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Research Article

Channel Impulse Response Length and Noise Variance Estimation for OFDM Systems with Adaptive Guard Interval

Van Duc Nguyen,[1] Hans-Peter Kuchenbecker,[2] Harald Haas,[3] Kyandoghere Kyamakya,[4] and Guillaume Gelle[5]

[1] *Department of Communication Engineering, Faculty of Electronics and Telecommunications, Hanoi University of Technology, 1 Dai Co Viet Street, Hanoi, Vietnam*
[2] *Institut für Allgemeine Nachrichtentechnik, Universität Hannover, Appelstrasse 9A, 30167 Hannover, Germany*
[3] *School of Engineering and Science, International University Bremen, Campus Ring 12, 28759 Bremen, Germany*
[4] *Department of Informatics-Systems, Alpen Adria University Klagenfurt, Universitätsstrasse 65-67, 9020 Klagenfurt, Austria*
[5] *CReSTIC-DeCom, University of Reims Champagne-Ardenne, Moulin de la Housse, BP 1039, 51687 Reims Cedex 2, France*

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A new algorithm estimating channel impulse response (CIR) length and noise variance for orthogonal frequency-division multiplexing (OFDM) systems with adaptive guard interval (GI) length is proposed. To estimate the CIR length and the noise variance, the different statistical characteristics of the additive noise and the mobile radio channels are exploited. This difference is due to the fact that the variance of the channel coefficients depends on the position within the CIR, whereas the noise variance of each estimated channel tap is equal. Moreover, the channel can vary rapidly, but its length changes more slowly than its coefficients. An auxiliary function is established to distinguish these characteristics. The CIR length and the noise variance are estimated by varying the parameters of this function. The proposed method provides reliable information of the estimated CIR length and the noise variance even at signal-to-noise ratio (SNR) of 0 dB. This information can be applied to an OFDM system with adaptive GI length, where the length of the GI is adapted to the current length of the CIR. The length of the GI can therefore be optimized. Consequently, the spectral efficiency of the system is increased.

1. INTRODUCTION

In OFDM systems, the multipath propagation interference is completely prevented, if the GI is longer than the CIR length, namely the maximum time delay of the channel. However, the GI carries no useful information. Therefore, the longer the GI is, the more the spectral efficiency will be reduced. The GI length is a system parameter which is assigned by the transmitter. However, the CIR length depends on the transmission environment. So, when the receiver moves from one transmission environment to another, the CIR length must be changed. The purpose of this paper is to design an OFDM system with adaptive GI length, where the GI is adapted to the CIR length of a transmission channel. This avoids unnecessary length of the GI, and thus, increases the spectral efficiency of the system. To implement this concept, we have to deal with the two following problems. Firstly, the CIR length must be estimated very precisely. Secondly, the network must be organized in such a way that the information of the currently estimated CIR length at the receiver can be fed back to the transmitter to control the GI length.

In a coherent OFDM system, the channel must be estimated for equalization. Generally, even though the channel is estimated, the CIR length remains unknown. This is because the estimated CIR is affected by additive noise and by different kinds of interference such as intercarrier interference, cochannel interference, or multiple-access interference. This task is more difficult for a time-varying channel, since both the channel coefficients and the CIR length are changeable.

In the literature, there are some methods to estimate the CIR length [1–6]. The method described in [1] estimates the CIR based on the estimated SNR. Similar to this method, the CIR length is estimated in [2] by comparing the estimated channel coefficients with a predetermined threshold. The method in [3] is based on the generalized Akaike information criterion [7]. It was shown in the mentioned reference that the CIR length is usually underestimated. The method in [4] is based on the minimization of the mean square error of the estimated channel coefficients for different predetermined CIR lengths. To apply this method, the channel window (the range between the minimal and the maximal CIR lengths) must be known. In [6], the estimation of the CIR length is based on a given factor R which is defined by the ratio of the channel variance to the variance of the estimated channel including the channel variance and the noise variance. The ratio R is defined in [6] as a constant factor in the interval $[0.9 \rightarrow 0.95]$. Since the noise variance and the channel variance are unknown, the estimation of the CIR length based on a given ratio R does not provide a precise solution.

To overcome the difficulties of CIR length estimation for OFDM systems in the presence of strong additive noise and on a time-varying channel, we suggest an auxiliary function to distinguish the statistical characteristics of the additive noise and the multipath channel. The difference between the statistical characteristics of the additive noise and the channel coefficients lies in the fact that the variance of the true CIR is distributed only in the area of the true CIR length, whereas variance of noise per channel tap is uniformly distributed on the whole length of the estimated CIR. Due to the relative movement between the receiver and the transmitter, the channel is time-variant. However, it is well known that the CIR length changes more slowly than the channel coefficients. This is due to the fact that the CIR length depends mainly on the propagation environment. In practice, a receiver cannot move from one environment to another, for example, indoor to outdoor, within less than a second. So, this time delay can be exploited to improve the channel coefficients, and thus to reduce the influence of the additive noise on the performance of the proposed algorithm.

The rest of this paper is organized as follows: the auxiliary function is introduced in Section 2. An algorithm combining noise variance and CIR length estimation is introduced in Section 3. Section 4 describes how to calculate the estimated SNR from the estimated noise variance. The performance of the proposed method is evaluated in Section 6. Finally, the paper is concluded in Section 7.

2. INTRODUCTION OF THE AUXILIARY FUNCTION

To establish the auxiliary function, we assume that the channel is already estimated by a conventional method, for example, [8]. Figure 1 shows simulation results of an estimated channel under the presence of strong additive noise (SNR = 5 dB). The exact CIR length N_P is equal to 8 sampling intervals and the estimated CIR length N_K is equal to 15. Figure 2 demonstrates an example of an estimated multipath channel profile of a time-varying channel.

In the following, we consider the estimated channel coefficient $\check{h}_{k,i}$ corresponding to the ith OFDM symbol and the kth channel tap index. If we assume that the channel taps are equidistant and distributed with the sampling interval t_a of the system, then the relationship between the channel tap index k and the corresponding propagation delay is $\tau_k = k \cdot t_a$. The estimated channel coefficient $\check{h}_{k,i}$ is composed of the true channel coefficient $h_{k,i}$ and the noise component $n_{k,i}$, that is,

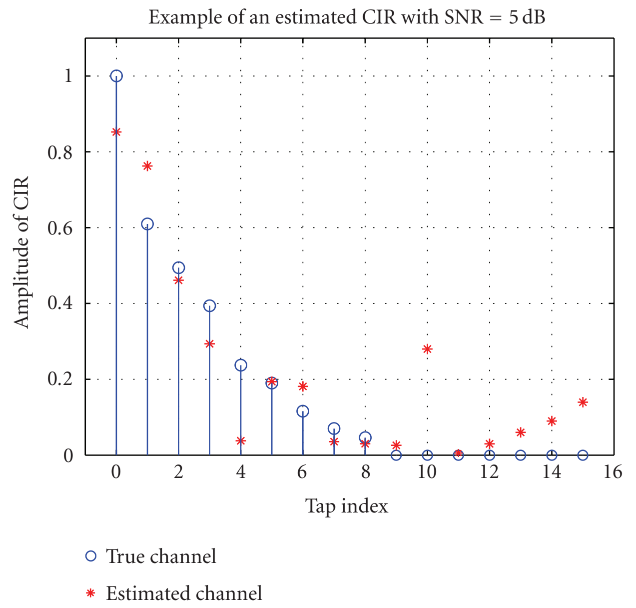

Figure 1: Estimated channel impulse response distorted by additive noise.

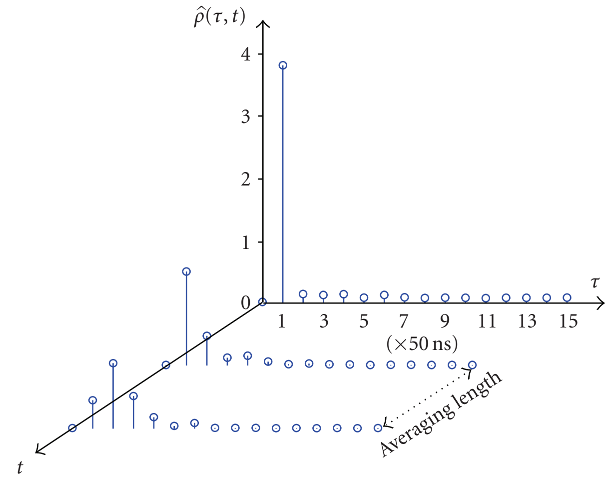

Figure 2: Estimated multipath channel profile of a time-varying channel observed at different observed times.

$$\check{h}_{k,i} = h_{k,i} + n_{k,i}, \tag{1}$$

where the noise term $n_{k,i}$ and the channel coefficient $h_{k,i}$ are statistically independent. The variance of the noise component of the tap k is

$$\sigma_n^2[k] = \mathrm{E}\left[\left|n_{k,i}\right|^2\right], \tag{2}$$

where $\mathrm{E}[|n_{k,i}|^2]$ is the expectation of $|n_{k,i}|^2$ over the OFDM symbol index i. In (1), the first term is the true channel coefficient and its variance depends on its position inside the length of the CIR. The second term is a stationary additive noise and its variance is equal in the whole length of the estimated CIR. Therefore, the channel tap index is omitted in the expression of the noise variance, that is, $\sigma_n^2[k]$ is replaced by σ_n^2.

If an arbitrary value L is supposed to be the true CIR length, then the new estimated channel $\tilde{h}_{k,i}^L$ coefficients can be formed by the first L samples of the estimated channel $\check{h}_{k,i}$ coefficients and are represented by

$$\tilde{h}_{k,i}^L = \begin{cases} \check{h}_{k,i}, & 0 \le k < L, \\ 0 & L \le k \le N_K - 1. \end{cases} \quad (3)$$

The supposed length L is in the range $[1, \dots, N_K - 1]$, since the true CIR length must be larger than zero and is assumed to be smaller than the estimated CIR length. The mean squared error $e(L)$ between $\tilde{h}_{k,i}^L$ and $\check{h}_{k,i}$ is

$$\begin{aligned} e(L) &= \mathrm{E}\left[\sum_{k=0}^{N_K-1} \left|\check{h}_{k,i} - \tilde{h}_{k,i}^L\right|^2\right] \\ &= \mathrm{E}\left[\sum_{k=L}^{N_K-1} \left|\check{h}_{k,i}\right|^2\right]. \end{aligned} \quad (4)$$

Thus, $e(L)$ is the cumulation of the average squared magnitude of the estimated channel taps from the Lth channel tap to the last channel tap. It is a function of L, and is henceforth named the cumulative function. Substituting $\check{h}_{k,i}$ from (1) into (4), it follows that

$$\begin{aligned} e(L) &= \mathrm{E}\left[\sum_{k=L}^{N_K-1} \left|h_{k,i} + n_{k,i}\right|^2\right] \\ &= \sum_{k=L}^{N_K-1} \left\{\mathrm{E}\left[\left|h_{k,i}\right|^2\right] + \mathrm{E}\left[\left|n_{k,i}\right|^2\right]\right\} \\ &= \sum_{k=L}^{N_K-1} \rho_k + (N_K - L)\sigma_n^2, \end{aligned} \quad (5)$$

where $\rho_k = \mathrm{E}[|h_{k,i}|^2]$ is the average power of the kth path. In (5), let $e_1(L) = \sum_{k=L}^{N_K-1} \rho_k$ be the first term and let $e_2(L) = (N_K - L)\sigma_n^2$ be the second term of the cumulative function $e(L)$, it can be seen that $e_1(L)$ stems completely from the channel, whereas $e_2(L)$ originates merely from the noise components. The cumulative function $e(L)$ illustrated in Figure 3 is a monotonously decreasing function which does not reveal any information of the CIR length. However, if the noise-related term $e_2(L)$ is perfectly compensated by adding the compensation term $L\sigma_n^2$ to the cumulative function $e(L)$, then the resulting function decreases only in the range of the CIR length and it is constant outside this range (see Figure 4). The breakpoint of the resulting function corresponds to the true CIR length. Henceforth, the resulting function is called the auxiliary function. In practice, the true noise variance is unknown. Thus, the true noise variance is replaced by a so-called presumed noise variance. Firstly, the

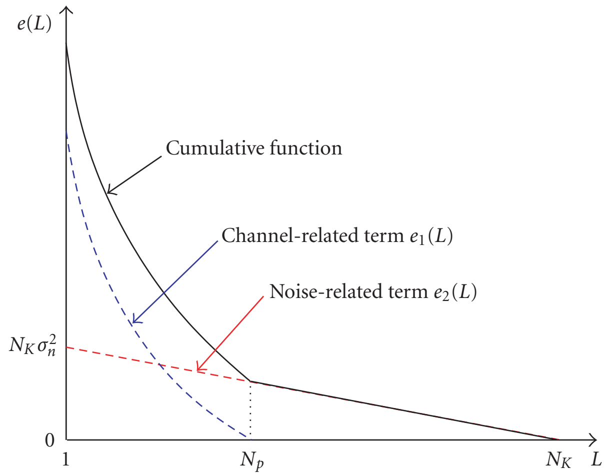

Figure 3: The cumulative function $e(L)$.

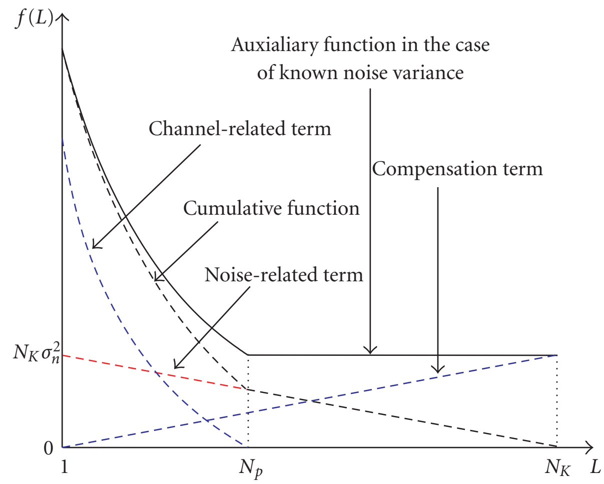

Figure 4: The auxiliary function $f(L)$ in the case of known noise variance.

presumed noise variance is initialized to be a possible maximum value of the true noise variance.[1] Then, the presumed noise variance will be gradually reduced till it approaches the true noise variance. This concept will be described precisely in Section 3.1. According to the compensation of the noise-related term $e_2(L)$, the mathematical description of the auxiliary function is written as

$$f(L) = \sum_{k=L}^{N_K-1} \rho_k + (N_K - L)\sigma_n^2 + L\sigma_{\text{pre}}^2, \quad (6)$$

or

$$f(L) = e_1(L) + e_2(L) + L\sigma_{\text{pre}}^2. \quad (7)$$

[1] It will be explained later in (9) that the initial value of the presumed noise variance can be computed from the estimated channel.

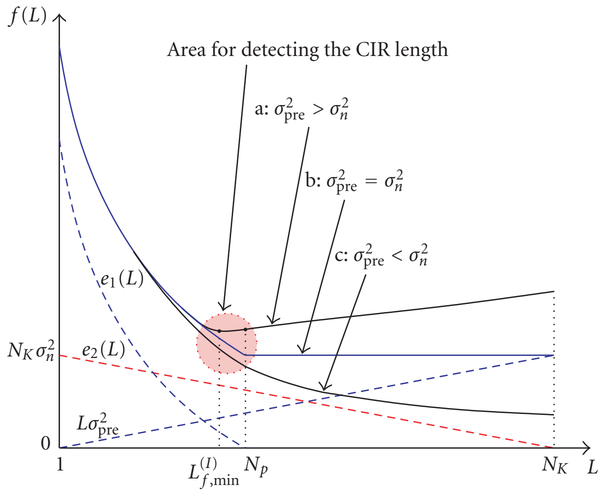

FIGURE 5: The auxiliary function $f(L)$ in different cases of the presumed noise variance σ_{pre}^2.

Based on (7), the auxiliary function $f(L)$ is roughly plotted in Figure 5. The characteristics of the auxiliary function depend on the following cases of the presumed noise variance.

(a) If the presumed noise variance is larger than the true noise variance: $\sigma_{\text{pre}}^2 > \sigma_n^2$, then there exists always a unique minimum value of the auxiliary function $f(L_{f,\min}) = \min(f(L))$, where $L_{f,\min} \leq N_P$. If σ_{pre}^2 closes to σ_n^2, then $L_{f,\min}$ also closes to N_P.

(b) If the presumed noise variance is exactly equal to the true noise variance, that is, $\sigma_{\text{pre}}^2 = \sigma_n^2$, then $f(L)$ becomes

$$f(L) = \sum_{k=L}^{N_K-1} \rho_k + N_K\sigma_n^2. \tag{8}$$

In this case, the auxiliary function $f(L)$ is a monotonously decreasing function within the true CIR length, and is equal to $N_K\sigma_n^2$ outside the true CIR length.

(c) If the presumed noise variance is smaller than the true noise variance: $\sigma_{\text{pre}}^2 < \sigma_n^2$, then $f(L)$ is a monotonously decreasing function within the whole length of the estimated CIR, and reaches the minimum value at $L = N_K - 1$.

Based on the characteristics of the auxiliary function $f(L)$, an algorithm called noise variance and CIR length estimation (NCLE) is proposed in the next section.

3. NEW ALGORITHM FOR THE NOISE VARIANCE AND THE CIR LENGTH ESTIMATION

According to the properties of the auxiliary function, if the presumed noise variance σ_{pre}^2 is step by step reduced from the possible maximum value to the possible minimum value of the true noise variance, then the curve of $f(L)$ will be changed from case (a) to case (c) as depicted in Figure 5. Each step is considered as one iteration towards the reduction of the presumed noise variance. The amount $\Delta\sigma^2$, which is used to reduce the presumed noise variance in each iteration, is called the step size. If this step size is very small in comparison with the true noise variance, then case (b) might appear. Otherwise, case (a) skips directly over to case (c) directly. When the case (c) appears for the first time, then the presumed noise variance of the previous iteration is very close to the true noise variance, and the decision of the estimated noise variance will be made. The shape of $f(L)$ at the previous iteration corresponds of course either to case (a) or to case (b).

If case (a) appears, then the estimated CIR length $\hat{N}_P$ is assigned to be $L_{f,\min}$, where $f(L_{f,\min}) = \min(f(L))$. As explained in case (a), the estimated CIR length is shorter or equal to the true CIR length.

Case (b) might appear, if the presumed noise variance is very close to the true noise variance. Since the theoretical auxiliary function $f(L)$ of the case (b) is constant over the range $L = N_P$ to $N_K - 1$ (see Figure 5), it follows that the function $f(L)$ does not have unique minimum value like in the case (a). However, if the minimum value of the auxiliary function $f(L)$ is still computed by a numerical method, then a minimum value can be found. This is due to the fact that the realized auxiliary function is practically not constant in the interval mentioned above. In this case, the value of L corresponding to the minimum value of $f(L)$, that is, $L_{f,\min}$, is always larger or equal to the true CIR length. The estimated CIR length can be assigned to be this value, and thus, it is also larger or equal to the true CIR length.

To ensure that the estimated CIR length is close to the true CIR length, the procedure of establishing the auxiliary function $f(L)$ and seeking its minimum value should be repeated N_E times. A single execution of this procedure is called an experiment. The estimated CIR length in each experiment is stored in a vector $\vec{\mathcal{L}}$. Analogously, the estimated noise variance is stored in a vector $\vec{\mathcal{N}}$. After N_E experiments, the final result of the estimated CIR length is the minimum element of the vector $\vec{\mathcal{L}}$. The final estimated noise variance is the average value of all elements of the vector $\vec{\mathcal{N}}$.

3.1. Procedure of the proposed algorithm

Based on above descriptions, the NCLE algorithm flowchart is depicted in Figure 6. The algorithm proceeds as follows.

Step 1. Initial phase of each experiment: determine the initial value of the presumed noise variance and the step size by which the presumed noise variance will be decreased in each iteration. The initial value of the presumed noise variance is the possible maximum value of the true noise variance, which is determined in the following way. Let us assume that the true CIR is a Dirac impulse, that is, $N_P = 1$. Then, the first sample of the estimated CIR $\check{h}_{0,i}$ is the direct path including additive noise, the other samples $\check{h}_{k,i}$, $k = 1, \ldots, N_K - 1$, are completely additive noise components. Hence, the initial value of the presumed noise variance can be determined by

$$\sigma_{\text{pre}}^2 = \sum_{k=1}^{N_K-1} \frac{\mathrm{E}[|\check{h}_{k,i}|^2]}{N_K - 1}. \tag{9}$$

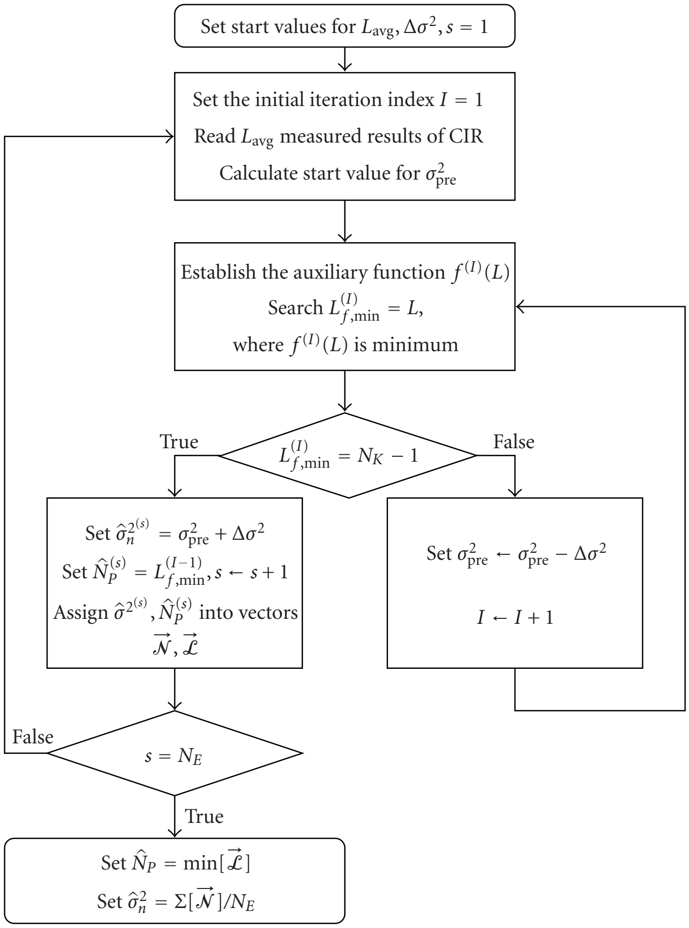

Figure 6: Flowchart of the NCLE algorithm.

It is clear that the true variance σ_n^2 is not larger than σ^2_{pre} in (9). This is due to the fact that if the CIR length is larger than one, then it follows in the initial phase that σ^2_{pre} consists of a fraction $1/(N_K - 1)$ of a part of channel power excluding the power of the direct path, and the noise variance.

The selection of the step size determines the accuracy of the estimated noise variance and the estimated CIR length, as well as the speed of the tracking process. The step size should be chosen as small as possible to obtain an accurate estimated noise variance, but not so small that the tracking process runs slowly.

In Appendix A, it will be proven that if the step size $\Delta\sigma^2$ is chosen to be smaller than the variance of the last channel tap ρ_{N_P-1}, that is,

$$\rho_{N_P-1} > \Delta\sigma^2, \tag{10}$$

then the CIR length can be precisely estimated.

Step 2. Establish the auxiliary function $f^{(I)}(L)$, where I represents the number of iterations in each experiment with the initial value $I = 1$, and seek the minimum value of the auxiliary function. These steps are explained in more detail as follows:

(1) calculate $f^{(I)}(L)$ according to (8);

(2) find $L^{(I)}_{f,\min} = L$, where $f^{(I)}(L)$ has a minimum;

(3) compare $L^{(I)}_{f,\min}$ with $N_K - 1$. If $L^{(I)}_{f,\min} = N_K - 1$, then go to Step 3. Otherwise, the following steps must be accomplished:

(i) reduce the presumed noise variance by the step size $\Delta\sigma^2$, that is,

$$\sigma^2_{pre} \longleftarrow \sigma^2_{pre} - \Delta\sigma^2; \tag{11}$$

(ii) increase the iteration index $I \leftarrow I + 1$;

(iii) repeat Step 2.

Step 3. The decision on the estimated noise variance $\check{\sigma}_n^{2^{(s)}}$ of the sth experiment is carried out by setting $\check{\sigma}_n^{2^{(s)}}$ to be the average of the presumed noise variance in the current and the previous iterations, that is,

$$\check{\sigma}_n^{2^{(s)}} = \sigma^2_{pre} + \frac{\Delta\sigma^2}{2}. \tag{12}$$

Store the estimated noise variance obtained from the sth experiment in a vector:

$$\check{\sigma}_n^{2^{(s)}} \longrightarrow \vec{\mathcal{N}} = [\check{\sigma}_n^{2^{(1)}}, \check{\sigma}_n^{2^{(2)}}, \dots, \check{\sigma}_n^{2^{(s)}}]. \quad (13)$$

Step 4. Store $\hat{N}_P^{(s)} = L_{f,\min}^{(I-1)}$, which corresponds to the minimum value of the auxiliary function of the previous iteration in a vector:

$$\hat{N}_P^{(s)} \longrightarrow \vec{\mathcal{L}} = [\hat{N}_P^{(1)}, \hat{N}_P^{(2)}, \dots, \hat{N}_P^{(s)}]. \quad (14)$$

Increase the experiment index $s \leftarrow s+1$, and repeat Steps 1 to 4 $(N_E - 1)$ times.

Step 5. Now, each of the vectors $\vec{\mathcal{L}}$ and $\vec{\mathcal{N}}$ has N_E elements. If the estimated noise variance $\check{\sigma}_n^2$ of an experiment is very close to the true value σ_n^2, then the associated element of $\vec{\mathcal{L}}$ is a random number in the interval $[N_P, N_K - 1]$. Otherwise, this element is smaller or equal to the true CIR length, because case (b) of the auxiliary function does not appear. To ensure that the estimated CIR length is close to the true CIR length, the final result of the estimated CIR length is assigned to be a minimum element of vector $\vec{\mathcal{L}}$:

$$\hat{N}_P = \min[\hat{N}_P^{(1)}, \hat{N}_P^{(2)}, \dots, \hat{N}_P^{(s-1)}]. \quad (15)$$

It can be proved that if the number of experiments is sufficiently large, then the probability that the CIR length is exactly estimated approaches one (see Appendix B).

Step 6. The estimated noise variances in the single experiments do not differ much from each other, because the step size is identical in all experiments. To improve the estimation result, the final result of the estimated noise variance can be obtained by averaging the results from all experiments, that is,

$$\check{\sigma}_n^2 = \frac{1}{N_E} \sum_{s=1}^{N_E} \check{\sigma}_n^{2^{(s)}}. \quad (16)$$

3.2. *Realization of the NCLE*

Theoretically, the definition of $f(L)$ in (6) is the sum of the expectation of $\sum_{k=L}^{N_K-1} |\check{h}_{k,i}|^2$ and $L\sigma_{\text{pre}}^2$. Practically, the expectation operation is replaced by an averaging operation over a finite number of OFDM symbols. That is, the cumulative function $e(L)$ in (4) and the initial value of the presumed noise variance in (9) are replaced by

$$\hat{e}(L) = \frac{\sum_{i=0}^{L_{\text{avg}}-1} \sum_{k=L}^{N_K-1} |\check{h}_{k,i}|^2}{L_{\text{avg}}}, \quad (17)$$

$$\hat{\sigma}_{\text{pre}}^2 = \frac{\sum_{i=0}^{L_{\text{avg}}-1} \sum_{k=1}^{N_K-1} |\check{h}_{k,i}|^2 / (N_K - 1)}{L_{\text{avg}}}, \quad (18)$$

where L_{avg} is the averaging length or the number of OFDM symbols which are taken into account in an averaging operation. Consequently, the auxiliary function $f(L)$ of the first iteration is replaced by

$$\hat{f}(L) = \hat{e}(L) + L \cdot \hat{\sigma}_{\text{pre}}^2. \quad (19)$$

It is clear that if L_{avg} is long enough, $\hat{f}(L)$ closes to $f(L)$. But it requires to be short enough, so that the estimated CIR length is up to date to the current transmission environment. The whole time requirement per estimate of noise variance and CIR length is calculated by $T_E = L_{\text{avg}} \cdot T_S \cdot N_E$ seconds, where T_S is the duration of an OFDM symbol in seconds.

4. CALCULATION OF THE SNR BASED ON THE ESTIMATED NOISE VARIANCE

The aim of this section is to explain how to obtain the SNR for OFDM systems using a conventional channel estimation method [8] when σ_n^2 is estimated.

In OFDM systems, the received signal $\check{R}_{l,i}$ in the frequency domain is given by

$$\check{R}_{l,i} = S_{l,i} H_{l,i} + N_{l,i}, \quad (20)$$

where $S_{l,i}$, $H_{l,i}$, and $N_{l,i}$ are the transmitted pilot symbol, the channel coefficient of the channel transfer function (CTF), and the noise term in the received signal. The index l denotes the subcarrier which carries the pilot symbols.

The estimated channel coefficient $\check{H}_{l,i}$ can be obtained by dividing the received pilot symbol by the transmitted pilot symbol as follows:

$$\check{H}_{l,i} = H_{l,i} + \frac{N_{l,i}}{S_{l,i}}. \quad (21)$$

We denote

$$N_{l,i}^H = \frac{N_{l,i}}{S_{l,i}} \quad (22)$$

as the noise component in the estimated CTF coefficient. This noise component is obtained by the DFT of the sequence $n_{k,i}$, $k = 0, \dots, N_K - 1$. The variance of the noise components in the estimated CTF is

$$\sigma_N^2 = \mathrm{E}[|N_{l,i}^H|^2] = \mathrm{E}\left[\left|\frac{N_{l,i}}{S_{l,i}}\right|^2\right]. \quad (23)$$

It can be proved that σ_N^2 and σ_n^2 have the following relationship [9]:

$$\sigma_N^2 = N_K \cdot \sigma_n^2. \quad (24)$$

The power of the transmitted pilot symbols is denoted by $P_{\text{P}} = \mathrm{E}[|S_{l,i}|^2]$. Since the noise component and the transmitted pilot symbol are statistically independent, it can be deduced from (23) that

$$\sigma_{\text{S}}^2 = \mathrm{E}[|N_{l,i}|^2] = \sigma_N^2 \cdot P_{\text{P}}. \quad (25)$$

The following equation describes the relationship between σ_{S}^2 and σ_n^2:

$$\sigma_{\text{S}}^2 = \sigma_n^2 \cdot N_K \cdot P_{\text{P}}. \quad (26)$$

Finally, the SNR is calculated by

$$\text{SNR} = \frac{P_{\text{S}}}{\sigma_{\text{S}}^2}, \quad (27)$$

where P_{S} is the signal power.

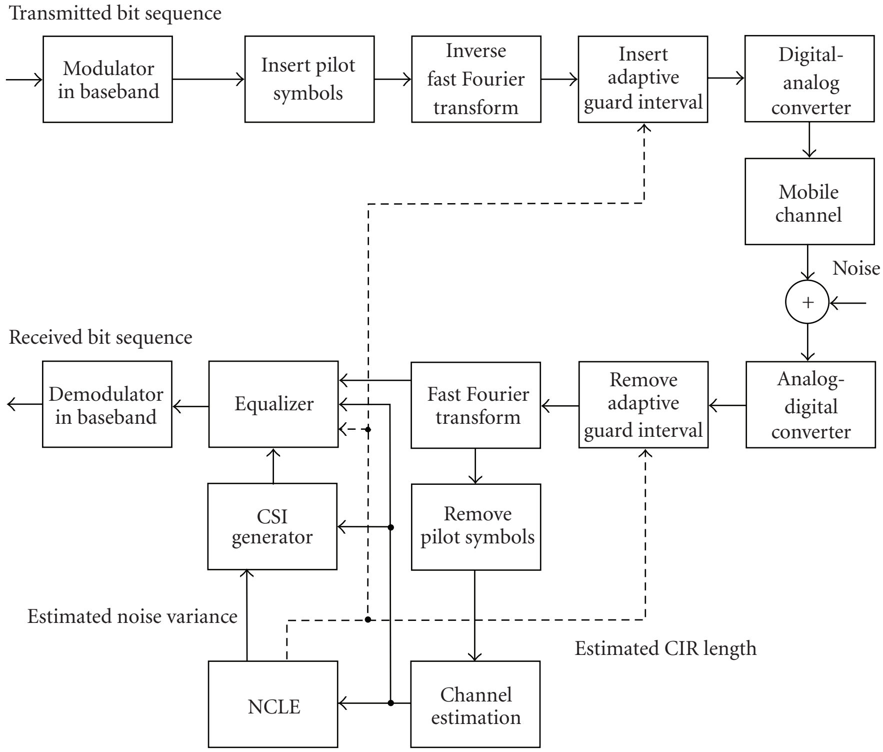

Figure 7: Structure of an OFDM system with adaptive guard interval (illustration in baseband).

5. STRUCTURE OF AN OFDM SYSTEM WITH ADAPTIVE GUARD INTERVAL

Figure 7 shows the structure of an OFDM system with adaptive guard interval, where the NCLE algorithm is applied. So it provides a reliable information of CIR length for both the receiver and the transmitter to adjust the GI length adaptively. Moreover, the estimated noise variance can be used for generation of the channel state information (CSI), which can be exploited to improve channel coding and data equalization performance.

Since the CIR length varies slowly, it is not necessary to adjust the GI length from OFDM symbol to OFDM symbol. So in a time interval, whereby the CIR length does not significantly change, the GI length is kept constant. From this point of view, the synchronization algorithm based on correlation of the guard interval can be applied for the proposed OFDM system as in a conventional OFDM system.

To implement the adaptive GI length concept for broadcasting OFDM systems, a feedback channel is required for signaling the CIR length information from the receiver to the transmitter. However, for network working in time-division duplex (TDD) mode, the estimated CIR length for the downlink channel is equivalent to that for the uplink channel. This is due to the fact that the channel is usually reciprocal in a TDD network. Therefore, when a mobile station or base station is in the receiving mode, it will estimate the CIR length by using the NCLE. The estimated CIR length can be used to control the GI length when it changes to transmitting mode. In this network, the proposed system does not require an additional signaling channel.

Due to the use of the GI, the spectral efficiency of the system and the achievable data rate are reduced by a factor $\eta = T_S/(T_S + T_G)$. The SNR is also reduced by this factor because of the missmatched filtering effect. In the case of the adaptive GI, the factor η changes dependent on the GI length, which is equal to the CIR length. The CIR length depends again on the transmission environment, where the communication pair is located. Thus, the gain of the achievable data rate by applying the adaptive GI technique relates to the location distribution of the active terminals in the network, and their lifetime in each transmission environment. A quantitative gain in terms of data rate can only be estimated for a specified scenario. This gain could be significant for a network covering large areas. In other cases, it could not be significant, because the CIR length does not change significantly.

6. SIMULATION RESULTS

6.1. System parameters and channel model

In our simulation environment, the channel simulated is adopted from the indoor channel model A described in [10]. The OFDM system parameters are taken from the hiperLAN/2 [11]. However, the minimum tap delay (10 nanoseconds) of the channel given in [10] does not match with the sampling interval of the OFDM system ($t_a = 1/B = 50$

Table 1: Discrete multipath channel profile.

Tap index k	Propagation delay τ_k (ns)	Channel tap power $\rho_k = \mathrm{E}[\lvert h_{k,i}\rvert^2]$
0	0	1.0
1	50	0.3714
2	100	0.2445
3	150	$0.155 \cdot 10^{-1}$
4	200	$0.562 \cdot 10^{-1}$
5	250	$0.361 \cdot 10^{-1}$
6	300	$1.343 \cdot 10^{-2}$
7	350	$4.886 \cdot 10^{-3}$
8	400	$2.134 \cdot 10^{-3}$

nanoseconds), and the time spacing between each tap is not uniform. Therefore, the channel model in this paper is established as follows. First, all the channel coefficients which do not coincide with the sampling position of the system are interpolated. Then, the channel coefficients defined in this paper are the channel coefficients of the channel model A [10], if the corresponding positions of these coefficients coincide with the sampling positions of the system. Otherwise, the interpolated coefficients are taken. The channel simulated in this paper is given in Table 1. It consists of 9 taps. Since the distance between two neighbor taps is equidistant, the maximal CIR length N_P is 9 samples, which corresponds to 400 nanoseconds. The variance of the last tap is $\rho_{N_P-1} = 2.134 \cdot 10^{-3}$.

The important OFDM system parameters for simulations are listed as follows:

(i) bandwidth of the system $B = 20$ MHz,
(ii) sampling interval $t_a = 1/B = 50$ nanoseconds,
(iii) FFT length $N_{\mathrm{FFT}} = 64$,
(iv) symbol duration $T_S = 3.2$ microseconds,
(v) guard interval length $T_G = 400$ nanoseconds.

6.2. Comparison of the proposed technique with Larsson's method

In [3], Larsson et al. proposed a method for estimating the CIR length based on the generalized Akaike information criterion (GAIC). The cost function is established by using the transmitted pilot symbols denoted as $\mathbf{p}$ in [3], the received pilot symbols as $\mathbf{r}$, and a factor γ,

$$C(L) = \ln \left\|\mathbf{W}\mathbf{r} - \mathrm{diag}\{\mathbf{p}\}\mathbf{W}\mathbf{h}(L)\right\|^2 + \gamma L, \qquad (28)$$

where $\mathbf{W}$ is the DFT matrix [3]. Similar to the proposed method, L is the presumed CIR length and is assigned to be the number of the pilot symbols N_K in the first step. The presumed CIR length L is decreased step by step till the cost function reaches its minimum value. The factor γ can be interpreted as a penalty factor which is constant and set to be 0.08. The constant penalty factor is the main drawback of Larsson's algorithm. In the proposed algorithm, the penalty factor is the noise variance σ_n^2 which is adaptively estimated

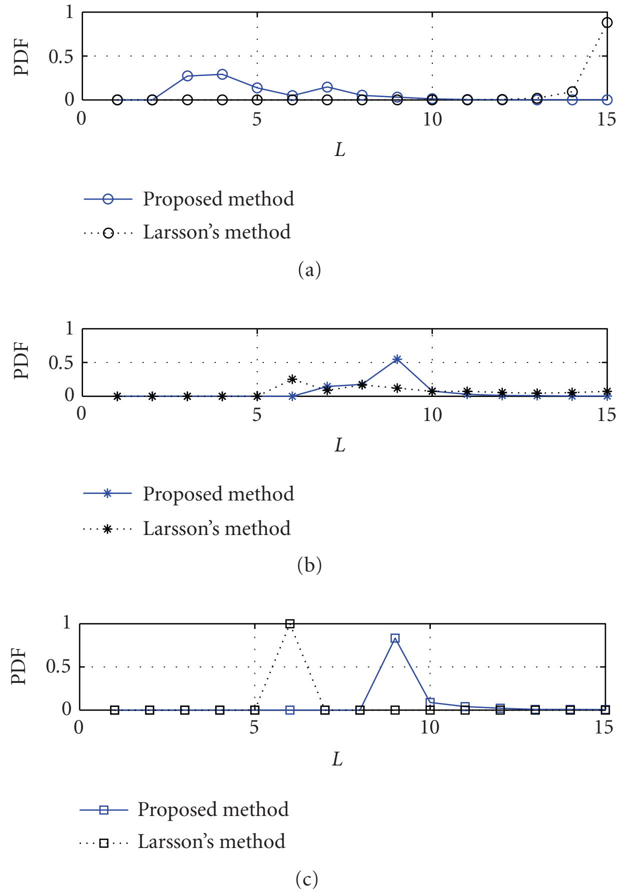

Figure 8: Comparison results of the PDF obtained by Larsson's and proposed methods, true CIR length $N_P = 9$ and (a) SNR = 0, (b) SNR = 10, and (c) SNR = 40 dB.

according to the channel condition. That is the reason why the proposed technique provides quite reliable CIR length information in any range of the SNR. In the case of constant penalty factor and for a given SNR, the CIR length can be underestimated, if this factor is too large than a suitable one. The suitable penalty factor is the one that corresponds to the actual SNR of the system. In other cases, the CIR length can be overestimated. This phenomenon can be observed in the simulation results shown in Figure 8. Larsson et al. reported also in their simulation results that the CIR length is underestimated in most realizations. Their argument for that result is that some last elements of the CIR are usually very small. Beside this argument, there is another reason that the penalty factor γ is selected to be too large for the simulated SNR in [3].

In order just to demonstrate the advantage of the adaptive penalty factor technique, which has been proposed in our algorithm, in comparison with the case of constant penalty factor used in [3], we simplify the auxiliary function as follows:

$$f_i(L) = \sum_{k=0}^{N_K-1} \left|\breve{h}_{k,i} - \tilde{h}_{k,i}^{L}\right|^2 + \sigma_n^2 L. \qquad (29)$$

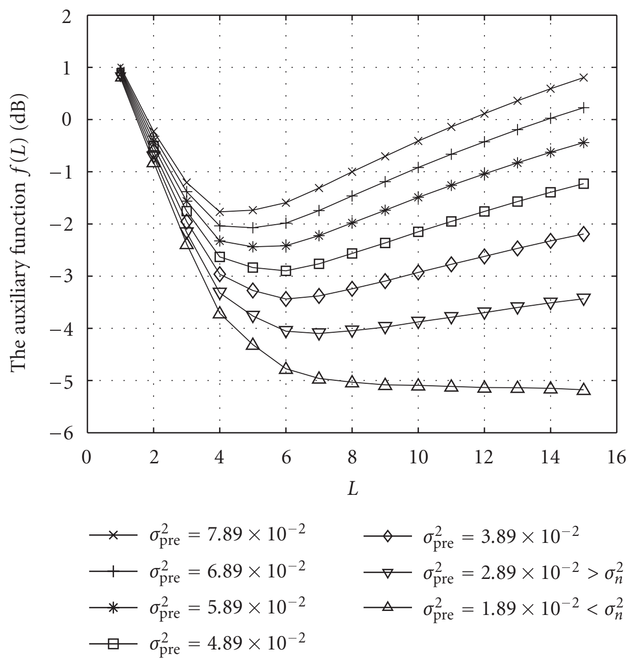

Figure 9: Simulation results of the auxiliary function $f(L)$ in different cases of the presumed noise variance $\check{\sigma}^2_{\text{pre}}$ and with step size $\Delta\sigma^2 = 10^{-2}$.

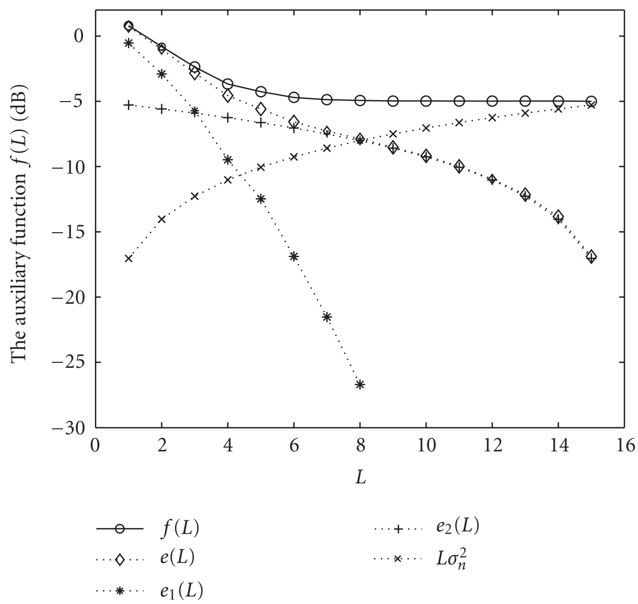

Figure 10: Simulation results of the auxiliary function $f(L)$, provided the noise variance is known (see also (7)).

We do not perform the step of time averaging, that is, $L_{\text{avg}} = 1$, and assume that the noise variance is perfectly known. Under this assumption, the auxiliary function is established in every OFDM symbol. The estimated CIR length corresponds to a value of L that minimizes the auxiliary function.

Comparison results are illustrated in Figure 8. The true CIR length corresponds to 9 sampling intervals ($N_P = 9$). In the case of SNR = 0 dB, the estimated CIR length obtained by Larsson's method in almost all realizations is $N_K - 1$, whereas the proposed technique gives the results in the range of 3 to 9 sampling intervals. In the case of SNR = 10 dB, it is clear to see that the proposed algorithm provides more precise information of CIR length than Larsson's method. This statement can also be verified in the case of SNR = 40 dB. Without time averaging, perfect CIR length information in all realizations cannot be achieved by the proposed algorithm. However, it has been shown that the adaptive penalty factor technique outperforms the constant one. In practice, the penalty factor is not available, and thus needs to be adaptively estimated. In the following, we investigate the performance of the complete proposed technique, which combines CIR length information with the noise variance estimation.

6.3. NLCE performance in dependence on the parameter selection

In the following, we consider a system having an SNR of 5 dB. We assume that the powers of the transmitted signal and the transmitted pilot symbols are normalized. According to (27), the noise variance in the received signal corresponding to 5 dB of SNR is $\sigma^2 = 1/(10^{5/10}) = 0.3162$. According to (26), the noise variance in the estimated CIR is $\sigma^2_n = \sigma^2/(N_K P_P) = 1.976 \cdot 10^{-2}$ (−17.04 dB). To implement the auxiliary function, the step size is set to be an arbitrary value (e.g., $\Delta\sigma^2 = 10^{-2}$). Clearly, this value is relatively larger than the variance of the last channel tap. The averaging length L_{avg} is set to be 1000 OFDM symbols. The presumed noise variance is reduced from $7.89 \cdot 10^{-2}$ to $1.89 \cdot 10^{-2}$, whereas the true noise variance σ^2_n is $1.976 \cdot 10^{-2}$. With this parameter setup, the auxiliary function is plotted in Figure 9. Since the condition of the step size in (10) is not fulfilled, the case (b) in Figure 5 does not occur. The last iteration of the algorithm is found when the presumed noise variance σ^2_{pre} is reduced to $1.89 \cdot 10^{-2}$. The decision on the estimated variance is made in the previous iteration, that is, $\check{\sigma}^2_n = 2.89 \cdot 10^{-2}$. The corresponding estimated CIR length is 7 samples, whereas the true CIR length N_P is 9 samples. In this case, two last taps of the CIR are not detected, and the CIR length is underestimated.

If the auxiliary function is established based on the already known noise variance ($\sigma^2_n = -17.04$ dB), then the case (b) of the auxiliary function appears as shown in Figure 10, where the different terms ($e(L)$, $e_1(L)$, and $e_2(L)$) of the auxiliary function are also plotted. It can be seen that the auxiliary function is monotonously decreasing within the maximal length of the CIR ($L < 9$) and is constant outside the range of the CIR length ($9 \leq L \leq 15$). Since the noise variance is usually unknown, the case (b) does not occur in practice. Nevertheless, a close form of the case (b) might occur if the step size is set to be small enough.

The performance of the NCLE depends on the selection of three parameters: the averaging length L_{avg}, the step size

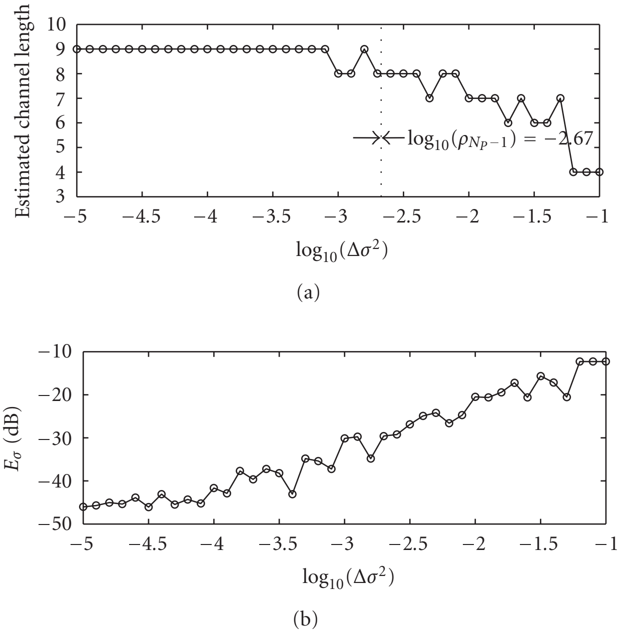

Figure 11: (a) Estimated CIR length $\hat{N}_P$ versus step size, (b) E_σ versus step size.

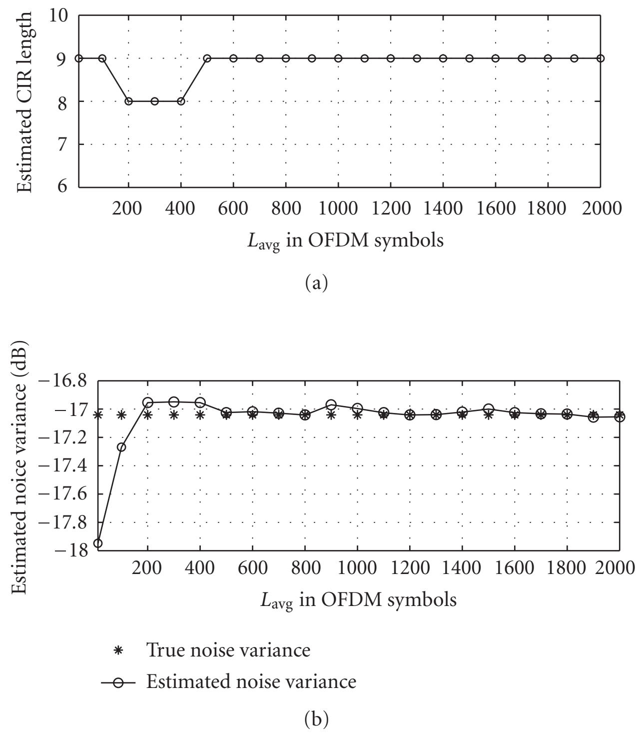

Figure 12: (a) Estimated CIR length $\hat{N}_P$ versus averaging length, (b) estimated noise variance error versus averaging length.

$\Delta\sigma^2$, and the number of experiments N_E. These dependences are considered as follows. First, the step size of the noise variance is varied, while the number of experiments and the averaging length are kept constant, $N_E = 10$, $L_{\text{avg}} = 1000$ OFDM symbols. The corresponding time duration of an estimation is $T_E = N_E \cdot L_{\text{avg}} \cdot T_S = 32$ milliseconds. The initial value of the presumed noise variance is determined according to (18). It can be seen in Figure 11(a) that if the step size $\Delta\sigma^2$ is small enough (less than 10^{-3}), then the CIR length is exactly estimated, that is, $\hat{N}_P = N_P$. To detect the last element of the CIR, according to (10), the selection of the step size must fulfill the following condition: $\Delta\sigma^2 < 2.134 \cdot 10^{-3}$ (or $\log_{10}(\Delta\sigma^2) < -2.67$), where $2.134 \cdot 10^{-3}$ is the last channel tap power of the simulated CIR (see Table 1). In the simulations, the step size should be chosen to be less than 10^{-3} to obtain the estimated CIR length which is equal to the true CIR length. In the range $10^{-3} \le \Delta\sigma^2 < 2.134 \cdot 10^{-3}$, the CIR length is sometimes underestimated. This is due to the fact that the last tap of the CIR has relatively small variance, and therefore it might be neglected in some simulations. When the step size of the noise variance increases, some later are neglected and the estimated CIR length tends to be shorter.

In order to evaluate the accuracy of the estimated variance of the noise components, the difference between the true noise variance and its estimated value $E_\sigma = |\sigma_n^2 - \hat{\sigma}^2|$ versus the step size is plotted in Figure 11(b). It can be confirmed that the smaller the step size is selected, the more accurate the noise variance can be estimated.

Now, the number of experiments and the step size are kept constant, for example $N_E = 10$, and $\Delta\sigma^2 = 10^{-4}$, while the averaging length is varied. It can be seen in Figure 12(a) that if the averaging length is larger than 500 OFDM symbols, then the exact estimated CIR length can be obtained. The corresponding time duration of the estimation is $T_E = N_E \cdot L_{\text{avg}} \cdot T_S = 16$ milliseconds.

The estimated noise variance versus the averaging length is shown in Figure 12(b), where the true noise variance of $\sigma_n^2 = -17.04$ dB is provided for reference. It can be observed that if the averaging length is large enough, then the estimated value converges to the true noise variance.

Finally, the step size and the averaging length are kept constant ($\Delta\sigma^2 = 10^{-4}$, and $L_{\text{avg}} = 1000$), while the number of experiments N_E is varied. The influence of the number of experiments N_E on the estimated CIR length $\hat{N}_P$ is illustrated in Figure 13(a). The simulation results show that the CIR length is exactly estimated after three experiments.

It is important to know up to which SNR level the NCLE algorithm still provides reliable results. This is the aim of the simulation shown in Figure 13(b). The parameters of the NCLE are chosen as follows: $\Delta\sigma^2 = 10^{-4}$, $N_E = 10$. The averaging length L_{avg} is varied. In the case of low SNRs, the channel is strongly impaired. The NCLE algorithm needs therefore a long averaging length to detect the true CIR length. As shown in the simulation results, even though the transmitted signal suffers from 0.0 dB of SNR, the CIR length can be exactly estimated with an averaging length L_{avg} over 2000 OFDM symbols. This is because the characteristics of the auxiliary function $f(L)$ are not dependent on the noise level. The corresponding time delay of the algorithm is $T_E = 64$ milliseconds.

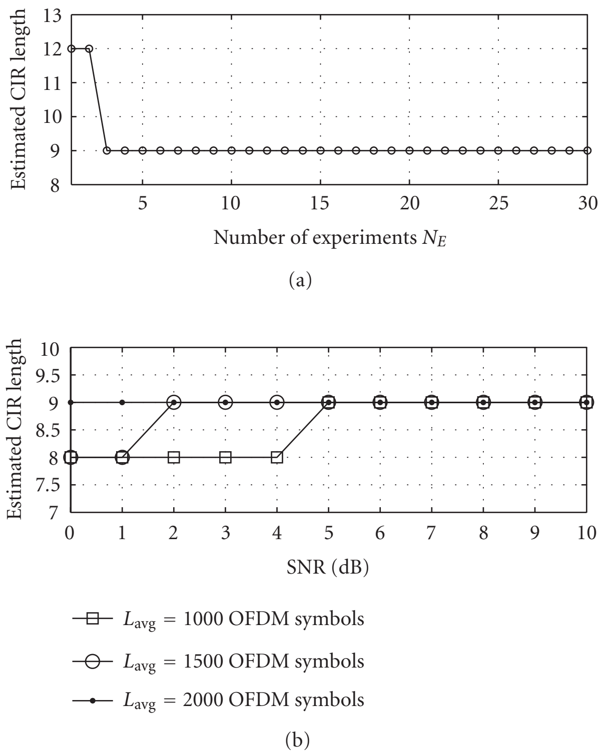

Figure 13: (a) Estimated CIR length $\hat{N}_P$ versus number of experiments N_E, $N_P = 9$, SNR = 5 dB (b) Estimated CIR length $\hat{N}_P$ versus SNR, $N_P = 9$.

The NCLE is also tested in more critical cases. Here, the channel is time-variant, and the system suffers from strong additive noise (SNR = 5 dB). The parameters of the NCLE are set as follows: $L_{\text{avg}} = 1000$, $\Delta\sigma^2 = 10^{-4}$, $N_E = 10$. The simulated channel consists of 9 taps as described above, but now the amplitude of each tap is Rayleigh distributed with Doppler spread $f_{\text{D,max}} = 50$ Hz on each tap. The variance of each tap is therefore time-variant. In this case, the estimated CIR length depends heavily on the variation of the variance of the last tap. If the variance of the last tap is larger than the step size, then this tap can be detected. Otherwise, it might be neglected. As shown in Figure 14, the probability for a correct estimated CIR length is 0.73. Assuming that the averaging length is long enough to obtain an accurate auxiliary function, and the number of experiments is large enough, this probability is also the probability that the variance of the last tap is larger than the step size. The probability that the last two taps are not detected is the probability that the sum of the variances of the last two taps is less than the step size, and so on.

6.4. System performance gain in terms of SER by applying the NLCE

The perpormance of a conventional channel estimation (CE) method proposed in [8] can be improved by applying the NLCE technique. If the CIR length is precisely estimated, the areas outside the true CIR length are regarded as additive noise and can be removed to enhance the CE performance. The improvement of the system performance is demonstrated in Figure 15, whereas the channel estimator with the CIR length information obtained by the NLCE outperforms the conventional one. Moreover, its performance approaches the case of perfect CE.

7. CONCLUSIONS

In this paper, a novel algorithm for CIR length and noise variance estimation has been proposed. The proposed algorithm uses an auxiliary function to distinguish the true CIR length from the estimated CIR. It has been shown by simulation results that this method provides reliable estimation results in terms of the CIR length and the noise variance, even though the OFDM systems suffer from the presence of strong additive noise on a time-variant channel. In addition, the proposed algorithm has low complexity, since its implementation requires no matrix operation. The time delay required for an estimate is significantly less than a second. It calls for a new class of OFDM systems with adaptive GI length, which optimizes the GI length according to the transmission environment. Our future research focuses on the quantitative increase of the data rate which can be gained by the proposed system in comparison with the conventional OFDM systems.

APPENDICES

A. CONDITION OF STEP SIZE TO OBTAIN A PRECISE ESTIMATED CIR LENGTH

As mentioned in Section 3, the step size $\Delta\sigma^2$ should be chosen to be as small as possible to achieve an accurate estimate of the noise variance. But it raises the question of how small the step size must be, to obtain a precise CIR length. This question is solved in the following: observing the case (a) in Figure 5, and taking two special points of $f(L)$ with $L = [L_{f,\min}, N_P]$ into account, the associated values of the auxiliary function are given by

$$f(L_{f,\min}) = \sum_{k=L_{f,\min}-1}^{N_P-1} \rho_k + (N_K - L_{f,\min})\sigma_n^2 + L_{f,\min} \cdot \sigma_{\text{pre}}^2,$$
$$f(N_P) = \sum_{k=N_P-1}^{N_K-1} \rho_k + (N_K - N_P)\sigma_n^2 + N_P \cdot \sigma_{\text{pre}}^2, \quad \text{(A.1)}$$

respectively. From (A.1), the condition $f(L_{f,\min}) < f(N_P)$ is equivalent to

$$\sum_{k=L_{f,\min}-1}^{N_P-1} \rho_k < (N_P - L_{f,\min})\Delta\text{E}, \quad \text{(A.2)}$$

where $\Delta\text{E} = \sigma_{\text{pre}}^2 - \sigma_n^2$. In this case, the last tap numbers $L_{f,\min} + 1, \ldots, N_P - 1$ of the CIR are not detected. In order

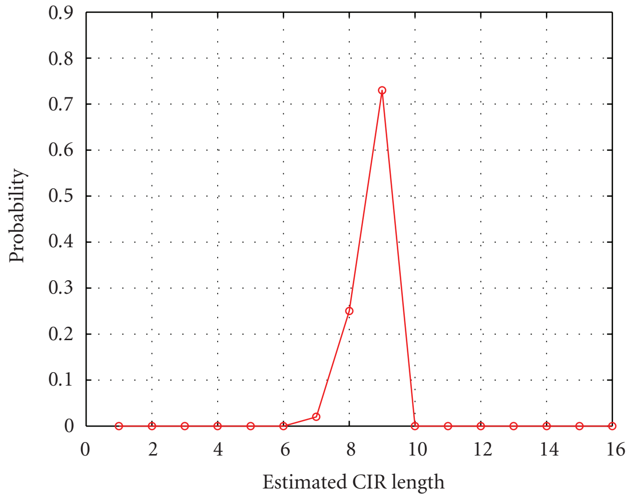

FIGURE 14: Estimated CIR length for a time-variant channel.

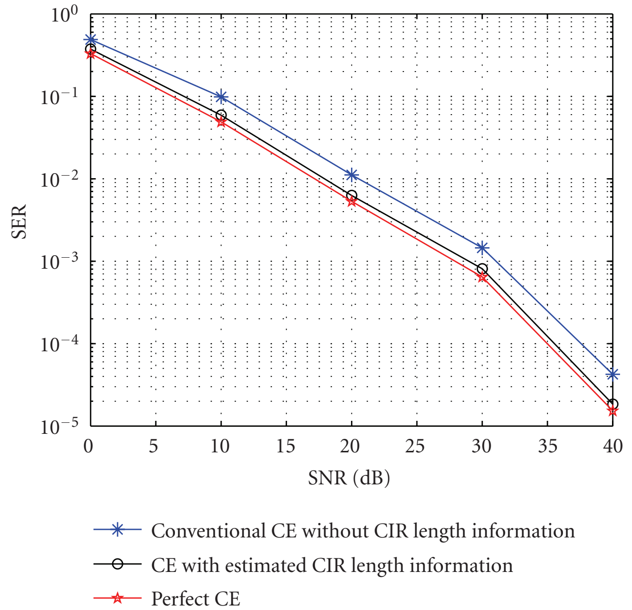

FIGURE 15: System performance gain in terms of SER by using the NLCE.

to detect the position of the last tap of the CIR,[2] that is $\widehat{N}_P = L_{f,\min} = N_P$, the following condition must be fulfilled: $f(N_P - 1) > f(N_P)$. The condition

$$\rho_{N_P-1} > \Delta\mathrm{E} \tag{A.3}$$

follow where ρ_{N_P-1} is the last sample of the delay channel profile. In the NCLE algorithm, if the case (c) of the auxiliary function appears for the first time, the difference of the presumed noise variance and the true noise variance must be smaller than the step size, that is, $\Delta\mathrm{E} < \Delta\sigma^2$. If the following condition fulfills

$$\rho_{N_P-1} > \Delta\sigma^2, \tag{A.4}$$

then the condition in (A.3) is also met. Equation (10) shows the condition of the step size to obtain a precise estimation of the CIR length.

B. PROBABILITY FOR AN EXACT ESTIMATED CIR LENGTH

The total number of the event

$$\widehat{N}_P^{(s)} = N_P, \tag{B.1}$$

which happens r times in any order of N_E independent experiments, is the total number of the event that the vector $\vec{\mathcal{L}}$ contains r elements having the value of N_P. According to Bernoulli trials [12], this total number is

$$\binom{N_E}{r} = \frac{N_E!}{r!(N_E - r)!}. \tag{B.2}$$

[2] The last tap of the CIR corresponds to the tap which has maximum propagation delay.

Assuming that the noise variance is perfectly estimated, $\widehat{N}_P^{(s)}$ takes a random value in the range of $[N_P \to N_K - 1]$. Therefore, the probability for the occurrence of the event $\widehat{N}_P^{(s)} = N_P$ is $p = 1/(N_K - N_P - 1)$. It follows that the probability for r times of the occurrence of the event $\widehat{N}_P^{(s)} = N_P$ in any order is calculated by

$$P\{\text{the event } L_{f,\min}^{\mathrm{I}} = N_P \text{ occurs } r \text{ times in any order}\} = \binom{N_E}{r} p^r q^{N_E - r}, \tag{B.3}$$

where $q = 1 - p$. Since $\widehat{N}_P = \min[\widehat{N}_P^{(1)}, \widehat{N}_P^{(2)}, \ldots, \widehat{N}_P^{(N_E)}]$, the event that $\widehat{N}_P = N_P$ occurs if there is at least one element of $\mathcal{L}$ which is equal to N_P. The corresponding probability for the occurrence of the event $\widehat{N}_P = N_P$ is given by

$$P\{\widehat{N}_P = N_P\} = \sum_{r=1}^{N_E} \binom{N_E}{r} p^r q^{N_E - r}. \tag{B.4}$$

Considering the case where the number of experiments N_E is large enough, that is $N_E \cdot p \cdot q \gg 1$, the right-hand side of (B.4) can be approximated by [12]

$$\sum_{r=1}^{N_E} \binom{N_E}{r} p^r q^{N_E - r} \approx \frac{1}{\sigma\sqrt{2\pi}} \int_1^{N_E} \mathrm{e}^{-(x - N_E p)^2/2\sigma^2} dx, \tag{B.5}$$

where $\sigma^2 = n \cdot p \cdot q$. By a suitable substitution, the right-hand side of (B.5) can be written as [12]

$$\frac{1}{\sigma\sqrt{2\pi}} \int_1^{N_E} \mathrm{e}^{-(x - N_E p)^2/2\sigma^2} dx = \frac{1}{\sigma\sqrt{2\pi}} \int_{1 - N_E \cdot p}^{N_E - N_E \cdot p} \mathrm{e}^{-(t)^2/2\sigma^2} dt. \tag{B.6}$$

If $N_E \cdot p$ tends to ∞, that is, $N_E \rightarrow \infty$, then the right-hand side of (B.6) is close to one. It can be concluded that

$$\lim_{N_E \cdot p \rightarrow \infty} P\{\hat{N}_P = N_P\} \longrightarrow 1. \quad \text{(B.7)}$$

The result in (B.7) states that if the number of experiments is sufficiently large, then the probability of an exact estimation of the CIR length approaches one.

Example for our simulated channel

The CIR length of our channel is $N_P = 9$. The length of estimated CIR is $N_K = 16$. The number of experiments is $N_E = 20$. It follows that $p = 1/6$ and $q = 5/6$. According to (B.4), the probability of an exact estimated CIR length is

$$P\{\hat{N}_P = N_P\} = \sum_{r=1}^{20} \binom{20}{r} \left(\frac{1}{6}\right)^r \left(\frac{5}{6}\right)^{20-r} = 0.9739. \quad \text{(B.8)}$$

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