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An Adaptive Mobility Estimator for the Estimation of Time-Variant OFDM Channels

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Abstract

An adaptive channel estimation technique for OFDM-based DTV receivers is proposed using a new mobility estimator. Sample mean techniques for channel estimation have displayed good performance in slow fading channels, because averaging reduces noise in channel estimation operation. This paper suggests an algorithm which selects the optimal number of symbols within which the sample mean of consecutive pilot data can be obtained. The designed mobility estimator determines the optimal number by comparing mobility variance and estimated noise variance. The algorithm using the mobility estimator obtains an optimal channel transfer function under time-invariant or time-variant multipath fading channels, thereby making the best BER performance.

Key words : Adaptive mobility estimator, Channel estimation, OFDM.

I. Introduction

Digital terrestrial television with orthogonal frequency division multiplexing (OFDM) uses a multi-amplitude modulation scheme of M-ary QAM to transmit high rate data[1]. When a wireless radio channel is frequency-selective, time-variant, and noisy, a precise channel estimation and tracking technique is a prerequisite to coherently detect the high level M-ary QAM signals which are very sensitive to noise and interference. To aid the operation of channel estimation, OFDM frames have training data in pre-assigned positions, i.e., pilot subcarriers. In the case of a 2k mode in European DVB-T (Digital Video Broadcasting-Terrestrial) standard, there are 176 known pilot subcarriers including scattered pilots and continual pilots among a total of 1,705 subcarriers in each symbol[1].

Many algorithms for pilot assisted OFDM channel estimation have been proposed[2-9]. To estimate the frequency response of the multipath fading channel, a linear minimum mean square error (LMMSE) estimator using the frequency correction of the channel has been proposed[6]. The linear interpolation method is very effective for fast fading channels and some modifications are made to improve its performance in the case of slow fading channels[7-9]. It is clear that the sample mean technique which uses average values of the consecutive pilot data with identical subcarriers effectively removes noise in channel estimation in the case of a time-invariant channel [9]. Kang and Song[9] compare a sample mean technique using fixed 16, 32 and 64 symbol averages with LS estimator and LMMSE estimator[6], and shows that the sample mean technique outperforms the LMMSE estimator for a wide range of SNRs. However, when the channel is time-variant, the channel estimation of sample mean technique involving high numbers of symbols induces large estimation errors, thereby degrading the receiver performance. Thus it is important that the number of symbols used in averaging should be properly selected according to the mobility of receivers. For fast fading channels, channel

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estimation should be done without averaging, but for time-invariant channels, the sample mean technique using many symbols generates better performance.

In this paper, we propose an algorithm which selects the optimal number of symbols with which the sample mean of consecutive pilot data can be obtained. Within the optimal number of consecutive symbols the channel attenuation and the transmitted pilot data can be considered constant. This algorithm uses the scattered and continual pilots of DVB-T standard. The proposed algorithm has an additional hardware block which is a mobility estimator, estimating the mobility of a receiver by calculating the dynamic status of the pilot subcarriers. By comparing mobility variance and noise variance, the proposed mobility estimator determines the optimal number of symbols which should be used in taking the averages. In this paper, the method of calculating mobility variance and noise variance is developed, and a selection algorithm for the optimal number of symbols in the sample mean is also proposed. The proposed scheme maximizes the SNR of OFDM receivers for any channel condition. The performance of the proposed scheme is analyzed using the OFDM frame structure of the DVB-T standard under a time-variant Rician and Rayleigh channel models.

The paper is organized as follows: in section Ⅱ, the pilot-based OFDM system and OFDM frame structure of the DVB-T standard are described briefly. Section Ⅲ discusses the operation of the proposed mobility estimator in detail and section Ⅳ presents the computer simulation results which indicate the best SNR and BER(bit error rate) performance of corrected signals at the optimally selected averaging symbol number. Finally, section Ⅴ concludes the paper.

Ⅱ. Time-variant OFDM channels

A conceptual block diagram of the DVB-T OFDM system with pilot-assisted channel estimator is shown in Fig. 1. In this paper, we use the 2k mode of the DVB-T standard, which has 1,705 subcarriers in each OFDM symbol. The binary information data are grouped and mapped into QAM signals. After pilots are inserted, the modulated signals are transformed by IFFT (Inverse FFT) and multiplexed to be $x(l,n)$ as

$$x(l,n)=\sum_{k=0}^{N-1} X(l,k)e^{j2\pi kn/N},\quad n=0,1,\ldots\ldots,N-1, \tag{1}$$

where $X(l,k)$ is a data in k'th subcarrier of l'th symbol, $x(l,n)$ is n'th sample of l'th symbol and N is the total number of subcarriers in a symbol. A guard interval is inserted to prevent ISI (Inter-

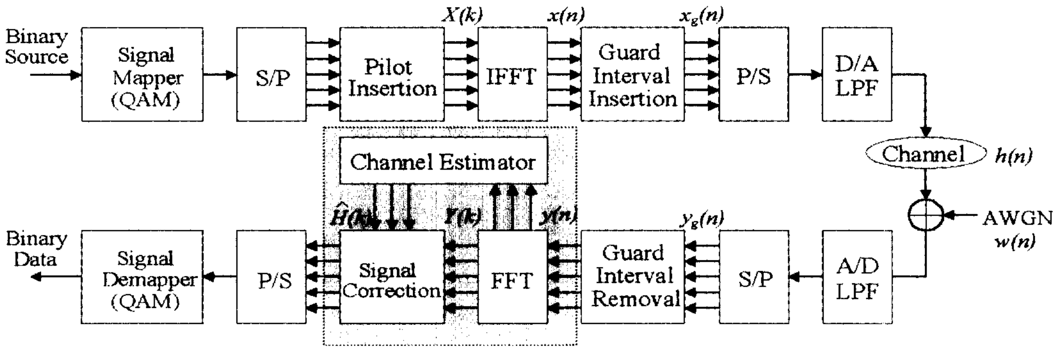


Fig. 1. OFDM transmitter and receiver with pilot-assisted channel estimator

Symbol Interference) in OFDM systems. The transmitted signal experiences multipath fading during propagation, therefore the time-domain received signal $y_g(l,n)$ is expressed as

$$y_g(l,n) = x_g(l,n) * h(l,n) + w(l,n), \tag{2}$$

where $x_g(l,n)$ is a transmitted signal with guard interval, $h(l,n)$ is the impulse response of channel, $w(l,n)$ is the AWGN (Additive White Gaussian Noise), indexes l and n are the symbol and sample number, respectively, and * denotes convolution. After removing the guard interval in the receiver equation (2) reduces to

$$y(l,n) = x(l,n) * h(l,n) + w(l,n). \tag{3}$$

Assume the channel consists of M multipath components, $h(l,n)$ is expressed as

$$h(l,n) = \sum_{m=0}^{M-1} h_m \delta(n + lN - \tau_m) e^{-j\theta_m}, \tag{4}$$

where M is the total number of propagation paths, h_m is the complex impulse response of the m'th path, τ_m is the delay of the m'th path, and θ_m denotes the phase shift of the m'th path. To prevent ISI, the guard interval should be longer than $\tau_{\max}$ which is the maximum delay among the M multipaths. After removing the guard interval, the received signals are demultiplexed through FFT operation. Because the demultiplexed samples of the l'th OFDM symbol are in the frequency-domain, by Fourier-transforming, equation (3) can be expressed as

$$Y(l,k) = X(l,k)H(l,k) + W(l,k), \quad k = 0, 1, \ldots\ldots, N-1 \tag{5}$$

where (l,k) represents the k'th subcarrier in the l'th symbol.

In the case of OFDM frame structure of DVB-T standard, channel estimation can be performed using the pre-inserted pilots and channel correction can be performed using equation (5) in the frequency domain. Fig. 2 shows the 2k mode OFDM frame structure of DVB-T.

An OFDM frame contains scattered pilots, continual pilots, and TPS (Transmission Parameter Signaling) carriers, in addition to the information data. Continual pilots are successively inserted into the same subcarrier positions of every symbol. There are 45 continual pilots per symbol in the 2k mode. As shown in Fig. 2, scattered pilots are repeated every twelfth subcarrier in all symbols and the first pilot position is repeated every fourth symbol. Scattered pilots and continual pilots are

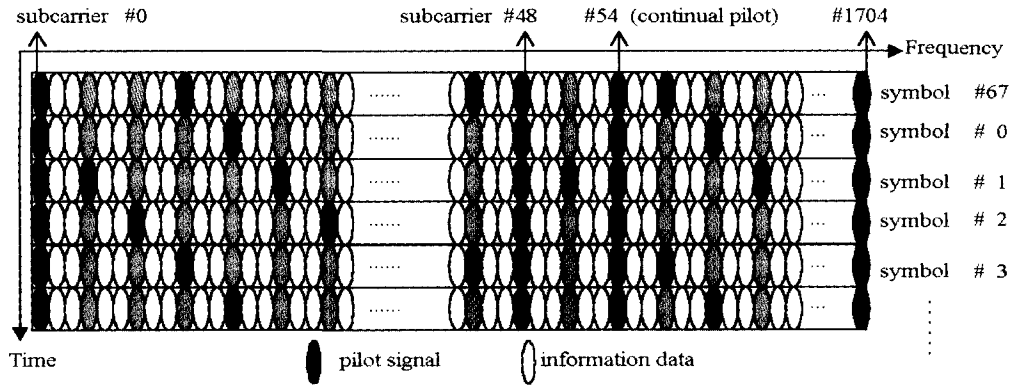


Fig. 2 2k mode OFDM frame structure of DVB-T.

always transmitted at the boosted power level compared with the power of the information data. By extracting the pilot signals, the channel transfer function in the known pilot subcarrier positions can be obtained as

$$\hat{H}(l,k)=\frac{Y(l,k)}{X(l,k)}=H(l,k)+\frac{W(l,k)}{X(l,k)} \qquad (6)$$

In this equation, index k is the position of only pilot subcarriers. So $X(l,k)$ is the known pilot signal data. If there is no noise, i.e., $W(l,k)=0$, the estimated channel transfer function $\hat{H}(l,k)$ becomes $H(l,k)$. However, if noise $W(l,k)$ is high or if $X(l,k)$ is small due to deep fading, the channel estimation error increases. We can notice that assuming $X(l,k)$ is constant, sample mean of $W(l,k)/X(l,k)$ for a fixed k reduces noise in channel estimation operation.

After an estimation of the channel transfer functions of the extracted pilots, the entire channel response including data subcarriers is obtained by linear interpolation[4][7]. The transmitted data samples can be recovered by an equation (7), where $Y(l,k)$ is the received signal as shown in equation (5) and $\hat{H}(l,k)$ is the estimated channel response.

$$\hat{X}(l,k)=\frac{Y(l,k)}{\hat{H}(l,k)}, \quad k=0,1,\ldots\ldots,N-1 \qquad (7)$$

Equation (7) shows that when $\hat{H}(l,k)$ is small, the channel estimation error enlarges the error in the recovered data $\hat{X}(l,k)$. Thus, obtaining the extract channel transfer function is very important to recovering error-free data.

Ⅲ. Proposed mobility estimation algorithm

Channel estimation for the OFDM system is performed in the frequency domain after FFT operation. Fig. 3 shows the channel estimation structure using the proposed mobility estimator for the OFDM-based DTV receivers. The channel estimator uses both the continual pilots and scattered pilots of the DVB-T frame shown in Fig. 2. The channel transfer function of pilot subcarriers is obtained by equation (6), symbol by symbol. Because scattered pilots are repeated every twelfth subcarrier in all symbols and the first position is repeated every fourth symbol, a four symbol block has at least one pilot in every 3rd subcarrier position. Symbol by symbol pre-interpolation is done to find the channel transfer function in every 3rd subcarrier position by using

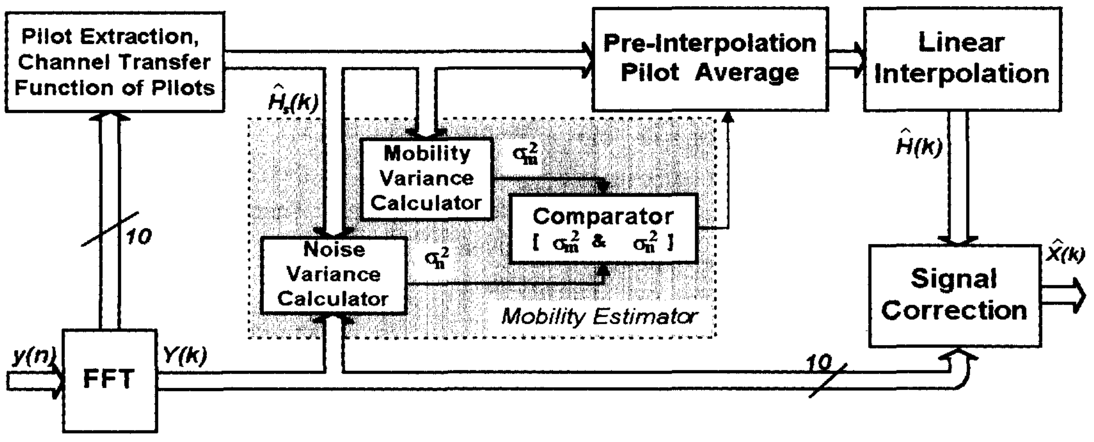


Fig. 3. OFDM channel estimation using the mobility estimator

the scattered and continual pilot subcarriers. Pilot average is done to remove noise in the channel estimation operation. The optimal symbol numbers for averaging is found in the mobility estimator. Finally the channel transfer function on every data point is obtained by using linear interpolation[4][7].

The mobility estimator determines the optimal symbol numbers with which the sample mean of consecutive pilot data can be obtained. Within the optimal consecutive symbol numbers the channel attenuation and the transmitted pilot data can be considered constant. For time-invariant or slow fading channels, sample mean technique that use many symbols will reduce channel estimation error. But very fast fading channels should estimate the channel transfer function using only one symbol by symbol interpolation technique. The mobility estimator is composed of a mobility variance calculator, noise variance calculator, and comparator. These functions will be described in detail.

Mobility is obtained by calculating the variance of the continual pilots extracted from received signals, which is called mobility variance. It is defined as:

$$\sigma_m^2 = \frac{1}{45}\sum_{k_c=1}^{45}\frac{1}{N_l}\sum_{l=1}^{N_l}\{[Y(l,k_c)-\mu_m(k_c)]^2\}, \qquad (8)$$

$$N_l = 0, 1, \ldots\ldots, l_{\max},$$

where $Y(l,k_c)$ is the received continual pilot in lth symbol, k_c is the index for 45 continual pilots assigned to the fixed subcarriers, $\mu_m(k_c)$ is the mean value of $Y(l,k_c)$ for a given pilot subcarrier k_c and N_l is the total number of symbols used. As shown in equation (8), therefore, mobility variance for fixed N_l is the average of 45 variances calculated from N_l continual pilots. Mobility variance should be calculated with more than 2 symbols. And $l_{\max}$ should be selected by considering hardware complexity, 68 symbols of 1 frame seems to be a reasonable size. So, a frame buffer is needed to store 68 symbol data.

The mobility variance is affected by two components, i.e. AWGN noise and time-variant multipaths. To know whether the value of the mobility variance is due to AWGN noise or time-variant multipaths, noise variance should be calculated as a reference. To find the noise component, preliminary channel estimation of equation (6) is done using only scattered pilots and the channel transfer function of continual pilot subcarriers is found by linear interpolation. A careful investigation reveals that symbol #0 has 33 continual pilots which don't coincide with scattered pilots, symbol #1, #2, and #3 have 34 continual pilots which don't coincide with the scattered pilots. Thus 33 or 34 continual pilots can be used to calculate the noise component $\hat{N}(l,k)$.

$$\hat{N}(l,k) = \left\{\frac{Y(l,k_n)}{\hat{H}_s(l,k_n)} - P_c\right\}\hat{H}_s(l,k_n), \qquad (9)$$

$$= Y(l,k_n) - P_c \times \hat{H}_s(l,k_n),$$

where $\hat{H}_s(l,k)$ is a preliminary estimated channel transfer function at k_n'th subcarrier of lth symbol, P_c is the transmitted continual pilot value which is known to the receiver, and index k_n denotes the 33 or 34 continual pilots which don't coincide with the scattered pilots.

Equation (9) shows that if there is no channel estimation error, $\hat{N}(l,k)$ represents the pure noise component $W(l,k_n)$. The larger the noise, the larger the estimation error, the larger the noise calculation error. Then estimated noise variance is given by

$$\hat{\sigma}_n^2 = \frac{1}{45}\sum_{l=1}^{N_l}\frac{1}{k_{n_{\max}}}\sum_{k_n=1}^{k_{n_{\max}}}\{[\hat{N}(l,k_n)-\mu_N]\}^2, \qquad (10)$$

$$N_l = 1, 2, \ldots\ldots, l_{\max},$$

where μ_N is the mean value of $\hat{N}(l,k)$ and $k_{n_{max}}$ is 33 for the $4q$'th symbols, $q=0, 1, 2, \ldots, 17$ and 34 for other symbols. We cannot use the continual pilots which coincide with the position of scattered pilots, because estimated noise is zero in the positions of scattered pilots.

The characteristics of mobility variance and noise variance will be described in detail. If noise variance is calculated using only one symbol, i.e, $N_l=1$, total sample number is 33 or 34. If $N_l=2$, total sample number will be doubled. So, if more symbols are used to calculate noise variance, more accurate noise variance is obtained. Consider when the channel has no multipaths and is time-invariant. Then if a large N_l is used, noise variance should be equal to mobility variance. But noise variance is somewhat larger than the mobility variance, because there is some error in preliminary channel estimation. This error is expressed by $P_c \times \hat{H}_s(l,k)$ in equation (9).

Mobility variance is calculated using the continual pilot data with the same subcarrier number, because the fading is frequency-selective. If two symbols are used, the mobility variance uses only two data of the same continual subcarrier. The mean value is the median value of two data, so the mobility variance is small. Even when the channel has only AWGN noise, mobility variance is small for a small N_l, it approaches the noise variance if N_l becomes larger. If the channel is time-variant, the mobility variance increases when N_l increases, because the received signal fluctuates. Because a small N_l of 2~68 is used to calculate the mobility variance, the number of sample data is not enough to find precise mobility variance. Thus, even if noise variance is obtained, it is not easy to extract the time-variant multipath components from mobility variance.

Based on careful investigation of various experiments of section Ⅳ, the optimal symbol number for averaging is decided where the mobility variance σ_m^2 is equal to noise variance $\hat{\sigma}_n^2$. This selection algorithm is described as follows.

i) Assume that the current optimal symbol number is N_l.
ii) If $\sigma_m^2 \geq \hat{\sigma}_n^2$, $N_l = N_l - 1$.
  If $\sigma_m^2 < \hat{\sigma}_n^2$, $N_l = N_l + 1$.
iii) If $N_l < 4$, $N_l = 1$.
iv) Continue operation ii) and iii) for every input symbol.

Operation iii) is added because in the case of fast fading channels, channel estimation using only one symbol has better performance. The validity of the proposed algorithm will be evaluated by computer simulation in section Ⅳ.

Ⅳ. Computer simulation

The proposed channel estimation algorithm is simulated using the 2k mode of DVB-T with a guard interval of one eighth of an useful symbol duration of 64-QAM modulation. Each symbol is composed of a useful part of duration T_u and a guard interval T_g. The guard interval consists of a cyclic continuation of the useful part and is inserted before the useful part. We assume that the timing recovery and carrier recovery are carried out and data bits are 10. Table 1 summarizes the OFDM system parameters used in the simulation.

Table 1. OFDM frame parameters

Transmission mode	**2k**
FFT size	2048
Channel bandwidth	**8MHz**
Useful channel bandwidth	7.61MHz
Number of subcarriers(N)	**1705**
Guard interval(Tg = Tu/8)	28 μsec
Sucarrier spacing(1/Tu)	**4464Hz**
Useful symbol duration(Tu)	224 μsec

Table 2. Time-variant Rician channel model

Path	Amplitude phase	Delay	Time variant (degree/sec)
1	1.000∠0°	0.0 μsec	None
2	0.400∠140°	0.1 μsec	3570° /sec
3	0.160∠0°	0.2 μsec	7140° /sec
4	0.063∠60°	0.3 μsec	14280° /sec
5	0.021∠180°	0.4 μsec	10710° /sec
6	0.010∠220°	0.5 μsec	3570° /sec

Table 3. Time-variant Rayleigh channel model

Path	Amplitude phase	Delay	Time variant (degree/sec)
1	0.50∠30°	0.0 μsec	None
2	1.00∠0°	0.2 μsec	None
3	0.63∠140°	0.5 μsec	-1980° /sec
4	0.25∠60°	1.6 μsec	2380° /sec
5	0.021∠180°	2.3 μsec	2780° /sec
6	0.010∠220°	5.0 μsec	-2180° /sec

The channel models used are Rician and Rayleigh recommended by GSM Recommendations 05.05 with parameters shown in Table 2 and 3 respectively. In Tables 2 and 3, the last column is monotonely increasing phase changes per second to give a time-variant effect for dynamic channel simulation. To find BER performance AWGN is added and varied.

Fig. 4 shows the channel transfer function for the Rician channel model in Table 2, and the channel transfer function of the Rayleigh channel model in Table 3 is shown in Fig.5. In Figs. 4 and 5, the horizontal axis represents the spectral range in MHz and vertical axis represents the signal strength. Because the k factor of the Rician channel model is 5.26, the spectral shape of the Rician channel model is very smooth, but that of the Rayleigh channel model is very rough. So if the channel transfer function is estimated by linear interpolation, the Rayleigh channel model will have more estimation error than the Rician channel model.

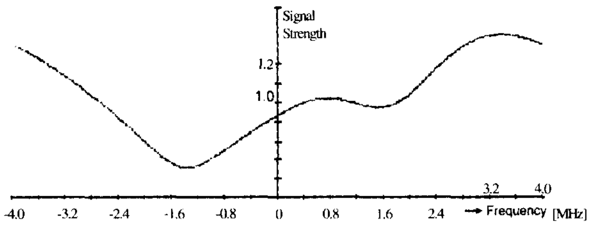


Fig. 4. Channel transfer function of the Rician channel model in the frequency domain

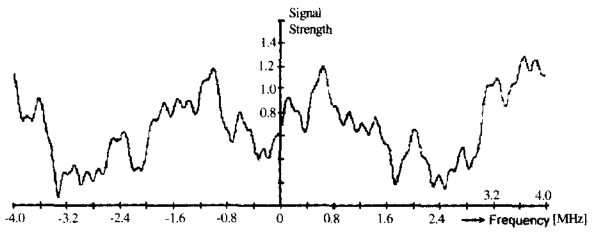
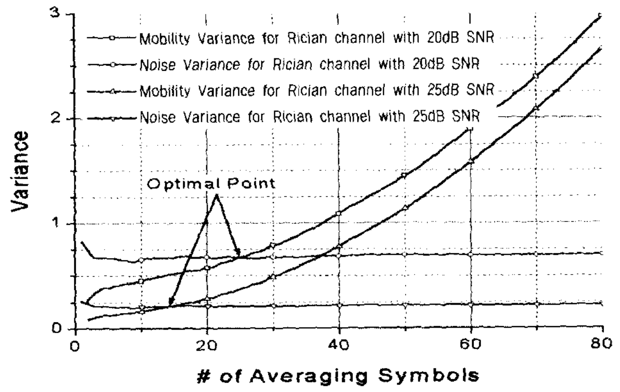


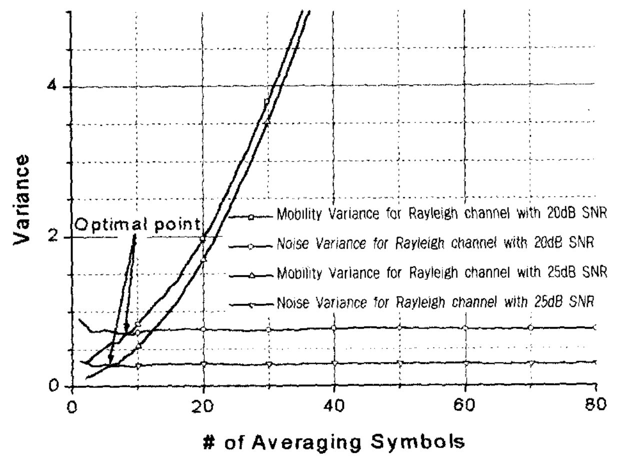
Fig. 5. Channel transfer function the of the Rayleigh channel model in the frequency domain

For the channel estimation, we used both scattered pilots located in a comb-type style and continual pilots located in the same subcarrier positions of every symbol successively.

The simulations are done to reveal that there is an optimal number of symbols for averaging where the receiver has the best BER. Fig. 6 plots the the mobility variance σ_m^2 in equation (8) and the estimated noise variance $\hat{\sigma}_n^2$ in equation (10) for the Rician and Rayleigh channel models. Two levels of AWGN are added to make SNR 20dB or 25dB. When signal levels of 64 QAM are ±1, ±3, ±5, ±7, the signal power is 21. The horizontal axis is the number of averaging symbols. Because the used channel model is time-variant, the more symbols are used for averaging, the larger the mobility variance is. But the noise variance is almost constant with respect to the number of averaging symbols. The mobility variance of the Rayleigh channel model increases more sharply than that of the Rician channel model, because the Rayleigh channel model has more complex channel



(a) Mobility variance and noise variance of Rician channel model



(b) Mobility variance and noise variance of Rayleigh channel model

Fig. 6. Comparison of mobility variance and noise variance

characteristics than the Rician channel model. And the noise variance of the Rayleigh channel model is larger than that of the Rician channel model, because the Rayleigh channel model has more errors in the pre-estimated channel response $\hat{H}_s(l,k)$ of equation (9) than the Rician channel model has.

The selection procedure of finding the optimal number of averaging symbols is to search the crossing point of the mobility variance σ^2_m and the estimated noise variance $\hat{\sigma}^2_n$. As shown in Fig. 6(a), the optimal averaging number is 25 in the case of Rician channel with 20dB SNR, and is 14 in the case of Rician channel with 25dB SNR. Fig. 6(b) shows that the optimal averaging number is 8 in the case of Rayleigh channel with 20dB SNR, and is 6 in the case of Rayleigh channel with 25dB SNR.

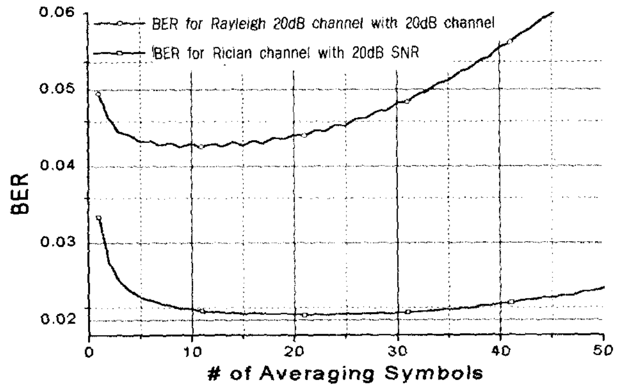


Fig. 7. Output BER according to the averaging symbol numbers

Fig. 7 shows the BER after channel correction of equation (7) according to the averaging symbol numbers. We notice that BER is minimized at around the optimal symbol number for averaging.

Fig. 8 plots the optimal symbol numbers according to input SNR. Clearly, the Rayleigh channel model has the optimal number at lower value than the Rician channel model, because the Rayleigh channel model has more dynamic multipaths.

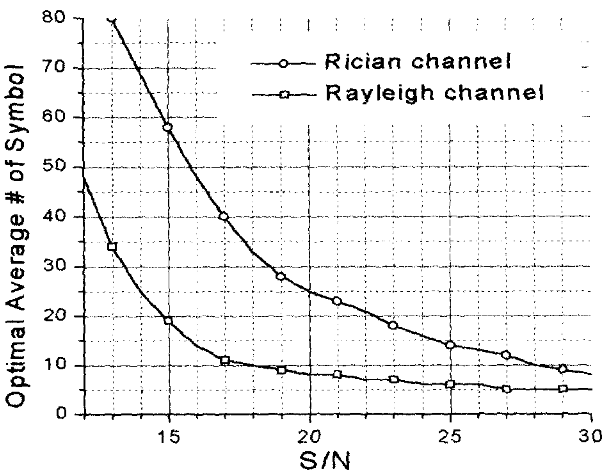


Fig. 8. Optimal number of symbol for averaging

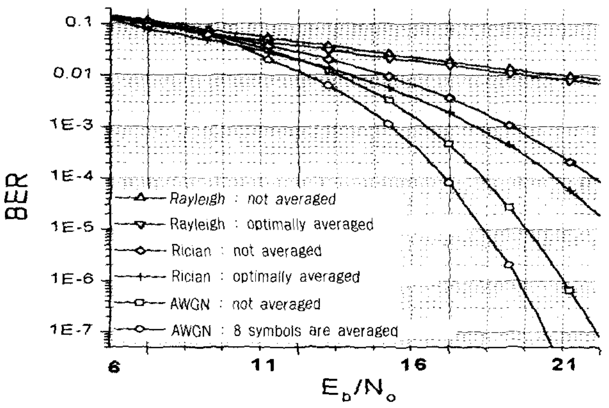


Fig. 9. Comparison of BER performance

Finally, Fig. 9 shows the BER performance according to E_b/N_o. For 64-QAM, E_b/N_o is equal to SNR minus 7.78 dB. Three channel models are used. One is the AWGN channel. To show the averaging effect in channel estimation operation, the graph of 8 symbols averages is plotted as an example. By averaging 8 fixed symbols for channel estimation there is about 1.3 dB improvement at 10^{-3} bit error rate. Another is the Rician channel model of Table 2, which shows about 1.2 dB improvement at 10^{-3} bit error rate. The BER curves of time-variant Rician and Rayleigh channel models use the optimal symbol number for averaging. The optimal symbol numbers are changed according to channel model and input SNR. The other is the Rayleigh channel model of Table 3. Because the channel transfer function is so complex, the channel estimation error increases greatly. But there is still some improvement in the BER curve.

V. Conclusion

In this paper, we propose and analyze an adaptive channel estimation algorithm using the mobility estimator for OFDM-based DTV receivers. This method has wide application capability for OFDM-based DTV receivers under both time-invariant channels and time-variant channels. For optimal channel estimation, noise that creates channel estimation error should be reduced as small as possible. Assuming the channel statistics are not variable, averaging by using as many symbols as possible effectively removes noise in channel estimation operation. In the case of the time-variant channel conditions, channel estimation by averaging too many symbols induces large estimation error due to non-constant channel characteristic, thereby degrading the receiver performance. Therefore, the number of symbols used in averaging should be adaptively determined according to the channel characteristic. That is, there is an optimal number of symbols which can be used in formulating averages for channel estimation. The channel estimation method using the proposed mobility estimator, which estimates mobility variance and noise variance, obtains the optimal channel transfer function by adaptively adjusting the number of symbols for averaging according to the time-variant channel condition.

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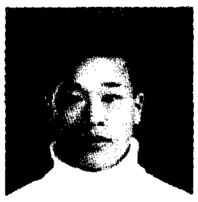

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