MATLAB sample codes for ZP-OTFS

Orthogonal time frequency space is a novel modulation scheme where the information symbols are multiplexed in the delay-Doppler domain resulting in all the information symbols experiencing roughly the same channel. This code package implements the OTFS system with maximal ratio combining based methods proposed for ZP-OTFS in [R1,R2] and other OTFS detectors in the literature [R3,R4].

The following detection methods are included in the MATLAB package for comparison:

(i) Maximal ratio combining (MRC) method (Algorithm 2 in [R1,R2])
(ii) Matched-Filtered Gauss Seidel method (Algorithm 3 in [R1])
(iii) MRC based efficient implementation of Algorithm 3 in [R1]
(iv) Message Passing detector (MPA) in [R4]
(v) Single tap time-frequency equalizer
(vi) Block-wise time domain LMMSE detection in [R3].

➢ MATLAB functions

MATLAB functions	**Description**
ZP_OTFS_MRC_system.m	main file to run for MRC detector in [R1]
ZP_OTFS_compare_detectors.m	Compare performance of detectors proposed in [R1] with other detectors proposed in the literature
Generate_2D_data_grid.m	Generate MxN 2-D information symbols
Generate_delay_Doppler_channel_parameters.m	Generate the gain, delay and Doppler-shift of the P propagation path according to EPA, EVA or ETU channel models
Gen_time_domain_channel.m	Generate **G** matrix (time domain channel matrix) and the DT channel response $g^s(l,q)$ in [R1] (gs[l,q] in MATLAB code).
Gen_discrete_time_channel.m	Generate only the DT channel response $g^s(l,q)$.
Gen_delay_time_channel_vectors	Generate the delay-time channel vectors $\tilde{\nu}_{m,l}$ in [R1] (nu_ml_tilda in the MATLAB code) from $g^s(l,q)$.
Generate_time_frequency_channel_ZP.m	Generate single tap time-frequency channel for low-complexity initial estimate
Gen_DD_and_DT_channel_matrices.m	Generate delay-time and delay-Doppler channel matrix according to [R1]
Generate_Algo3_GS_iteration_matrices.m	Generate the Gauss Seidel iteration matrices for Algorithm 3 in [R1]
MRC_delay_time_detector.m	MRC detection (Algorithm 2 in [R1])
Algorithm3_detector.m	Matched Filtered Gauss-Seidel Method (Algorithm 3 in [R1])

Algorithm3_low_complexity_detector.m	MRC based low-complexity implementation of Algorithm 3 in [R1]
MPA_detector.m	Message passing detector in [R4]
TF_single_tap_equalizer.m	Time frequency single tap equalizer in [R3]
Block_LMMSE_detector.m	Block-wise time domain LMMSE detector in [R3]

Remarks

- Run ZP_OTFS_MRC_system.m for the delay-time MRC detector code. This is the fast implementation of MRC.
- Run ZP_OTFS_compare_detectors.m for comparing the MRC based detectors in [R1] with other detectors in the literature.
- Note that the MPA in [R4] and LMMSE detectors may consume more time for large frame sizes due to high complexity. If the users want to compare the different variants of MRC implementation (Algorithm 2 and Algorithm 3 in [R1]), the users may comment out the functions calling the MPA, LMMSE detectors and related functions to make the code run faster.

➢ Additional information

- MRC_delay_time_detector.m and Algorithm3_low_complexity_detector.m are the delay-time and time domain variants of the same MRC algorithm in [R1,R2] with the same complexity of order O(NML), where L is the number of unique delay taps. They differ in the order in which the time domain samples are estimated in each iteration. Delay-time and time domain samples are related by the row-column interleaver matrix **P,** [R1]**.** The P matrix is given in Gen_DD_and_DT_channel_matrices.m function.

- The damping factor variable 'omega' can be adjusted to improve the performance. It is recommended to use smaller values for higher order modulation schemes like 64-QAM and 256-QAM to improve convergence. The users may also consider optimizing 'omega' in each iteration to improve convergence or error performance.

```
%damping parameter - reducing omega improves error performance at the cost of increased detector it
omega=1;
if(M_mod>=64)
    omega=0.25;     % set omega to a smaller value (for example: 0.05) for modulation orders greate
end
decision=1; %1-hard decision, 0-soft decision
init_estimate=1; %1-use the TF single tap estimate as the initial estimate for MRC detection, 0-ini
%(Note: it is recommended to set init_estimate to 0 for higher order modulation schemes like 64-QAM
```

Figure 1: Piece of code in the main MATLAB file where the decision and init_estimate flag is set.

- A single tap TF equalizer is used to provide a low-complexity initial estimate for the MRC detection. For higher order modulation schemes like 64-QAM and 256-QAM, the initial estimate may not be reliable and the MRC detection works better without the initial estimate. Therefore, it is recommended to set the 'init_estimate' flag (shown in the code snippet in Figure 1) to 0.

- MRC detection code can be easily extended to the OTFS case without ZP (i.e., using multiple CPs or one CP per frame). The detection, turbo decoding and channel estimation methods and MATLAB code for all OTFS variants (with one ZP/CP or multiple ZP/CPs) are provided in [R3].

➢ Sample simulation plots

- Below we provide a sample BER plot for MRC detection (see Figure 2) using the following parameters

Frame size	N=M=64
Channel model	Extended Vehicular – A (EVA)
Maximum UE speed	500 km/hr
QAM size	4 –QAM, 16-QAM and 64-QAM

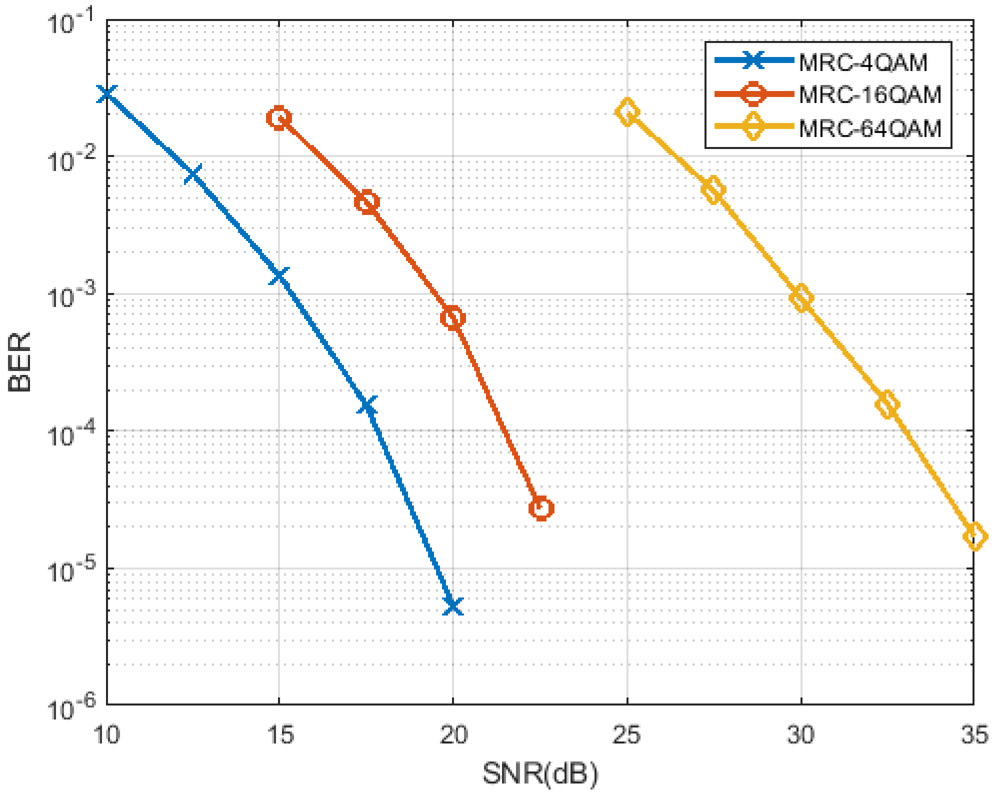

Figure 2: OTFS BER performance with the MRC delay-time detector.

- Below we provide a sample BER plot comparing the various detectors (see Figure 3) using the following parameters:

Frame size	N=16,M=64
Channel model	Extended Vehicular – A (EVA)
Maximum UE speed	500 km/hr
QAM size	4-QAM
Maximum number of iterations for all iterative detectors	5 (for MRC based methods) and 15 (for MPA)

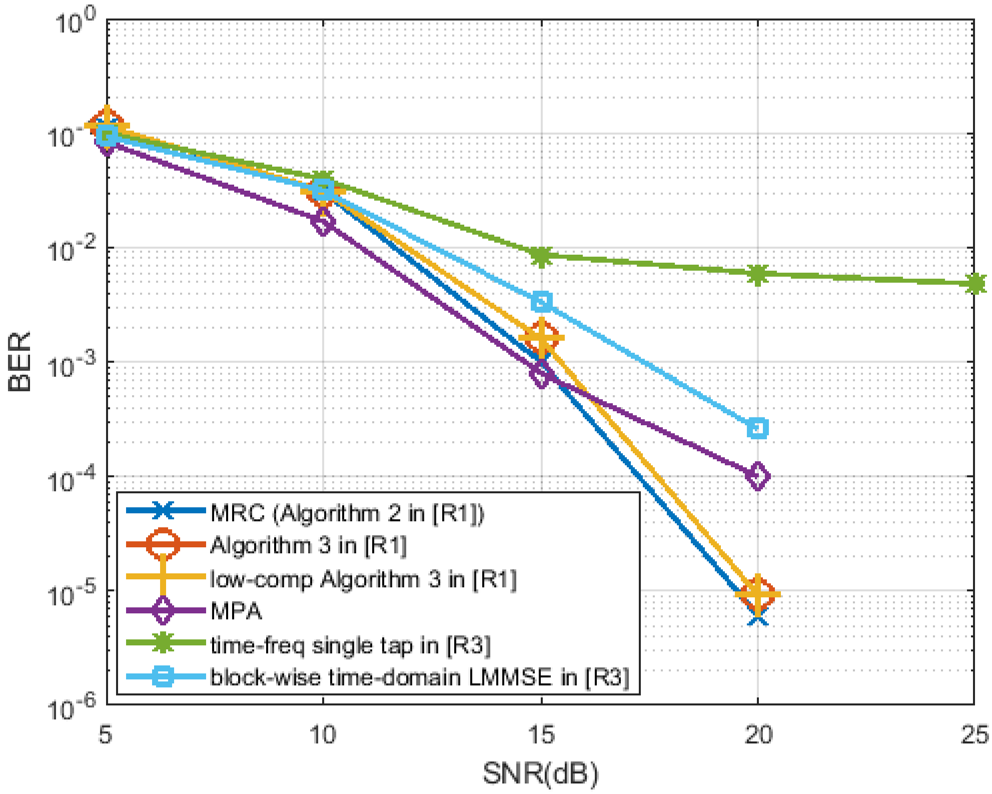

Figure 2: 4-QAM OTFS BER performance with different detectors

➢ References

[R1]. T. Thaj and E. Viterbo,``Low Complexity Iterative Rake Decision Feedback Equalizer for Zero-Padded OTFS Systems'', in IEEE Transactions on Vehicular Technology, vol. 69, no. 12, pp. 15606-15622, Dec. 2020, doi: 10.1109/TVT.2020.3044276.

[R2]. T. Thaj and E. Viterbo,``Low Complexity Iterative Rake Detector for Orthogonal Time Frequency Space Modulation'' *2020 IEEE Wireless Communications and Networking Conference (WCNC)*, 2020, pp. 1-6, doi: 10.1109/WCNC45663.2020.9120526.

[R3]. Y. Hong, T. Thaj, E. Viterbo, ``Delay-Doppler Communications: Principles and Applications'', Academic Press, 2022, ISBN:9780323850285

[R4]. P. Raviteja, K. T. Phan, Y. Hong and E. Viterbo,``Interference Cancellation and Iterative Detection for Orthogonal Time Frequency Space Modulation'' in *IEEE Transactions on Wireless Communications*, vol. 17, no. 10, pp. 6501-6515, Oct. 2018, doi: 10.1109/TWC.2018.2860011.