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Effective Soft Decision Feedback Equalizer for Channels with Low SNR in Underwater Acoustic Communications

Xiaoxia YANG

State Key Laboratory of Acoustics
Institute of Acoustics
Chinese Academic of Sciences
Beijing, China 100190
Email: xiaoxiayang1987@gmail.com

Sebastien HOUCKE

and Christophe LAOT
Institut Mines-Telecom
TELECOM Bretagne;
Universit eropenne de Bretagne
Brest, France 29238

Haibin WANG

State Key Laboratory of Acoustics
Institute of Acoustics
Chinese Academic of Sciences
Beijing, China 100190

Abstract—Decision feedback equalizer (DFE) uses the past decisions in the feedback filter to mitigate the intersymbol interference (ISI). Its tap coefficients are associated with the multipath spread of the channel. For the underwater acoustic channel, the impulse response often covers tens to hundreds of symbols, requiring at least tens of taps in the feedback filter. The error propagation easily occurs when the signal to noise ratio (SNR) decreases. In order to improve the DFE performance, a soft decision device is used in the feedback loop. Differently with the hard DFE, the soft DFE takes into account the reliability of the decisions, and the likelihood of these decisions is feedback to mitigate the ISI. The soft DFE is demonstrated to be useful from two aspects in the real sea test: 1). It can overcome the SNR lose brought by the timing synchronization error; 2). In the decision-directed mode, the hard DFE easily diverges facing the occasional powerful noises, while the soft DFE is robust to converge again without the new training sequence.

I. INTRODUCTION

The underwater acoustic (UWA) channel is often characterized by long multipath spread, rapid time-variation and severe fading. Multipath propagation usually covers tens to hundreds of symbols, resulting in severe intersymbol interference (ISI). The optimal receiver is based on maximum-likelihood sequence estimation (MLSE) principle [1]. However, MLSE has a computational complexity that grows exponentially with the length of the channel time dispersion. It is not suitable for the UWA channel from the practical consideration. So we often use an equalizer to compensate for ISI. Decision feedback equalizer (DFE) is an effective way to mitigate ISI and is widely used in the UWA communication.

The feedforward filter of DFE is used to combat the precursor ISI, while the post-cursor ISI contributed by the channel and the feedforward filter is estimated by transmitting the past decisions in the feedback filter. In the data-aided (DA) mode of DFE, the decisions are the known training data sequence; while in the decision-directed (DD) mode, the detected decision replaces the training data. Therefore, if the decision is false, the detection of the next few symbols may suffer from this error, which is known as the error propagation. This phenomenon easily occurs when the signal to noise ratio

(SNR) decreases. Synchronization mismatch influences the input SNR of the equalizer. Usually the synchronization is performed using the most powerful path, and a slight sampling delay may induce a certain lose of SNR. On the other hand, sometimes the data is corrupted by some unexpected powerful noises, and they also bring severe error propagation, which may make the DFE diverge.

In order to overcome the error propagation caused by the low SNR, we use a symbol-spaced DFE with a soft decision device in the feedback loop. The knowledge of the "soft" concept is initially used in the channel codec field, and then in the iterative receivers combining the equalization and the channel decoding [3] [4]. Here, we only consider the soft decision DFE apart from the channel decoding.

In the hard DFE, a false decision implies a high probability of error propagation. However, this will not be the case with the soft DFE, as the soft decision contains an information about all the possible decisions. Indeed, it is a sum of the symbols weighted by the probability of the symbols given the observation. The information of each decision in the feedback filter is related to the detection probability. When the probability is large, the decision should have a leading role for combating the ISI. On the contrary, a less influence should be awarded to the decision which has a low probability.

When the channel is time-invariant and the equalizer works in the DD mode, a sudden powerful noise may make the equalizer deviate from the convergence state. Facing the extra powerful noise, the hard DFE may easily diverge, and it needs the new training sequence to update the equalizer. This decreases the effective bit rate, especially when there are frequent powerful noises. However, we show by simulation that the soft DFE always converges again quickly without the new training sequence. Simulation and the sea test results show that the soft DFE has a better performance compared to the hard DFE.

The paper is organized as follows. Section II describes the system model and the soft DFE. Section III and IV presents the simulation results and the sea test results, respectively. Finally,

conclusions are summarized in Section V.

II. SYSTEM MODEL

The sequence data $d(k)$ is M-ary modulation signal from a finite complex alphabet $\mathcal{S} = [d_1, d_2, \dots, d_M]$. Assuming that $d(k)$ is zero-mean independent identically distributed (i.i.d.), and its variance is denoted as σ_d^2 . The received data $r(k)$ is given by

$$r(k) = \sum_{i=0}^L h(i)d(k-i) + n(k), \quad (1)$$

where $h(k)$ is the discrete channel response with the order of L , and $n(k)$ is the independent additive zero-mean white noise with variance of σ_n^2 . The structure for the single input single output (SISO) communication system with DFE is shown by Fig.1.

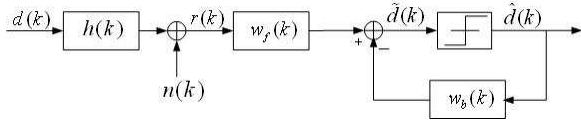


Fig. 1. The structure of SISO system with DFE

The output of the DFE is

$$\begin{aligned} \tilde{d}(k) &= \sum_{i=0}^{N_1} w_f(i)r(k+i) - \sum_{i=1}^{N_2} w_b(i)\hat{d}(k-i) \\ &= \mathbf{W}_f^T \mathbf{R}_k - \mathbf{W}_b^T \mathbf{D}_k = \mathbf{W}^T \mathbf{X}_k, \end{aligned} \quad (2)$$

In (2)

$$\begin{aligned} \mathbf{W}_f &= [w_f(0), w_f(1), \dots, w_f(N_1)]^T \\ \mathbf{W}_b &= [w_b(1), w_b(2), \dots, w_b(N_2)]^T \\ \mathbf{W} &= [\mathbf{W}_f; \mathbf{W}_b] \\ \mathbf{R}_k &= [r(k), r(k+1), \dots, r(k+N_1)]^T \\ \mathbf{D}_k &= [\hat{d}(k-1), \dots, \hat{d}(k-N_2)]^T \end{aligned}$$

\mathbf{W}_f and \mathbf{W}_b are the feedforward filter and feedback filter, respectively. In the training period, $\tilde{d}(k) = d(k)$. In the DD mode for the hard DFE, $\tilde{d}(k)$ is always detected to the decision $\hat{d}(k)$ with which it has the smallest Euclidean distance,

$$\hat{d}(k) = \underset{d_i}{\operatorname{argmin}} |\tilde{d}(k) - d_i|, d_i \in \mathcal{S}. \quad (3)$$

Actually, $\tilde{d}(k)$ is the expected decision plus residual ISI and noise. When there is a small noise and low ISI, $\tilde{d}(k)$ is very close to the decision $\hat{d}(k)$, which is shown as the case 1 in Fig.2. In this case $\tilde{d}(k)$ has a high reliability to be detected to $\hat{d}(k)$. If the equalizer works well, this detection is always correct. However, if the noise level is large, $\tilde{d}(k)$ is far away from the correct decision like case 2 shown in Fig.2. At this time, $\tilde{d}(k)$ is in the middle of some decisions. Since the distances between these decisions and $\tilde{d}(k)$ are almost the same, it's difficult to decide which decision is correct. Once the false detection occurs, there is no information of the correct

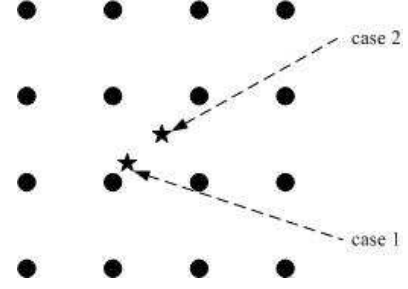


Fig. 2. The dots stands for the decisions, and the stars presents the equalizer output $\tilde{d}(k)$. Case 1 shows that $\tilde{d}(k)$ is close to one decision, while case 2 shows that $\tilde{d}(k)$ is in the middle of some decisions.

decision is feedback, and the DFE performance may easily degrade in the low SNR. The above phenomenon can also be explained from the viewpoint of the equalizer adaptation. Based on the minimum mean square error (MMSE) criteria, the adaptation of the \mathbf{W} with RLS algorithm in the DD mode is given by

$$\mathbf{W}_{k+1} = \mathbf{W}_k + \mathbf{K}(\hat{d}(k) - \tilde{d}(k)) = \mathbf{W}_k + \mathbf{K}e(k), \quad (4)$$

while $\hat{d}(k)$ is replaced by $d(k)$ in the DA mode. In (4), \mathbf{K} is the kalman gain, and $e(k)$ is the error signal. A large noise results in a large error signal. When the channel is time-invariant and DFE has already obtained its optimal weight vector in the DD mode, from (4) the large error signal results a distinct change of \mathbf{W} , and this makes the equalizer deviate from the optimal state.

Therefore, in order to improve the DFE performance, a soft decision $\hat{d}_{soft}(k)$ is used in the feedback loop. Assuming that the noise-plus-residual ISI is approximately by a Gaussian distribution, the *a posteriori* probability of the decision $P(d(k) = d_i | \tilde{d}(k))$ is also Gaussian, where $d_i \in \mathcal{S}$. So $\hat{d}_{soft}(k)$ can be defined as the mathematical expectation of the possible decisions,

$$\hat{d}_{soft}(k) = \sum_{i=1}^M P(d(k) = d_i | \tilde{d}(k)) d_i, \quad d_i \in \mathcal{S}. \quad (5)$$

From (5), we can see the information of all the possible decisions is included in $\hat{d}_{soft}(k)$. $P(d(k) = d_i | \tilde{d}(k))$ presents the reliability of these decisions, and it controls the proportion of each decision in the feedback filter. When the decision d_i is reliable, it takes a more important role in the feedback signal to mitigate the ISI; whereas a less reliable decision is weighted by a small value to decrease its bad effect in the feedback loop. On the other hand, $\hat{d}_{soft}(k)$ in (5) is much more closer to $\tilde{d}(k)$ compared to that of the hard decision when there is a large noise. That is to say, the decision-directed error signal is much smaller, which keeps the equalizer stationary.

To obtain $\hat{d}_{soft}(k)$, $P(d(k) = d_i | \tilde{d}(k))$ should be firstly known. Based on Bayes theorem, $P(d(k) = d_i | \tilde{d}(k))$ can

also be expressed as,

$$\begin{aligned} P(d(k) = d_i | \tilde{d}(k)) &= \frac{f(\tilde{d}(k) | d(k) = d_i) P(d(k) = d_i)}{f(\tilde{d}(k))} \\ &= \frac{f(\tilde{d}(k) | d(k) = d_i) P(d(k) = d_i)}{\sum_{i=1}^M f(\tilde{d}(k) | d(k) = d_i) P(d(k) = d_i)} \end{aligned} \quad (6)$$

$f(\tilde{d}(k) | d(k) = d_i)$ is *a priori* probability of $\tilde{d}(k)$, and it can be approximately by a Gaussian pdf,

$$f(\tilde{d}(k) | d(k) = d_i) = \frac{1}{\sqrt{2\pi\sigma_{n'}^2}} \exp\left(-\frac{|\tilde{d}(k) - d_i|^2}{2\sigma_{n'}^2}\right). \quad (7)$$

Substituting (6) and (7) into (5), we have

$$\hat{d}_{soft}(k) = \frac{\sum_{i=1}^M d_i \exp\left(-\frac{|\tilde{d}(k) - d_i|^2}{2\sigma_{n'}^2}\right)}{\sum_{i=1}^M \exp\left(-\frac{|\tilde{d}(k) - d_i|^2}{2\sigma_{n'}^2}\right)} \quad (8)$$

For QPSK ($d_i = \pm 1/\sqrt{2} \pm j\sqrt{2}$), (8) can be simplified into

$$\hat{d}_{soft}(k) = \frac{1}{\sqrt{2}} \left(\tanh\left(\frac{\text{Re}(\tilde{d}(k))}{\sqrt{2}\sigma_{n'}^2}\right) + j \tanh\left(\frac{\text{Im}(\tilde{d}(k))}{\sqrt{2}\sigma_{n'}^2}\right) \right). \quad (9)$$

For the high-order modulation (e.g. 16QAM), we only consider the decisions around $\tilde{d}(k)$ to get $\hat{d}_{soft}(k)$ which decreases the computational complexity.

III. SIMULATION RESULTS

A. DFE Performance versus SNR

To evaluate the performance of the DFE versus the SNR, we present the simulation results under the static channel,

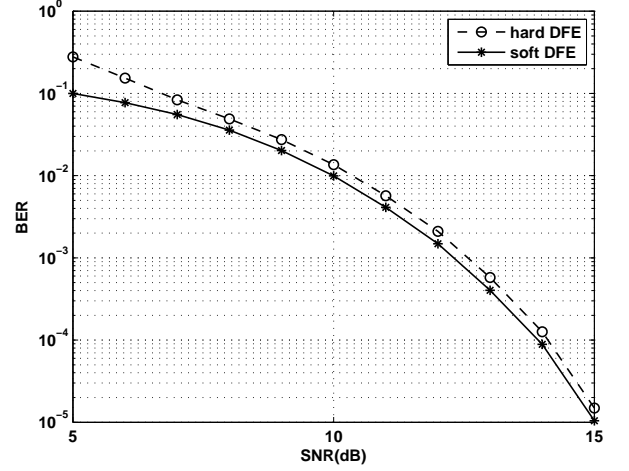
$$\mathbf{H} = [2 - 0.4j, 1.5 + 1.8j, 1, 1.2 - 1.3j, 0.8 + 1.6j].$$

QPSK and 16QAM signals are transmitted through the multipath channel with additive white Gaussian noise.

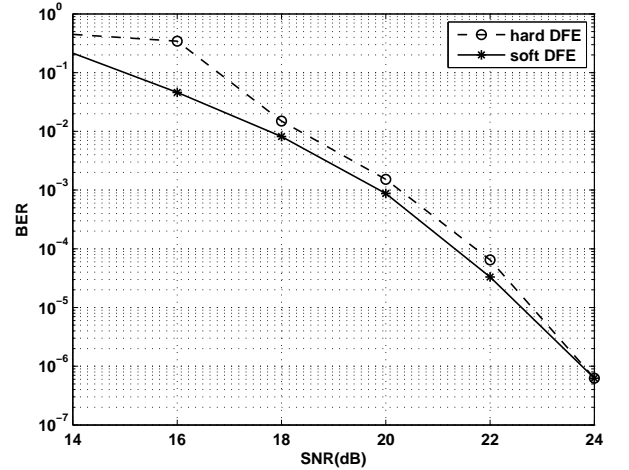
Since the feedback filter is used to estimate the post-cursor ISI, its tap number depends on the channel multipath delay. The tap number of the feedforward filter is associated with the spread of the precursor ISI, but there is not so much restriction on it. 5 taps feedback filter and 15 taps feedforward filter are used in the simulation. 1000 known symbols are used to be the training sequence. Fig. 3 shows the compared bit error rate (BER) performances between the hard DFE and the soft DFE in the case of QPSK modulation and 16QAM. The BER is given as a function of the input SNR. From these results, we can see that the soft DFE has a better performance than the hard DFE, especially when the SNR is low.

B. DFE Performance with Sudden Powerful noises

In this part we show the DFE performance when there is a sudden powerful noise in the DD mode. The simulation channel is shown by Fig. 4(a). It is an estimated channel response from one sea test, and the multipath is significant. The order of the channel is 20, so we set the tap number of the feedback filter and the feedforward filter to be 20 and 15,



(a) The BER performance in the case of QPSK



(b) The BER performance in the case of 16QAM

Fig. 3. The compared performance between the hard DFE and soft DFE

respectively. In the simulation, QPSK signals are transmitted and the training sequence length is also set to be 1000. The SNR is 15dB, but the noise power becomes large from 2001 samples to 2100 samples in the DD mode. Results have been obtained using 100 Monte Carlo simulations.

Fig. 4(b) shows the true MSE between the hard DFE and the soft DFE. Facing the sudden powerful noises in the DD mode, the hard DFE diverges; while the soft DFE converges again quickly. In this simulation, the powerful noises make the hard DFE deviate from its convergence state, and it needs the new training sequence to update the equalizer again, which decreases the effective bit rate. However, the soft DFE can overcome the error propagation brought by the sudden powerful noises.

IV. EXPERIMENTAL RESULTS

In order to demonstrate the improved performance of the soft DFE, we undertook two shallow water experiments. One

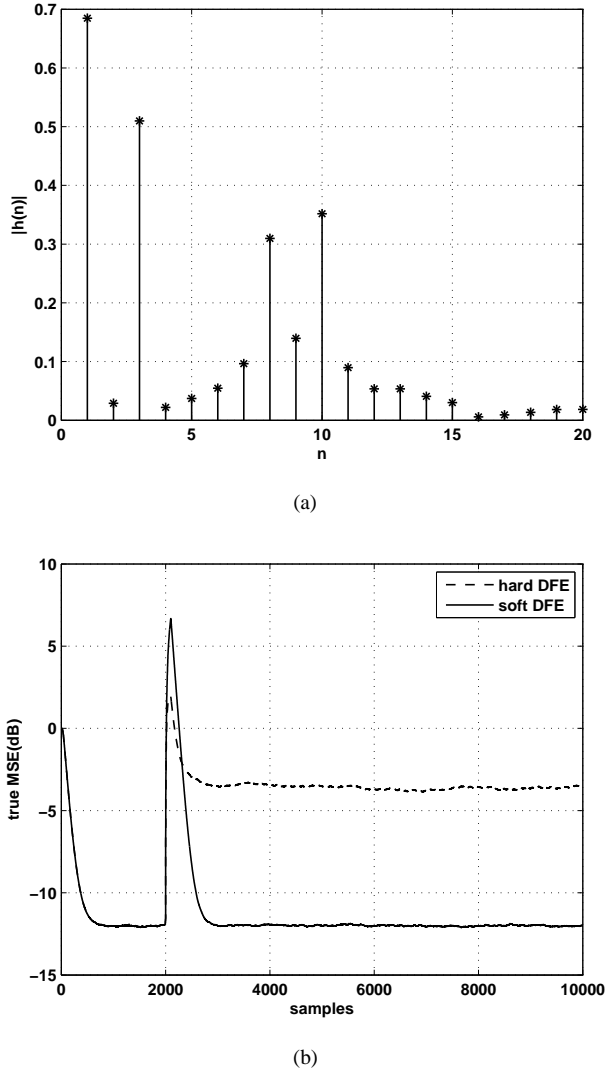


Fig. 4. (a). The simulation channel response. (b). The compared true MSE between the hard DFE and the soft DFE in the case of sudden powerful noise

is a SISO system, and it is used to prove that the soft DFE overcomes the lose of SNR brought by the timing synchronization error. The other sea test is based on the single input multiple output (SIMO) system, and it shows the soft DFE can still work well even if the noise becomes suddenly more powerful.

A. Sea Test with SISO System

The shallow water experiment with a SISO system was performed in China South Sea in July 2011. Digital communication uses QPSK modulation with a carrier frequency of 4 KHz, and the bit rate is 2 kb/s. The transmission range is about 3.3 nautical miles. Linear frequency modulated (LFM) signals are used to complete the carrier and timing synchronization. The proper sampling should be according to the most powerful path of the channel, and any sampling delay may induce a certain lose of SNR.

TABLE I
THE PERFORMANCE COMPARISON BETWEEN THE HARD DFE AND THE SOFT DFE WITH DIFFERENT TIMING DELAY

sampling delay	0	$0.1T_s$	$0.2T_s$	$0.3T_s$	$0.4T_s$
P_s	0.0482	0.0477	0.0459	0.0437	0.0418
N_{hard}	36	49	65	317	3871
N_{soft}	27	32	53	126	336

In order to test the improved performance of the soft DFE in low SNR, we add different sampling delays on the received data. Table. I shows the compared performance between the hard DFE and the soft DFE with five different timing delay. T_s is the symbol duration. We estimate the variance of the sampled data as the data power P_s for each timing delay. From Table. I, we can see that the larger the sampling delay, the smaller the P_s . Since the power of the noise keeps steady, the SNR is a decreasing function of the sampling delay. We compare the error symbol number N_{hard} , N_{soft} out of 18000 symbols between the soft DFE and the hard DFE. The results show that the soft DFE always performs better than the hard DFE. When the sampling is far away from the optimal one, it's at the edge of each symbol, where the sampling data has the lowest power. In this case the hard DFE does not work any more since the error propagation is severe. However, the soft DFE can mitigate the error propagation to keep in its convergence state.

B. Sea Test with SIMO System

The shallow water experiment with a SIMO communication system was taken in China Yellow Sea in December 2011. The sea depth is about 130m. A vertical array of four hydrophones were used, and the source-receiver range is approximately 18.5 km. QPSK signals of a bandwidth of 2000 Hz were transmitted with a carrier frequency of 4 kHz, and the bit rate is 2 kb/s.

In the sea test, the hydrophones were binded to the rope, but they were not fixed well. So the received data were corrupted by the noise which was created by the knock between the hydrophone and the rope. The knocking noises have a much higher power than the communication signals, and they happen frequently. Since the waves resulted in a severe knocking noises for the upper two receivers, we only use the data received by the bottom two hydrophones. However, there are also occasionally knocking noises in these data.

A multichannel DFE is considered to recover the transmitted signal. As the channel multipath spread is long, 50 taps feedback filter and 51 taps feedforward filter are equipped. RLS algorithm with a forgetting factor $\lambda = 0.995$ is used to update the equalizer coefficients. 1000 symbols are known as the training sequences. Fig. 5 shows the true MSE and the directed-decision MSE (DDMSE) of the hard DFE. After the training mode, there exists the knocking noises. At the beginning, the hard DFE can work with the powerful noise. But when the knock becomes frequent, the hard DFE does not converge back when the next powerful noise is coming, and then the error propagation occurs. Fig. 6 gives the results

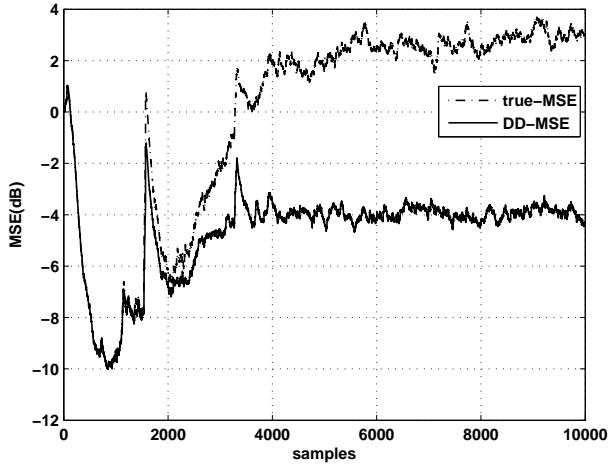


Fig. 5. The performance of the hard DFE faced to sudden knocking noises. True MSE — dotted line; DDMSE — solid line.

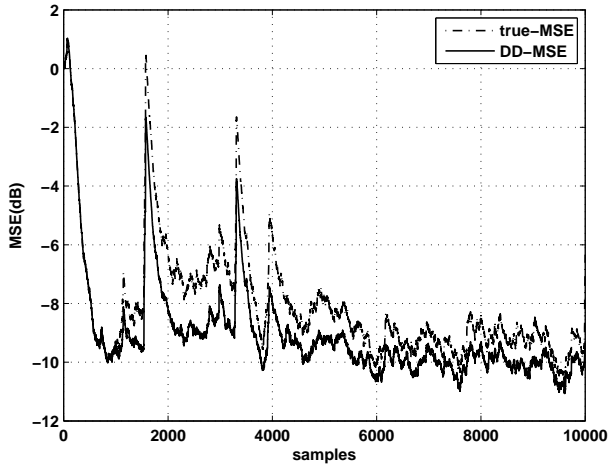


Fig. 6. The performance of the soft DFE faced to sudden knocking noises. True MSE — dotted line; DDMSE — solid line.

of the soft DFE. Although the soft DFE also gets a large MSE facing the knocking noises, it can converge again quickly with DD-RLS. The soft DFE exhibits a good performance for overcoming the error propagation. Fig. 7 is the compared constellation, we can see the soft DFE gets a very clear eye diagram.

V. CONCLUSIONS

The soft DFE uses the expectation of the decision as the feedback signal. It overcomes the drawback in the hard DFE that there is no correct information to feedback when the decision is wrong. This soft DFE has a better performance, especially when the SNR is low. This performance is useful for the real sea test. On the one hand, it can combat the lose of the SNR brought by the timing synchronization. On the other hand, since the ocean channel is complicated and uncertain, it is inevitable that the received data is corrupted

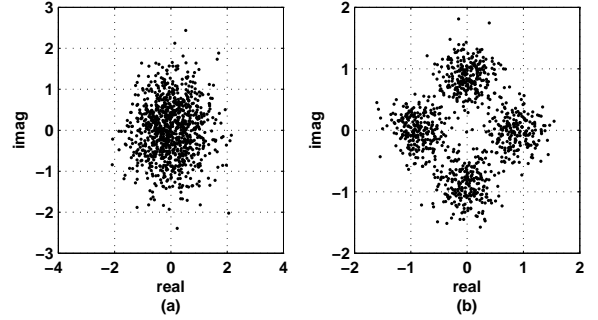


Fig. 7. The compared constellation between the hard DFE and the soft DFE faced to sudden knocking noises. (a). the hard DFE; (b). the soft DFE.

by the occasional powerful noises. The conventional hard DFE often diverges if these powerful noises occur in the DD mode. But the soft DFE exhibits to have the ability for overcoming the powerful noises by the simulation and sea test results.

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