

MATLAB DMTTEQ Toolbox  
User's Manual

Time Domain Equalizer Design for  
Discrete Multitone Modulation

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# 1 Introduction

The MATLAB DMTTEQ Toolbox is a collection of MATLAB functions to design and test the following time domain equalizer design methods:

- Minimum mean squared error – unit energy constraint [1],
- Minimum mean squared error – unit tap constraint [1],
- Maximum shortening signal to noise ratio method [2],
- Maximum geometric SNR method [3],
- Divide and conquer – cancellation (designed and implemented by Biao Lu) [4],
- Divide and conquer – minimization (designed and implemented by Biao Lu) [4],
- Maximum channel capacity method [5],
- Minimum intersymbol interference method [5],
- Matrix pencil design method (designed and implemented by Biao Lu) [4],
- Modified matrix pencil design method (designed and implemented by Biao Lu) [4].

The toolbox has a graphical user interface (GUI) which enables the design of a TEQ by one of the methods above and the testing of its performance. A snapshot of the GUI is shown in Fig. 1.

# 2 Description

In the upper right of the control window is a pulldown menu from which a design method can be chosen. Below this pulldown menu are the following editable text windows which are used to set the design and simulation parameters:

- Shortened impulse response (SIR) length. This is the desired length of the channel after equalization. For example, it should be set to 33 (one plus the cyclic prefix length) for the ANSI and G.DMT ADSL standards.
- Time domain equalizer (TEQ) length. Defines the number of taps of the TEQ.
- Fast Fourier transform (FFT) size. Sets the FFT size used in DMT modulation. It is twice the number of subchannels.

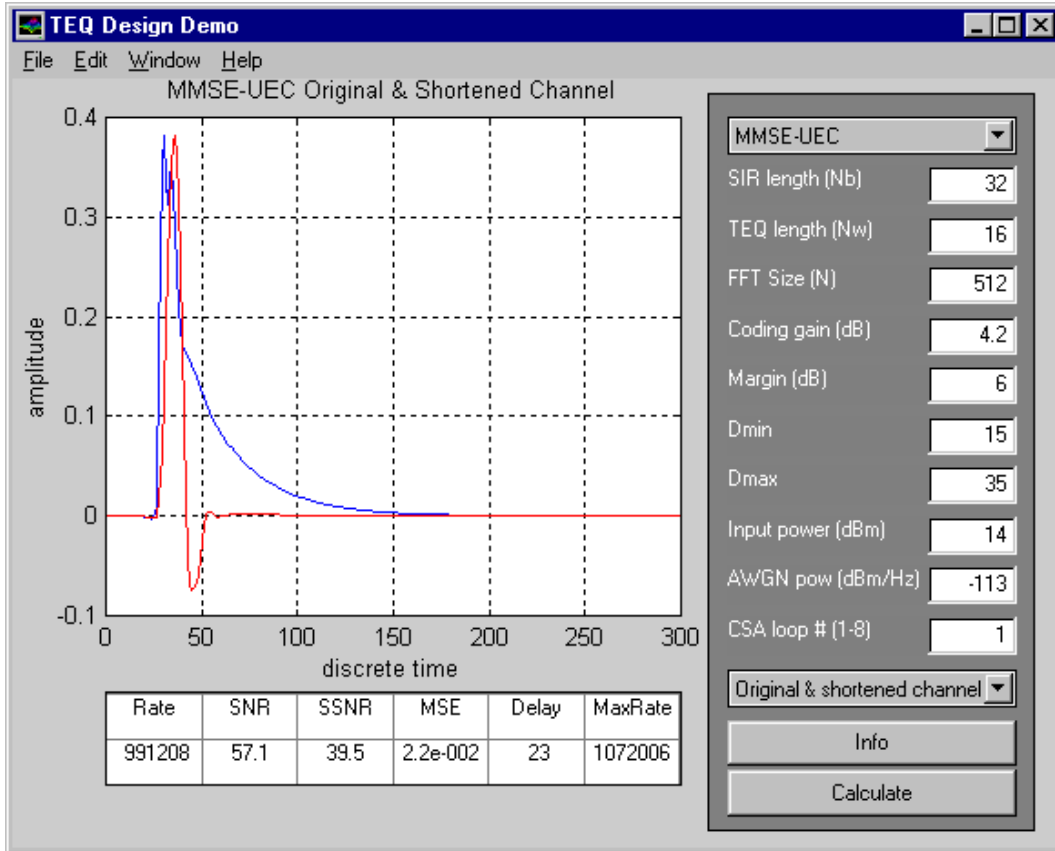


Figure 1: TEQ designed with the MMSE-UEC design method in the MATLAB DMT-TEQ toolbox.

- Coding gain (dB). Defines a coding gain in dB which is used during capacity calculations [6].
- Margin (dB). Sets the desired system margin in dB. This is also used in capacity calculations [6].
- Dmin and Dmax. The interval of  $\Delta \in [D_{min} D_{max}]$  in which to search for the optimal delay value.
- Input power (dBm). Defines the input signal power in dBm.
- AWGN power (dBm/Hz). Sets the amount of additive white Gaussian noise in dBm/Hz. AWGN is added to the near-end crosstalk noise.
- CSA loop # (1-8). Selects the desired ADSL channel on which to run the simulation. Currently the eight standard CSA loops are supported citecioffi:dsl.

Below the editable text windows is another pull-down menu which is used to select the desired graph to be displayed. The following graphics can be selected:

- Target & shortened channel. Displays the shortened channel impulse response and the target channel impulse response for the MMSE and geometric SNR methods. For all other methods, the location of the target window is displayed instead of a target impulse response.
- TEQ impulse response. Shows the impulse response of the TEQ.
- TEQ frequency response. Shows the frequency response of the TEQ.
- SNR & MFB. The SNR and matched filter bound to the SNR is displayed as a function of frequency (subchannels).
- Original & shortened channel. Displays the channel impulse response before and after equalization.
- Noise power spectrum. Shows the power spectrum of the noise which consists of NEXT noise plus AWGN.
- Delay plot. Displays the performance measure (i.e., MSE, SSNR, channel capacity) of the method with respect to the delay.
- Equalized channel frequency response. Displays the frequency response of the channel after equalization.

The two remaining buttons in the control frame are

- Info. Displays information on how to use the GUI.
- Calculate. Starts the calculation and performance evaluation of the TEQ.

The following performance measures are calculated and listed in the table:

- Rate. Gives the achievable bit rate with the given channel and TEQ settings.
- SNR. Shows the SNR at the output of the equalizer in dB.
- SSNR. Shows the shortening SNR in dB. This is defined as the ration of the energy of the shortened channel impulse response in the target window the the energy outside the target window.
- MSE. Gives the MSE for the MMSE and geometric SNR methods.
- Delay. Shows the optimal delay for the system.
- Max Rate. Shows the absolute maximum achievable bit rate given the channel and equalizer settings. It is calculated from the MFB.

Once all of the design and simulation parameters are set to the desired values and the design method is chosen, the user hits the “Calculate” button to start the calculations. The simulator first loads the channel information and generates the channel noise according to the parameter values. Then, it will generate a transmit sequence and pass it through the channel to obtain a received signal. In the next step, the simulator estimates the power spectra of the transmitted signal and channel noise. It also estimates the magnitude square of the channel frequency response. Based on these estimates, the SNR in each subchannel is estimated.

The simulator then calls the desired TEQ design function to calculate the equalizer taps, target impulse response (if it exists for that method), and optimal delay. All of the results are then passed to a performance evaluation function which returns the six performance measures. The selected graph is plotted and the results are written in the table. For different graphs the simulations does not need to be run again, all results are saved.

It is possible to load the equalizer taps, target impulse response, and optimal delay as well as other results into MATLAB workspace by typing “load teqresults”. The variables used to pass parameters and get the results are listed in Table 1

### 3 TEQ Design Functions

#### UTC.M

*Description:* Minimum mean-squared error time domain equalizer design using the unit-tap constraint

*Usage:*  $[B, W, D, MSE, I, Dv] = UTC(X, Y, N, H, Nb, Nw, Dmin, Dmax)$

Returns the optimal target impulse response  $B$ , the time domain equalizer  $W$ , the delay  $D$ , and the unit tap index  $I$ . Optimal is in the sense of minimum mean-squared error under the constraint of a unit-tap.  $MSE$  is the resulting mean-squared error and  $Dv$  is a vector containing the mean-squared error for delay values between  $Dmin$  and  $Dmax$ .

$X$  is the transmitted data vector.  $Y$  is the received data vector (without channel noise).  $N$  is the channel noise vector.  $H$  is channel impulse response.  $Nb$  is the number of taps in the target impulse response and  $Nw$  the number of taps in the time domain equalizer.  $Dmin$  and  $Dmax$  define the search interval for the optimal delay.

#### UEC.M

*Description:* Minimum mean-squared error time domain equalizer design using the unit-energy constraint.

*Usage:*  $[B, W, D, MSE, Dv] = UEC(X, Y, N, H, Nb, Nw, Dmin, Dmax)$

Variable	Content
TEQequalizerTaps	equalizer taps
TEQtargetImpulseResp	target impulse response
TEQoptimalDelay	optimal delay
TEQoriginalChannel	original channel impulse response
TEQequalizedChannel	equalized channel impulse response
TEQmatchedFilterBoundPerChannel	matched filter bound in subchannels
TEQSNRperChannel	SNR in subchannels
TEQoriginalChannelFreqResp	channel frequency response
TEQequalizerFreqResp	equalizer frequency response
TEQequalizedChannelFreqResp	equalized channel frequency response
TEQchannelNoisePowerSpecAfterEqual	noise power spectrum after equalization
TEQchannelNoisePowerSpecBeforeEqual	noise power spectrum before equalization
TEQperformanceVersusDelay	performance for various delays
TEQDmin	minimum delay
TEQDmax	maximum delay
TEQNb	desired equalized channel length
TEQNw	number of taps in the TEQ
TEQN	FFT size of the DMT modulation

Table 1: Global variable names used in the DMTTEQ Toolbox

Returns the optimal target impulse response  $B$ , the time domain equalizer  $W$ , and the delay  $D$ . Optimal is in the sense of minimum mean-squared error under the unit-energy constraint. MSE is the resulting mean-squared error and  $Dv$  is a vector containing the mean-squared error for delay values between  $D_{min}$  and  $D_{max}$ .

$X$  is the transmitted data vector.  $Y$  is the received data vector (without channel noise).  $N$  is the channel noise vector.  $H$  is channel impulse response.  $N_b$  is the number of taps in the target impulse response and  $N_w$  the number of taps in the time domain equalizer.  $D_{min}$  and  $D_{max}$  define the search interval for the optimal delay.

## MINISI.M

*Description:* Minimum-ISI TEQ design.

*Usage:*  $[W, D, Dv] = \text{MINISI}(S_x, S_n, S_h, H, N, N_b, N_w, D_{min}, D_{max}, M)$

Returns the time domain equalizer in  $W$  and the delay in  $D$ .  $Dv$  is a vector containing the remaining ISI power for delay values between  $D_{min}$  and  $D_{max}$ .

$S_x$  is the input data frequency spectrum.  $S_n$  is the channel noise frequency spectrum.  $S_h$  is the magnitude square of the channel frequency response.  $H$  is the channel impulse response.  $N$  is the FFT size in the discrete multitone modulation.  $N_b$  is target window size (target length of the equalized channel).  $N_w$  is the number of taps in the time domain equalizer.  $D_{min}$  and  $D_{max}$  define the search interval for the optimal delay.  $M$  is a string defining what method to be used for the generalized eigenvalue decomposition. Choices are:

- 'AUTOMATIC' automatic selection of best method
- 'GENEIGEND' direct generalized eigenvalue decomposition
- 'CHOLESKYD' Cholesky decomposition based method
- 'MINEIGEND' convert to normal minimum eigenvalue decomposition
- 'MAXEIGEND' convert to normal maximum eigenvalue decomposition

## GEO.M

*Description:* Geometric TEQ design.

*Usage:*  $[B, W, D, MSE, Dv] = \text{GEO}(X, Y, N, N_b, N_w, D_{min}, D_{max}, MSE_{max}, U)$

Returns the optimal target impulse response  $B$ , time domain equalizer  $W$ , and delay  $D$ . Optimal is in the sense of maximizing the approximate geometric SNR. MSE is the resulting mean-squared error.  $Dv$  is a vector containing the mean-squared error for delay values between  $D_{min}$  and  $D_{max}$ .

$X$  is the transmitted data vector.  $Y$  is the received data vector (without channel noise).  $N$  is the channel noise vector.  $N_b$  is the number of taps in the target impulse



response and  $N_w$  the number of taps in the time domain equalizer.  $D_{\min}$  and  $D_{\max}$  define the search interval for the optimal delay.  $MSE_{\max}$  the upperbound on the mean-squared error.  $U$  is a binary vector of size  $N/2+1$  with 1s for used subchannels and 0s for unused ones.

Optimization Toolbox Version 1.5.1 has been used in this function

### **MCC.M**

*Description:* Maximum channel capacity TEQ design.

*Usage:*  $[W, D, Dv] = OPT(Sx, Sn, H, N, Nb, Nw, Dmin, Dmax, Wo, G, I)$

Returns the optimal time domain equalizer  $W$ , and delay  $D$ . Optimal is in the sense of maximum channel capacity.  $Dv$  is a vector containing the objective value for delays between  $D_{\min}$  and  $D_{\max}$ .  $I$  is a scalar which is multiplied with  $N_w$  to determine the number of iterations to be run for the optimization.

$S_x$  is the transmitted signal power spectrum.  $S_n$  is the channel noise power spectrum.  $H$  is the channel impulse response.  $N$  is the FFT size in the discrete multitone modulation.  $N_b$  is the target length of the equalized channel.  $N_w$  is the number of taps in the time domain equalizer.  $D_{\min}$  and  $D_{\max}$  define the interval over which the delay is being searched.  $W_o$  is the initial starting point for the optimization.  $G$  is the SNR gap (not in dB).  $I$  is the number of iteration to be used in the optimization procedure.

### **MELS.M**

*Description:* Maximum shortening signal-to-noise ratio TEQ design.

*Usage:*  $[W, D, Dv] = MELS(H, Nb, Nw, Dmin, Dmax)$

Returns the optimal time domain equalizer, and delay. Optimal in the sense of maximizing the shortening signal to noise ratio.  $Dv$  is a vector containing the remaining tail power for delay values between  $D_{\min}$  and  $D_{\max}$ .

$H$  is the channel impulse response.  $N_b$  is the target length of the shortened impulse response.  $N_w$  is the number of taps in the TEQ.  $D_{\min}$  and  $D_{\max}$  define the search interval for the optimal delay.

## **4 Performance Evaluation Functions**

### **PERFORM.M**

*Description:* Evaluate the performance of an TEQ in terms of SSNR, SNR, geometric SNR, and channel capacity.

*Usage:*  $[SS, S, Si, Sg, Mg, Bf, Bm, Rf, Rm, Hw, Fh, Fw, Nc, Phw] =$   
 $PERFORM(W, B, H, D, Nb, NN, X, N, Ph, Px, Pn, M, C, Fs, Mi)$

Returns the shortening SNR in  $SS$ , the SNR at the output of the equalizer in  $S$ , the SNR distribution over the subchannels in the vector  $Si$ .  $Sg$  is the real geometric SNR achieved with the TEQ and  $Mg$  is the geometric SNR that can be achieved in the case of zero ISI ( $Mg$  is calculated using the MFB distribution while  $Sg$  is calculated with the SNR distribution.).  $Bf$  is the number of bits per symbol achievable with the TEQ and  $Bm$  is the upperbound on bits per symbol.  $Rf$  is the channel capacity achieved with the TEQ and  $Rm$  is the upperbound on the channel capacity.  $Hw$  is a vector containing the equalized channel impulse response.  $Fh$  is a vector containing the frequency response of the original channel and  $Fw$  is vector containing the equalizer.  $Nc$  is a vector of the power spectrum of the channel noise after equalization and  $Phw$  is a vector containing the magnitude square of the frequency response of the equalized channel.

$W$  is TEQ impulse response.  $B$  is the target impulse response (for MMSE based techniques).  $H$  is the channel impulse response.  $D$  is the optimal delay with TEQ.  $Nb$  is the target window size.  $NN$  is the FFT size used in the DMT modulation.  $X$  is the transmitted signal.  $N$  the channel noise.  $Ph$  is the magnitude square of the channel frequency response.  $Px$  is the power spectrum of the transmitted signal.  $Pn$  is the power spectrum of the channel noise.  $M$  is the desired system margin in dB which is used for channel capacity calculations.  $C$  is the coding gain in dB assumed for channel capacity calculations.  $Fs$  is the sampling frequency.  $Mi$  is the matched filter bound distribution over frequency.

### **GEOSNR.M**

*Description:* Geometric SNR, bit per symbol, and bit rate.

*Usage:*  $[G, B, R] = \text{GEOSNR}(\text{SNR}, M, C, N, Nb, Fs)$

Returns the geometric SNR in  $G$  (dB), bit per symbol in  $B$ , and bit rate in  $R$ .

$SNR$  is a vector containing the SNRs in each used subchannel.  $M$  is the system margin in dB.  $C$  is the coding gain of any code applied in dB.  $N$  is the FFT size in the discrete multitone modulation.  $Nb$  is the cyclic prefix length.  $Fs$  is the sampling frequency.

## **5 Utility Functions**

### **TEQDEMO.M**

*Description:* Demonstrates time-domain equalizer design functions in the DMTTEQ Toolbox.

*Usage:* TEQDEMO

### **SETPROGBAR.M**

*Description:* Setup a progress bar.

*Usage:* [Hf, Hs] = SETPROGBAR(S)

Sets up a progress bar with the title given in the string S.

Hf is the handle to the figure and Hs is the handle to the status of the progress bar.

### **UPDATEPROGBAR.M**

*Description:* Update progress bar by increasing it one step.

*Usage:* UPDATEPROGBAR(H,S,M)

Updates the progress bar with handle H by an amount of 1/M. So that in M steps the progress bar is full (100%).

### **SPECESTIM.M**

*Description:* Frequency spectrum estimation.

*Usage:*[Sx, Sn, Sh] = SPECESTIM(X, N, H, NN)

Returns the frequency spectrum of the transmitted data in Sx, the channel noise in Sn and the magnitude square frequency response of the channel in Sh.

X is the transmitted data vector. N is the channel noise vector. H is the channel impulse response. NN is the FFT size in the discrete multitone modulation.

### **OBJECTIVE.M**

*Description:* Objective function to maximize approximate geometric signal-to-noise ratio.

*Usage:* [F, G] = OBJECTIVE(B, D, N, Rd, MSE, MSEmax, U)

Returns the negative of the approximate geometric SNR in F. G returns a negative number when the constraints are satisfied, non-negative otherwise.

B is the target impulse response. D is the delay. N is the FFT size of the discrete multitone modulation. Rd is the MSE matrix. MSEmax the upperbound on the mean-squared error. U is a binary vector of size N/2+1 with 1s for used subchannels and 0s for unused ones.

### **OBJ.M**

*Description:* Objective function to be minimized to maximize channel capacity.

*Usage:* F = OBJ(W, N, A, B, G)

Returns the objective value which is the negative of the bit rate.

W is a vector containing the tap values of the time domain equalizer. N is the number of used subchannels. A and B are 3 dimensional arrays containing N matrices. A contains the signal matrices and B the distortion matrices. G is the SNR gap (not in dB).

## DSL.M

*Description:* Simulate a standard digital subscriber line.

*Usage:*  $[Y, H, N] = \text{DSL}(X, \text{channelName}, P, S, U)$

Returns the received signal  $Y$  (without channel noise), channel impulse response in  $H$ , and channel noise in  $N$ . The channel noise consists of NEXT noise of  $U$  users and AWGN of power  $P$ .

$X$  is the transmitted signal.  $\text{channelName}$  is a string containing the channel name. The channel data should be in a subdirectory "channel". Currently supported channels are the CSA loops from 1 to 8. The name format is "csaloo# $\#$ " where  $\# = 1, 2, \dots, 8$ .  $P$  is the AWGN power.  $S$  is a subsampling factor. The default length of  $H$  is 512 samples. A shorter channel can be generated by subsampling  $H$  by a factor of  $S$ .  $U$  is the number of users causing NEXT noise.

## MINEIG.M

*Description:* Minimum eigenvalue and the corresponding eigenvector.

*Usage:*  $[L, Q] = \text{MINEIG}(A)$

Returns the minimum eigenvalue  $L$  and the corresponding eigenvector  $Q$  of the square matrix  $A$ . Minimum is in the sense of absolute value if complex eigenvalues exist.

*Usage:*  $[L, Q] = \text{MINEIG}(A, B)$

Returns the minimum generalized eigenvalue  $L$  and the corresponding generalized eigenvector  $Q$  of the square matrix  $A$ . Minimum is in the sense of absolute value if complex eigenvalues exist.

## MAXEIG.M

*Description:* Maximum eigenvalue and the corresponding eigenvector.

*Usage:*  $[L, Q] = \text{MAXEIG}(A)$

Returns the maximum eigenvalue  $L$  and the corresponding eigenvector  $Q$  of the square matrix  $A$ . Maximum is in the sense of absolute value if complex eigenvalues exist.

*Usage:*  $[L, Q] = \text{MAXEIG}(A, B)$

Returns the maximum generalized eigenvalue  $L$  and the corresponding generalized eigenvector  $Q$  of the square matrix  $A$ . Maximum is in the sense of absolute value if complex eigenvalues exist.

## EIGEN.M

*Description:* Solves the eigenvalue problem in design of the unit-energy constrained minimum mean-squared error time domain equalizer.

*Usage:*  $[B, W, D, \text{MSE}, R, D_v] = \text{EIGEN}(R_{XX}, R_{YY}, R_{XY}, D_{\min}, D_{\max}, N_b, N_w,$

L)

Returns the optimal target impulse response  $B$ , the time domain equalizer  $W$ , and the delay  $D$ . Optimal is in the sense of minimum mean-squared error under the unit-energy constraint.  $MSE$  is the resulting mean-squared error.  $R$  is the input-output cross-correlation matrix obtained with the the optimum delay  $D$ , and  $Dv$  is a vector containing the mean-squared error for delay values between  $D_{min}$  and  $D_{max}$ .

$R_{XX}$  is the input autocorrelation matrix.  $R_{YY}$  is the output autocorrelation matrix.  $R_{XY}$  is the input-output cross-correlation vector used to generate the input-output cross-correlation matrix depending on the current delay.  $D_{min}$  and  $D_{max}$  define the search interval for the optimal delay.  $N_b$  is the number of taps in the target impulse response and  $N_w$  the number of taps in the time domain equalizer.

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