Time-Domain Signal Recovery for OFDM System in the Industrial Environment

Chengbo Liu*, Na Chen*, Yafei Hou†, Minoru Okada*
* Nara Institute of Science and Technology, Japan
E-mail: {liu.chengbo.ks7, chenna, mokada}@is.naist.jp
† Okayama University, Japan
E-mail: yfhou@okayama-u.ac.jp

***Abstract*—This paper will utilize a method to recover the damaged time-domain signal of the OFDM system over the WLAN channel in the industrial environment. We assume that the channel is perfectly detected. The simulated results show that the OFDM system using M-algorithm can achieve better BER performance compared to that of the conventional OFDM system in the AWGN channel when 1/2 time-domain signal is missing. On the other hand, the BER performance of the OFDM system with M-algorithm using ZF is better than that of the conventional OFDM system when 1/4 and 1/2 time-domain signal is missing in the WLAN channel. In addition, the BER performance of the OFDM system with M-algorithm using MMSE is better than that of the OFDM system with M-algorithm using ZF in the WLAN channel when 1/8, 1/4 and 1/2 time-domain signal is missing.**

Keywords: Signal rebuilt, OFDM system, M-algorithm, 5G, WLAN model

I. Introduction

Smart factory in Industry 4.0 [1] is rapidly developing to solve the labour shortage and economic cost problems under the 5th Generation (5G) wireless communication system which has high data rate, high energy efficiency, low latency and high reliability [2]. However, the lack of commonalities between different use cases such as autonomous vehicles, camera is challenging in 5G. On the other hand, Wireless Local Area Networks (WLAN) can be utilized to the applications with less latency requirements to release the system burden. Therefore, WLAN coped with 5G is the important technology in the smart factory [3].

With the increasing demand of the industrial wireless devices connected to the Internet, the productivity efficiency may be reduced due to frequent occurrence of defects in the factory production process. On the other hand, the received signals may be damaged due to metallic pillars and machines in the industrial environment [4] such as steel works factory which result in the incidents such as malfunctioning robots that sometimes hurt people. Therefore, it is necessary to keep the reliable wireless communication with more and more devices connecting to the Internet.

The adaptive bit loading [5]-[6] is utilized to transmit the data on the subcarriers with high SNRs to avoid the signal damaged. However, the feedback at the transmitter limits the loading efficiency and increases the complexity. The oversampled OFDM with Cyclic Prefix (CP-OFDM) [7]-[8] has been proposed to recover the damaged signal in the simple channel model such as Rayleigh channel. To further recover the damaged signal in the WLAN channel model, M-algorithm [9] which is a optimal MLSE is utilized with the considerable complexity. The contribution of the paper is to recover the damaged signal of OFDM system over the WLAN channel model in the industrial environment. The simulated results show that the OFDM system using M-algorithm can improve the BER performance over the WLAN channel when the partial time-domain signal is missing assuming that the channel information is perfectly detected.

The remainder of the paper is described as follows. Section II introduces the details of the time-domain signal recovery for OFDM system. The damaged time-domain signal recovery method is described in Section III. Section IV simply discusses the performance of the OFDM system with M-algorithm in the WLAN channel when the channel is perfectly detected. Section V concludes with a brief summary.

II. System Model

Fig.1 describes the structure of the OFDM system using M-algorithm when some time-domain symbols are missing. Assume that K_b data bits of each symbol are transmitted using N subcarriers. First of all, at the transmitter, the data bits $x(i)$ mapped by BPSK are padded with N zero amplitude points for oversampling. After Inverse Discrete Fourier Transform (IDFT), the output of IDFT is

$$y(k) = \frac{1}{\sqrt{2N}} \sum_{i=0}^{N-1} x(i) e^{\frac{j2\pi ik}{2N}}, k \in [0, \dots, 2N-1]. \quad (1)$$

CP which is the kind of Guard Interval (GI) is added to remove the Inter-Symbol Interference (ISI) due to multipath. Thus the time-domain symbols are transmitted via Parallel-to-Serial (P/S) and Digital-to-Analog (D/A) converter over the channel. Here, the impulse response is,

$$h(t) = \sum_{i=1}^{L_p} a_i(t) e^{-j\theta_i(t)} \delta(t - \tau_i), \quad (2)$$

with $t \in [0, T + T_{cp}]$. Note that T is the length of the OFDM symbol and T_{cp} is the length of the CP. L_p is the number of the multiple paths where the path has the attenuation $a_i(t)$, phase rotation $\theta_i(t)$ and delay τ_i.

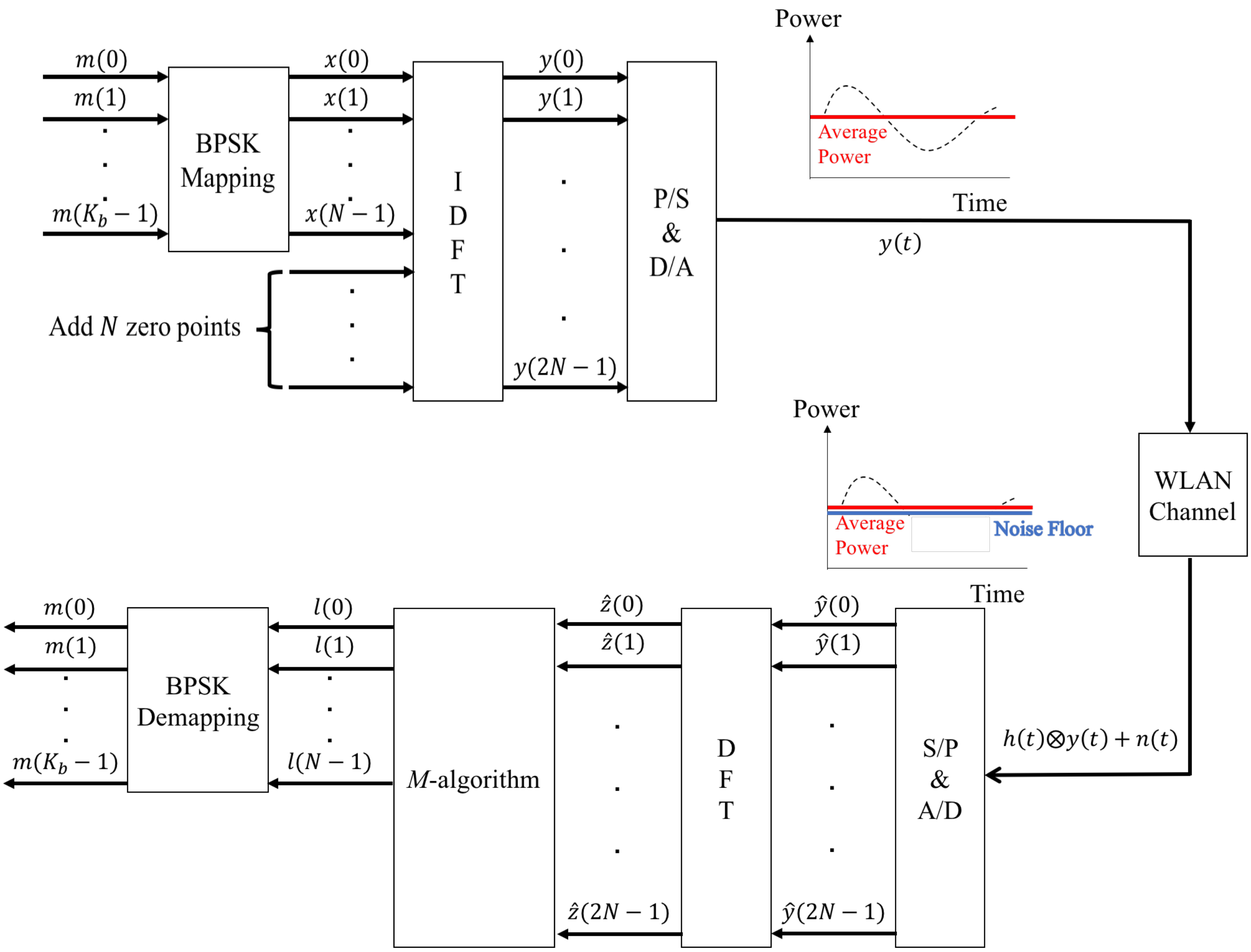

Fig. 1. Structure of OFDM system with BPSK modulation using M-algorithm when the partial time-domain symbols are missing.

At the receiver, the received signal over the WLAN channel is

$$\begin{aligned}\hat{y}(t) &= h(t) \otimes y(t) + n(t) \\ &= \sum_{i=1}^{L_p} a_i(t) e^{-j\theta_i(t)} y(t-\tau_n) + n(t)\end{aligned} \tag{3}$$

where the $n(t)$ is the complex AWGN noise. Note that some values of the $y(t)$ are set to be zero due to some time-domain symbols blocked by metallic pillars and machines etc..

After S/P and A/D, the discrete samples $\hat{y}(k)$ are represented as

$$\begin{aligned}\hat{y}(k) &= y(k) + n(k) \\ &= \sum_{i=1}^{L_p} a_i e^{-j\theta_i} \sum_{m=0}^{N-1} x(m) e^{\frac{j2\pi m(k-N_{\tau_i})}{2N}} + n(k),\end{aligned} \tag{4}$$

with $k \in [0, \dots, 2N-1]$. Assume that a_i and θ_i of each path are constant during the whole OFDM symbol. Here $n(k)$ is the discrete samples of the complex AWGN noise and some values of $y(k)$ are zero. N_{τ_i} is the duration corresponding to the delay τ_i.

After DFT, the $2N$ received samples, $\hat{y}(k)$ yield $\hat{\mathbf{Z}}$=$[\hat{z}(0), \dots, \hat{z}(2N-1)]$ which are represented as

$$\begin{aligned}\hat{z}(l) &= \frac{1}{\sqrt{2N}} \sum_{k=0}^{2N-1} \hat{y}(k) e^{\frac{-j2\pi lk}{2N}} \\ &= \frac{1}{2N} \sum_{k=0}^{2N-1} \Bigg(\sum_{i=1}^{L_p} a_i e^{-j\theta_i} \times \\ &\quad \sum_{m=0}^{N-1} x(m) e^{\frac{j2\pi m(k-N_{\tau_i})}{2N}} + n(k) \Bigg) e^{\frac{-j2\pi lk}{2N}}.\end{aligned} \tag{5}$$

On the other hand, the Zero Forcing (ZF) equalization and Minimum Mean Square Error (MMSE) equalization are utilized to suppress the impact of the channel. Assume that the channel information is perfectly detected, therefore, the

Frequency Impulse Response (FIR) of the channel is expressed as,

$$\begin{aligned} H(k) &= \sum_{l=0}^{2N-1} h(l) e^{\frac{-j2\pi lk}{2N}} \\ &= \sum_{l=0}^{2N-1} \sum_{i=1}^{L_p} a_i e^{-j\theta_i} e^{\frac{-j2\pi l N_{\tau_i}}{2N}}, \end{aligned} \tag{6}$$

The ZF equalization of the channel is expressed as,

$$H_{ZF}(k) = \frac{1}{H(k)}. \tag{7}$$

The MMSE equalization of the channel is expressed as,

$$H_{MMSE}(k) = \frac{H(k)^*}{\mid H(k) \mid^2 + N_0}, \tag{8}$$

where $[\cdot]^*$ is the conjugate of the value, $|\cdot|$ stands for the absolute value and N_0 expresses the power of the AWGN noise.

Therefore, the output of the received symbols via equalization is

$$l(k) = \hat{z}(k) \times H(k), \tag{9}$$

where $H(k)$ expresses H_{ZF} or H_{MMSE} depending on the ZF or MMSE equalization. Finally, the damaged symbols can be recovered using M-algorithm and demapped by BPSK.

III. Signal Recovery Method

Since the received symbols $\hat{y}(t)$ have lost their orthogonality due to partial time-domain signal missing, the samples $\hat{z}(k)$ contain the Inter-Carrier Interference (ICI) component which cannot be demodulated independently by each subcarrier.

In this case, we can utilize MLSE to demodulate the received symbols. Here MLSE can be represented as

$$\hat{\mathbf{X}} = \arg\min |\hat{\mathbf{Z}} - \mathbf{H_v} \times \hat{\mathbf{X}}|^2, \tag{10}$$

with $\mathbf{H_v}$=$[H(0), \ldots, H(2N-1)]^T$, $\hat{\mathbf{X}}_{N\times 1}$=$[\hat{x}(0), \ldots, \hat{x}(N-1)]^T$. Note that $\hat{x}(i)$ belongs to $\{-1, 1\}$ and $i = 0, 1, \ldots, N-1$. The theory of the MLSE is to compare all possible values with the received signals to achieve a good BER performance at the cost of the computational complexity which increases exponentially as N^P with the number of subcarriers N and the number of constellation subsets of $\{-1, 1\}$, P.

The aim of the M-algorithm is to reduce the complexity of the MLSE with a considerable BER performance. The theory of the M-algorithm is to remove some candidates depending on the Euclidian distances between received signals and all possible values in every iteration. Therefore, the complexity increases linearly as MP with the number of the candidates and the number of constellation subsets of $\{-1, 1\}, P$ for BPSK. Next, there is a simple explanation of the M-algorithm utilized in the OFDM system when some partial signal is missing.

Define $\hat{\mathbf{X}}^{(i)(j)}$ as the jth candidate constellation points of the ith iteration process. Assume that P is the number of constellation subset of $\{-1, 1\}$. Firstly, the number of the initial candidate constellation points is U, namely, $\hat{\mathbf{X}}^{(1)(u)}$ =$[\hat{x}(0), \ldots, \hat{x}(U-1), \ldots, 0]$ with $\hat{x}(k) \in \{-1, 1\}$ and $k \in [0, \ldots, U-1]$. Therefore, P^U kinds of $\hat{\mathbf{X}}^{(1)(u)}$ are utilized to calculate the Euclidian distances in the first iteration. $\mathbf{Z}_u^{(1)}$ = $[z_u^{(1)}(0), \ldots, z_u^{(1)}(2N-1)]$ are presented as

$$\mathbf{Z}_u^{(1)} = \mathbf{H_v} \times \hat{\mathbf{X}}^{(1)(u)} \tag{11}$$

with $u \in [1, \ldots, P^U]$.

Therefore, the Euclidian distances $d_u^{(1)}$ between $\mathbf{Z}_u^{(1)}$ and the received samples $\hat{\mathbf{Z}}$ are evaluated as

$$d_u^{(1)} = \left(\sum_{l=0}^{U-1} |z_u^{(1)}(l) - \hat{z}(l)|^2 + \sum_{l=N}^{2N-1} |z_u^{(1)}(l) - \hat{z}(l)|^2 \right)^{1/2}. \tag{12}$$

Depending on the ascending sorted $d_u^{(1)}$, $M(M < P^U)$ candidate constellation points are selected to calculate in the next iteration as $\mathbf{Z}_{(k)}^{(1)}$ $(k = 1, \ldots, M)$. The $\hat{\mathbf{X}}^{(1)(u)}$ are stored as $\hat{\mathbf{X}}^{(1)(k)}(k = 1, \ldots, M)$. Secondly, $\hat{\mathbf{X}}^{(2)(u)}(u = 1, \ldots, MP)$=$[\hat{\mathbf{X}}^{(1)(k)}, \hat{x}(U)\ , 0, \ldots, 0]$ and $\hat{x}(U) \in \{-1, 1\}$. Therefore, MP kinds of vector $\mathbf{Z}_u^{(2)} = [z_u^{(2)}(0)\ ...z_u^{(2)}(2N-1)]$ are presented as

$$\mathbf{Z}_u^{(2)} = \mathbf{H_v} \times \hat{\mathbf{X}}^{(2)(u)}. \tag{13}$$

The Euclidian distances $d_u^{(2)}(u = 0, \ldots, MP-1)$ between $\mathbf{Z}_u^{(2)}$ and the received samples $\hat{\mathbf{Z}}$ are evaluated by

$$d_u^{(2)} = \left(\sum_{l=0}^{U} |z_u^{(2)}(l) - \hat{z}(l)|^2 + \sum_{l=N}^{2N-1} |z_u^{(2)}(l) - \hat{z}(l)|^2 \right)^{1/2}. \tag{14}$$

Thus, $M(M < P^U)$ $\mathbf{Z}_u^{(2)}$ candidate constellation points are selected to calculate in the next iteration as $\mathbf{Z}_{(k)}^{(2)}$ $(k = 1, \ldots, M)$ depending on the Euclidian distances. $\hat{\mathbf{X}}^{(2)(u)}$ are stored as $\hat{\mathbf{X}}^{(2)(k)}(k = 1, \ldots, M)$. Repeat the same operation until $\hat{\mathbf{X}}$ are all evaluated.

IV. Simulated Results

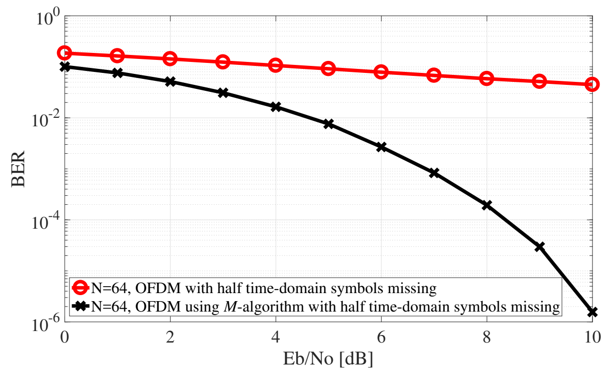

Fig. 2. BER performance of the OFDM system with BPSK modulation using M-algorithm compared of that of the conventional OFDM system when half time-domain symbols are missing in the AWGN channel.

We simulate the OFDM system using M-algorithm over an AWGN channel with the number of the subcarriers N = 64 when half time-domain symbols are missing. The BER performance of the OFDM system using M-algorithm is described in Fig. 2. Since the M-algorithm compares all the possible values with the received signal in every iteration, the BER performance of the OFDM system using M-algorithm is better than that of the conventional OFDM system in the AWGN channel even half time-domain symbols missing.

TABLE I
PARAMETERS OF THE OFDM SYSTEM WITH M-ALGORITHM

Parameters	Specification
FFT size	64
Guard Interval	1/4
Modulation	BPSK
Equalization	ZF / MMSE
M-algorithm(U,M)	(3, 32)
Carrier frequency	5GHz
Bandwidth	40MHz
Channel model	WLAN model (Model B)
Propagation scenarios	Indoor

TABLE II
MODEL B POWER DELAY PROFILE

Tap number	Power [dB]	Delay [ns]
1	0	0
2	-5.43	10
3	-2.52	20
4	5.89	30
5	-9.16	40
6	-12.51	50
7	-15.61	60
8	-18.71	70
9	-21.82	80

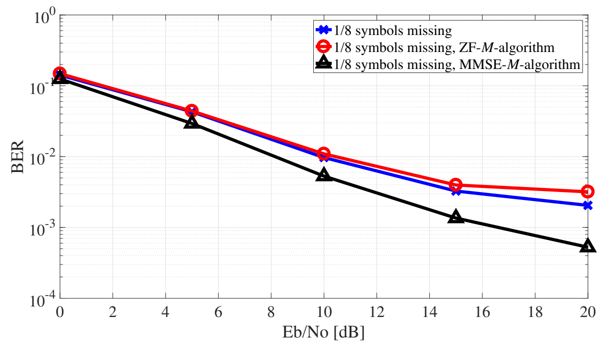

Fig. 3. BER performance of the OFDM system for BPSK modulation using M-algorithm with ZF or MMSE compared of that of the conventional OFDM system when 1/8 time-domain symbols are missing in the WLAN channel model.

We also simulate the OFDM system using M-algorithm in the WLAN channel. Table I and Table II [10] are the parameters of the OFDM system using M-algorithm and Model B power delay profile of the WLAN model, respectively. For M-algorithm, we set the number of initial estimators as

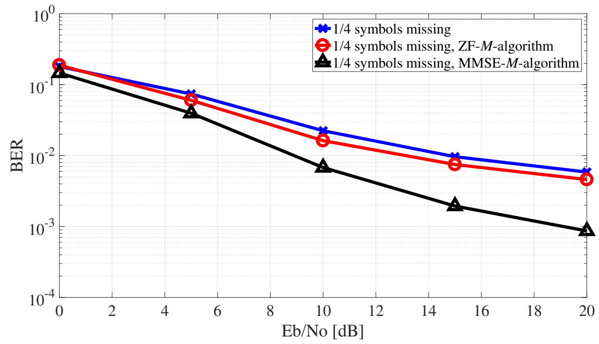

Fig. 4. BER performance of the OFDM system for BPSK modulation using M-algorithm with ZF or MMSE compared of that of the conventional OFDM system when 1/4 time-domain symbols are missing in the WLAN channel model.

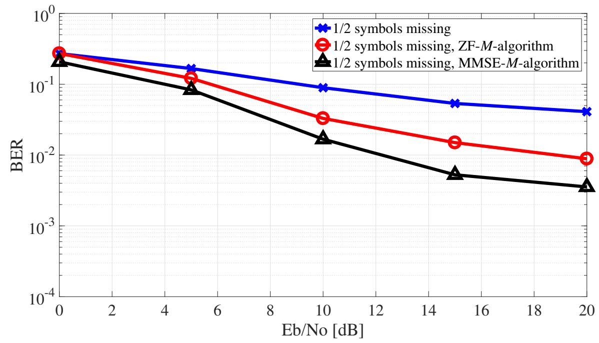

Fig. 5. BER performance of the OFDM system for BPSK modulation using M-algorithm with ZF or MMSE compared of that of the conventional OFDM system when 1/2 time-domain symbols are missing in the WLAN channel model.

$U = 3$ and the number of candidate points as $M = 32$. To compensate the weak signal, the ZF equalizer simultaneously amplifies the signal and the noise, however, MMSE equalizer suppresses the noise enhancement. Therefore, the OFDM system with M-algorithm using MMSE equalization has better BER performance than that of the OFDM system with M-algorithm using ZF shown in Fig. 3 - Fig. 5. However, the BER performance of the OFDM system using ZF-M-algorithm is still better BER performance than that of the conventional OFDM system when 1/4 and 1/2 time-domain symbols are missing.

V. CONCLUSIONS

This paper utilized the M-algorithm to recover the damaged signal caused by the metallic structure etc.. OFDM with M-algorithm can achieve better BER performance compared to that of OFDM in the AWGN channel. On the other hand, OFDM with ZF or MMSE using M-algorithm can achieve better BER performance compared to that of OFDM in the WLAN channel model. Moreover, the BER performance of the OFDM with MMSE using M-algorithm is better than that of the conventional OFDM system with ZF using M-algorithm.

REFERENCES

[1] S. Wang, J. Wan, D. Li, and C. Zhang, "Implementing smart factory of industrie 4.0: An outlook," *Int. J. Distrib. Sensor Netw.,* vol. 12, no. 1, pp. 1-10, 2016.

[2] J. G. Andrews et al., "What will 5G be?," *IEEE J. Sel. Areas Commun.,* vol. 32, no. 6, pp. 1065-1082, June 2014.

[3] M. S. Carmo, S. Jardim, A. V. Neto, R. Aguiar and D. Corujo, "Towards fog-based slice-defined WLAN infrastructures to cope with future 5G use cases," *2017 IEEE 16th International Symposium on Network Computing and Applications (NCA),* Cambridge, MA, 2017, pp. 1-5.

[4] Javier Ferrer Coll, "Channel Characterization and Wireless Communication Performance in Industrial Environments," Doctoral Thesis in Information and Communication Technology Stockholm, Sweden, June 2014.

[5] D. Wang,Y. Cao and L. Zheng, "Efficient two-stage discrete bit-loading algorithms for OFDM systems," *IEEE Trans. Veh. Technol.,* vol. 59, no. 7, pp. 3407-3416, September 2010.

[6] E. H. Choi, W. Choi, J. G. Andrews and B. F. Womack, "Power loading using order mapping in OFDM systems with limited feedback," *IEEE Signal Process. Lett.,* vol. 15, no. 5, pp. 545-548, September 2008.

[7] A. Rahmati and P. Azmi, "Iterative reconstruction of oversampled OFDM signals over deep fading channels," in *Circuits and Systems for Communications, 2008. ECCSC 2008. 4th European Conference on*, 2008, pp. 289-294.

[8] A. Rahmati, K. Raahemifar, T. A. Tsiftsis, A. Anpalagan and P. Azmi, "OFDM Signal Recovery in Deep Faded Erasure Channel," in *IEEE Access,* vol. 7, pp. 38798-38812, 2019.

[9] Y. Hou, M. Hamamura, "Collision recovery for OFDM system over wireless channel," *IEICE Trans. on Fundamentals,* vol. E90-A, no. 7, pp. 1312-1322, July 2007.

[10] Erceg, V. L. Schumacher, P. Kyritsi, et al., TGn Channel Models, Version 4. IEEE 802.11-03/940r4, May 2004.