Case Study for Ship Ad-hoc Networks under a Maritime Channel Model in Coastline Areas

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Abstract

ITU-R M.1842-1, as a well-known specification dedicated to maritime mobile applications, has standardized wireless transmission protocols according to the particular characteristics of a maritime communications scenario. A time division multiple access (TDMA) frame structure, along with modulation schemes to achieve a high data rate, has been described clearly in ITU-R M.1842-1. However, several specification items are still under "to be decided" status, which brings ambiguity to research works. In addition, the current version of ITU-R M.1842-1 is focused mainly on maritime transmissions in open-sea areas, where the cyclic prefix (CP) is set to zero and only 16-QAM is used in the multi-carrier (MC) system. System performance might be dramatically degraded in coastline areas due to the inter-symbol interference (ISI) caused by selective fading. This is because there is a higher probability that the signal will be reflected by obstacles in coastline areas. In this paper, we introduce the transmission resource block (TRB) dedicated to ITU-R M.1842-1 for a ship ad-hoc network (SANET), where the pilot pattern of TRB is based on the terrestrial trunked radio (TETRA). After that, we evaluated SANET performance under the maritime channel model in a coastline area. In order to avoid noise amplification and to overcome the ISI caused by selective fading, several strategies are suggested and compared in the channel estimation and equalization procedures, where the link-level simulation results finally validate our proposals.

Keywords: ITU-R M.1842-1, SANET, TETRA, Channel Estimation, Channel Equalization

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1. Introduction

Maritime communications systems, such as the global maritime distress/safety system and the automatic identification system (AIS) [1-3], have focused applications on ship security, location tracking, identification, and so on. Recently, there has been a gradual demand in maritime communications for various multimedia services, such as marine video surveillance and underwater video sensing. Without loss of generality, a satellite system is a good candidate for realizing multimedia services, especially for ships that rarely find other neighboring ships. However, when ships can easily locate neighboring ships, a satellite system becomes burdensome due to its remarkably high cost. The ship ad-hoc network (SANET) [4-10], a maritime counterpart of the terrestrial vehicle ad-hoc network, thus needs to provide those diverse multimedia services in a maritime communications system. Based on a survey of terrestrial vehicle ad-hoc networks and the maritime communications environment, we realized that simply implementing the radio transmission technology (RTT) of a terrestrial vehicle ad-hoc network for maritime communications holds many challenges and open problems. For the purpose of enhancing the service quality of maritime communications, RTT for SANET is designed with multi-hop functionality in our previous work [4-9]. Reference [6] focused on the design of the SANET physical layer, where a novel frame structure was proposed based on Ad-hoc Self-organizing Time Division Multiple Access (ASO-TDMA) scheme as provided in [8] and [9]. Different from [8] and [9], the proposed frame structure in [6] considered the special topology of SANET, where the number of ships located near seashore is usually more than the area far from seashore. Reference [7] presented the SANET transmission resource block and evaluated the performance of channel equalization based on the measured maritime wireless channel model, and References [4] and [5] tried to improve the link reliability for SANET by employing multiple antennae.

ITU-R M.184-1 was released as a recommendation that characterizes very high frequency (VHF) radio systems for data exchange in maritime mobile services [11]. In Annex-5 of ITU-R M.184-1, the VHF data link protocols for maritime mobile services are described along with a time division multiple access (TDMA) frame structure to achieve high data–rate maritime applications. However, several specification items in ITU-R M.184-1 are still under “to be decided” status, which brings ambiguity to research works. For example, Annex 5 in ITU-R M.184-1 specifies 2,250 timeslots in a data frame, whereas the details for the transmission resource block (TRB) of a timeslot are not provided. The system performance of a SANET should be examined based on the information of the TRB, including training sequence pattern, length of a symbol, number of symbols in the TRB, and so on. On the other hand, for the current version of ITU-R M.1842-1, the cyclic prefix (CP) is set as zero and only 16-QAM is used in the multi-carrier (MC) system, to keep the spectrum efficiency because it mainly focuses on the maritime transmission in the open-sea area. Therefore, the system performance is usually evaluated under the flat fading channel with a line-of-sight (LOS) signal component. System performance might be dramatically degraded in a coastline area due to the inter-symbol interference (ISI) caused by selective fading. This is because there is a higher probability that the signal will be reflected by obstacles in coastline areas [12].

In this paper, the TRB for ITU-R M.1842-1 along with the positioning of training sequences by referring to the Terrestrial Trunked Radio (TETRA) specification [13] is introduced, where 72 pilot symbols are arranged within the TRB in order to allow a reasonable sampling of the channel time-frequency response without incurring considerable efficiency loss. Based on the TRB with a TETRA-like pilot pattern, we evaluated SANET performance under a coastline maritime channel model. To avoid noise amplification and to overcome the ISI caused by selective fading, several novel and practical strategies are suggested and compared in the channel estimation and equalization procedures, where the simulation results finally validate our proposals.

The rest of this paper is organized as follows. Section 2 describes the transmission scenario of a SANET in a coastline area, and Section 3 presents the TRB with a TETRA-like pilot pattern for ITU-R M.1842-1. In Section 4, we examine three channel estimators with the capability of validation to avoid noise amplification, and in Section 5, a decision feedback equalizer is suggested to overcome the ISI effect under a coastline maritime channel model. Finally, we conclude this paper in Section 6.

2. SANET Transmission Scenario in Coastline Areas

Fig. 1 depicts the SANET transmission scenario in coastline areas, where there is a higher probability that the signal will be reflected by obstacles in the coastline area. Signal transmissions colored white in Fig. 1 represents multi-hop transmission. System performance might be degraded dramatically by simply employing the ITU-R M.184-1 specification in such an environment due to the inter-symbol interference (ISI) caused by selective fading. The maritime VHF channel model for both open-sea and coastline areas is described by Kim [14], and channel parameters are listed in **Table 1**. According to **Table 1**, we notice that the channel environment on a coastline is a two-path fading channel composed of the first Rician distributed path and the second Rayleigh distributed path. The relative delay of the second path is 5 μs, and its power decay is -3 dB. The mathematical description of a coastline two-path channel model is given as

$$\begin{aligned} g_{i,k}(t) &= h_{i,k}^{Rician} + h_{i,k}^{Rayleigh} \\ &= \sqrt{\frac{M}{M+1}}\left(\sqrt{\frac{K}{K+1}} + \sqrt{\frac{K}{K+1}} h_{i,k}^{1}(t)\right)\delta(t) \\ &\quad + \sqrt{\frac{M}{M+1}} h_{i,k}^{2}(t)\,\delta(t-\tau), \end{aligned} \tag{1}$$

where $h_{i,k}^{1}(t)$ and $h_{i,k}^{2}(t)$ are two independent Rayleigh paths. $h_{i,k}^{1}(t)$ is used to generated the Rician path $h_{i,k}^{Rician}$ via the Rician K-factor. M is the normalization factor for two paths, and τ is the relative delay of the second path.

3. Transmission Resource Block Design for ITU-R M.1842-1

According to the TDMA frame structure demonstrated in **Fig. 2** [11], we notice that one TDMA hyper-frame contains five super-frames with each covering 12 seconds. A super-frame

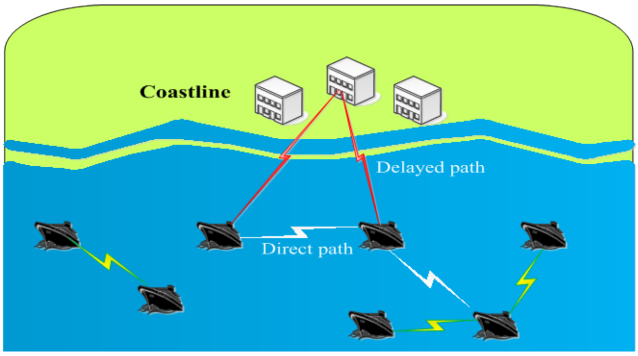

Fig. 1. SANET transmission scenario in coastline areas.

Table 1. Maritime channel model

Scenario	Path Index	Delay Spread (us)	*K* (dB)	Average Relative Power (dB)
Coastline	0	0	10	0
	1	5	0	-3
Open sea	0	0	15	0

has 15 multi-frames, with each of them covering 800 ms. There are five data frames holding six time slots in one multi-frame, and each time slot covers about 26.667 ms and includes 64 time symbols. Therefore, the symbol length [11] is around 416.667 µs. According to the above descriptions, and referring to the TRB structure provided [13], the TRB for ITU-R M.184-1 is illustrated in **Fig. 3**.

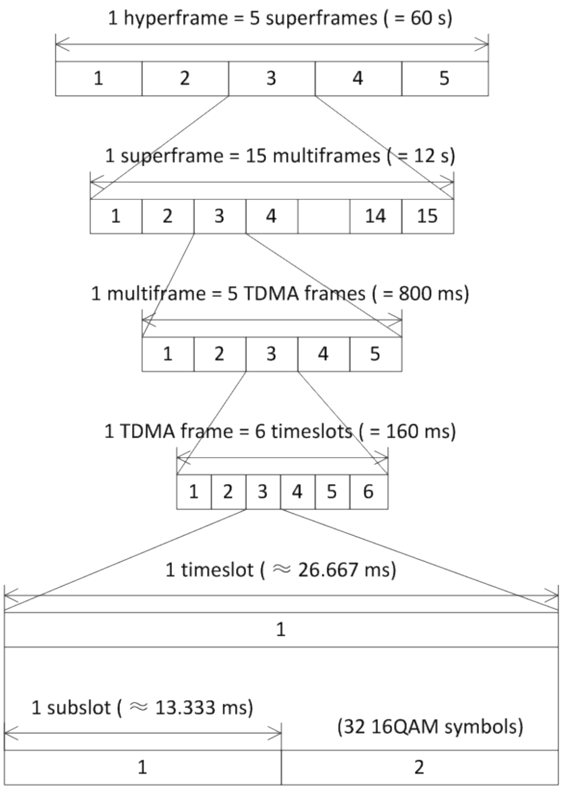

Fig. 2. TDMA frame structure in ITU-R M.184-1.

In **Fig. 3**, there are 16 sub-carriers with a spacing of 3.125 kHz that occupy a 50 kHz bandwidth. The symbol sequence on each sub-carrier starts with two preambles that are intended for frequency and time clock synchronization recovery. Note that the frequency accuracy must be within ± 100 Hz [13], while the timing difference from the logic clock should not exceed 125/9 μs. By the TRB, there are 72 pilot symbols arranged within the frequency/time grid for a reasonable sampling of the channel time-frequency response without incurring considerable efficiency loss. The pilot spacing in the time and frequency dimensions has been chosen so that an accurate estimation of the channel response can be achieved even under the selective fading channel described in Section 2.

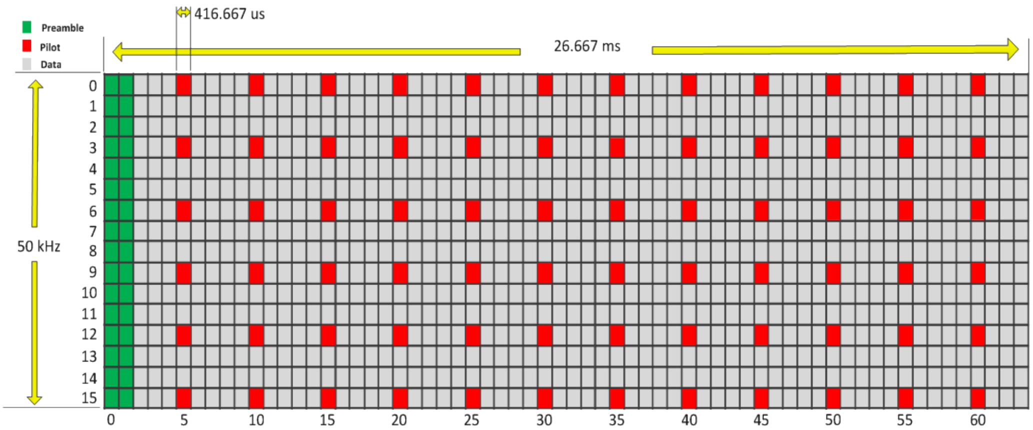

Fig. 3. TRB structure with a TETRA-like pilot pattern for ITU-R M.184-1 (50 kHz bandwidth).

For the training sequence generation, TETRA specifies a phase locus where the detailed phase value for 25, 50, 100, and 150 kHz MC systems can be found [13]. In this paper, we compare the autocorrelations among those four types of training sequence, as demonstrated in **Fig. 4**. According to **Fig. 4**, we observe that the training sequence employed for a 150 kHz MC system, compared with other cases, is the most random, with a comparative lower autocorrelation value. On the other hand, it is long enough to support all the preamble and pilot symbols given by **Fig. 3**. As a result, the training sequence employed for the 150 kHz MC system [13] is suggested for use under ITU-R M.184-1. Note that the preamble and pilot symbols used for ITU-R M.184-1 share the same phase locus [13].

4. Performance Enhancement by Channel Estimator

In order to maintain SANET performance when employing the ITU-R M.184-1 specification under a maritime channel model in a coastline area, we examine three channel estimation schemes in this section. The examined channel estimation schemes include the 2*1-Dimensional Wiener Filter Estimator (2*1-D WFE) [15], the 2-Dimensional Wiener Filter Estimator (2-D WFE) [16], and the Maximum Likelihood Estimator (MLE) [17]. This is because these three channel estimation schemes are well-designed with a better performance than the conventional channel estimator, e.g., zero-forcing (ZF) estimator, for the orthogonal frequency division multiplexing (OFDM) system. On the other hand, they are practical and commercialized algorithms that are adaptive for the ITU-R M.184-1 specification also.

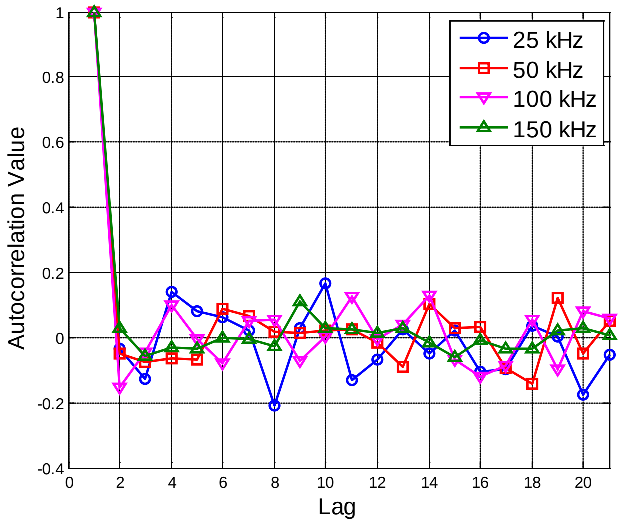

Fig. 4. Autocorrelations of pilot sequences in TETRA.

4.1 2*1-Dimensional Wiener Filter Estimator

For 2*1-D WFE, the frequency dimension Wiener filter was intended to enable channel estimation at first. Let $d(i)$ and $p(j)$ denote the positions of the i^{th} datum and the j^{th} reference signal sub-carrier in the frequency dimension, respectively, and R_{hp} and R_{pp} are cross-correlation and auto-correlation functions defined by Nee and Prasad [15], we have the estimated channel in the frequency domain as

$$\hat{H}_f = R_{hp}^f \left(R_{hp}^f + \sigma^2 I \right)^{-1} \hat{H}_p , \tag{2}$$

where $\hat{H}_p$ is the channel information of the reference signal. After that, the time-dimension Wiener filter is applied with the results of frequency dimension estimation as

$$\hat{H} = R_{hp}^t \left(R_{hp}^t + \sigma^2 I \right)^{-1} \hat{H}_f . \tag{3}$$

4.2 2-Dimensional Wiener Filter Estimator

2-D WFE is based on a minimum mean-square error (MMSE) criterion and has good effect in avoiding noise amplification. It has high complexity but better performance than 2*1-D WFE. The 2-D WFE channel estimator is given as

$$\hat{H} = R_{h\hat{p}} R_{\hat{p}\hat{p}} \hat{H}_p , \tag{4}$$

where $R_{h\hat{p}}$ and $R_{\hat{p}\hat{p}}$ are the cross-correlation and auto-correlation matrix between h and the reference signal estimates p, respectively, given as

$$R_{h\hat{p}} = E\left\{H\hat{H}_p^H\right\}, \tag{5}$$

$$R_{\hat{p}\hat{p}} = E\left\{H\hat{H}_p^H\right\} = R_{pp} + \frac{1}{SNR}I, \tag{6}$$

4.3 Maximum Likelihood Estimator

MLE can be interpreted as a translation of the frequency response of the reference signal channel information to the time domain, which is followed by a linear transformation and retranslation to the frequency domain [18]. Based on a maximum likelihood algorithm and the channel information at the reference signal position, we can get the channel information of one estimated symbol, which contains reference signals, with the following:

$$\hat{H}_{MLE}(n) = \sum_{m=0}^{N_p-1} \hat{H}_p(m) p_{MLE}(n,m). \tag{7}$$

The maximum likelihood matrix p_{MLE} is defined by

$$p_{MLE}(n,m) = \sum_{k=0}^{L-1}\left[\left(B^H B\right)^{-1} B^H\right]_{k,m} e^{-j2pnk/N}, \tag{8}$$

$$\left[B\right]_{n,k} = e^{-j2pki_n/N}, \tag{9}$$

where B represents the Fourier transform matrix of reference signals, and i_n is the index of the reference signal. The MLE is based on the assumption that $\hat{H}_{MLE}$ is a deterministic but unknown vector. The estimate of $\hat{H}_{MLE}$ is derived from the linear model (7), where p_{MLE} is the maximum likelihood matrix, which is composed of Fourier transform matrix of reference signals position.

4.4 Performance Evaluation with Channel Estimators

Fig. 5 compares the bit-error-rate (BER) performances of the above three channel estimators for ITU-R M.184-1 under the maritime channel model in coastline areas. Note that throughout the paper, channel coding is not employed, and the symbol modulation is 16-QAM. According to **Fig. 5**, using frequency domain 1-tap equalization (FDOE) provides the worst performance, where the BER error floor starts at 30 dB and never reaches 10^{-3}. This is mainly because the MC system performance without CP under a maritime channel model in coastline areas is seriously limited by the ISI caused by selective fading. The 2*1-D WFE can increase BER performance; however, the BER of 2*1-D WFE also does not reach 10^{-3}. Compared with 2*1-D WFE, MLE shows a better capability to improve BER performance, where it can reach the target BER of 10^{-3} at 45 dB. However, with good capability to avoid noise amplification, 2-D WFE has the best performance compared with other estimators that can achieve the target

BER of 10^{-3} at 36 dB of Eb/N0. Consequently according to the simulation results demonstrated by **Fig. 5**, 2-D WFE is suggested for use in the SANET when ships communicate with each other in coastline areas.

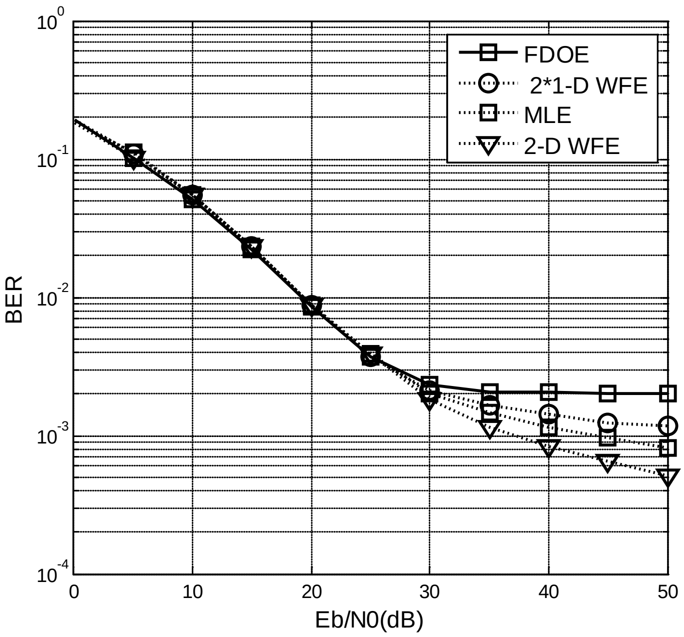

Fig. 5. BER performance enhancement by channel estimator.

5. Performance Enhancement by Channel Equalization

OFDM system performance is reduced dramatically because the length of the CP is not long enough to eliminate the ISI effects. Thus, an OFDM system with a small CP cannot perform well with a comparatively large delay. In ITU-R M.184-1 [11], the CP is set to zero, where the iterative techniques can be employed to overcome the problem of CP insufficiency [19]-[27]. In this paper, we employ the residual inter-symbol interference cancellation (RISIC) algorithm for the SANET under a maritime channel model in a coastline area [18], where a symbol hard decision block (SHDB) is additionally proposed based on the RISIC algorithm.

To obtain the desired system output along with the residual ISI, two steps are proposed by Kim and Stuber [19]. 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 reconstruction, respectively. The overall procedure of the RISIC algorithm can be described with Equation (10), 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 Equation (10) to avoid ICI via the iteration process. In Equation (10), N denotes the fast Fourier transform (FFT) size, h_m refers to the m^{th} delayed channel with a delayed spread of d_m, and * is the notation of convolution.

$$\hat{r}_{i,k} = r_{i,k} - \sum_{k=N-d_m}^{N-1} h_m * x_{i-1,k} + \sum_{k=0}^{d_m-1} h_m * x_{i,k}. \quad (10)$$

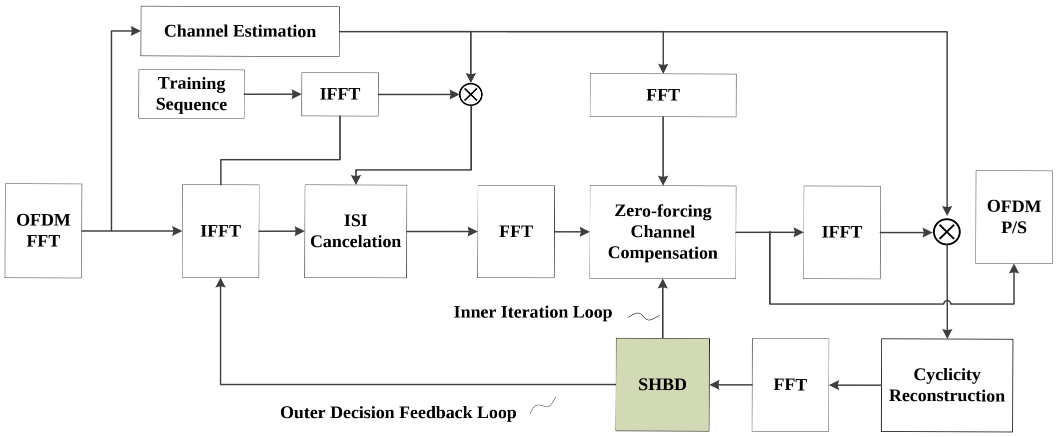

Fig. 6. Structure of the proposed RISIC with SHDB.

In order to further enhance RISIC performance, we modify the RISIC algorithm by adding the SHDB, as shown in **Fig. 6**, where the SHBD is carried out after the 'converting the decided signal to the frequency domain' step of Kim and Stuber [19]. The SHDB is implemented for the decision on frequency-domain symbol sequence associated with correct constellation positions. The usage of the SHBD can prevent the outputs from the error propagations, which are fed back to the outer and inner loops in **Fig. 6**.

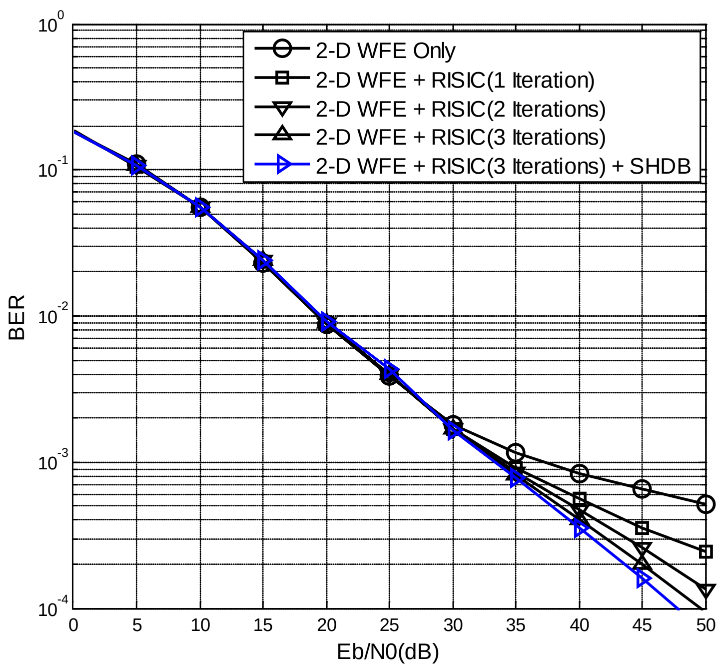

Fig. 7. BER performance enhancement by the proposed RISIC with SHDB.

Based on the TRB of **Fig.3** and 2-D WFE, **Fig. 7** demonstrates the BER performance when the RISIC algorithm is employed. According to **Fig. 7**, we observe that situations with the RISIC algorithm can achieve more than 3 dB signal-to-noise ratio (SNR) gain at the target BER of 10-3 compared with situations not employing the RISIC algorithm for ITU-R M.184-1 under the coastline maritime channel model. In addition, BER performance is increased with a higher number of iterations for the inner loops. **Fig. 7** also shows the efficiency of the proposed SHDB, where the SNR gain is obtained by implementing the SHDB based on RISIC. For example, almost 2 dB SNR gain is achieved in the case of the proposed RISIC with the SHDB at a target BER of 10-4. This confirms the validity of the proposed SHDB for preventing the outputs from the error propagations that are fed back to the outer and inner loops, as illustrated in **Fig. 6**.

5. Conclusions

For the purpose of providing high data–rate services, the RTT design standardized by ITU-R M.184-1 for a SANET is discussed in this paper, where the physical layer parameters of ITU-R M.184-1 are contrived to meet the requirements of modern maritime applications. However, according to our studies, several specification items are still under "to be decided" status. The SANET performance evaluation could not be examined without details about those items, especially for the physical layer. In this paper, we analyzed the TRB with a TETRA-like pilot pattern for ITU-R M.184-1. Based on the analyzed TRB, we evaluated the SANET performance under a coastline maritime channel model. In order to avoid noise amplification and overcome the ISI caused by selective fading, several novel and practical strategies are suggested and compared in the channel estimation and equalization procedures. According to the link-level simulation results, 2-D WFE used in channel estimation and the proposed RISIC with SHDB employed in channel equalization are recommended for use in ship-to-ship communications in coastline areas.

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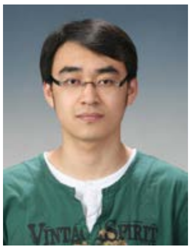

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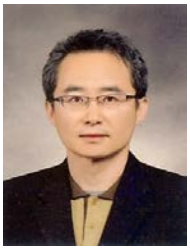

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