Robust Decision Feedback Equalizer for OFDM System under Severe ISI Channel

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Received February 10, 2014; revised April 3, 2014; accepted April 26, 2014; published June 27, 2014

Abstract

Inter-symbol interference (ISI) problem is inevitable when the guard interval (GI) is shorter than the delay spread (DS) for an orthogonal frequency division multiplexing (OFDM) system. Iterative techniques have been proposed to overcome such a problem. However, most of existing algorithms are not efficient for an OFDM system with a small GI working under the channel with a large DS. Especially in the case of the DS spans a longer time than the half of the OFDM symbol duration. On the other hand, conventional algorithms, which can reduce the effects of the severe ISI, often employ several impractical assumptions to support the conclusions. In this paper, we present a robust decision feedback equalizer (DFE) for the OFDM system to overcome the severe ISI problem. The proposed DFE removes the ISI in a same manner as the residual inter-symbol interference cancellation (RISIC) algorithm. However, the inter-carrier interference (ICI) is reduced via cyclicity removal instead of the cyclicity restoration used in the conventional algorithms. The link-level simulation (LLS) results indicate that our proposed DFE scheme can dramatically improve the BER performance when the DS spans longer than the half of ODFM symbol duration.

Keywords: DFE, OFDM, ISI, ICI, cyclicity removal.

This work was supported by the MSIP(Ministry of Science, ICT and Future Planning), Korea, under the ITRC(Information Technology Research Center) support program (NIPA-2014-H0301-14-1042) supervised by the NIPA(National IT Industry Promotion Agency), and (10044540, Development of small cell base station supporting IMT-Advanced TDD radio technology for evolution of TDD network).

http://dx.doi.org/10.3837/tiis.2014.06.006

1. Introduction

OFDM system performance degrades severely when the length of guard interval (GI) is not sufficient to eliminate the effects of delay spread (DS). Therefore, an OFDM system with a small GI cannot perform well in the environments with a comparatively large DS. For example, the IEEE 802.11p (WAVE) OFDM system uses 64 subcarriers, including 48 data carriers, 4 pilots, and 11 virtual carriers, which occupy a channel bandwidth of 10 MHz [1]. In this case, among 80 samples of one OFDM symbol, the GI uses 16 samples covering 1.6 μs and the fast Fourier transform (FFT) interval holds 64 samples expending 6.4 μs. However, the measured channel with the DS of several microseconds in [2] and [3] inevitably leads the WAVE system into a severe inter-symbol interference (ISI) environment, where the length of the DS is usually longer than half of the symbol duration. Along with the ISI, the inter-carrier interference (ICI) that arises from the loss of the sub-channel orthogonality in an OFDM symbol is known to limit the performance of the system. Simply increasing the length of GI in order to reduce the ISI, however, results in drawbacks due to the tradeoff regarding the spectral efficiency.

Iterative techniques have been proposed in order to overcome the problem of GI insufficiency [4]-[11]. Let D and G represent the length of DS and GI in unit of OFDM sample, respectively. The RISIC algorithm presented in [4] and RISIC-based algorithms [5]-[11] are effective when the $(D-G)$ difference is moderate. However, as the difference becomes larger, they cannot obtain a reliable signal in its initial step for the iteration, thereby causing degradation in the bit-error-rate (BER) performance. In [8], a reconstruction procedure of the cyclic prefix is proposed to restore the cyclicity of the i-th received symbol by adding the weighted (i+1)-th received symbol to the i-th received symbol. Hence, it can obtain a reliable estimation of the i-th transmitted symbol before the first iteration that mitigates the problem caused by the increased $(D-G)$. The simulation results show that this procedure can maintain the system performance effectively as the D is incremented up to 55% of the symbol duration. However, several impractical assumptions are made in [8], including that the ISI removal is perfect and the noise is negligible. As is known, the ISI becomes severe with the DS increment, which leads to inaccurate symbol estimation. It is also known that the required signal for the cyclicity reconstruction of the i-th received symbol cannot be easily found in the first $(D-G)$ samples, which are already severely affected by ISI, of the (i+1)-th received symbol. Therefore, we conclude that the cyclicity of the i-th symbol cannot be easily reconstructed by adding the weighted (i+1)-th received symbol to the i-th received symbol due to the severe ISI. In this paper, we modify the RISIC scheme using several strategies which enable the modified RISIC (M-RISIC) to work efficiently under the severe ISI scenario.

The proposed decision feedback equalizer (DFE) in this paper removes the ISI in a same manner as the RISIC [4]-[11]. However, the ICI is reduced via cyclicity removal instead of the cyclicity restoration used in [4]-[11]. Additionally, the hard decision block (HDB) in the frequency-domain is implemented for the decision on frequency-domain symbol sequence associated with correct constellation positions. The usage of the hard decision can prevent the outputs from the error propagations of which are fed back to the outer and inner loops. According to the simulation results, we verify that the proposed DFE outperforms the conventional RISIC in terms of the BER performance with a less number of iterations, e.g., 3. And compared with scheme in [8] as mentioned above, the proposed M-RISIC is more practical since it is suggested without the assumptions of ISI perfect removal and no additive noise.

The rest of this paper is orgnized as follows. In section 2, the system model is described. Section 3 illustrates the proposed M-RISIC along with the discussion of the realiability. The link level simulation (LLS) results of the M-RISIC are given and discussed in Section 4. And finally, we conclude this paper in section 5.

2. System Model

Throughout this paper, a perfect channel estimation by using the preamble is assumed. We use an OFDM packet, which is composed of a preamble and several OFDM data symbols, for the investigation of the proposed M-RISIC. Let p_k and P_k denote the preamble in the time and frequency-domain, respectively. The N-point inverse fast Fourier transform (IFFT) output sequence for the preamble is given by

$$p_k = \frac{1}{\sqrt{N}}\sum_{k=0}^{N-1} P_k \exp\left(j\frac{2\pi nk}{N}\right), \quad 0 \le k \le N\text{-}1\,. \tag{1}$$

where k denotes the sample index. In addition, let $x_{i,k}$ and $X_{i,k}$ denote the i-th OFDM data symbol of the packet in the time and frequency-domain, respectively. The N-point IFFT output sequence is calculated as

$$x_{i,k} = \frac{1}{\sqrt{N}}\sum_{k=0}^{N-1} X_{i,k} \exp\left(j\frac{2\pi nk}{N}\right), \quad 0 \le k \le N\text{-}1. \tag{2}$$

By (1) and (2), $\{P_k\}_{k=0}^{N-1}$ and $\{X_{i,k}\}_{k=0}^{N-1}$ represent the frequency-domain symbol sequences with FFT size of N. If the GI is a cyclic extension of the IFFT output sequence, then the IFFT output sequence with the addition of the GI are

$$p_k^g = p_{(k+N-G)_N}, \quad 0 \le k \le N+G-1, \tag{3}$$

$$x_{i,k}^g = x_{i,(k+N-G)_N}, \quad 0 \le k \le N+G-1, \tag{4}$$

where G is the length of the GI in the unit of sample, and $(k)_N$ is the residue of the k modulo N. Sequences of $\{p_k^g\}_{k=0}^{N+G-1}$ and $\{x_{i,k}^g\}_{k=0}^{N+G-1}$, where '$g$' represents the signal after GI extension, are then passed through a digital-to-analog (D/A) converter at a sampling frequency of $1/Ts$. And Ts is the sample duration of the OFDM signal.

By assuming the channel impluse response (CIR) is constant over a packet period, the received preamble $\tilde{p}_k^g$ and the i-th OFDM symbol $r_{i,k}^g$ at Rx in the time-domain then can be represented as

$$\tilde{p}_k^g = \sum_{k=0}^{K-1} h^m(D^m) * p_k^g + n_k, \tag{5}$$

$$r_{i,k}^g = \sum_{k=0}^{K-1} h^m(D^m) * x_{i,k}^g + n_k, \tag{6}$$

where * is the notation of convolution, h^m $(m = 1, 2, 3, \ldots, M)$ refers the *m*-th CIR with the DS of D^m in the time-domain and n_k denotes the additive white Gaussian noise (AWGN) at the *k*-th sample. The GI is then removed from the received signal to obtain $\tilde{p}_k$ and $r_{i,k}$, which will be converted back to the frequency-domain via FFT operation for subsequent demodulation processes in an OFDM system.

3. The Proposed M-RISIC Algorithm

To obtain the desired system output along with the residual ISI, two steps are proposed in the time-domain of the RISIC algorithm [4]. The first step is to remove the residual ISI from the previously received OFDM symbol, and the second step is to use reconstruction to restore the cyclicity in order to avoid the ICI. These two steps are called tail cancellation and cyclicity restoration, respectively. The overall procedure of RISIC algorithm can be described as (7), where the residual ISI, denoted as the second term, is removed from the received signal sequence $\{r_{i,k}\}_{k=0}^{N-1}$ before the iteration process. Cyclicity, on the other hand, is restored by the last term in (7) to avoid ICI via the iteration process.

$$\hat{r}_{i,k} = r_{i,k} - \sum_{k=N-C^m}^{N-1} h^m(D^m) * x_{i-1,k} + \sum_{k=0}^{C^m-1} h^m(D^m) * x_{i,k}. \tag{7}$$

Fig. 1 illustrates an example of a two-path channel model with the ISI. According to **Fig. 1**, the residual ISI exists in the tail, which spans from the $(N-1-C^m)$-th to the $(N-1)$-th samples, of the $(i\text{-}1)$-th OFDM symbol from the second path. Here, $C^m = D^m - G$. And, the ICI comes from the first to $(N - C^m)$-th samples of the *i*-th OFDM symbol on the second path.

In the conventional algorithms [4]-[11], the last term in (7) tries to restore the cyclicity of the *i*-th OFDM symbol by adding the estimated sequence, i.e., from the first to $(C^m - 1)$-th samples of the *i*-th OFDM symbol, via the iteration process. However, as illustrated in **Fig. 1**, if the DS value D^m increases, the length of the estimated sequence is extended since the value of C^m becomes larger. It inevitably brings more errors into the initial step before the iteration. In M-RISIC, we modify RISIC by performing cyclicity removal (i.e., directly subtracting ICI of *i*-th symbol from the second path as illustrated in **Fig. 1**) instead of cyclicity reconstruction to restore the cyclicity of the *i*-th OFDM symbol. Thus, (7) is modified as

$$\hat{r}_{i,k} = r_{i,k} - \sum_{k=N-C^m}^{N-1} h^m(D^m) * x_{i-1,k} - \sum_{k=0}^{N-C^m-1} h^m(D^m) * x_{i,k}, \tag{8}$$

which indicates that the ICI, i.e., from the first to the ($N - C^m - 1$)-th samples, of the i-th OFDM symbol in delayed paths should be removed by the last term of (8).

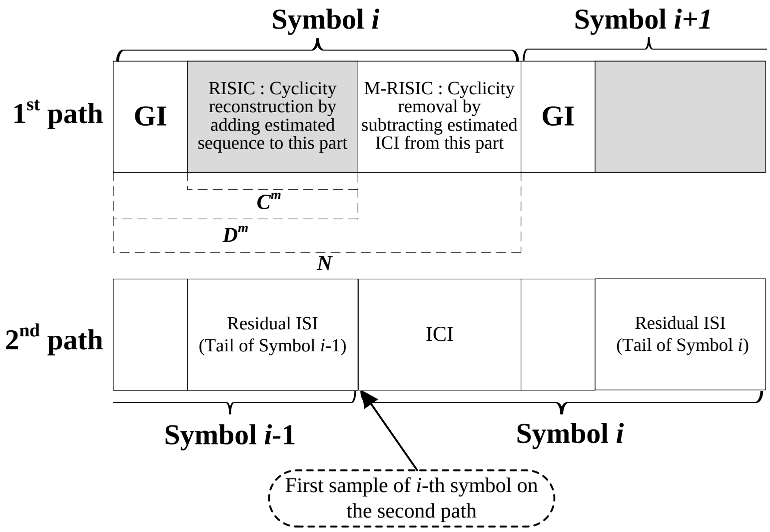


Fig. 1. An example of a two-path channel model with the ISI.

A. Discussion on Reliability of RISIC and M-RISIC

In this part, the reliability of the RISIC and M-RISIC algorithms are analyzed according to the iteration procedure, which refers the steps of ICI iterative cancellation in RISIC-based algorithms.

1) Before the iteration procedure

The amount of the ISI for both RISIC and M-RISIC are same, and they are removed by the second terms in (7) and (8), respectively. The difference between (7) and (8) comes from their last term. That is, according to [8], the estimation error fed into the loops of iteration is proportional to the length of estimated sequence. When the condition of $C^m > (N-G)/2$ is fulfilled, the estimation error of the RISIC algorithm is more than the M-RISIC algorithm since the length of estimated sequence of the former is longer than the latter. The estimation error for both algorithms are same when $C^m = (N-G)/2$ is fulfilled, and the estimation error of the proposed M-RISIC is more than the RISIC when $C^m < (N-G)/2$. Thus, we can obtain a relationship between the estimation error and C^m based on the last term of (7) and (8) as

$$\begin{cases} \textit{estimation error}_{\text{RISIC}} > \textit{estimation error}_{\text{M-RISIC}}, & C^m > (N-G)/2 \\ \textit{estimation error}_{\text{RISIC}} = \textit{estimation error}_{\text{M-RISIC}}, & C^m = (N-G)/2 \\ \textit{estimation error}_{\text{RISIC}} < \textit{estimation error}_{\text{M-RISIC}}, & C^m < (N-G)/2 \end{cases} . \tag{9}$$

2) After the iteration procedure

In the perspective of the desired power of $\hat{r}_{i,k}$, the RISIC uses the cyclicity restoration to save the desired power of the delayed path, while the M-RISIC subtracts the effect of the delay path. Therefore, compared with the RISIC, the proposed M-RISIC is not SNR efficient. However, as is known, the key condition affecting the performance is the amount of error fed into the iteration process. If an accurate estimated sequence $\{\hat{R}_{i,k}^{(I)}\}_{k=0}^{N-1}$ shown in **Fig. 2** cannot be obtained, the power of the delayed paths becomes the interference that degrades the system performance.

According to the analysis above, we can conclude that the proposed M-RISIC is a robust iteration algorithm for an OFDM system which can perform well when the DS spans longer than the half of the OFDM symbol duration.

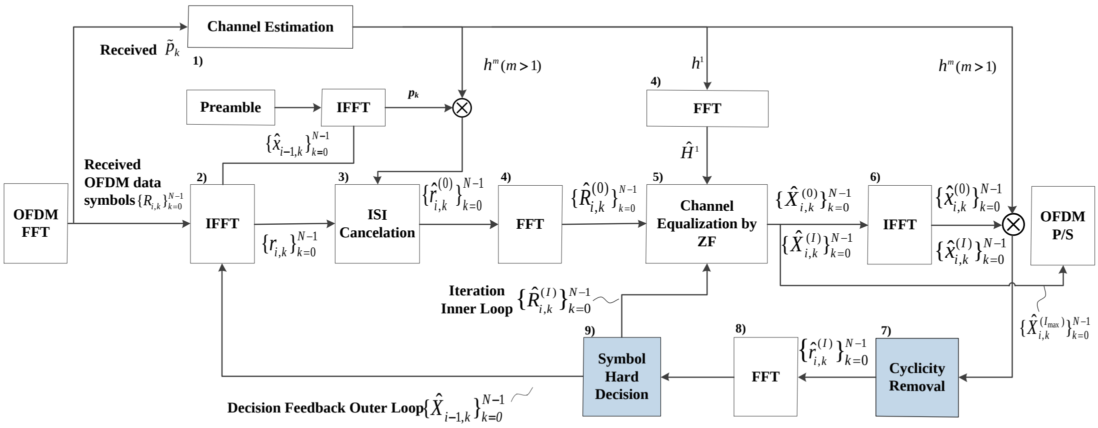


Fig. 2. DFE structure of the M-RISIC algorithm.

B. The Operation Procedures of the Proposed M-RISIC

In order to overcome the severe ISI problem, we modify the RISIC algorithm as shown in **Fig. 2**, where the modified blocks are filled by color. The details are described as follows:

1) A perfectly channel estimation is assumed. And, the first block in **Fig. 2** is assumed to have the preambles which are used for the removal of residual ISI in the information symbols.

2) At the receiver, after the GI removal and FFT process, decisions regarding the transmitted samples $\{\hat{X}_{i-1,k}\}_{k=0}^{N-1}$ on symbol (*i-1*) are obtained and converted back to the time-domain by using IFFT, given as $\{\hat{x}_{i-1,k}\}_{k=0}^{N-1}$, for use in the tail cancellation.

3) For the *i*-th symbol, the M-RISIC performs its tail cancellation by calculating the residual ISI and subtracts it from $\{r_{i,k}\}_{k=0}^{N-1}$ via the second term of (8) to obtain $\{\hat{r}_{i,k}^{(0)}\}_{k=0}^{N-1}$, where '(0)' represents the state before the iteration.

4) The $\{\hat{r}_{i,k}^{(0)}\}_{k=0}^{N-1}$ obtained in Step 3 and h^1 are converted to the frequency-domain as $\{\hat{R}_{i,k}^{(0)}\}_{k=0}^{N-1}$ and H^1, respectively.

5) Then, the zero forcing (ZF) strategy can be used for the frequency-domain channel equalization to make the decisions on $\{\hat{X}_{i,k}^{(0)}\}_{k=0}^{N-1}$.

6) Afterwards, the decisions are converted back to the time-domain as $\{\hat{x}_{i,k}^{(0)}\}_{k=0}^{N-1}$.

7) The ICI is generated by convolution of $\{\hat{x}_{i,k}^{(0)}\}_{k=0}^{N-1}$ and h^m in the time domain, and the cyclicity removal is performed as the third term of (8) by subtracting the ICI from $\{\hat{r}_{i,k}^{(0)}\}_{k=0}^{N-1}$. This step mitigates the ICI in the received symbol and yields $\{\hat{r}_{i,k}^{(I)}\}_{k=0}^{N-1}$, where I represents an iteration number with an initial value of I = 1.

8) Then $\{\hat{r}_{i,k}^{(I)}\}_{k=0}^{N-1}$ is converted to the frequency-domain as $\{\hat{R}_{i,k}^{(I)}\}_{k=0}^{N-1}$.

9) In **Fig. 2**, the last block is the proposed hard decision block (HDB) in the frequency-domain. The HDB is implemented for the decision on frequency-domain symbol sequence $\{\hat{R}_{i,k}^{(I)}\}_{k=0}^{N-1}$ associated with correct constellation positions. The usage of the hard decision can prevent the outputs from the error propagations of which are fed back to the outer and inner loops in **Fig. 2**. This block completes the I-th iteration in the M-RISIC algorithm.

10) For further iterations, convert the $\{\hat{R}_{i,k}^{(I)}\}_{k=0}^{N-1}$ to $\{\hat{r}_{i,k}^{(I)}\}_{k=0}^{N-1}$ and repeat Steps 5 to 9 with I replaced by (I + 1). Note that, when the iteration is done, i.e., $I = I_{max}$, the equalized decisions $\{\hat{X}_{i,k}^{(I_{\max})}\}_{k=0}^{N-1}$ are the output of M-RISIC, which will be forwarded to the OFDM parallel-to-serial (P/S) block for further demodulation.

C. Combination of RISIC and M-RISIC Algorithms

Since the performances of RISIC and the proposed M-RISIC are related with the difference of $(D-G)$, i.e., C^m, we further suggest a DFE system with the combination of the RISIC and the M-RISIC algorithms. That is, the selection on DFE algorithm for an OFDM system to overcome the effect of ISI should be based on the estimated value of C^m. **Fig. 3** shows the function of the suggested DFE structure associated with the combination of the RISIC and M-RISIC algorithms.

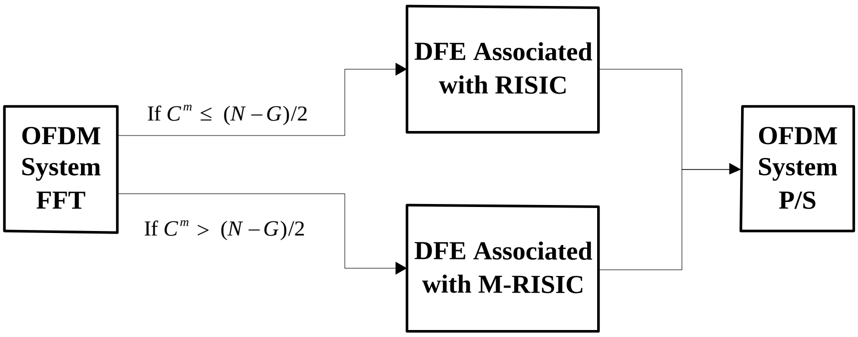


Fig. 3. DFE structure with the combination of the RISIC and M-RISIC algorithms at the receiver.

4. Performance Verification of M-RISIC

A. Simulation Environment

The details of the WAVE OFDM system parameters under test are described in **Table 1**. We consider a scenario of [2] where the first path is a Rician distributed path generated by the line-of-sight (LOS) component, and the second is a Rayleigh distributed path generated by the non-LoS component. With the assumption that each path is constant over a packet period, the mathematical channel modeling is given by

$$g_k(t) = \underbrace{\sqrt{\frac{R}{R+1}}\left[\sqrt{\frac{K_f}{K_f+1}} + \sqrt{\frac{1}{K_f+1}}h_k^1(t)\right]}_{\text{Rician path } (h^1)}\delta(t) + \underbrace{\left[\sqrt{\frac{1}{R+1}}h_k^2(t)\right]}_{\text{Rayleigh path } (h^2)}\delta(t-D)\ , \tag{10}$$

where $h_k^1(t)$ and $h_k^2(t)$ are two independent Rayleigh distributions. $h_k^1(t)$ is used to generate the Rician path by the K-factor (K_f). R is the relative power decay of the Rayleigh path, and D is the relative delay of the Rayleigh path to the first LOS path. Note that the delay of the Rayleigh path was set to 5 μs, which spans 62.5% of the OFDM symbol duration.

Moreover, we set the maximum relative mobility between the transmitter and the receiver as 50 Km/h, and they communicate in an SISO transceiver manner.

Table 1. Link-level Simulation Parameters

ODFM System Parameters	Value
Carrier Frequency	2.075 GHz
Bandwidth	10 MHz
Sampling Duration (T_s)	0.1 μs
Subcarrier Spacing	156.25 kHz
FFT Size (N)	64
Effective OFDM Symbol Duration (N*T_s)	6.4 μs
GI Duration (G*T_s)	1.6 μs
OFDM Symbol Duration	8 μs
Packet Size	1 Preamble + 10 Data Symbols
Convolutional Coding	Coding Rate: 1/2 Constraint Length : 7
Modulation	QPSK
Antenna Configuration	SISO

Channel Model Parameters	**Value**
Nr. of Paths	2 (LOS & Non-LOS)
Rician *K*-factor (K_f)	9 dB
Rayleigh Path Power Decay	6 dB
Second Path Delay	5 μs (62.5% of OFDM Symbol)
Mobility	50 Km/h

B. Performance Verification

We compare the link-level performances of the RISIC and M-RISIC algorithms, where both of them work associated with the perfect time-domain channel estimation. **Fig. 4** shows the BER performances of the RISIC and M-RISIC. According to the figure, we observe that the WAVE with 1-tap frequency-domain equalizer (FDE) has the highest BER under severe ISI condition, where the error floor continues around 10^{-2}. The RISIC yields a higher BER compared with the proposed M-RISIC when the DS spans 62.5% of the OFDM symbol duration. And the proposed M-RISIC can achieve the target BER of 10^{-4} with the I_{max} equaling to three.

Fig. 4 also shows the efficiency of the proposed HDB, and the gain of SNR is obtained when the HDB is implemented. For example, 0.6dB gain is achieved in the case of RISIC with the HDB at target BER of 10^{-2}. And 0.5dB SNR loss at the target BER of 10^{-3} if no HDB is used in the M-RISIC. In addition, the lower bound curve obtained by using a large I_{max} value, (e.g., 50) for the M-RISIC is given as a comparison. Note that, when the packet size increases, the DFE performances inevitably become worse due to the error propagation. This is because the current symbol is determined based on the previous one.

For further comparison on the RISIC and M-RISIC with various DS values, we fix Eb/N0 as 15 dB and observe the BER performance based on the different channel DS. According to **Fig. 5**, we observe that the performance of RISIC algorithm is better than M-RISIC when the ratio less than or equal to 0.5, i.e., the channel DS spans less than or equal to 50% of the OFDM symbol duration. And the performance of RISIC algorithm becomes worse when the ratio is larger than 0.5, which validates our reliability analysis in Section 3. At the ratio of 0.5, RISIC outperforms M-RISIC mainly due to that RISIC is SNR efficient by saving power of the delayed path. Therefore, the combination of the RISIC and M-RISIC can adaptively choose the cyclicity restoration or cyclicity removal scheme to reduce the amount of estimation error based on C^m.

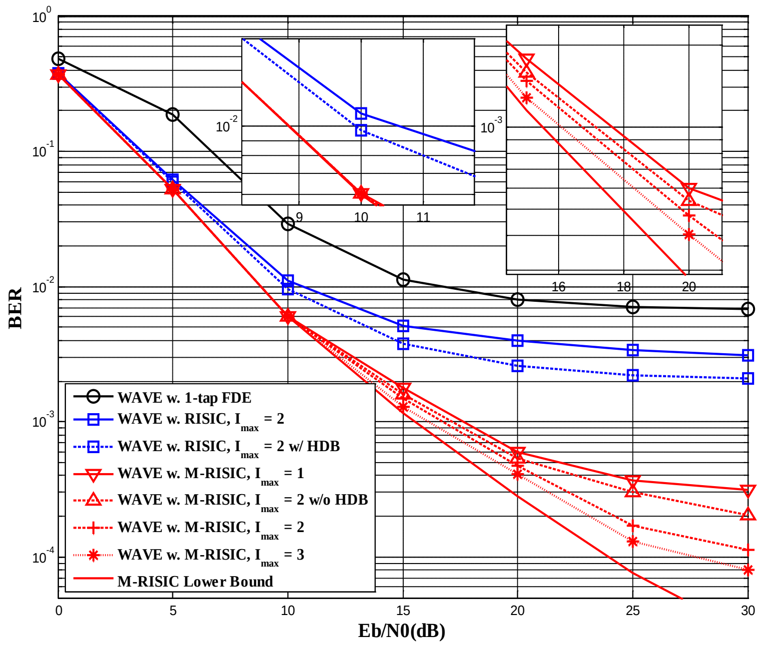


Fig. 4. BER performance of the WAVE with RISIC and M-RISIC.

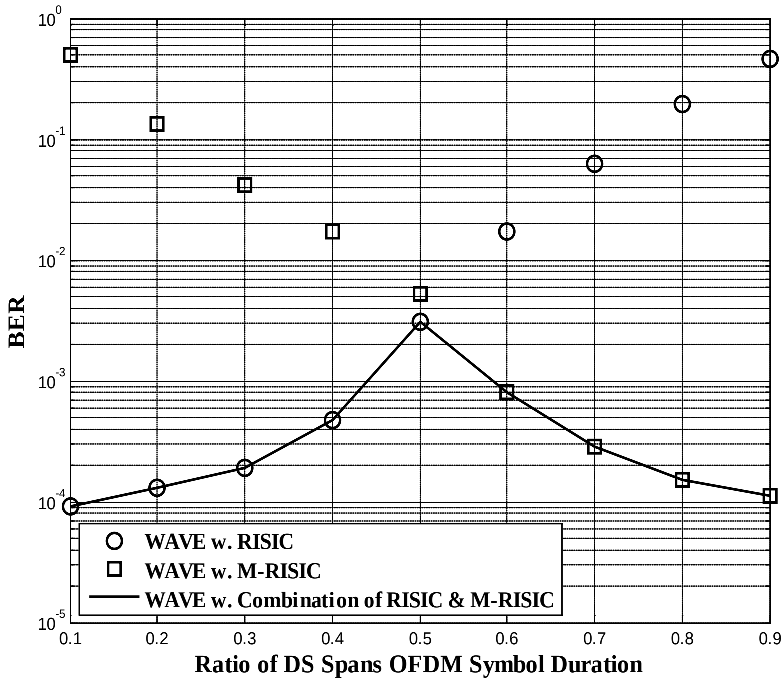


Fig. 5. BER performance at the different channel DS span.

5. Conclusions

The main contribution of this paper is that we propose a robust DFE structure for OFDM systems in order to overcome the effect of severe ISI channel. By implementing several strategies, such as cyclicity removal and symbol hard decisions in the M-RISIC, our proposed receiver structure can achieve the target BER with less number of iterations compared with the conventional algorithm. When the HDB is implemented, additional SNR gain can be achieved under the channel having a comparatively larger delay spread, e.g., spanning 62.5% of an OFDM symbol duration. In addition, by the algorithm reliability analysis, the selection of DFE for the OFDM system should be based on the index of C^m. Referring the BER performances of RISIC and M-RISIC, though the M-RISIC outperforms RISIC when the DS spans a longer time than half of OFDM symbol duration, there exists tradeoff between DS and the performance. Thus, the RISIC and M-RISIC can be adaptively selected to maintain the system performance.

References

[1] IEEE Std. 802.11-2007, Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications, June, 2007. Article (CrossRef Link)

[2] ETSI TR 102 580 (V1.1.1), Technical report: Terrestrial trunked radio (TETRA); Release 2; Designer's guide; TETRA high-speed data (HSD); TETRA enhanced data service (TEDS), 2007. Article (CrossRef Link)

[3] K. Yang, T. Roste, F. Bekkadal, and T. Ekman, "Channel characterization including path loss and Doppler effects with sea reflections for mobile radio propagation over sea at 2 GHz," in *Proc. of WCSP Int. Conf.*, pp. 1-6, Oct. 2010. Article (CrossRef Link)

[4] D. Kim and G. L. Stuber, "Residual ISI Cancellation for OFDM with application to HDTV broadcasting," *IEEE Journal on Selected Areas in Communication*, vol. 16, no. 8, pp. 1590-1599, Oct. 1998. Article (CrossRef Link)

[5] Z. Yang, W. Bai, and Z. Lin, "A decision-aided residual ISI cancellation algorithm for OFDM systems," in *Proc. of ICOSP Int. Conf.*, pp. 20-23, Nov. 2006. Article (CrossRef Link)

[6] Z. Yang, W. Bai, and Z. Lin, "A novel residual ISI cancellation for OFDM system with applications to wireless LAN," in *Proc. of IET Int. Conf.*, pp. 1-4, Nov. 2006. Article (CrossRef Link)

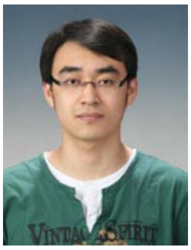
[7] W. Zhong and Z. G. Mao, "Efficient time-domain residual ISI cancellation for OFDM-based WLAN systems," *IEEE Trans on Consumer Electronic*, vol. 52, no. 2, pp. 321-326, May 2006. Article (CrossRef Link)

[8] C. Park and G. Im, "Efficient cyclic prefix reconstruction for coded OFDM systems," *IEEE Communications Letters*, vol. 8, no. 5, pp. 274-276, May, 2004. Article (CrossRef Link)

[9] J Zhu, W. Ser, A. Nehorai, "Channel equalization for DMT with insufficient cyclic prefix," in *Prof. of Signals, Systems and Computers*, pp. 951-955, Oct. 2000. Article (CrossRef Link)

[10] Lesch, Wolfgang. Impulse Response Shortening for OFDM in a Single Frequency Network. *MS thesis*, Royal Institute of Technology, Stockholm, 1998. Article (CrossRef Link)

[11] S. K. Ahn and Y. C. Yang, "A novel subblock-based frequency-domain equalizer over doubly-selective channels," *IEEE Communications Letters*, vol. 17, no. 8, pp. 1517- 1520, August, 2013. Article (CrossRef Link)



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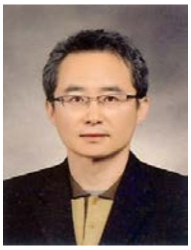

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