A Higher Data-Rate T-DMB System Based on a Hierarchical A-DPSK Modulation

Dae-Ken Kwon, Wan-Jin Kim, Ki-Hwan Suh, Hyoungsoo Lim, and Hyoung-Nam Kim, *Member, IEEE*

***Abstract*—Hierarchical modulation can be effectively used to enhance terrestrial digital multimedia broadcasting (T-DMB) or digital audio broadcasting (DAB) systems in response to both the demand for higher data-rate and the need to be backward compatible with legacy receivers. QAM-type modulations are well-liked for hierarchical transmission but require coherent detection based on pilot symbol aided channel estimation. In the T-DMB or the DAB system using DQPSK modulation, however, any available pilot symbols except for the phase reference symbol do not exist. Differential amplitude phase shift keying (DAPSK) modulation is easily applied to the T-DMB system for a hierarchical modulation but may be susceptible to fast fading. As a good candidate for a hierarchical modulation of T-DMB to solve the above problems, we propose an amplitude differential phase shift keying (A-DPSK) modulation which is robust to fast fading by estimating only amplitude coefficients of the channel transfer function with the use of amplitude pilots. To raise the accuracy of channel estimation, we arrange the amplitude pilots in a come-type and introduce a noise-reduction scheme of averaging estimated channel coefficients. Simulation results show that the proposed A-DPSK provides a good choice for achieving a higher data-rate over other possible modulation schemes for advanced T-DMB or DAB systems.**

***Index Terms*—A-DPSK, DAB, DAPSK, DMB, hierarchical modulation.**

I. Introduction

TERRESTRIAL digital multimedia broadcasting (T-DMB) service was launched in Korea to provide an effective solution for mobile broadcasting [1]. The T-DMB system is based on the European digital audio broadcasting (DAB) system known as Eureka-147 [2]. This system adopts coded orthogonal frequency division multiplexing (COFDM) and differential quadrature phase shift keying (DQPSK). As well as audio services in DAB, T-DMB has provided video services very similar to terrestrial DTV contents with enhanced bit error immunity supported by additional Reed-Solomon coding and convolutional interleaving of MPEG-4 encoded video data [3].

The video service in T-DMB provides a maximum picture resolution of 352×288 and thus may be appropriate for a 5–7 inch LCD display [1]. This resolution is acceptable in the current services for handheld or small vehicle-equipped receivers. However, the T-DMB service is expected to be extended to public transportation, such as buses, trains, and excursion ships, which are mostly equipped with large-size displays. The data rate of the current T-DMB system is insufficient for an appropriate quality of video service on such large-size displays. To solve this problem, we have recently explored increasing the data rate of T-DMB.

A typical way of increasing data rate is to increase the number of constellation points. We note that the backward compatibility should be secured though the transmission scheme is modified when achieving these higher data-rates. Hierarchical modulation can be effectively used for satisfying both the two demands of the increase of data rate and the assurance of backward compatibility with legacy receivers. One of the typical hierarchical modulation methods is hierarchical QAM modulation [4]. This method should be coherently detected for meaningful data acquisition and thus it requires channel estimation with the help of pilot symbols [5]–[7]. Since the original T-DMB system does not include any available pilot symbols except for the phase reference symbol [2], the QAM modulation may not be appropriate for the modulation scheme of a higher data-rate T-DMB system. Another considered scheme is differential amplitude phase shift keying (DAPSK) [8]–[11], which does not require any pilot symbols, channel estimation, or equalization. This property makes it possible to reduce computational complexity in the receiver. However, DAPSK may be limited in its use to only that of slow fading channels where the channel coefficients are relatively constant over at least two consecutive symbol intervals because the differential detection of DAPSK does not consider channel variation between two symbols.

As a good alternative to overcome the problems of the QAM-type and the DAPSK modulations, we propose a hierarchical modulation scheme of amplitude differential phase shift keying (A-DPSK), where additional data are modulated by amplitude shift keying on the existing DQPSK-modulated T-DMB data. A-DPSK is robust to fast fading by estimating only amplitude coefficients of the channel transfer function with the use of amplitude pilots which can be inserted in some parts of the additional data. Since it is important to accurately estimate a channel to enhance the detection performance of additional data, we use a come-type arranging method of the amplitude pilots and introduce a noise-reduction scheme of averaging estimated channel coefficients.

This paper is organized as follows. In Section II, we introduce hierarchical modulation schemes to enhance the data rate of the T-DMB system and we discuss the effects of the hierarchical modulations. A design of an advanced T-DMB (AT-DMB)

Manuscript received October 23, 2007; revised November 09, 2008. Current version published February 25, 2009.

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Digital Object Identifier 10.1109/TBC.2008.2010374

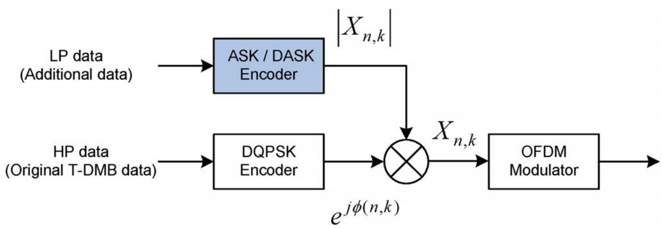

Fig. 1. Hierarchical modulation for an advanced T-DMB system.

system is presented in Section III. Simulation results presented in Section IV show that the performance of A-DPSK is superior to DAPSK for the transmission scheme of AT-DMB. Finally in Section V, we conclude the paper.

II. Hierarchical Modulation for the T-DMB System

Hierarchical modulation consists of a basic constellation used in the original T-DMB system and a secondary constellation carrying additional data for higher data rates. QAM-type modulation is one of the possible hierarchical modulation methods but may suffer from difficulty in implementing coherent detection requiring both phase and amplitude information of a channel. This information cannot be precisely estimated only with the phase-reference symbol of the existing T-DMB system without a highly complex channel estimation method such as the coded decision-directed (CDD) method [12], [13]. The CDD estimation method may be useful for coherent detection of QAM-type hierarchical modulated data but this method requires high computational complexity, resulting in an increase of the price of T-DMB receivers. Considering the smooth spread of advanced T-DMB receivers, we focus on the development of hierarchical modulation methods requiring a simple detection method with the assurance of mobility. For this reason, we deal with hierarchical modulations based only on the amplitude information for additional data. This information can be simply demodulated because it does not need phase information.

Fig. 1 shows a block diagram of the hierarchical modulation, where amplitude-modulated additional data are combined with conventional DQPSK-modulated T-DMB data. The complex modulated symbol $X_{n,k}$ is given by

$$X_{n,k} = |X_{n,k}| \cdot e^{j\phi(n,k)} \tag{1}$$

where the subscript n denotes a time index, k is a frequency index of each subcarrier, $\phi(n,k)$ are the phases of DQPSK modulated T-DMB symbols, and $|X_{n,k}|$ is the amplitude-modulated symbol from additional data. Amplitude modulation varies with the type of the selected hierarchical modulation method. We use the term high priority (HP) data for the original T-DMB data. Additional data for a higher data-rate T-DMB system are named as low priority (LP) data. For convenience, we define the following terminology:

T-DMB system	The existing T-DMB system
T-DMB receiver	A T-DMB receiver that is only capable of receiving DQPSK modulation
AT-DMB system	A higher data-rate T-DMB system with hierarchical modulation
AT-DMB receiver	A new receiver that is designed to operate in the hierarchical mode and is capable of receiving both HP and LP data

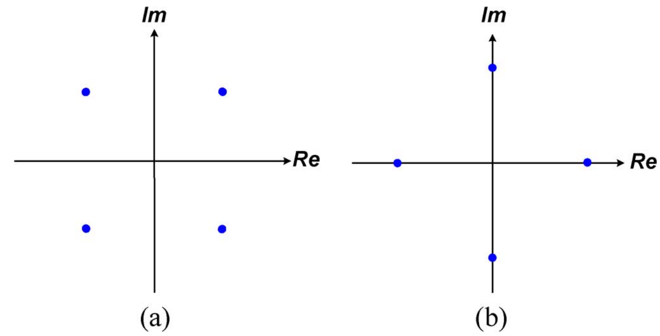

Fig. 2. $\pi/4$–DQPSK constellations: (a) odd-th order symbol; (b) even-th order symbol.

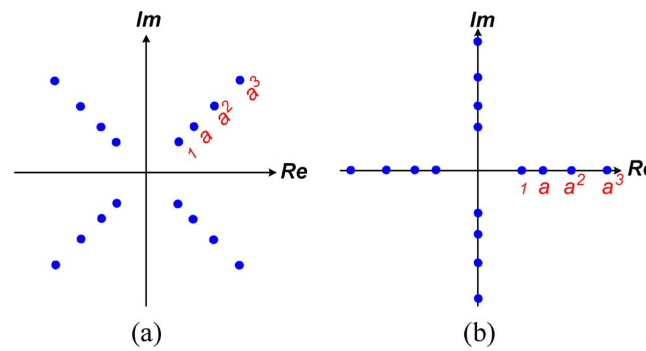

Fig. 3. DAPSK hierarchical: (a) odd-th order symbol; (b) even-th order symbol.

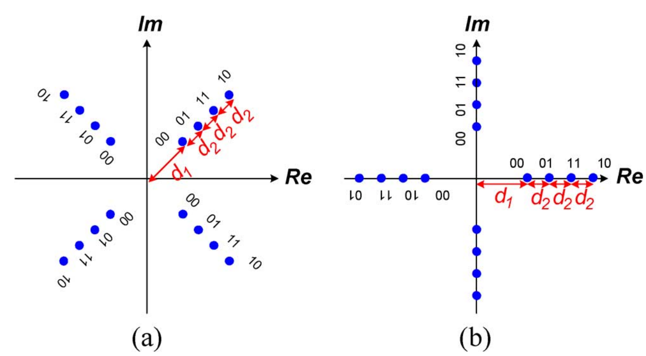

Fig. 4. ADPSK hierarchical constellations: (a) odd-th order symbol; (b) even-th order symbol.

Fig. 2 shows DQPSK constellations adopted in the T-DMB system. Figs. 3 and 4 show DAPSK and A-DQPSK hierarchical constellations where HP data are modulated by DQPSK and LP data are amplitude-modulated. In DAPSK, the transmitted amplitude $|X_{n,k}|$ of the constellation diagram in Fig. 3 is determined by the previous amplitude state with the LP bits indicated in Table I. Note that, in Figs. 2 and 3, the constellations are not normalized. For real transmission, however, the hierarchically

TABLE I
DIFFERENTIAL AMPLITUDE MODULATION FOR DAPSK [8]

Previous amplitude state	LP bits (b_0^L, b_1^L)			
	00	01	11	10
1	**1**	**a**	$\mathbf{a^2}$	$\mathbf{a^3}$
a	**a**	$\mathbf{a^2}$	$\mathbf{a^3}$	1
a^2	$\mathbf{a^2}$	$\mathbf{a^3}$	**1**	**a**
a^3	a^3	**1**	**a**	$\mathbf{a^2}$

modulated symbols using DAPSK and A-DPSK are normalized respectively by

$$NF_{DAPSK} = \frac{1}{\sqrt{\left(1^2 + (a)^2 + (a^2)^2 + (a^3)^2\right)/4}} \quad (2)$$

and

$$NF_{ADPSK} = \frac{1}{\sqrt{(d_1^2 + (d_1+d_2)^2 + (d_1+2d_2)^2 + (d_1+3d_2)^2)/4}}. \quad (3)$$

The amplitude factor "a" is an important parameter to characterize the performance of LP symbol detection and the backward compatibility of the system. It is possible to select the direction of differential encoding in time or frequency according to the channel characteristics and the design parameters of the OFDM systems. In a T-DMB environment, the maximum Doppler spread is about 37 Hz when the velocity of a moving receiver is 200 km/h and the carrier frequency is 200 MHz. The reciprocal coherence time to the maximum Doppler spread is about 27 ms. When a channel has a multipath spread of 5 μs, the coherence bandwidth becomes 200 kHz. Since the duration of one OFDM symbol is 1.246 ms and the subcarrier interval is 1 kHz for the transmission mode I of T-DMB system, the frequency-direction coherence is greater than the time-direction coherence in considering COST207 TU6 channel characteristics given in [14]. Therefore, in this case, it is desirable to perform differential modulation in the frequency direction.

In A-DPSK, the transmitted amplitude $|X_{n,k}|$ is gray mapped as shown in Fig. 4. The hierarchical modulation parameter "λ" in A-DPSK is defined by

$$\lambda = \frac{d_1}{d_2} \quad (4)$$

where d_1 is the minimum distance between the origin and the LP symbol and d_2 is the minimum distance between two adjacent LP symbols. The parameter "λ" affects the backward compatibility and the bit error rate (BER) of the LP symbols in the AT-DMB system.

The AT-DMB system may assure backward compatibility in the sense that legacy T-DMB receivers do not have any problem in demodulating received data except for a small increase in the threshold of visibility (TOV). Addition of LP symbols shifts HP symbols, some of which have shorter Euclidean distances than those of the original T-DMB symbols as shown in Figs. 3 and 4. The shortened distances seem to be amplitude noise in legacy receivers. Though amplitude noise does not affect DQPSK demodulation of HP symbols, its effect may be appeared in the

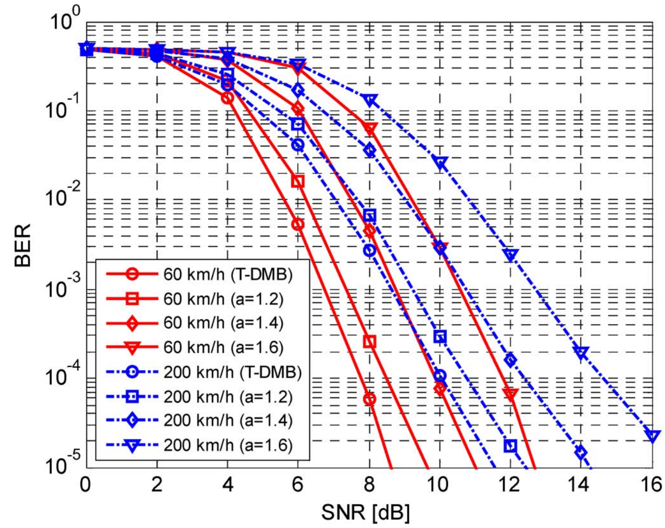

Fig. 5. The performance degradation of a T-DMB system with DAPSK varying with the vehicle speed at the Viterbi decoder output.

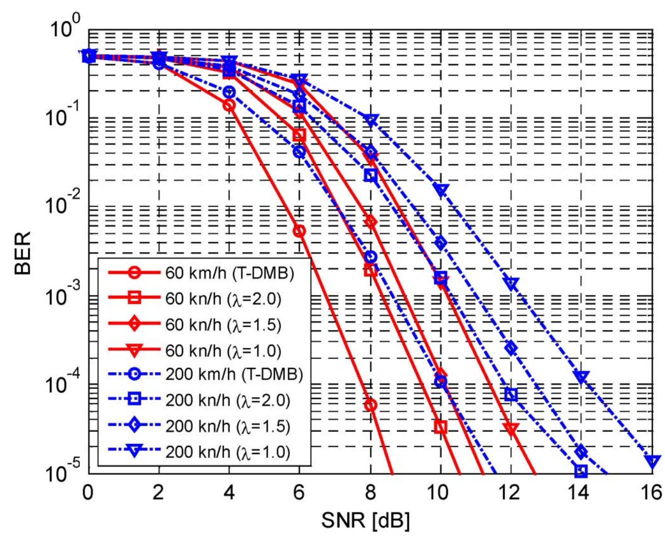

Fig. 6. The performance degradation of a T-DMB system with A-DPSK varying with the vehicle speed at the Viterbi decoder output.

soft-decision Viterbi decoder. For soft-decision decoding, log-likelihood ratio (LLR) or channel state information (CSI), which are related to amplitudes of symbols, is commonly used as inputs of the decoder to maximize its performance. The LP insertion, however, causes the distortion of amplitude information, resulting in the performance degradation of the decoder. The degradation grows serious as the amplitude factor "a" increases or the hierarchical modulation parameter "λ" decreases. Therefore, the added secondary-constellation in the AT-DMB system raises the TOV in legacy receivers.

To fairly compare two hierarchical methods, the effect on legacy receivers should be firstly analyzed because the amount of the performance degradation of legacy receivers is a crucial factor to which we choose a new modulation method for the AT-DMB system. In this respect, we firstly tried to find the amplitude factor "a" in DAPSK and the hierarchical modulation parameter of "λ" in A-DPSK causing the same degradation in

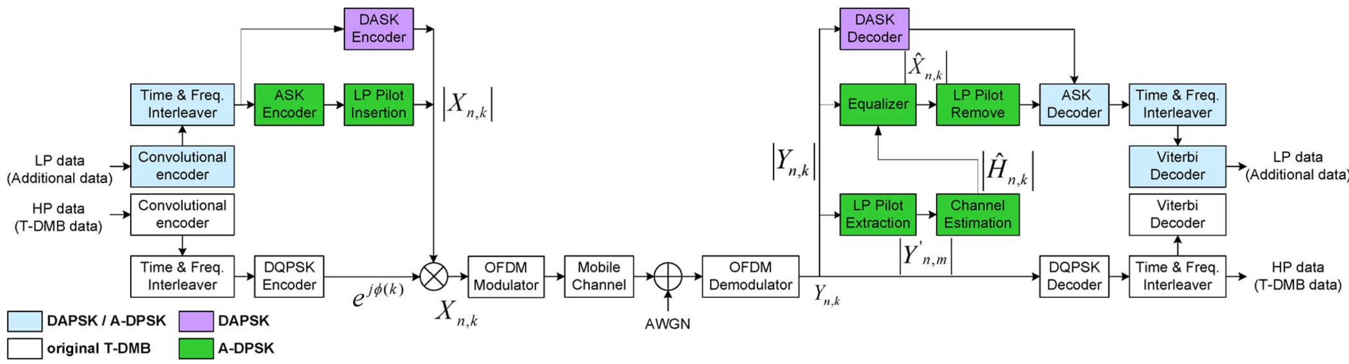

Fig. 7. The AT-DMB System with the hierarchical DAPSK/A-DPSK modulation.

TABLE II
THE PERFORMANCE DEGRADATION IN TERMS OF THE REQUIRED SNRS SATISFYING THE BER OF 10^{-4} IN LEGACY T-DMB RECEIVERS

[dB]

	DAPSK			A-DPSK		
	$a = 1.2$	$a = 1.4$	$a = 1.6$	$\lambda = 2.0$	$\lambda = 1.5$	$\lambda = 1.0$
60 km/h	0.7	2.13	4	1.7	2.37	3.6
200 km/h	0.76	2.4	4.6	1.82	2.65	4.2

legacy receivers. To obtain these parameters, we performed simulations with the AT-DMB system presented in Fig. 7. In COST 207 TU6 channel [14], we used the vehicle speed of 60 and 200 km/h and checked the performance of HP after the soft-decision Viterbi decoder under various "λ" and "a" values.

In legacy T-DMB receivers, the BER level should go down to 10^{-8} for stable transmission and reception of moving picture data [1]. This has been achieved by the addition of the Reed-Solomon coding and convolutional interleaving when the BER level at the Viterbi decoder output is less than 10^{-4} [3]. Figs. 5 and 6 show that the performance degradation in terms of the required signal-to-noise ratios (SNRs) satisfying a BER of 10^{-4} in legacy receivers for various values of "a" and "λ." Here, the SNR is defined at the output of a channel, that is, the ratio of the signal power including channel gain and the power of added noise to the signal. The results are summarized in Table II. We found that DAPSK with "$a = 1.4$" and A-DPSK with "$\lambda = 1.5$" show similar degradation in legacy receivers. To fairly compare the performance of the hierarchical modulations, we compare the performance of LP symbol detection with the above two cases.

III. THE DESIGN OF AN AT-DMB SYSTEM

An AT-DMB system based on hierarchical modulations of DAPSK and A-DPSK is shown in Fig. 7. At the transmitter, HP and LP data are convolutionally encoded and interleaved in time and frequency directions, respectively. Then both sets of data are hierarchically modulated according to each mapping rule for DAPSK and A-DPSK. That is, the hierarchically- modulated symbol $X_{n,k}$ in each subcarrier is made up of the HP bits (b_0^H, b_1^H) and the LP bits (b_0^L, b_1^L) which are separately convolutionally encoded and interleaved.

Suppose that the guard interval is longer than the length of channel impulse response, there is no inter-symbol interference between two consecutive OFDM symbols. Then, letting $H_{n,k}$ be the channel coefficient corresponding to the kth subcarrier, the received symbol $Y_{n,k}$ is given by

$$Y_{n,k} = H_{n,k}X_{n,k} + I_{n,k} + N_{n,k} \tag{5}$$

where $N_{n,k}$ is additive white Gaussian noise (AWGN) and $I_{n,k}$ is the intercarrier interference (ICI) for the kth subcarrier of the nth OFDM symbol after FFT [6].

At the receiver, the received symbol $Y_{n,k}$ is itself used for HP demodulation while only the magnitude of $Y_{n,k}$ is needed for LP demodulation. For the use of a channel decoder such as a Viterbi decoder, soft-decision outputs are generally preferred. This means that the output of a demodulator should be produced as a soft output, not a hard-decision output. However, the soft-decision output values of the demodulator vary with types of modulation [10]. The demodulation of HP symbols is the same as that used in legacy T-DMB receivers. It is performed by the differential detection of the DQPSK demodulation where the optimal soft output corresponding to the log-likelihood ratio (LLR) for the use of the input of the soft Viterbi decoder, is determined by [15]

$$\begin{aligned} LLR\left(b_0^H\right) &= \mathrm{Re}\left\{Y_{n,k} \cdot Y_{n,k-1}^*\right\}, \\ LLR\left(b_1^H\right) &= \mathrm{Im}\left\{Y_{n,k} \cdot Y_{n,k-1}^*\right\} \end{aligned} \tag{6}$$

where superscript $*$ denotes complex conjugate. Note that the performance of the Viterbi decoder is improved by the soft output of the DQPSK demodulator considering the amplitude information of the two consecutive DQPSK symbols as well as the phase information as given in (6). The use of the amplitude information does not affect symbol error rates at the demodulator.

Demodulation of the LP symbols is differently performed depending on each hierarchical modulation method:

A. LP Demodulation for Hierarchical DAPSK Modulation

In DAPSK modulation, the information is carried by differential amplitude of two consecutive symbols as shown in Table I. The previous symbol, thus, should be remembered to demodulate the present symbol like other differential demodulation

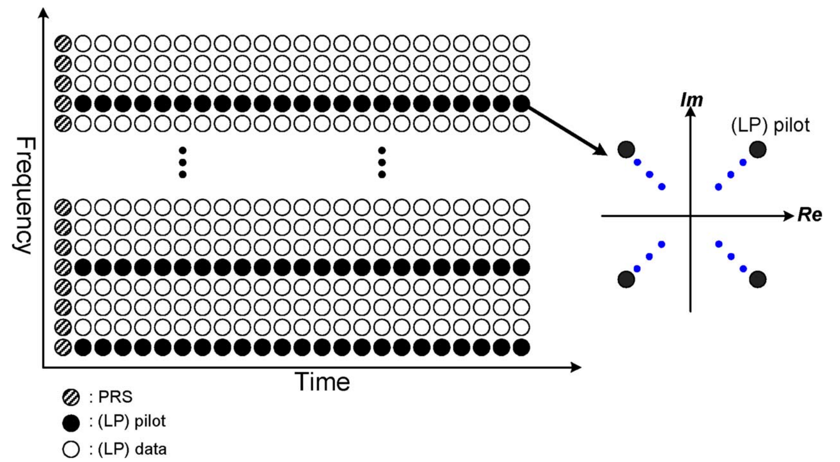

Fig. 8. A comb-type LP pilot arrangement for the hierarchical A-DPSK modulation.

schemes. The DAPSK decoder first produces the output by dividing the amplitude of the present symbol by that of the previous symbol as follows:

$$R_{n,k} = \frac{|Y_{n,k}|}{|Y_{n,k-1}|}. \tag{7}$$

If a given channel does not rapidly change between two adjacent subcarriers, the decoded result $R_{n,k}$ may not be affected by the channel coefficient $H_{n,k}$. In this case, equalization is not needed in DASK decoding. This means that there is no need to perform channel estimation and thus pilot symbols are not required. This simple decoding method for DASK results in the reduction of computational complexity and the increase of data payload.

For soft-decision output, the decoded result in (6) may not be optimal. By considering the reliability of two adjacent subcarriers, it is possible to perform soft-decision decoding for the differentially encoded amplitude, which was introduced in [9] with the use of the parameter $U_{n,k}$ and the random variable $V_{n,k}$ defined by

$$U_{n,k} = \ln\left|\frac{X_{n,k}}{X_{n,k-1}}\right|, \quad V_{n,k} = \ln\left|\frac{Y_{n,k}}{Y_{n,k-1}}\right|. \tag{8}$$

For application's simplicity, we convert the symbol metric obtained in [9] into a soft-decision bit metric for DASK by applying the LLR approximation functions presented in [16], which are given by

$$\begin{aligned} LLR\left(b_0^L\right) &= YI_{n,k}^2 \cdot D_{n,k,0}, \\ LLR\left(b_1^L\right) &= YI_{n,k}^2 \cdot D_{n,k,1} \end{aligned} \tag{9}$$

where

$$YI_{n,k}^2 = \frac{1}{\frac{1}{|Y_{n,k}|^2} + \frac{1}{|Y_{n,k-1}|^2}} \tag{10}$$

and

$$D_{n,k,0} = \begin{cases} V_{n,k} - 1.5\ln a & (V_{n,k} \geq 0) \\ -V_{n,k} - 0.5\ln a & (-1.5\ln a \leq V_{n,k} < 0) \\ V_{n,k} + 2.5\ln a & (V_{n,k} \leq -1.5\ln a) \end{cases}$$

$$D_{n,k,1} = \begin{cases} -V_{n,k} + 2.5\ln a & (V_{n,k} > 1.5\ln a) \\ V_{n,k} - 0.5\ln a & (0 < V_{n,k} \leq 1.5\ln a) \\ -V_{n,k} - 1.5\ln a & (V_{n,k} < 0). \end{cases} \tag{11}$$

Note that $D_{n,k}$ describes the reliability of the bits according to the position of the received symbols in the constellation diagram and $YI_{n,k}^2$ is information about the reliability of the subcarriers (reliability information) [9].

B. LP Demodulation for Hierarchical A-DPSK Modulation

While there is no method to insert pilot symbols on the unknown HP data symbols in the QAM-type hierarchical modulations for a T-DMB system, the amplitude information can be used for known amplitude pilot symbols in the proposed A-DPSK modulation. These known amplitude symbols are denoted LP pilots which make it possible to equalize the amplitude of the received symbols by precisely estimating the channel amplitude response.

To cope with time-varying channels, LP pilots are inserted in the form of a comb-type pilot arrangement as shown in Fig. 8. This is similar to that used in pilot-symbol-assisted modulation [6], [7]. For a comb-type pilot arrangement, N_p pilot symbols $|X'_{n,m}|$, $m = 0, 1, \ldots, N_{p-1}$ are uniformly inserted into the amplitude -modulated symbols $|X_{n,k}|$. That is, the total $N = 1536$ subcarriers are divided into N_p groups each of which has $L = N/N_p$ subcarriers. The value of L corresponds to the pilot overhead in the LP data. The OFDM signal modulated on the kth subcarrier can be expressed as

$$|X_{n,k}| = |X_{n,mL+l}| = \begin{cases} |X'_{n,m}|, & l = 0 \\ \text{LP data}, & l = 1, 2, \ldots, L-1 \end{cases}. \tag{12}$$

Fig. 9 shows a block diagram of channel estimation and equalization for LP signal detection in hierarchical A-DPSK modulation. Since the transmitted LP pilot $|X'_{n,m}|$ is known to the receiver, the channel amplitude response corresponding to pilot subcarriers can be estimated by

$$\left|\tilde{H}'_{n,m}\right| = \left|\frac{Y'_{n,m}}{X'_{n,m}}\right| = \left|H'_{n,m} + \frac{I'_{n,m} + V'_{n,m}}{X'_{n,m}}\right| \tag{13}$$

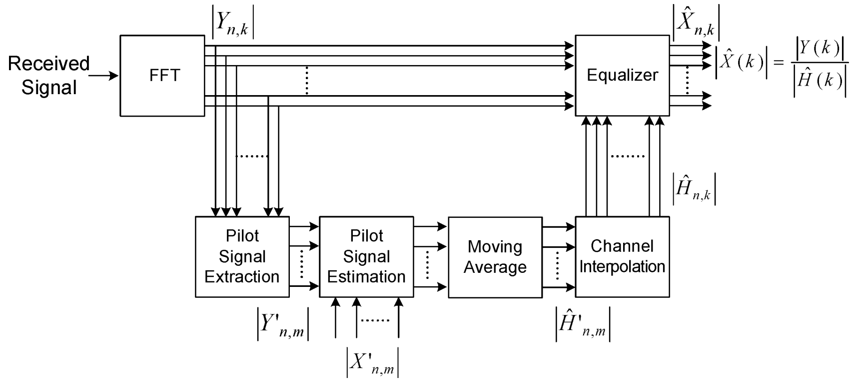

Fig. 9. Channel estimation and equalization for LP signal detection in hierarchical A-DPSK modulation.

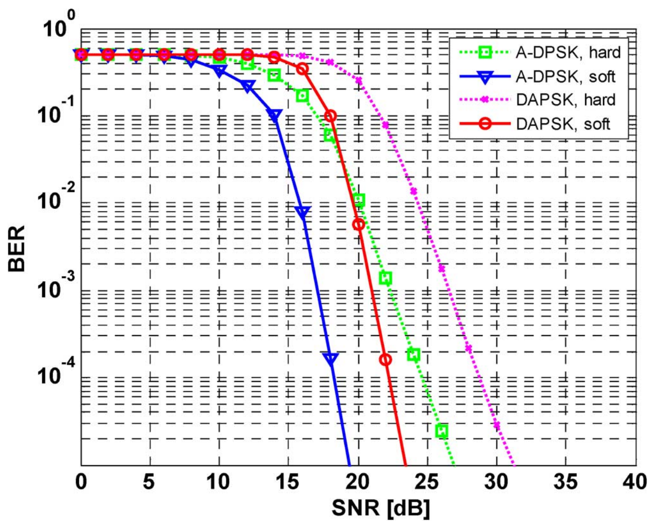

Fig. 10. The LP signal performance of A-DPSK ($\lambda = 1.5$) and DAPSK ($a = 1.4$) with a vehicle speed of 60 km/h.

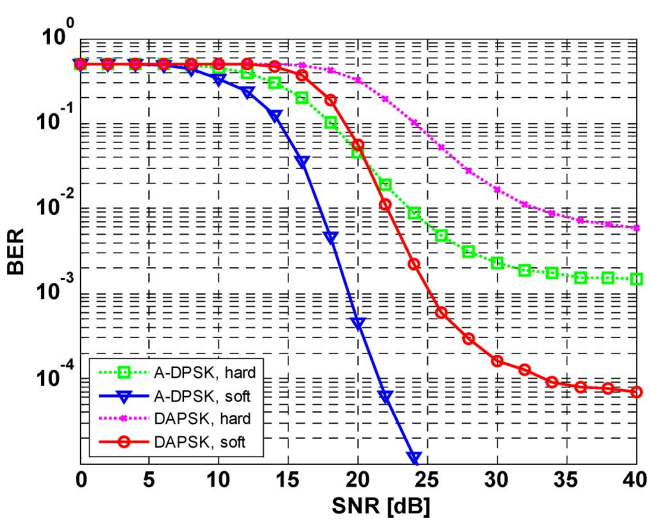

Fig. 11. The LP signal performance of A-DPSK ($\lambda = 1.5$) and DAPSK ($a = 1.4$) with a vehicle speed of 200 km/h.

where the received pilot signals $|Y'_{n,m}|$ are extracted from $|Y_{n,k}|$.

Since amplitude information is relatively sensitive to noise compared to phase information, we require a noise reduction method to increase the accuracy of the estimated channel coefficients. Moving average methods in the time and frequency directions are used:

$$\left|\breve{H}'_{n,m}\right| = \frac{\sum_{s=\max(0,n-2)}^{\min(75,n+2)} \left|\tilde{H}'_{s,m}\right| \cdot W_5(s)}{\sum_{s=\max(0,n-2)}^{\min(75,n+2)} W_5(s)} \tag{14}$$

and

$$\left|\hat{H}'_{n,m}\right| = \frac{\sum_{p=\max(0,m-3)}^{\min(1535,m+3)} \left|\breve{H}'_{n,p}\right| \cdot W_7(p)}{\sum_{p=\max(0,m-3)}^{\min(1535,m+3)} W_7(p)} \tag{15}$$

where $|\breve{H}'_{n,m}|$ and $|\hat{H}'_{n,m}|$ are the moving-averaged channel coefficients in the time and frequency directions, respectively. The windowing function of $W_M(\cdot)$ is the M-length Hamming window given by [17]

$$W_M(n) = \begin{cases} 0.54 - 0.46\cos(2\pi n/M), & 0 \le n < M \\ 0, & \text{otherwise.} \end{cases} \tag{16}$$

The length of the averaging window may vary with channel condition, such as the level of multipath fading, the velocity of the receivers and the received signal-to-noise ratio, etc. Through extensive simulations, we have found secure values of "5" and "7" for the window sizes in the time and frequency directions, respectively.

At the non-pilot subcarrier positions, channel coefficients can be estimated through linear interpolation using the coefficients of consecutive pilot subcarriers obtained in (15). They are produced by

$$|\hat{H}_{n,k}| = |\hat{H}_{n,mL+l}| = \left|\hat{H}'_{n,m}\right| + \frac{l}{L}\left(\left|\hat{H}'_{n,(m+1)}\right| - \left|\hat{H}'_{n,m}\right|\right), \quad k = 0,\ldots,1535; \quad 0 \le l \le L. \tag{17}$$

The amplitudes of the estimated channel coefficients $|\hat{H}_{\mathrm{n,k}}|$ are used for equalization of the received data by simply dividing the received data:

$$|\hat{X}_{n,k}| = \frac{|Y_{n,k}|}{|\hat{H}_{n,k}|}. \tag{18}$$

TABLE III
SIMULATION PARAMETERS

Parameters	Specifications
DAB transmission mode	**mode I**
Carrier frequency	**200 MHz**
Bandwidth	**1,536 MHz**
No. symbols/frame	76
No. sub-carriers/symbol (N)	1536
Total symbol duration (T_s)	1.246 ms
Useful symbol duration (T_u)	1 ms
Guard interval duration (△)	246 μs
Frame duration (T_f)	96 ms
FFT size	2048
Modulation	Hierarchical DAPSK / A-DPSK
Convolutional code (R_c)	R_c = 1/2, constraint length = 7
Time interleaving	Depth = 384 ms
Frequency interleaving	Width = 1.536 MHz
Channel model	COST 207 TU6

TABLE IV
CHANNEL PROFILE (COST 207 TU6)

Path Number	Average Power (dB)	Delay (μs)	Doppler Spectrum
1	-3.0	0.0	Rayleigh
2	0.0	0.2	Rayleigh
3	-2.0	0.5	Rayleigh
4	-6.0	1.6	Rayleigh
5	-8.0	2.3	Rayleigh
6	-10.0	5.0	Rayleigh

For soft-decision Viterbi decoding of the amplitude-modulated signal, we adopt a simplified algorithm for the soft-output demapper for the 16-QAM and 64-QAM constellations presented in [16]. The soft bit-metrics are given by

$$LLR\left(b_0^L\right) = |\hat{H}_{n,k}|^2 \cdot D_{n,k,0}$$
$$LLR\left(b_1^L\right) = |\hat{H}_{n,k}|^2 \cdot D_{n,k,1} \quad (19)$$

where the squared channel amplitude response $|\hat{H}_{n,k}|^2$ may represent the channel state information (CSI) proportional to the SNR in the kth subcarrier of the nth OFDM symbol and

$$D_{n,k,0} = |\hat{X}_{n,k}| - (d_1 + 1.5d_2)$$
$$D_{n,k,1} = \begin{cases} |\hat{X}_{n,k}| - (d_1 + 0.5d_2) \\ -|\hat{X}_{n,k}| + (d_1 + 2.5d_2). \end{cases} \quad (20)$$

Note that for the soft-decision decoding, the received amplitude values should be converted into soft bit-information weighted by the CSI coefficients. This is because, in a multicarrier OFDM system, subcarriers suffer from different channel attenuation levels and thus data conveyed by subcarriers with a high SNR are *a priori* more reliable than data transmitted in subcarriers with a low SNR [16].

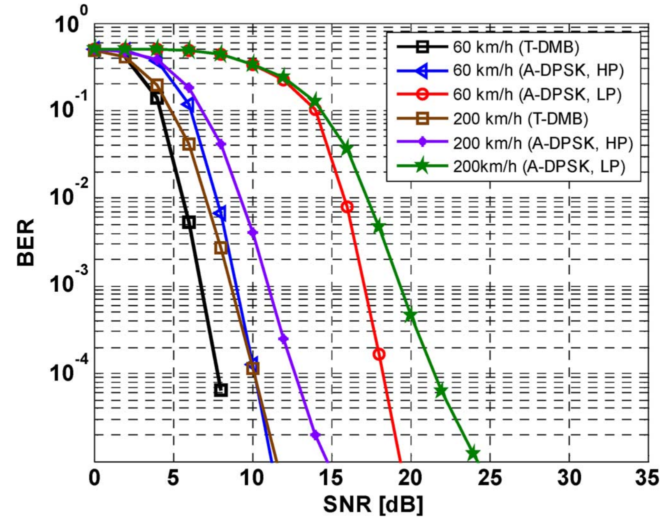

Fig. 12. The performance of an HP signal and LP signal A-DPSK ($\lambda = 1.5$) with the soft-decision.

IV. SIMULATION RESULTS

Computer simulations were performed by determining the required SNR for a fixed BER of 10^{-4} in order to verify the performance of the proposed hierarchical A-DPSK and DAPSK modulation for the AT-DMB system. The system parameters for AT-DMB used in the simulation are given in Table III. Simulation was performed in a transmission mode I environment of DAB [1]. In A-DPSK, the pilot was inserted every 10 subcarriers in frequency direction (154 pilots per OFDM symbol) and the overhead of L was 10.03 %. The channel profile was COST 207 TU6 [14]. The channel parameters are shown in Table IV.

With hard-decision decoding, the BER curves of LP signal using DAPSK ($a = 1.4$) and A-DPSK ($\lambda = 1.5$) for a vehicle speed of 60 and 200 km/h are shown in Fig. 10. The SNR difference at the BER of 10^{-4} was 4.9 dB for a vehicle speed of 60 km/h. The target BER cannot be achieved for 200 km/h.

The BER performances of soft-decision decoding of the LP signal are shown in Fig. 11. The SNR difference at the BER of 10^{-4} was 4 dB for the vehicle speed of 60 km/h. DAPSK needed about 11 dB higher SNR than the A-DPSK when a vehicle speed was 200 km/h. The results of Figs. 10 and 11 show that the DAPSK did not work well in fast fading channels caused by high-speed moving receivers. The results mean that the hierarchical A-DPSK modulation was superior to the DAPSK modulation scheme for higher data-rate transmission.

Figs. 12 and 13 show the BER performances of the A-DPSK with "$\lambda = 1.5$" and "$\lambda = 2.0$". Considering the required performance of backward compatibility with legacy T-DMB receivers, the hierarchical modulation parameter "λ" may be chosen. When backward compatibility with legacy receivers was allowed to be less than 2.7 dB, a hierarchical modulation parameter "$\lambda = 1.5$" can be used. However, if the allowed SNR degradation of legacy receivers was below 1.9 dB, a hierarchical modulation coefficient "$\lambda = 2.0$" should be selected. As shown in Figs. 12 and 13, the choice of a larger hierarchical modulation coefficient caused a performance degradation of

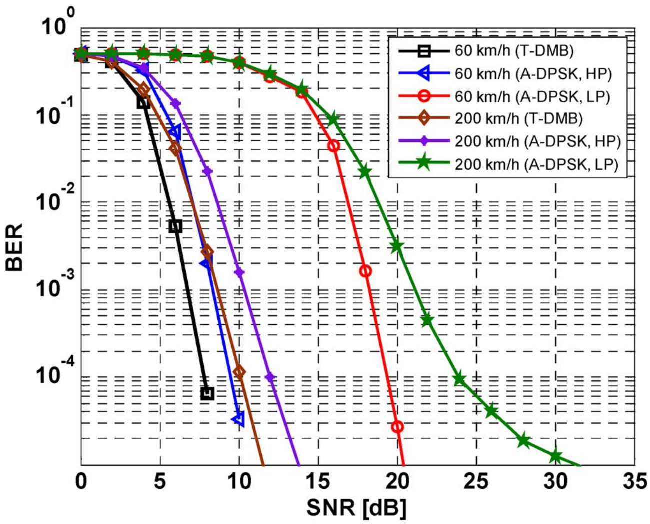

Fig. 13. The performance of an HP signal and LP signal A-DPSK ($\lambda = 2.0$) with the soft-decision.

the LP demodulation and thus it was required to use an appropriate value of the modulation coefficient depending on the performance limit of legacy receivers.

The performance difference between A-DPSK and DAPSK is mainly due to detection strategy. As mentioned in the Section III, A-DPSK is based on the coherent detection and DAPSK adopts non-coherent detection. It is generally known that the performance of the coherent detection is better than that of non-coherent detection [18]. Once we precisely estimate channel coefficients in A-DPSK, the coherent detection of A-DPSK yields a better performance than the non-coherent detection of DAPSK. In our A-DPSK system, LP pilots make it possible to precisely estimate channel coefficients.

V. Conclusion

A hierarchical A-DPSK modulation scheme can be effectively used for a higher data-rate T-DMB or DAB system when demodulation of the LP data is stably performed with backward compatibility with legacy receivers. We showed that the purpose of increasing the data rate of a T-DMB or a DAB system might be achieved with the aid of come-type arranged LP pilots and a noise-reduction method of estimated channel coefficients without the burden of hardware complexity in advanced receivers. Compared to a hierarchical DAPSK modulation, the A-DPSK showed better BER performance with similar performance in terms of backward compatibility with legacy T-DMB receivers, especially in a mobile environment.

Since a channel coding, in conjunction with the hierarchical modulation parameter "λ" and the pilot overhead of L, ultimately will determine the actual bit rate of a T-DMB or a DAB system, channel coding for the additional LP data should be studied to optimize the performance of the advanced system as this study considered only a convolutional coding. The issue of finding an optimal channel coding for an advanced system remains for further research.

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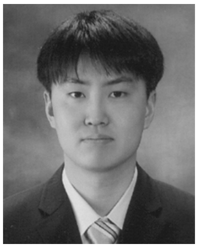

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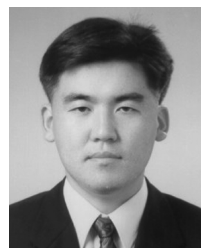

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