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Title: OTFS Performance Evaluation for High Speed Use Case
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1. Introduction

The high-speed use case has been identified as an important use case and one of the cases that candidate modulation waveforms should be evaluated against. In [1], a Way Forward was agreed that includes simulation assumptions for the evaluation of different waveforms for this use case.

In this contribution, we evaluate the performance of OTFS (Orthogonal Time Frequency Space) for this use case and we compare to the performance to OFDM. OTFS is a novel modulation technique presented in [2], [3] for the high-speed case. OTFS modulation is a scheme that comprises of a 2-D FFT based preprocessing block on top of an OFDM multicarrier system resulting in improved performance, especially in the presence of high Doppler.

The results in the next section show that OTFS outperforms OFDM and is especially well suited for the high-mobility use case.

2. Simulation Results

We evaluate the performance of OTFS versus OFDM using link level simulation and present BLER comparison results. The Doppler spread in all simulations is 1820 Hz, corresponding to a UE speed of 500 Km/h at a carrier frequency of 4 GHz. A subcarrier spacing of 15 KHz is used for both OTFS and OFDM systems. While it is known that high Doppler robustness is improved with increasing the subcarrier spacing, this comes at the expense of increased CP overhead (for a given channel spread), and is not used in these results. The channel delay profile used is Rural Macro and the MIMO correlation is low.

We start with ideal channel estimation and no control overhead in this comparison while we later present some results with realistic channel estimation. We use an ML receiver for OFDM and a turbo equalizer for OTFS. The turbo equalizer iterates between the decoder and a linear equalizer improving the performance in each iteration. Up to four iterations of the turbo equalizer were allowed in this simulation.

Table 1 summarizes the simulation parameters.

Table 1: Simulation Parameters

Parameter	Value
Carrier frequency	4 GHz
System BW	10 MHz
TTI length	1 msec
Subcarrier spacing	15 KHz
FFT size	1024
CP length	4.7 usec

Receivers	OTFS: Turbo equalizer, OFDM: ML
Coding	Turbo code, 6144 max code-block length
MCS	QPSK ½, 16-QAM ½, 64-QAM ½ ,
Control overhead	No overhead
Channel estimation	Ideal, MMSE (part of turbo receiver)
Channel profile	Rural Macro TDL profile
MIMO Correlation	Low

Figure 1 focuses on a SISO system and shows BLER curves for OTFS (solid line) vs OFDM (dashed line) for QPSK, 16-QAM and 64-QAM in different line colors. In order to focus exclusively on the ICI effects, in this figure ideal channel estimation is assumed for both systems. Notice that OTFS outperforms OFDM for all MCS's with the gap increasing with constellation size. At 64-QAM OFDM fails while OTFS can still maintain better than 1e-1 BLER demonstrating the robustness of OTFS to ICI.

In the same figure, a comparison is also shown between OTFS and OFDM when perfect genie-aided ICI cancellation is present. OTFS (dash-dotted line) still outperforms OFDM (dotted line) but in a less dramatic fashion. In this case for 64 QAM a performance gap of 4 dB is observed. The results in this figure show that OTFS has two advantages: (i) it better handles the channel variability due to Doppler even when ICI is removed and (ii) it is more robust to the presence of ICI.

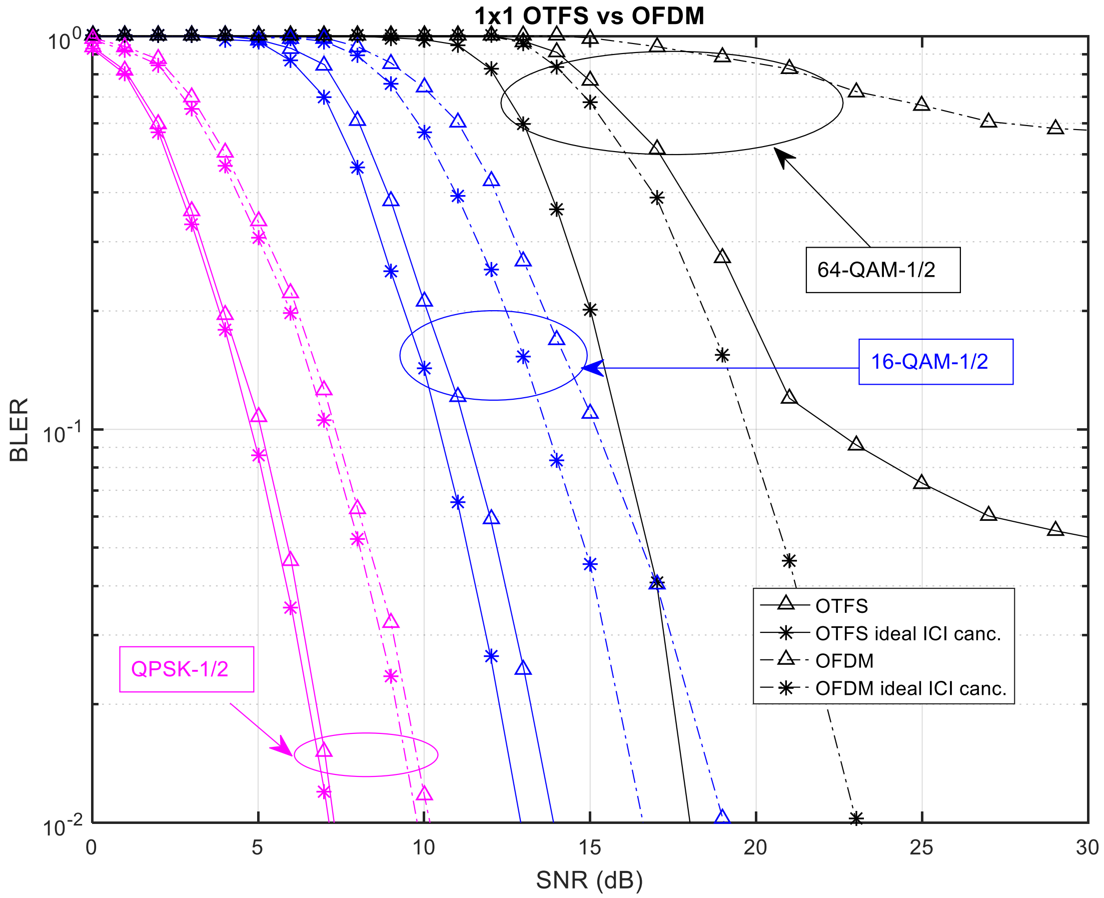

Figure 1: BLER for 1x1 OTFS vs OFDM (with and without Perfect ICI Cancellation)

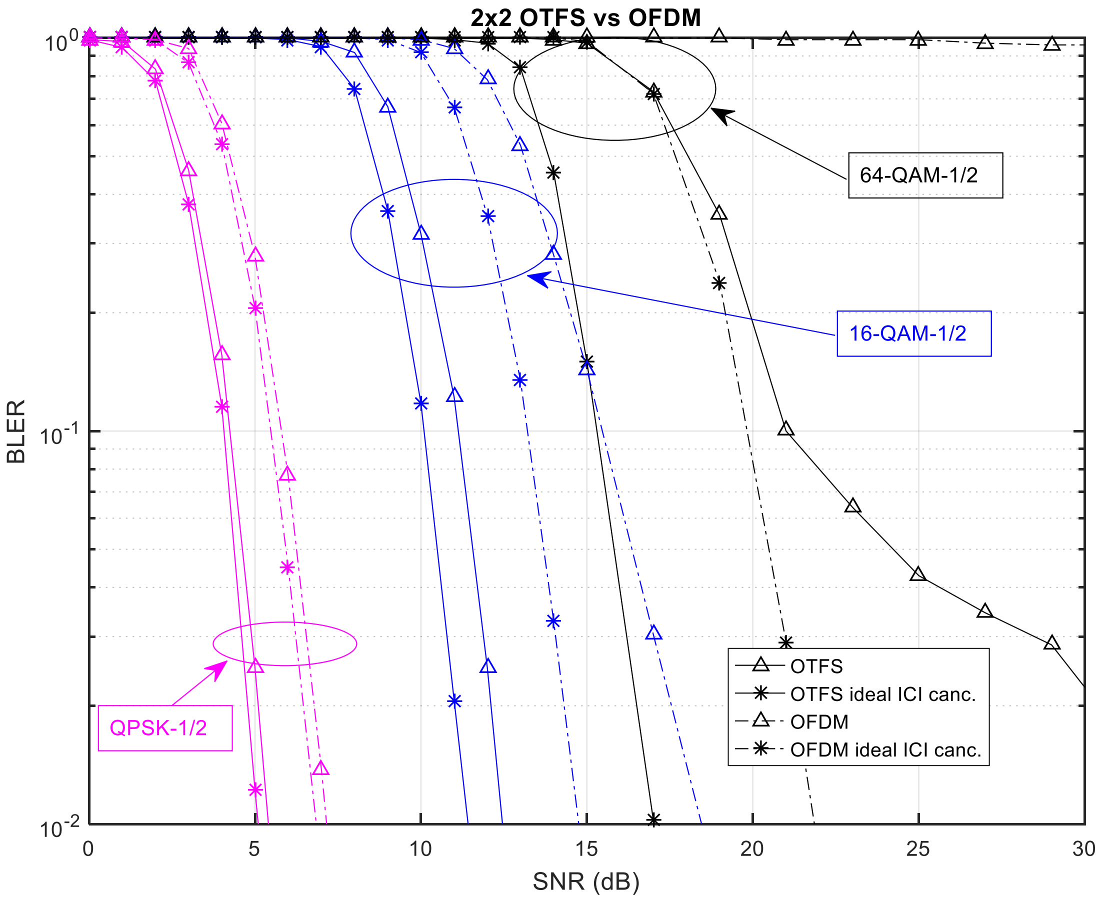

Figure 2: BLER Curves for 2x2 OTFS vs OFDM (with and without Perfect ICI Cancellation)

In Figure 2 we present similar results for a 2x2 MIMO system. Similar, if not bigger performance gaps are observed in this case as well. Notice that in this case OFDM completely fails for 64 QAM rate ½ modulation.

In the following table, we summarize the OTFS performance gains vs OFDM for the operating point of 1e-1.

Table 2: OTFS vs OFDM Performance Difference at BLER = 0.1

	1x1	2x2
QPSK R 1/2	2.1 dB	1.5 dB
16 QAM R 1/2	4.5 dB	4.1 dB
64 QAM R 1/2	inf	inf

Next, we turn our attention to possible simple ways we can further mitigate ICI with OTFS systems. In OFDM systems, ICI distortion from neighboring subcarriers is created when the channel cannot be assumed to be time invariant for the duration of the OFDM symbol. In OTFS (as well as SC-FDMA) systems, the mechanism of the distortion is different. The channel acts as a two-dimensional convolution in the delay Doppler domain; in the presence of strong Doppler, the convolution kernel is not invariant, but slowly changes along the delay dimension. A similar phenomenon is present in SC-FDMA with a one-dimensional convolution that is slowly varying. In both cases the channel effect is only locally invariant. If this variation is ignored at the receiver, the equalizer will equalize the “average” channel and will result in residual ISI distortion. If the receiver employed an equalizer that used the local channel when equalizing a local portion of the data along the delay dimension the residual ISI due to channel variations would be reduced.

In the simplest form of this idea, one can divide the TTI data into two (or more) segments along the delay dimension and equalize each segment using an equalizer derived from the average channel over that segment. A high-level view of this architecture is shown in Figure 3.

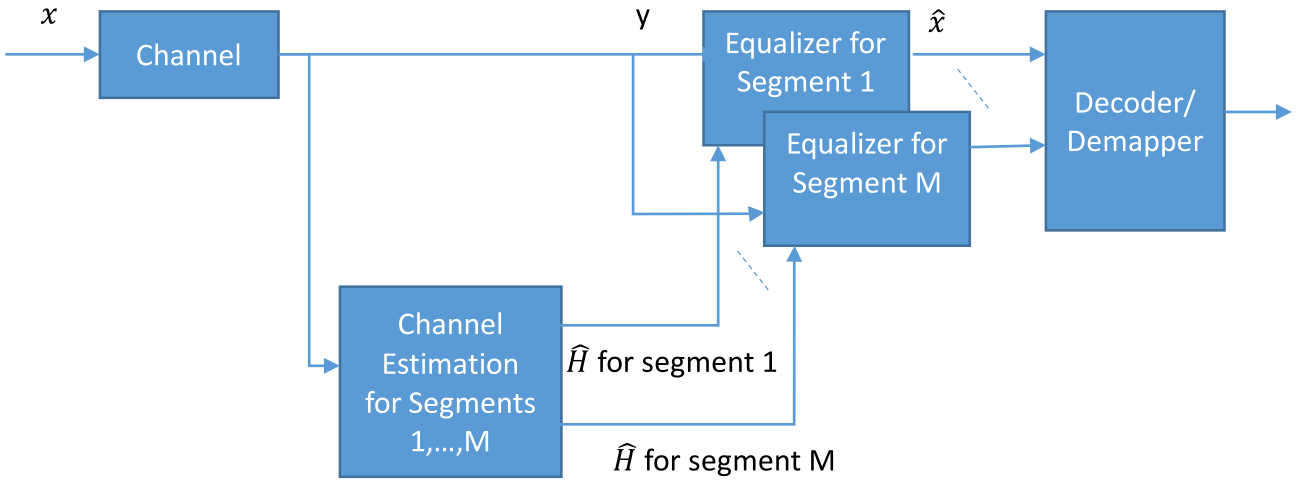

Figure 3: Receiver Architecture with Localized Equalization

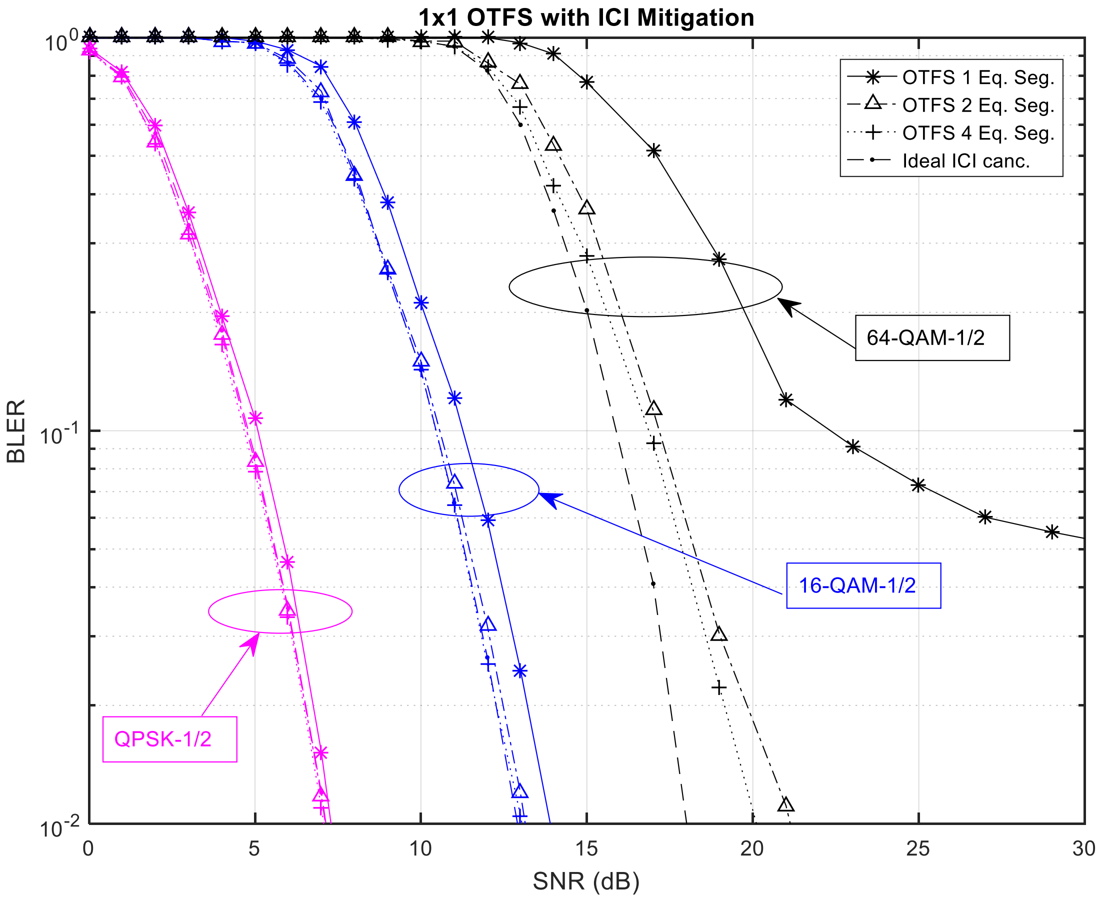

Figure 4: BLER Curves for 1x1 OTFS for 1, 2 and 4 Equalization Segments

Figure 4 explores the performance gains of this approach. The 1x1 OTFS BLER performance is shown for an equalizer using one segment (average channel), two segments (two channel estimates for two segments along delay) and four segments. Also in dashed line, the limit of perfect ICI cancellation performance is shown for comparison. Notice that this simple scheme improves the ICI robustness, especially for high constellations, and approaches the ICI free performance. Also notice that most of the gain is achieved with only two segments (two equalizers). For example, for 64-QAM an improvement of over 5 dB is observed. This benefit would require performing the frequency domain equalization step twice (one for each segment).

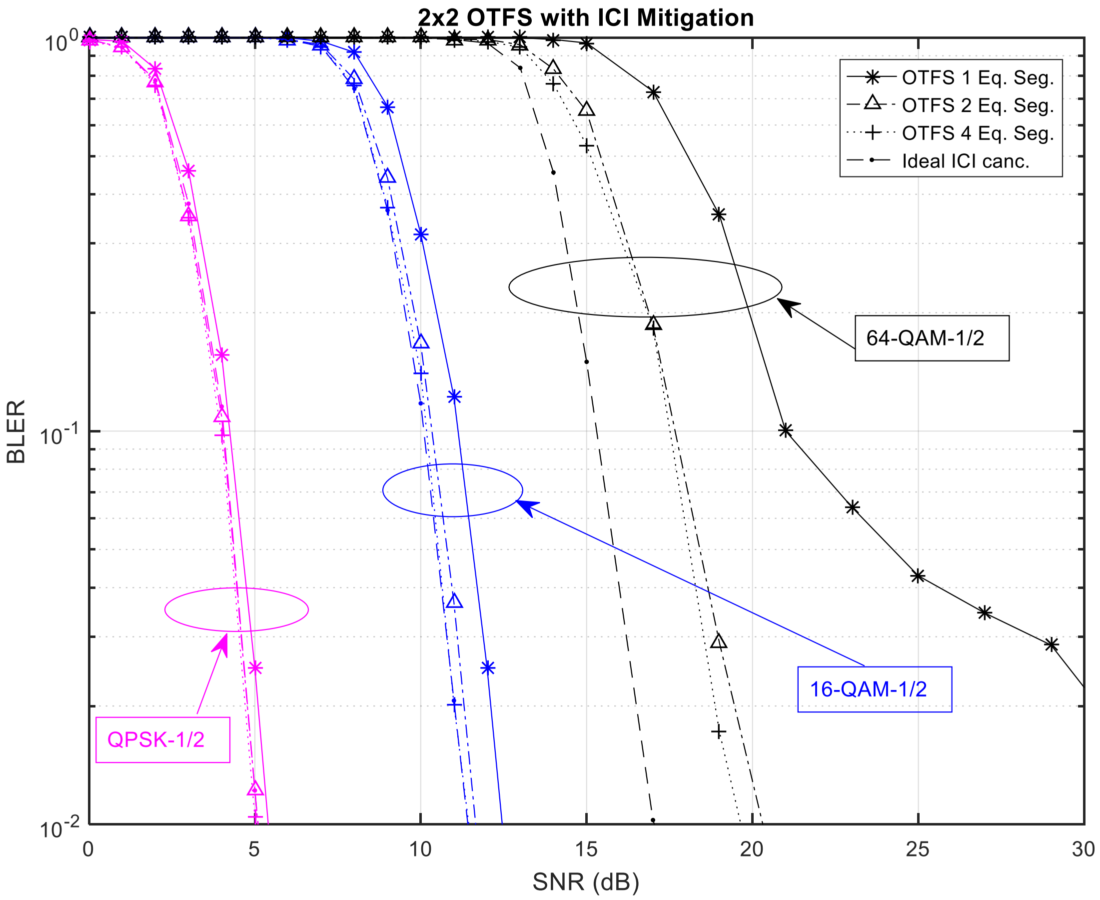

Figure 5: BLER Curves for 2x2 OTFS for 1, 2 and 4 Equalization Segments

In Figure 5 we present similar result for a 2x2 system. The same conclusions hold here as well and a segmentation along the delay dimension provides ICI robustness in the MIMO case as well.

Finally, we present performance comparisons between ideal and realistic channel estimation. In Figure 6 we show the BLER curves for an 1x1 OTFS system with ideal channel (solid line) as well as estimated channel (dashed line). Notice that a reasonable degradation of no more than 1 dB is observed.

A word of explanation is in order at this point to describe the approach taken for channel estimation. A pilot superposition scheme was used, that is, on the pilot grid points the data were not removed but remained superimposed with the pilots, i.e., each pilot grid point carried both pilot and data. The system used an iterative (turbo) receiver/equalizer. On the first iteration, the channel was estimated from the pilot grid considering the data as interference. In subsequent iterations, given some data priors, the data interference was removed from the pilot grid and a better channel estimate was obtained.

In these results, a pilot grid of one every six subcarriers was used. Along time, the pilot grid was present in every OFDM symbol. This pilot overlay grid is depicted in

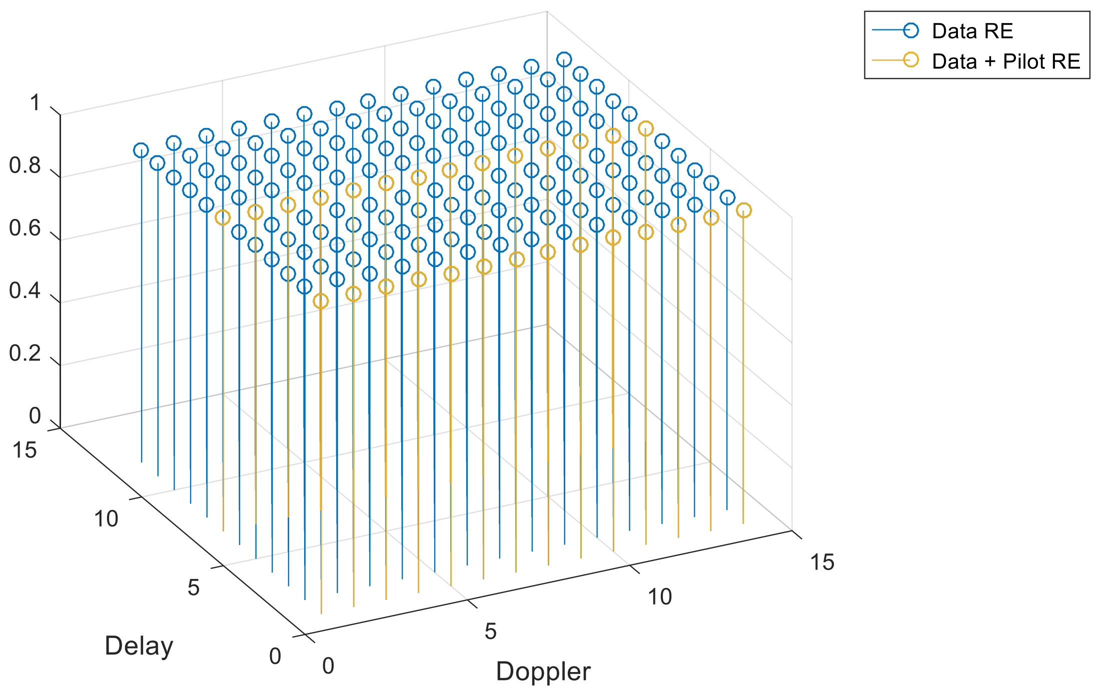

Figure 7. Notice that this pilot overlay scheme does not suffer from any bandwidth pilot overhead, i.e., the pilots consume zero degrees of freedom of the channel; the scheme only suffers a power overhead. Typical pilot placements often suffer both bandwidth and power overhead. This elimination of pilot bandwidth overhead is significant especially for higher order MIMO system that require considerable pilot resources.

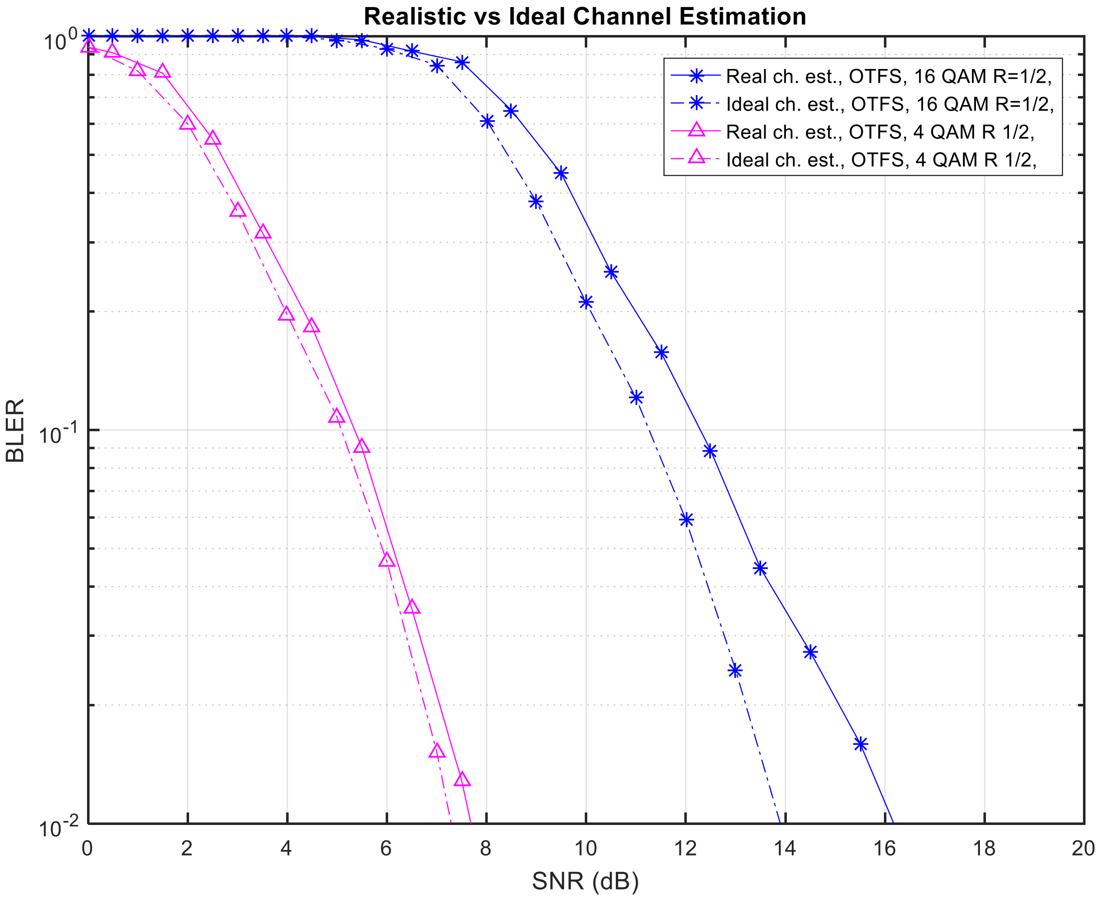

Figure 6: Comparison of OTFS 1x1 Ideal vs Realistic Channel Estimation Performance

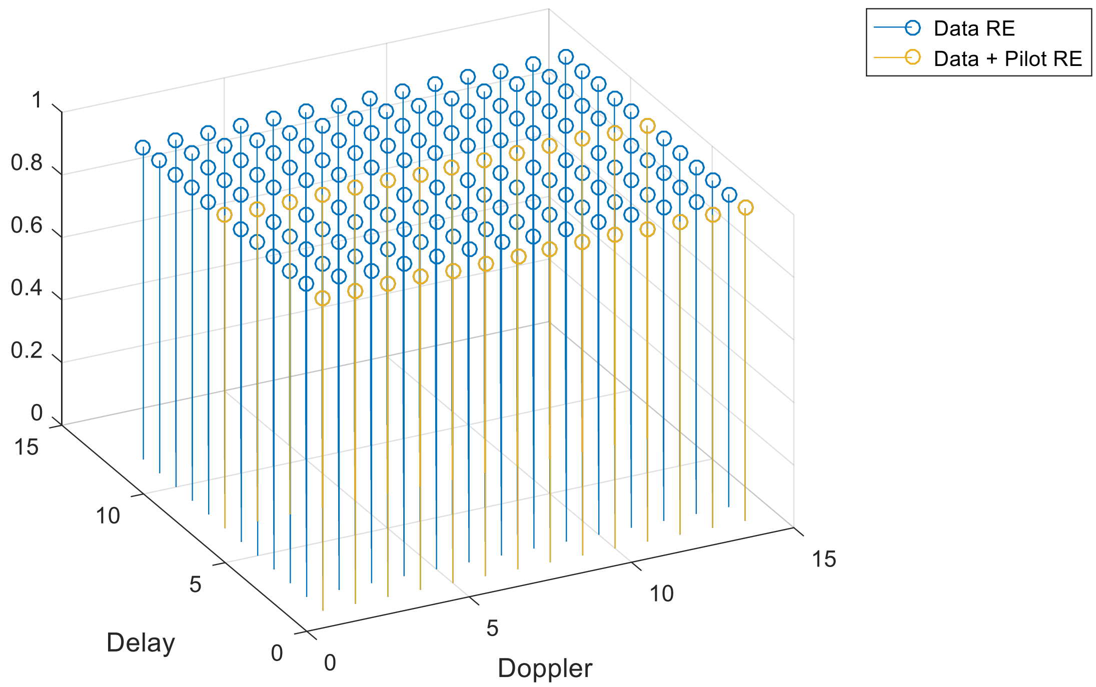

Figure 7: Data and Pilot Overlay on one PRB

3. Conclusion

The performance comparisons in this paper indicate the superior performance of OTFS for this high Doppler (high mobility) use case. Gains of more than 4 dB are seen for 16 QAM constellations and 64 QAM transmission becomes possible in this extreme Doppler scenario, something that is not supported by OFDM.

4. References

[1] R1-166031, “Way forward on High Speed Link Level evaluation”, Source: Cohere, AT&T, CMCC, DT, InterDigital, National Taiwan University, Orange, Spreadtrum, Telefonica, Telstra

[2] R1-163619, “OTFS Modulation Waveform and Reference Signals for New RAT,” Source: Cohere Technologies

[3] R1-162929, “Overview of OTFS Waveform for Next Generation RAT,” Source: Cohere Technologies