69120}{16} = 64800. \quad (7)$$

Fig. 15 and Fig. 16 show BER characteristics of the stream for mobile and fixed reception under the multipath environment, respectively. In the legend of Fig. 15, "BST-OFDM" denotes the BER characteristics under the case of using the conventional BST-OFDM scheme to which LDM is not applied. "Symbol Puncturing Scheme" denotes the performances under the case of using proposed puncturing scheme that punctures symbols in the stream for fixed reception. In the

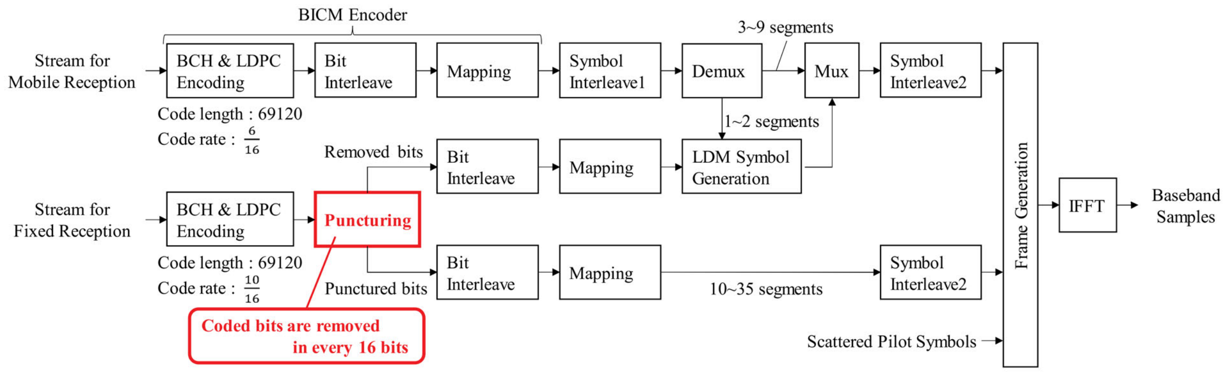

Fig. 18. The structure of the proposed transmitter in the bit puncturing scheme.

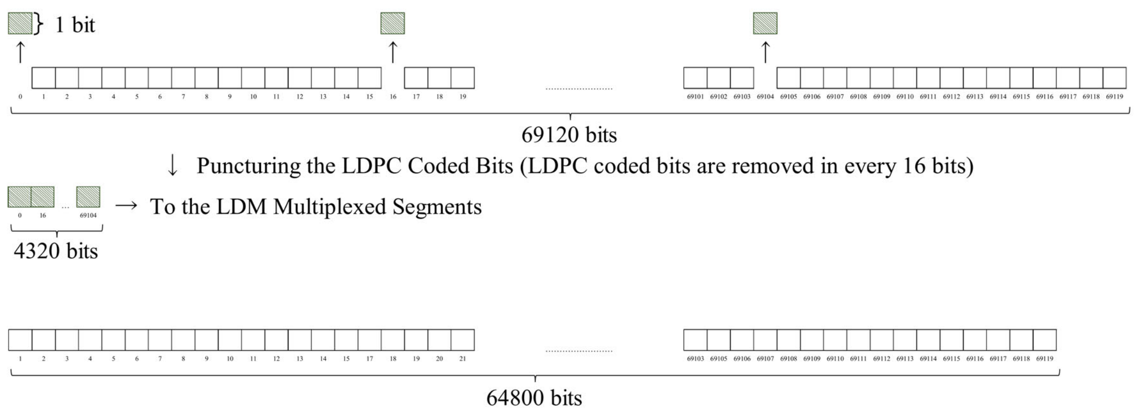

Fig. 19. Schematic diagram of bit puncturing at transmitter in the bit puncturing scheme.

legend of Fig. 16, "Symbol Puncturing Scheme with LDM Demodulator" denotes BER performances of the proposed symbol puncturing scheme using receivers that support LDM demodulation. "Symbol Puncturing Scheme without LDM Demodulator" shows BER characteristics of the scheme using receivers that do not support LDM demodulation as shown in Fig. 13. From Fig. 15, the required CNR of 0.2∼0.7dB at the mobile reception of the symbol puncturing scheme is deteriorated as compared to BST-OFDM scheme by the influence of symbols for fixed reception multiplexed by LDM. In this paper, the required CNR is defined as the CNR that BER first becomes lower than 10^{-6}. From the symbol puncturing scheme without LDM demodulator in Fig. 16, the required CNR of 0.25dB is deteriorated as compared to BST-OFDM scheme because removed symbols by puncturing are zeroed at the fixed receiver. On the other hand, the required CNR of 0.4∼0.7dB can be improved as compared to BST-OFDM scheme in the symbol puncturing scheme with LDM demodulator.

BER performances of the symbol puncturing scheme are shown in Fig. 15 and Fig. 16. However, these results show reception characteristics under the case that only about 2 segments of the partial reception band are used. Thus, it is possible to increase LDM sub-carriers up to 9 segments. Fig. 17 shows the required CNR of stream for mobile reception and fixed reception under the multipath environment if the number of LDM sub-carriers and LDM power ratio, α, are changed and MRC is adopted. In Fig. 17, "x Sets of LDM Carriers" denotes the BER characteristics under the case that x sets of LDM sub-carriers of the stream for fixed reception are multiplexed in other sub-carriers. The LDM power ratio, α, is changed in the range of 0.02 to 0.20. As shown in Fig. 17, the required CNR of maximum 1.1dB approximately at fixed reception can be improved by MRC. On the other hand, required CNR of mobile reception is deteriorated further. Therefore, this MRC method is used only in the case that greatly deterioration of required CNR of the stream for mobile reception is allowed. Under the case that the required CNR of the stream for mobile reception is determined, it is possible to select optimize LDM parameters such as average LDM power ratio and the number of LDM sub-carriers to improve the reception characteristics of the stream for fixed reception.

V. LDM-BST-OFDM Scheme That Punctures LDPC Coded Bits Before Symbol Modulation

A. System Model

The system that performs per symbol puncturing in Section IV is easy to be implemented from existing systems. However there is a problem that burst error occurs. Therefore, the system that performs per bit puncturing is proposed in this section. Fig. 18 shows the block diagram of the transmitter in the proposed bit puncturing scheme. In the proposed scheme, the LDPC coded bits for the fixed reception are punctured in every 16 bits as shown in Fig. 19. Then, the LDPC coded bits removed by puncturing are bit-interleaved

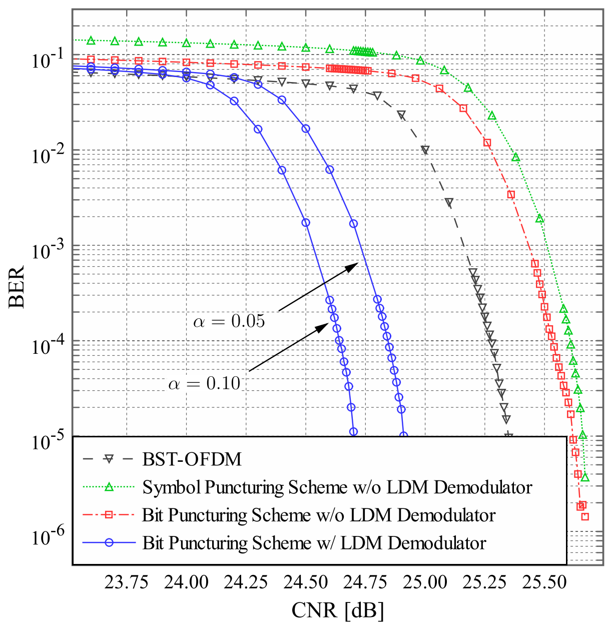

Fig. 20. BER characteristics of the stream for fixed reception in the bit and symbol puncturing schemes under the multipath environment.

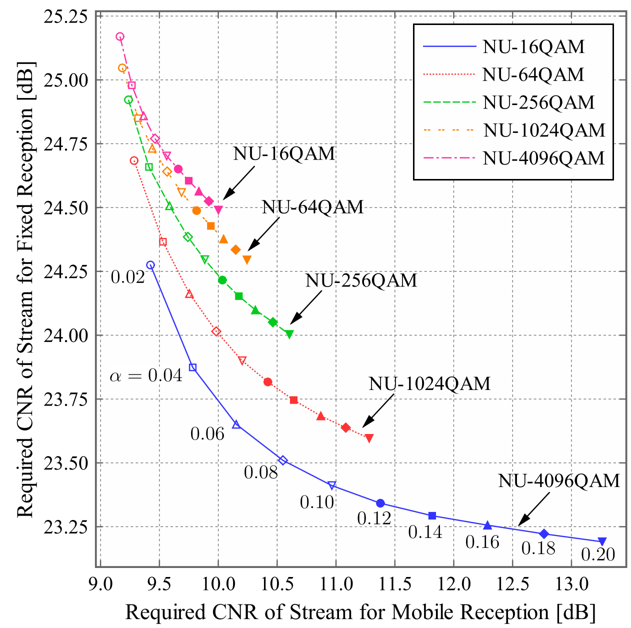

Fig. 21. Required CNR of stream for mobile and fixed Reception under the multipath environment.

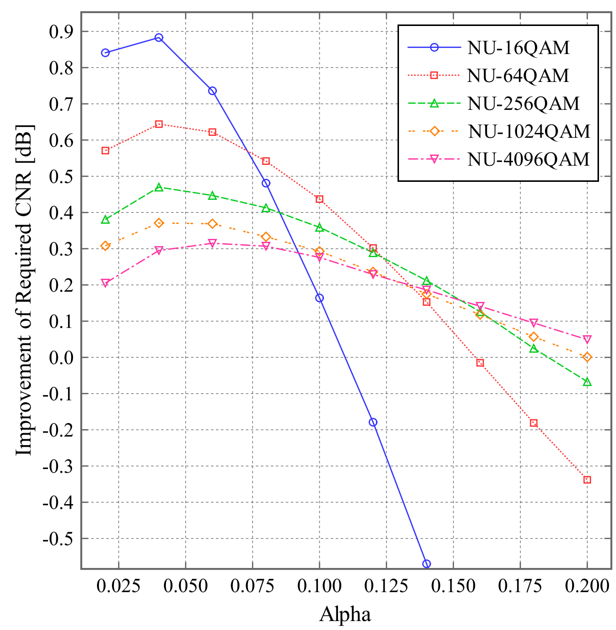

Fig. 22. Total improvement of required CNR in mobile and fixed reception.

and modulated. After that, the symbols are multiplexed to the transmitted symbols for mobile reception by LDM. Since this system punctures before modulation, the modulation scheme can be flexibly selected.

B. Computer Simulations

In this section, the characteristics of the proposed bit puncturing scheme under the multipath environment is evaluated by computer simulations. The simulation parameters and multipath model are same as those in TABLE III and TABLE IV, respectively. Fig. 20 shows BER characteristics of the stream for fixed reception under the multipath environment. "BST-OFDM" denotes the BER characteristics under the case of using the BST-OFDM scheme to which LDM is not applied. "Symbol Puncturing Scheme without LDM Demodulator" denotes the BER characteristics under the case of using the symbol puncturing scheme in Section IV and using receivers that do not support LDM demodulation. "Bit Puncturing Scheme" denotes the BER characteristics under the case of using the proposed bit puncturing scheme that performs per bit puncturing. As shown in Fig. 20, the required CNR of the bit puncturing scheme can achieve better performance as compared to the symbol puncturing scheme. Also, the required CNR can be improved by using LDM in the bit puncturing scheme with LDM demodulator.

Fig. 21 shows the required CNR of stream for mobile reception and fixed reception under the multipath environment if the symbol modulation scheme of the removed bit data by puncturing and LDM power ratio are changed. As shown in Fig. 21, the required CNR under fixed reception can be improved approximately by maximum 2.0dB at fixed reception can be improved by changing symbol modulation scheme. Under the case that the required CNR of the stream for mobile reception is determined, it is possible to select optimal LDM parameters such as average LDM power ratio and the sub-carrier modulation scheme to improve the reception characteristics of the stream for fixed reception.

Fig. 22 shows the total improvement of required CNR (improvement in mobile reception + improvement in fixed reception) as compared to the BST-OFDM scheme if the LDM power ratio, α, and symbol modulation scheme for removed bits by puncturing are changed. From Fig. 22, total improvement of required CNR is maximum 0.9dB if $\alpha = 0.04$ and NU-16QAM is employed.

VI. Conclusion

In this paper, the LDM-BST-OFDM scheme is proposed. As the results of computer simulations, it is possible to improve reception characteristics of the fixed reception by the proposed scheme. Furthermore, we proposed LDM-BST-OFDM using punctured LDPC code that can decode the stream for fixed reception even if symbols multiplexed by LDM are not demodulated. As the results of computer simulations, it is possible to improve reception characteristics of the fixed reception by the proposed scheme. In the further study, we will investigate optimization of parameters such as puncture patterns.

Acknowledgment

The part of this research is being performed under the auspices of the Ministry of Internal Affairs and Communications, Japan as part of its program titled "Research and Development for Advanced Digital Terrestrial TV Broadcasting System".

References

[1] A. Sato, T. Shitomi, T. Takeuchi, M. Okano, and K. Tsuchida, "Transmission performance evaluation of LDPC coded OFDM over actual propagation channels in urban area. Examination for next-generation ISDB-T," in *Proc. IEEE Int. Symp. Broadband Multimedia Syst. Broadcast.*, Jun. 2017, pp. 1–5.

[2] S. Ik Park, G. Lee, H. M. Kim, N. Hur, S. Kwon, and J. Kim, "ADT-based UHDTV transmission for the existing ATSC terrestrial DTV broadcasting," *IEEE Trans. Broadcast.*, vol. 61, no. 1, pp. 105–110, Mar. 2015.

[3] *Digital Video Broadcasting (DVB); Frame Structure Channel Coding and Modulation for a Second Generation Digital Terrestrial Television Broadcasting System (DVB-T2), V1.4.1*, ETSI Standard EN 302 755, Jul. 2015.

[4] *ATSC Standard: Physical Layer Protocol (A/322)*, document A/322, Adv. Television Syst. Committee, Washington, DC, USA, 2016.

[5] *Ministry of Internal Affairs and Communications (MIC): Follow-Up Meeting on 4K and 8K Roadmap (6th Meeting), Handouts (in Japanese)*. Accessed: Nov. 1, 2018. [Online]. Available: http://www.soumu.go.jp/main_sosiki/kenkyu/4k8kroadmap/02ryutsu11_03000046.html

[6] S. Saito *et al.*, "8K terrestrial transmission field tests using dual-polarized MIMO and higher-order modulation OFDM," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 306–315, Mar. 2016.

[7] M. Nakamura *et al.*, "A study on the transmission system of an advanced ISDB-T," in *Proc. IEEE Int. Symp. Broadband Multimedia Syst. Broadcast.*, Jun. 2019, pp. 1–5.

[8] N. Shirai *et al.*, "Laboratory experiments and large-scale field trials for evaluating the advanced ISDB-T," in *Proc. IEEE Int. Symp. Broadband Multimedia Syst. Broadcast.*, Jun. 2019, pp. 1–5.

[9] C. Regueiro *et al.*, "LDM core services performance in ATSC3.0," *IEEE Trans. Broadcast.*, vol. 62, no. 1, pp. 244–252, Mar. 2016.

[10] K. Higuchi and A. Benjebbour, "Non-orthogonal multiple access (NOMA) with successive interference cancellation for future radio access," *IEICE Trans. Commun.*, vol. E98-B, no. 3, pp. 403–414, Mar. 2015.

[11] P. A. Hoeher and T. Wo, "Superposition modulation: Myths and facts," *IEEE Commun. Mag.*, vol. 49, no. 12, pp. 110–116, Dec. 2011.

[12] T. Fuse, H. Otsubo, A. Nakamura, and M. Itami, "A study on LDM partial reception for next generation band segmented digital terrestrial TV broadcasting," in *Proc. IEEE Int. Symp. Broadband Multimedia Syst. Broadcast.*, Jun. 2017, pp. 1–6.

[13] G. H. M. G. de Oliveira, C. Akamine, and Y. P. Maciel, "Implementation of ISDB-T LDM broadcast system using LDPC codes," in *Proc. IEEE Int. Symp. Broadband Multimedia Syst. Broadcast.*, Jun. 2016, pp. 1–4.

[14] H. Yamamoto, A. Nakamura, and M. Itami, "A study on LDM-BST-OFDM using punctured LDPC code in partial reception band," in *Proc. IEEE Int. Symp. Broadband Multimedia Syst. Broadcast.*, Jun. 2018, pp. 1–5.

[15] A. Nakamura, S. Nabatame, T. Kuge, K. Ohno, and M. Itami, "Estimation of delay profile for measurement of direction of propagation in digital terrestrial television broadcasting," in *Proc. IEEE Int. Conf. Commun. Syst.*, Nov. 2010, pp. 611–615.

Hiroto Yamamoto (M'18) received the B.E. degree in electronics engineering from the Tokyo University of Science, Japan, in 2018. His current research interests include wireless communication and broadcasting using OFDM modulation.

Akira Nakamura (M'09) received the B.E., M.E., and Ph.D. degrees in electronics engineering from the Tokyo University of Science, Japan, in 2009, 2011, and 2013, respectively, where he is an Assistant Professor with the Department of Applied Electronics. His current research interests include wireless communication and broadcasting using OFDM modulation. He is a member of ITE and IEICE.

Makoto Itami (M'84) received the B.Eng., M.Eng., and Dr.Eng. degrees from the University of Tokyo in 1984, 1986, and 1989, respectively. In 1989, he joined the Department of Applied Electronics, Tokyo University of Science, Japan, where he has been a Professor since 2008. His research interests are in the fields of communication systems and digital signal processing. He is a member of ITE and IEICE.