Early Results on the Design of Adaptive Equalizer for HF Communications System on Equatorial Region

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Abstract

Wideband HF channel (3–30 MHz) using Ionosphere layer as a reflection medium is very potential for an affordable long-distance communication system. The main challenge to realize HF communication is its time-variant multipath characteristic which causes fading, Doppler spread, and ISI (Inter-Symbol Interference) at the received signal. Consequently, adaptive signal processing in HF receiver system plays its important role to reconstruct transmitted signal that has gone through multipath fading. Our study focuses on the design of adaptive DFE (Digital Feedback Equalization) for HF communications based on channel estimation. The performance of adaptive DFE is measured in MSE (Mean Square Error) and convergence rate using either the LMS (Least Mean Square) or RLS (Recursive Least Square) algorithm. The design is to be based on HF channel impulse response measurement made in Indonesia, a typical equatorial region, on a 3036 km link.

1. Introduction

Wideband HF (3–30 MHz) communication system using Ionosphere layer as the reflector is very potential for long distance and affordable communication. Today HF communication can be useful for telemedicine, emergency communication [1], e-learning video conference [2], broadcasting, amateur radio both the fixed and mobile radio [3]. The most challenging aspect is to realize wideband HF communication through time-varying multipath channels. These time-varying channel characteristics manifest themselves in fading, Doppler spread and delay spread, the latter being likely to cause severe ISI (Interference Inter Symbol) of received signals. This is especially true for equatorial HF channels, which are influenced by such natural phenomena as the ESF (Equatorial Spread-F) and Sporadic E. Consequently, adaptive equalization in HF receiver system plays its important role to reconstruct transmitted signal that has gone through multipath fading.

Previous research related to the performance of HF receiver only looks at SNR (Signal to Noise Ratio) [4], [5], [6], whereas wideband communication systems employing adaptive equalizers shall also consider the MSE and the convergence rate of the adaptive technique. Experiments by simulations and measurements had also been done using adaptive DFE techniques with the transmitter and receiver being 90 kilometers apart [5]. In fact, HF communication with 90 kilometers link distance between transmitter and receiver was most likely dominated by the ground-wave mode, instead of the sky-wave mode. Some channel estimation-based algorithms were also introduced to analyze their performance, but not really sensitive if they were applied in real conditions. [7]. DFE equalizer is able to adapt to the time-varying HF environment by updating its coefficients using adaptive algorithms, LMS and RLS.

Our study focuses on the design of DFE equalizer for HF communication systems in equatorial region and examination of their performance in terms of MSE and convergence rate. Complex impulse response estimates of actual HF channels are obtained from a 3036 km radio measurement link in Indonesia, a typical equatorial region.

2. Digital Feedback Equalization

A DFE consists of two filters, a (K_1+1)-tap feed-forward transversal filter and a K_2-tap feedback transversal filter. Tap coefficients optimization of a DFE can be solved using MSE criterion. Symbol sequence at the output of DFE equalizer can be expressed in input sequences $\{v_k\}$ and previous detected symbols $\{\check{I}_k\}$ as follow:

$$\hat{I}_k = \sum_{j=-K_1}^{0} c_j v_{k-j} + \sum_{j=1}^{K_2} c_j \check{I}_{k-j} \tag{5}$$

where $\{c_j, j = -K_1, ..., K_2\}$ denotes DFE tap coefficients. We derive the coefficients based on assumption that previous detected symbols are correct to minimize MSE: $J(K_1, K_2) = E\left|I_k - \hat{I}_k\right|^2$ which results in the following linear equations [8]:

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$$\sum_{j=-K_1}^{0} \psi_{lj} c_j = f_{-l}^{*} \quad l = -K_1, \dots, -1, 0 \tag{6}$$

where:

$$\psi_{lj} = \sum_{m=0}^{-l} f_m^{*} f_{m+l-j} + N_0 \delta_{lj} \quad l, j = -K_1, \dots, -1, 0 \tag{7}$$

Then, the feedback filter coefficients c_k of DFE are given in terms of the feed-forward coefficients by the following expression:

$$c_k = -\sum_{j=-k_1}^{0} c_j f_{k-j} \; k = 1, 2, \dots, K_2 \tag{8}$$

The values of the feedback coefficients will result in complete elimination of inter symbol interference from previous detected symbols according to the main condition that previous decisions are correct.

3. Adaptive Equalization

Due to time variation of the ionosphere, impulse response of the HF sky-wave channel also changes in time. An adaptive equalizer is designed to adapt its tap coefficients $\mathbf{w}(n)$ to the changing HF channel impulse response. The most common adaptation algorithms used by DFE equalizers are LMS and RLS. These algorithms are evaluated on the convergence rate to describe how fast an equalizer reaches its steady-state condition. Both LMS and RLS algorithms are illustrated in Table 1. LMS is initialized by determining step-size parameter μ, setting the number of equalizer taps M with zero values, computing error correction $\mathbf{e}(n)$ and updating tap weights. Whereas RLS is initialized by computing the inversed correlation matrix $\mathbf{P}(n)$, setting zero tap weights, computing gain vector $\mathbf{k}(n)$ and error correction $\boldsymbol{\xi}(n)$, and updating tap weights. Forgetting factor λ is selected from positive fractional numbers close to but less than 1.

Table 1. LMS and RLS Algorithms [9]

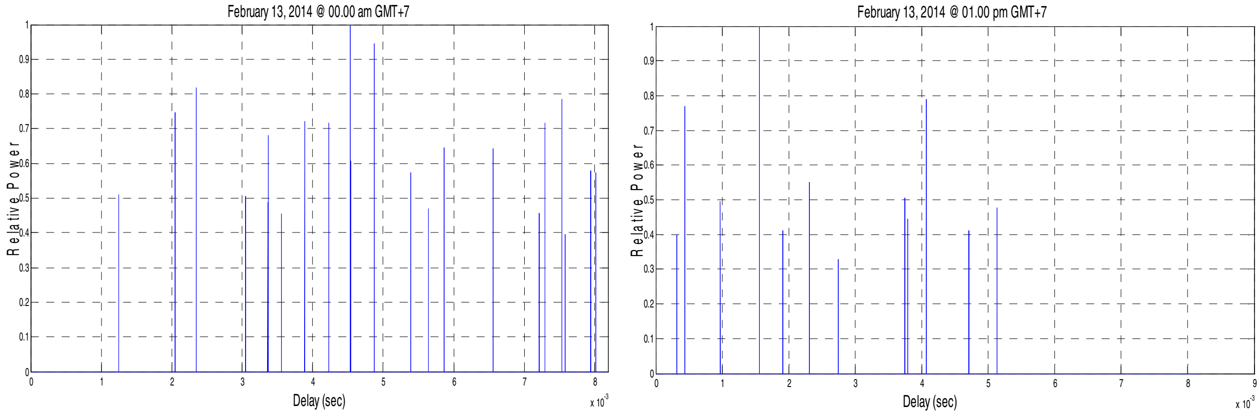
LMS	RLS
1. Parameter initialization: number of taps M, step-size parameter μ (0< μ<2/tap-input power) and tap coefficients $\mathbf{w}(0) = \mathbf{0}$. 2. Equalizer output calculation: $y(n) = \hat{w}^H(n)u(n)$ 3. Error estimation: $e(n) = d(n) - y(n)$ 4. Taps weight adaptation: $\hat{\boldsymbol{w}}(n+1) = \hat{\boldsymbol{w}}(n) + \mu \boldsymbol{u}(n) e^{*}(n)$	1. Parameter initialization: inversed correlation matrix $\mathbf{P}(0) = \delta^{-1}\mathbf{I}$ with δ denotes small integer number between 0 and 1, I denotes Identity matrix and taps coefficients $\mathbf{w}(0) = \mathbf{0}$. 2. Gain vector calculation: $\mathbf{k}(n) = \frac{\lambda^{-1}\mathbf{P}(n-1)\mathbf{u}(n)}{1+\lambda^{-1}\mathbf{u}^H(n)\mathbf{P}(n-1)u(n)}$ 3. Error estimation: $\xi(n) = d(n) - \hat{\mathbf{w}}^H(n-1)\mathbf{u}(n)$ 4. Taps weight adaptation: $\hat{\mathbf{w}}(n) = \hat{\mathbf{w}}(n-1) + \mathbf{k}(n)\xi^{*}(n)$ 5. Inversed correlation matrix update: $\mathbf{P}(n) = \lambda^{-1}\mathbf{P}(n-1) - \lambda^{-1}\mathbf{k}(n)\mathbf{u}^H(n)\mathbf{P}(n-1)$

5. Equalization Analysis

Equalization analysis is based on averaged MSE and convergence rate to achieve its steady-state condition. Firstly, derivation of the power delay profile is simulated from impulse response measurement. Secondly, adaptation parameter analysis of LMS and RLS used in DFE equalizer.

5.1 Impulse Response Measurement

HF impulse response measurement is conducted using dipole antenna at both the transmitter and receiver side. The transmitter using USRP (Universal Software Radio Peripheral) is located in Surabaya (latitude -7.2818S, longitude 112.7591E) and the receiver is located in Merauke (latitude -8.4963S, longitude 140.3878E) separated by a distance of 3036 kilometers. PN sequences of order 12 (2^{12}-1 = 4095 bits per period) are BPSK modulated at 7 MHz, 14 MHz and 21MHz in turns are transmitted and then received after severe multipath fading, attenuation and noises. The output of the USRP receiver is a baseband complex sequence of in-phase (I) and quadrature (Q) components. A complex impulse response is derived from cross-correlation between the transmitted sequence and the received IQ sequence at 7 MHz, 14 MHz and 21MHz. Impulse responses from four consecutive periods are used to determine the time-averaged PDP (Power Delay Profile). Thus, we generate the random complex normal Gaussian with zero mean and certain variance from PDP profile parameter to characterize the HF channel response, shown in Figure 1.

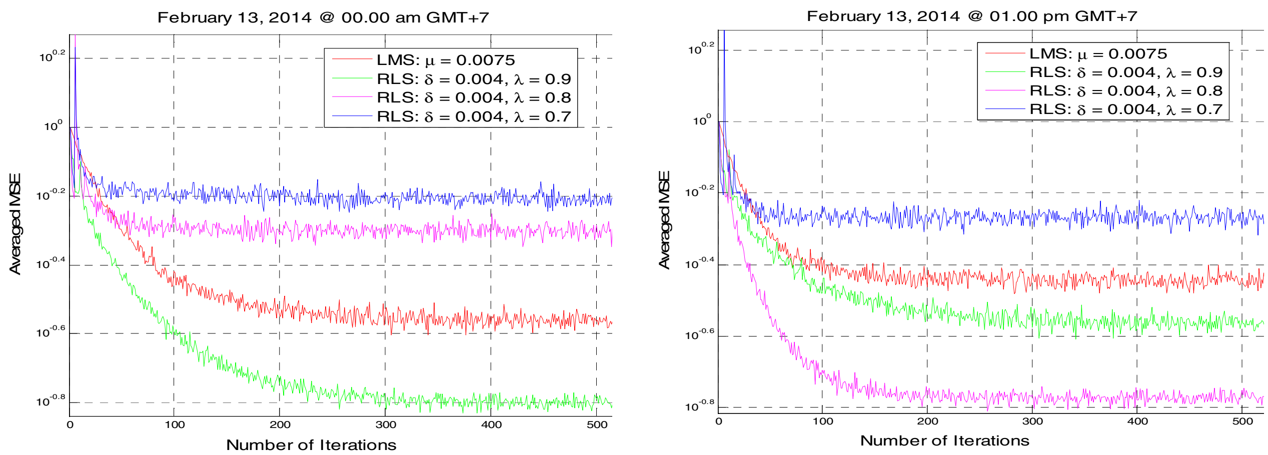


(a) PDP at the Night (b) PDP at the Daytime

Figure 1. Power Delay Profile

5.2 Adaptive DFE Parameters Determination

Adaptation algorithms in this research are simulated using the LMS with step-size parameter μ = 0.0075 and RLS with forgetting factor λ between 0.9-0.7. Symbol period T_s = 100 μs, equivalent to data rate transmission of 10 kbaud, is assumed to simulate the DFE equalizer. From 7 MHz measurement made at night as depicted in figure 2a, an 11-tap DFE LMS achieves its convergence rate at 352 iterations and averaged MSE 0.2697 with tap weights of K_1 and K_2 denoted by $\mathbf{w}(n)$ = [0.6431 -0.0067 0.0227 0.0106 0.0052 -0.0849 -0.0246 -0.0029 -0.0154 -0.0399 0.1510] while DFE RLS λ = 0.9 shows its convergence after 323 iterations and averaged MSE 0.1541 with tap weights $\mathbf{w}(n)$ = [0.1845 -0.0486 0.0429 -0.0049 -0.0206 0.0100 0.0317 -0.0050 -0.0190 0.0073 0.4799]. From the daytime measurement, figure 2b shows that DFE LMS converges at 199 iterations and has the averaged MSE 0.365 with its tap weights $\mathbf{w}(n)$ = [0.1827 0.0167 -0.0348 -0.0015 -0.0084 0.6118 -0.0126 0.0124 0.0366 -0.0260 -0.3047] while DFE RLS λ = 0.8 converges rate at 176 iterations and has averaged MSE 0.1683 with its tap weights $\mathbf{w}(n)$ = [-0.4149 -0.0196 0.0077 -0.0188 0.0215 1.1266 0.0135 0.0140 0.0054 0.0271 -0.1534].



(a) Convergence Rate at the Night (b) Convergence Rate at the Daytime

Figure 2. Convergence Rate of LMS and RLS

From the above descriptions, we may conclude that the DFE RLS with λ = 0.9 has the faster convergence rate and smaller averaged MSE than DFE LMS for the night channel. Whereas at the daytime, DFE RLS with λ = 0.8 has the faster convergence rate and smaller averaged MSE than DFE LMS. From the mid-latitude measurement of [10] and [11] using 1 MHz instantaneous bandwidth with assumed symbol rate 100 kbaud, the largest delay were 35 μs and 62 μs respectively. We can use 5 taps weight equalizer to compromise 35 μs delay and 7 tap weights for 62 μs delay.

Optimum DFE RLS parameter for [10] is set to λ = 0.7 and $\mathbf{w}(n)$ = [0.0011 0.0001 1.5566 0.0035 0.0031] to result in average MSE 0.0002342 at 158 iterations. Meanwhile, [11] is set to λ = 0.7 and $\mathbf{w}(n)$ = [-0.0012 0.0014 -0.0015 -0.9205 -0.0027 -0.0013 0.0002] to give averaged MSE 0.0001028 at 168 iterations. From the mid-latitude and auroral measurement of [12], the largest delay 240 µs must be compromised with 25 tap weights $\mathbf{w}(n)$ = [-0.0001 0.0007 0.0003 0.0000 0.0003 -0.0010 0.0001 -0.0006 0.0015 -0.0005 0.0007 -0.0018 1.0288 -0.0003 -0.0002 -0.0001 -0.0001 0.0013 -0.0011 0.0012 0.0003 -0.0006 0.0006 -0.0009 0.0002] and λ = 0.7 to result averaged MSE 0.0001358 and converge at 284 iterations.

6. Conclusion

For the two conditions investigated above, we conclude that at night DFE RLS adapts faster than DFE LMS when its parameter is set with λ = 0.9 and results in averaged MSE 0.1541. However, at the daylight condition DFE RLS shows its best performance when to be set at λ = 0.8. We can adaptively conclude that the selection of the DFE RLS parameter λ must be adaptable to the HF time-varying channel impulse response. This conclusion will be verified with more HF impulse response measurements to be made.

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