Cross Evaluation of Multiple Access Schemes Using Post-Experimental Field Data for Underwater Acoustic Communications

Xiangzhao Qin[1,2], Y. Rosa Zheng[2], and Fengzhong Qu[1]
[1] – Key Laboratory of Ocean Observation-Imaging Testbed of Zhejiang Province,
Zhejiang University, Zhoushan, Zhejiang 316021, China.
[2] – Dept. of ECE, Lehigh University, Bethlehem, PA 18015-3084, USA.

Abstract*—This paper proposes a post-experimental field data reuse method to test the single carrier modulation (SCM) and orthogonal frequency division multiplexing (OFDM) signals interchangeably for multiple access underwater acoustic (UWA) communications. We call this approach the cross evaluation that transforms a set of SCM or OFDM post-experimental field data to their corresponding OFDM or SCM scheme under test (SUT) via linear matrix operation such as fast Fourier transform (FFT) and its inverse (IFFT). At the receiver side, we derived a general framework of turbo equalization (TEQ) that alters the two physical layer schemes but keeps the passband transmitted and received data unchanged. Inherently, some efficient techniques such as pre-cursor and post-cursor interference cancellation (IC), and overlap adding (OLA) operations enhance the equivalence of input and output (I/O) system model between the SCM and OFDM. The proposed approach will bring the gap between the SCM and OFDM, and evaluate the two physical layer schemes under similar or tougher test conditions. The experimental results of the undersea 2008 Surface Processes and Acoustic Communications Experiment (SPACE08) have verified the feasibility of the cross evaluation approach in terms of the BER benchmark.

Key words: Data reuse, single carrier modulation (SCM), orthogonal frequency division multiplexing (OFDM), cross evaluation , multiple access (MA), underwater (UWA) acoustic communications.

I. Introduction

Underwater acoustic (UWA) communication channels lack of explicit models that can capture the underlying physical characteristics of sound propagation in ocean telemetry [1]. Therefore, many researches in the field of UWA communications prefer sea trial measurement to evaluate their transceiver algorithms. Spending so much effort to acquire the field data is often labour expensive, time consuming, and prone to many types of failures. Besides these difficulties, the acquired data is often privately protected by the individual research groups and merely shared to the public. Thus, the data reusability is vulnerable. However, due to the lack of the readily and standard channel models, the sea-going campaigns are still the most comprehensive way that the researchers evaluate their newly proposed algorithms while it's often difficult to measure all the environment factors accurately that may impact the performance of signals or the proposed algorithms.

As the increasingly computational capacity of the computers, the numerical channel simulator based test benches have emerged rapidly as the substitutes of the field experiment to evaluate a new communication algorithm. The earliest toolbox can directly track back to the BELLHOP model [2], [3] which produces the eigenray to character the energy propagation of UWA, whose green function is the prototype of the channel impulse response (CIR). However, this kind specified UWA propagation model hardly meets the communication requirement due to the failure in capturing the dynamics of the UWA communication channels. By incorporating the dynamic fluctuation and Doppler impact of the sea boundary into the statistical channel model, [4] proposes a reproducible narrow bandwidth channel simulator. A wide bandwidth time-varying underwater acoustic channel simulator is developed [5] based on an approximately quantitative model with rough surface, where the simulation result shows that the simulated channels are consistent with the real channels acquired from the sea trials in terms of reproducing fine time-scale Doppler and delay distortions. A baseband direct channel playback approach is proposed in [6], [7], which uses the baseband equivalent channel impulse response (CIR) estimated from some existing experimental signals to replace the computer simulated CIRs. The scheme under test (SUT) in passband is first demodulated to baseband and convoluted with the estimated CIRs, then re-modulated to the passband to yield the signals as the received signals of the SUT. This approach may capture the time varying characteristic of the CIR by updating the convolution process in a fine time scale, but still suffer the information loss of the non-linear components of true passband UWA channels, and channel the SUT passing by is still a wide-sense stationary uncorrelated scattering (WSSUS) approximation that is unable to reflect the accuracy of the channel parameterization. As a result, they often provide over-optimized performance prediction that weakens the fidelity the newly proposed algorithms to be hold in practice.

Recently, a new approach that reuses the field experimental data for evaluating new transceiver designs has been proposed [8], [9]. This approach alters the channel coding or modulation schemes but keeps the passband transmitted and received data unchanged, therefore, enabling the field experimental data to be reused to evaluate new transceiver algorithms. The post-experimental results of a variety of coded modulation schemes rely on the linearity of the channel components and the channel equalization. Motivated by the insight of the post-experimental data reuse methodology, this paper expands the approach to test the SCM and OFDM signals interchangeably for multiple access schemes with turbo equalization. The target of the data reuse test will bridge the gap between SCM and OFDM, finally evaluating the two physical layer schemes under similar or tougher test conditions.

II. System Model

Consider an $N \times M$ MIMO communication system with spatial multiplexing, where N and M are numbers of the transducers and hydrophones, respectively. The system diagram is depicted in 1 where at the transmitter side, the incoming information bits are serial-to-parallel converted into N parallel streams $\{\mathbf{a}_n\}_{n=1}^{N}$ transmitted by N transducers. At the nth transmit branch, the information bits are encoded and interleaved. Every q interleaved bits $\mathbf{c}_{n,k} \triangleq [c_{n,k}^1, c_{n,k}^2, \ldots, c_{n,k}^q]^T$ are mapped into one modulated symbol $s_{n,k}$ taken from a 2^q-ary constellation set $\mathcal{S} = \{\alpha_1, \alpha_2, \ldots, \alpha_{2^q}\}$. The mapped baseband symbols are precoded and formatted into transmission blocks. For the SCM, the linear precoder is simply an identity matrix with the block size K, and the block formatting may or may not include CP/ZP insertion. For the OFDM scheme, the linear precoder is the inverse fast Fourier transform (IFFT) matrix, and the block formatting is the CP/ZP insertion. The output of the block formatting is the baseband waveform streams $x_{n,k}$ with $n = 1, \cdots, N$ and $k = 1, \cdots, K$.

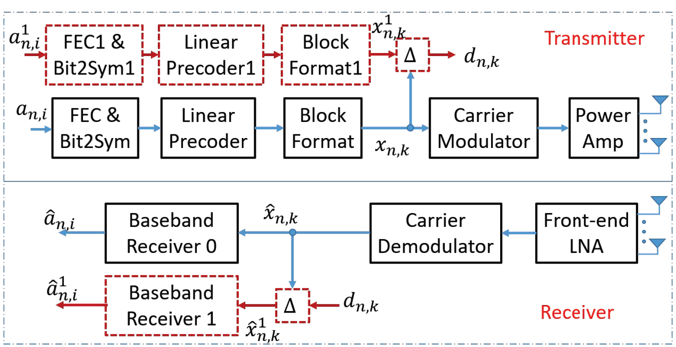


Fig. 1. System block diagrams of wireless transmitter and receiver.

Parallel to the original transmission scheme is the new SUT. The new information bits $a_{n,i}^1$ are encoded, interleaved, and bit mapped by a different scheme into the baseband symbols $s_{n,k}$. Different linear precoder and block formatting schemes are also employed and the resulting baseband waveform streams are $x_{n,k}^1$ with $n = 1, \cdots, N$ and $k = 0, \cdots, K^1 - 1$. Note $K^1 \leq K$, i.e., the length of baseband symbol block under test exceeds no longer than that of the existing scheme. The new SUT shares the same passband modulation and power amplification with the original scheme so that the experimental data preserves the physical channel properties. To facilitate the cross evaluation of the new SUT, a dithering block Δ is added to compute the difference between symbols $x_{n,k}$ and $x_{n,k}^1$. The output of the dithering block is $d_{n,k} = \Delta(x_{n,k}, x_{n,k}^1)$ for $k = 0, \cdots, K^1 - 1$. At the receiver, the demodulated baseband signals are soft symbols $\hat{x}_{n,k}$. The inverse dithering operation Δ^{-1} is used to yield $\hat{x}_{n,k}^1 = \Delta^{-1}(\hat{x}_{n,k}, d_{n,k})$. The new receiver scheme is then tested with the new baseband signals. Special care in the dithering and inverse dithering operations is often needed when handling different block formatting schemes.

Assuming the channel is time-invariant during the block processing, the equivalent baseband signal of the mth hydrophone at time instant k is expressed as

$$y_{m,k} = \sum_{n=1}^{N} \sum_{l=0}^{L-1} h_{m,n}(l) x_{n,k-l} + z_{n,k} \qquad (1)$$

where L is the maximum length of the channel impulse response (CIR), $h_{m,n}(l)$ is the invariant channel tap of (m,n)th link regardless of the time instant, and $z_{n,k}$ is the additive white Gaussian noise (AWGN) with zero mean and variance σ^2.

The discrete-time input and output (I/O) model is expressed in matrix as

$$\mathbf{y} = \mathbf{H}\mathbf{x} + \mathbf{w} \qquad (2)$$

with

$$\begin{aligned}
\mathbf{y} &= [\mathbf{y}_1^T, \mathbf{y}_2^T, \cdots, \mathbf{y}_M^T]^T \in \mathcal{C}^{(MK^1)\times 1} \\
\mathbf{y}_m &= [y_{m,0}, y_{m,1}, \cdots, y_{m,K_1-1}]^T \in \mathcal{C}^{K^1\times 1} \\
\mathbf{x} &= [\mathbf{x}_1^T, \mathbf{x}_2^T, \cdots, \mathbf{x}_N^T]^T \in \mathcal{C}^{(NK^1)\times 1} \\
\mathbf{x}_n &= [x_{n,0}, x_{n,1}, \cdots, x_{n,K^1-1}]^T \in \mathcal{C}^{K^1\times 1} \\
\mathbf{w} &= [\mathbf{w}_1^T, \mathbf{w}_2^T, \cdots, \mathbf{w}_M^T]^T \in \mathcal{C}^{(MK^1)\times 1} \\
\mathbf{w}_m &= [w_{m,0}, w_{w,1}, \cdots, w_{m,K^1-1}]^T \in \mathcal{C}^{K^1\times 1}
\end{aligned}$$

and $\mathbf{H}$ is the $M \times N$ block diagonal channel matrix with the (m,n)th subblock being the circulant channel matrix $\mathbf{H}_{m,n} \in \mathcal{C}^{K^1\times K^1}$ whose first column is $[h_{m,n}(0), \cdots, h_{m,n}(L-1), 0, \cdots, 0]^T$.

III. Cross Evaluation

A. Single Carrier Modulation Under Test (SCM-SUT)

For the SCM-SUT, one has the Linear Precoder1 in Fig. 1 as a diagonal matrix, thus, $\mathbf{x}^1 = \mathbf{s}$ with $\mathbf{s} = [\mathbf{s}_1^T, \mathbf{s}_2^T, \ldots, \mathbf{s}_N^T]^T$ and $\mathbf{s}_n = [s_{n,0}, s_{n,2}, \ldots, s_{n,K^1-1}]^T$ being the output of the Bit2Sym1 block. For the existing OFDM data set, the Linear Precoder is IFFT matrix $\mathbf{F}^H$ with $\mathbf{F}$ denoting the FFT operator. If we want to map the SCM to the existing OFDM, the dithering operator Δ is an IFFT matrix to guarantee that $\mathbf{x}_n = \mathbf{F}^H\mathbf{x}_n^1 = \mathbf{F}^H\mathbf{s}_n$. The equivalent SCM system of (2) with the OFDM data set is expressed as

$$\mathbf{y} = \begin{bmatrix} \mathbf{H}_{1,1}\mathbf{F}^H & \cdots & \mathbf{H}_{1,N}\mathbf{F}^H \\ \vdots & \ddots & \vdots \\ \mathbf{H}_{M,1}\mathbf{F}^H & \cdots & \mathbf{H}_{M,N}\mathbf{F}^H \end{bmatrix} \begin{bmatrix} \mathbf{s}_1 \\ \vdots \\ \mathbf{s}_N \end{bmatrix} + \begin{bmatrix} \mathbf{w}_1 \\ \vdots \\ \mathbf{w}_M \end{bmatrix} \qquad (3)$$

where $\mathbf{s}_n = [s_{n,0}, \ldots, s_{n,K^1-1}]^T$ is the new SCM SUT vector.

To estimate the symbol vector $\mathbf{s}_n$ in the SCM-SUT, a possible solution is block-wise MMSE time domain equalization by computing matrix inverse with the size $(MK^1) \times (NK^1)$ which results in a large computational complexity but enjoys good performance. The SCM schemes evaluated in this paper adopts this kind of equalizer. To reduce the complexity, we can also perform FFT on both sides of (3), leading to

$$\mathbf{y}' = \mathbf{H}'\mathbf{s} + \mathbf{w}' \tag{4}$$

where $\mathbf{y}' = [(\mathbf{F}\mathbf{y}_1)^T, \ldots, (\mathbf{F}\mathbf{y}_M)^T]^T$, and $\mathbf{H}'$ is a symmetric matrix whose (m,n)th sub-matrix is $\mathbf{H}'_{m,n} = \mathbf{F}\mathbf{H}_{m,n}\mathbf{F}^H$. Then we can adopt the one-tap frequency domain equalization (FDE) to detect the SCM-SUT signal.

B. Orthogonal Frequency Division Multiplexing Scheme Under Test (OFDM-SUT)

For the OFDM-SUT, the Linear Precoder1 is a IFFT matrix yielding $\mathbf{x}_n^1 = \mathbf{F}^H\mathbf{s}_n$. For the existing SCM data set, The Linear Precoder is diagonal matrix. If we want to map the OFDM to the existing SCM, the dithering operator Δ is potentially selected as $\mathbf{F}$ to guarantee $\mathbf{x}_n = \mathbf{F}\mathbf{x}_n^1$. The equivalent OFDM system model under SCM data set is given as

$$\mathbf{y} = \begin{bmatrix} \mathbf{H}_{1,1}\mathbf{F} & \cdots & \mathbf{H}_{1,N}\mathbf{F} \\ \vdots & \ddots & \vdots \\ \mathbf{H}_{M,1}\mathbf{F} & \cdots & \mathbf{H}_{M,N}\mathbf{F} \end{bmatrix} \begin{bmatrix} \mathbf{F}^H\mathbf{s}_1 \\ \vdots \\ \mathbf{F}^H\mathbf{s}_N \end{bmatrix} + \begin{bmatrix} \mathbf{w}_1 \\ \vdots \\ \mathbf{w}_M \end{bmatrix} \tag{5}$$

Similarly, if we want to estimate the symbol vector $\mathbf{s}_n = [s_{n,0}, \ldots, s_{n,K^1-1}]^T$ under OFDM-SUT, one must perform the matrix inverse of size $(MK^1) \times (MK^1)$. The FDE design can be also achieved by performing IFFT on both sides of (5), leading to

$$\mathbf{y}' = \mathbf{H}'\mathbf{s}' + \mathbf{w}' \tag{6}$$

with $\mathbf{y}' = [(\mathbf{F}^H\mathbf{y}_1)^T, \ldots, (\mathbf{F}^H\mathbf{y}_M)^T]^T$, $\mathbf{H}'$ is diagonally symmetric matrix whose (m,n)th sub-matrix is $\mathbf{H}'_{m,n} = \mathbf{F}^H\mathbf{H}_{m,n}\mathbf{F}$. Then we can adopt the one-tap FDE to detect signal $\mathbf{s}' = [(\mathbf{F}^H\mathbf{s}_1)^T, \ldots, (\mathbf{F}^H\mathbf{s}_N)^T]^T$. Finally, the OFDM-SUT signal $\mathbf{s}_n$ is detected by performing FFT operation on $\mathbf{s}'_n = \mathbf{F}^H\mathbf{s}_n$.

C. Interference Cancellation (IC) and Overlap Adding (OLA)

For the OFDM-SUT scheme, the SCM signal is converted to test the OFDM signal, but in most case, the SCM block size K is usually larger than that of the OFDM. To fit the standard OFDM data block, the SCM data block needs to be partitioned into several subblocks of size K_{sb} to guarantee $K^1 = K_{sb}$. Meanwhile, the brute subblock truncation will induce the interblock interference (IBI) between the adjacent subblocks of SCM, where the OFDM scheme utilizes the cyclic prefix (CP) or zero padding (ZP) to remove the IBI. Besides, for the FDE design, we prefer the equivalent channel matrix $\mathbf{H}_{m,n}$ to be a perfectly circulant matrix. Therefore, two steps should be performed before truncating the SCM subblock with the length of K_{sb}: 1) remove the pre-cursor and post-cursor interference induced by the previous and future subblocks; 2) shuffle the tails of the current block and perform overlap adding (OLA). Figure 2 illustrates how to eliminate IBI between the adjacent SCM subblocks and produce the standard OFDM symbol block.

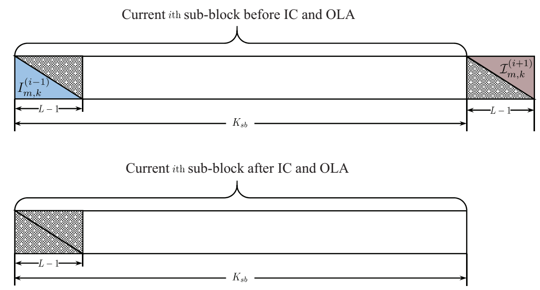


Fig. 2. Pre and post-cursor interference cancellation and overlap adding upon ith SCM subblock.

In order to eliminate the pre-cursor interference from the previous $(i-1)$th subblock $\mathbf{y}_m^{(i-1)}$ to the ith current subblock $\mathbf{y}_m^i$. Essentially, the pre-cursor interference should be reconstructed, and then removed as

$$I_{m,k}^{(i-1)} = \sum_{n=1}^{N}\sum_{l=k+1}^{L-1} \hat{h}_{m,n}^{(i-1)}(l)x_{n,K_{sb}-l+k}^{(i-1)} \tag{7a}$$

$$y_{m,k}^{(i)} := y_{m,k}^{(i)} - I_{m,k}^{(i-1)}, \text{ for } 0 \le k \le L-2 \tag{7b}$$

where $x_{n,K_{sb}-l+k}^{(i-1)}$ is the $(K_{sb}-l+k)$th symbol of the $(i-1)$th subblock

$$\mathbf{x}_n^{(i-1)} = [x_{n,0}^{(i-1)}, x_{n,1}^{(i-1)}, \cdots, x_{n,k_{sb}-1}^{(i-1)}]^T \tag{8}$$

and $\{\hat{h}_{m,n}^{(i-1)}(l)\}_{l=0}^{L=1}$ is the lth estimated channel tap corresponding to the (n,m)th channel link, $I_{m,l}^{(i-1)}$ is the reconstructed pre-cursor interference from the $(i-1)$th subblock to the ith subblock, and $\{y_{m,l-1}^{(i)}\}_{m=1}^{M}$ is the $(l-1)$th samples of the ith received subblock $\mathbf{y}_m^{(i)} = [y_{m,0}^{(i)}, y_{m,1}^{(i)}, \cdots, y_{m,K_{sb}-1}^{(i)}]^T$.

After the pre-cursor interference is removed from all the M hydrophones, the remained subblock $\mathbf{y}_m^{(i)}$ contains only intersymbol interference (ISI). Meanwhile, pre-cursor IC operation is insufficient to convert SCM to OFDM. Therefore, we use the OLA method to convert the linear channel to the cyclic channel. Since $(L-1)$-length tail of the current ith subblock becomes pre-cursor interference of the $(i+1)$th subblock, if we want to extract the tail of the current ith subblock out of the $(i+1)$th head frame, the convolved symbols corresponding to the head frame of the $(i+1)$th subblock needs to be reconstructed and removed by

$$\mathcal{I}_{m,k}^{(i+1)} = \sum_{n=1}^{N}\sum_{l=0}^{k} h_{m,n}^{(i+1)}(l)x_{n,k-l}^{(i+1)} \tag{9a}$$

$$\tilde{y}_{m,k}^{(i+1)} := y_{m,k}^{(i+1)} - \mathcal{I}_{m,k}^{(i+1)}, \text{ for } 0 \le k \le L-2 \tag{9b}$$

The residual $\tilde{y}_{m,k}^{(i+1)}, k = 0, 1, \cdots, L-2$ is then used as the overlap onto the current ith head frame, i.e.,

$$y_{m,k}^{(i)} := y_{m,k}^{(i)} + \tilde{y}_{m,k}^{(i+1)}, \text{ for } 0 \le k \le L-2. \tag{10}$$

Thus, the refined ith symbol block is ready to be converted to the OFDM block.

IV. Experimental Results

The sea trial field data used in the proposed test bench is acquired from the SPACE08 experiment conducted by the WHOI, the transmitted signal format was designed by the Missouri University. Here, we won't repeat the tedious experimental specifications. The symbol interval was $T_s = 0.1024$ ms and the carrier frequency was $f_c = 13$ kHz. Both of the SCM and OFDM scheme took a rate-1/2 convolutional channel encoder with generator polynomial $[G_1, G_2] = [17, 13]_{\text{oct}}$. Also, they shared the different transmission frame structure which is illustrated in Fig. 3. The liner frequency modulation (LFM) signals padded before and after the transmission frame were utilized to estimate the carrier frequency offset (CFO), perform coarse timing synchronization and channel length measurement. We adopted the 2×12 MIMO system with the communication distance 1000 m. The payload symbols with QPSK, 8PSK, and 16QAM were transmitted in payload blocks.

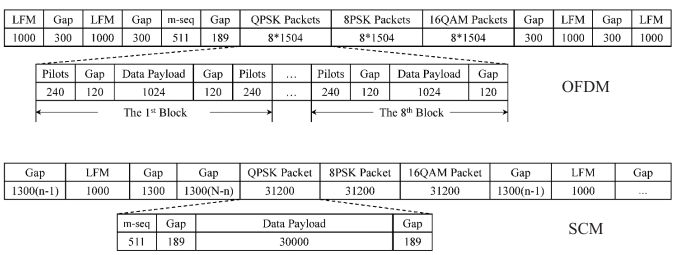
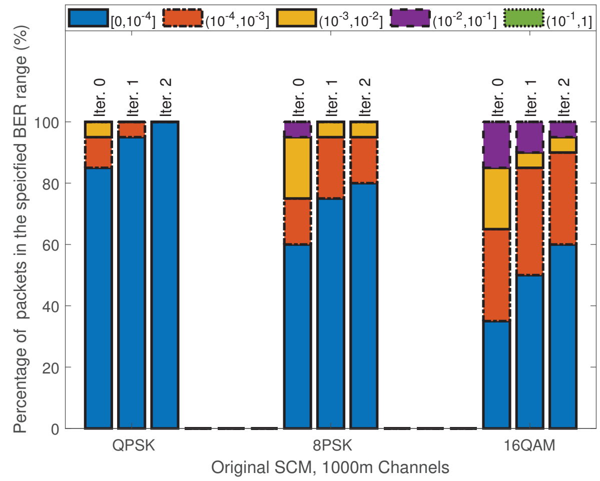


Fig. 3. Data structure of SCM and OFDM in the SPACE08 experiment.

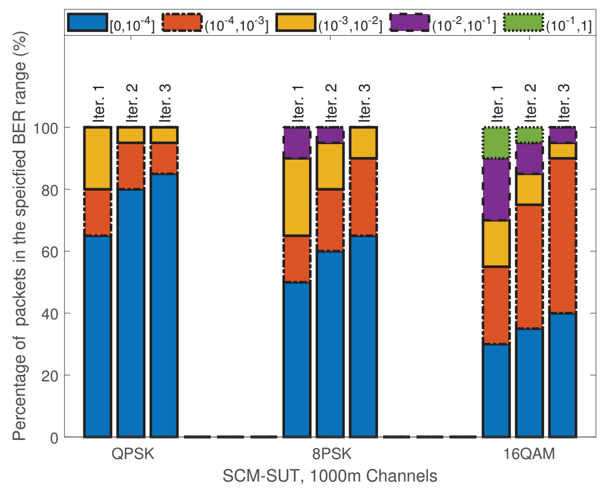
The test bench had two groups of counterparts, the first group is the comparison of the original SCM scheme and SCM-SUT, the second group is the comparison of the original OFDM and OFDM-SUT. For each of the group, we processed 20 files in the format illustrated in Fig. 3. Although the data files with SCM and OFDM carried different data payload, the performance evaluation is under the averaged BER benchmark which is still fair for the comparison. Figures 4 and 6 demonstrate the BER performance between the cross evaluation and their original counterparts using the general turbo equalization.

For the SCM scheme, the original SCM scheme had slight better BER performance than the SCM-SUT, which comes from two reasons: 1) SCM-SUT utilized the OFDM signal to perform the cross evaluation, where the OFDM signal suffered high peak to average power ratio (PAPR). Although we tried to refine the energy, there still may be the performance degradation; 2) The pilot sequence size used for channel estimation in OFDM signal was only 240 available , whereas the size of the pilot sequence in SCM signal was 511 (m-sequence). The pilot sequence may be insufficient to estimate the channel for OFDM signal. 3) The gap between the pilot sequence and OFDM payload failed to cover the channel length, energy leakage of the pilots contaminated the received OFDM signal as depicted in Fig. 5.

For the OFDM scheme, the OFDM-SUT showed better BER performance than the original OFDM scheme because the



(a)



(b)

Fig. 4. Results of BER comparison between the original SCM scheme and the SCM-SUT under 1000 m channel.

SCM signal used to evaluate the OFDM-SUT had lower PAPR than the original OFDM signal. Moreover, the original SCM scheme outperformed the OFDM-SUT even if they shared the same SCM data set. Since we used IC and OLA operation whose accuracy depends heavily on the channel estimation which will result in the error propagation in the OFDM-SUT. Anyway, the original SCM and the SCM-SUT still have almost the same performance.

V. Conclusion

This paper enhances the passband data reusability not just limited to the bit and symbol mapping playback. Moreover, it provides the design philosophy of cross evaluation for multiple access in a higher level, based on which the equalizer will be more flexible according to the channel conditions. Experimental results demonstrate that the proposed approach achieves the passband data reusability between OFDM and SCM on the waveform level even if they have different kinds

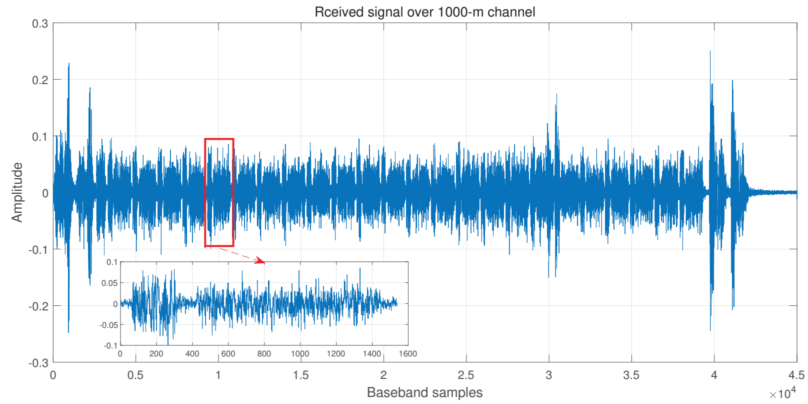
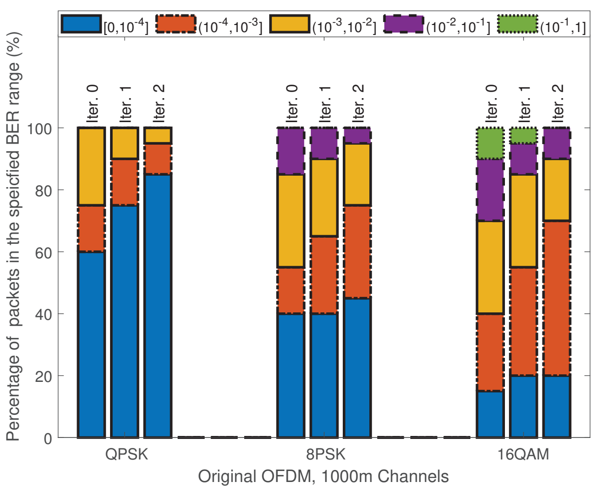
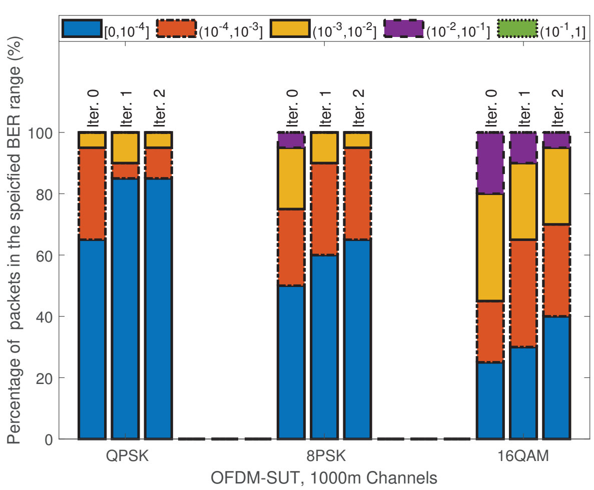


Fig. 5. Example of the received OFDM signals in 1000 m transmission.



(a)



(b)

Fig. 6. Results of BER comparison between the original OFDM scheme and the OFDM-SUT under 1000 m channel.

of signal format. However, there are some issues remained for the proposed approaches, e.g., when using the sophisticated OFDM data set, the PAPR problem should be considered and we ignored the signal contamination of the pilots on the OFDM signal, which results in the performance degradation for both the original OFDM and SCM-SUT evaluation. All of these topics shall be suspended in the future research.

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