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Title: OTFS PAPR Analysis

Agenda item: 8.1.1.1

Document for: Discussion

1. Introduction

In the context of the Way Forward agreed [1] on the evaluation of different waveforms, the importance of PAPR performance of various waveforms on the selection of the appropriate waveform for NR has been discussed in the previous meeting. A number of documents justifying the importance of PAPR performance on the selection of the appropriate waveform for NR has treated this topic [1]-[6]. Therein, consideration of the link budget requirements set for NR, as well as the requirement for low energy consumption for certain number of devices is mentioned as the main driver for maintaining a relatively low PAPR in NR. Therefore, a Way Forward on low PAPR techniques for both uplink [7] and downlink [8] for NR has been proposed.

In this contribution, we analyze the performance of OTFS (Orthogonal Time Frequency Space) in terms of PAPR. Comparison with both OFDM and SC-FDMA systems is done. The discussion below focuses on the comparison of OTFS versus SC-FDMA. Therefore, the discussion herein treats the uplink. PAPR analysis indicates that OTFS performs equally well as SC-FDMA for small number of physical resource block (PRB) allocations. Hence, OTFS can lead to relatively low PAPR values as SC-FDMA while offering the inherent OTFS property of higher diversity in the frequency domain yielding higher reliability and enhanced link margins. This places OTFS as a candidate waveform for NR.

2. OTFS Transmission Principles

Traditional OFDM modulation operates in the frequency-time domains. An OFDM resource elements (RE) occupies one subcarrier on one particular OFDM symbol. In contrast, OTFS modulation operates in the Delay spread-Doppler plane domains, which are related to frequency and time by the symplectic Fourier transform, a two-dimensional discrete Fourier transform. Similarly, to SC-FDMA, OTFS can be implemented as a preprocessing step on top of an underlying OFDM signal. The following Figure **1** illustrates the relationships between different domains.

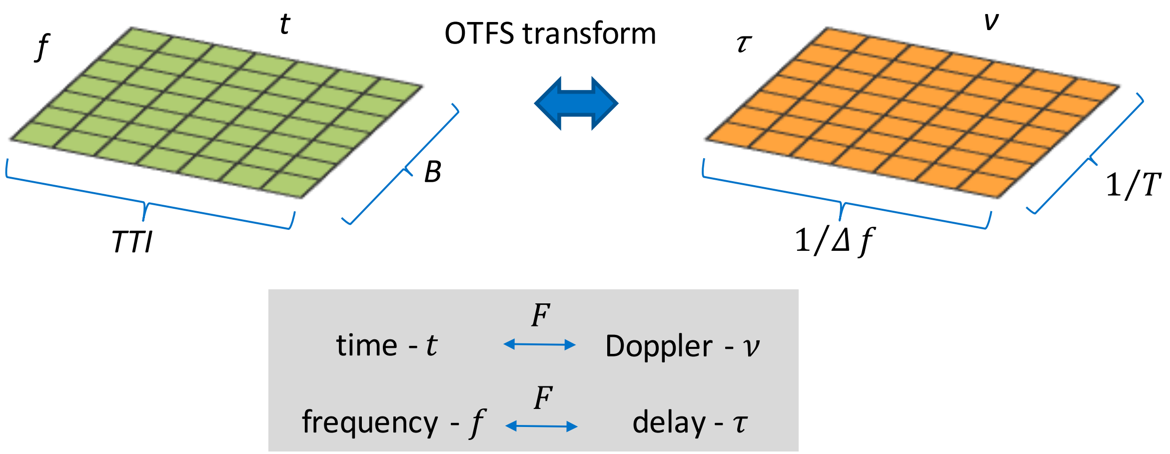

Figure 1**. Illustration of OTFS transform.**

In OTFS, resource elements are defined in the delay-Doppler domains, which provide a two-dimensional grid similar to OFDM. The size of the delay-Doppler resource grid is related to the size of the frequency-time plane by the signal properties, i.e. bandwidth, TTI duration, sub-carrier spacing, and symbol length. These relationships are expressed by the following equalities:

$$N_{S,\tau} = B/\Delta f$$

$$N_{S,\nu} = TTI/T$$

where $N_{S,\tau}$ denotes the number of bins in the Delay Spread domain and $N_{S,\nu}$ the number of bins in the Doppler domain in the OTFS grid. B stands for the allocated bandwidth, Δf is the subcarrier spacing and T is the symbol duration. Note that in this example there is an exact matching between the delay spread and frequency domains, and, similarly, between the Doppler and time domains. Therefore, the number of delay dimensions equals the number of active subcarriers in the OFDM signal, while the number of Doppler dimensions equals the number of OFDM symbols in the TTI.

An OTFS Physical Resource Block (PRB) can be defined as the number of symbols corresponding to the number of resource elements within an OFDM PRB, but in the Delay Spread-Doppler domains. For example, an OTFS PRB may be defined as a region occupying $N_{RB,\tau}$x$N_{RB,\nu}$ RE, where, the total number of RE $N_{RB} = N_{RB,\tau}N_{RB,\nu}$ equals the number of RE in an OFDM PRB. Different OTFS PRB configurations might be considered. Eg. in one particular case, we may define a PRB to span $N_{RB,\tau}$x1 RE, i.e. this specific OTFS PRB occupies a single Doppler dimension.

Denote the discrete OTFS signal in the delay-Doppler plane by $x(\tau,\nu)$, which corresponds to the τ^{th} delay bin and ν^{th}Doppler bin. After the symplectic transform, the following signal is obtained in the frequency-time plane:

$$X[n,m] = \frac{1}{N_{S,\tau}N_{S,\nu}}\sum_{k=0}^{N_{S,\nu}-1}\sum_{l=0}^{N_{S,\tau}-1} x[k,l]\, e^{-j2\pi\left(\frac{ml}{N_{S,\tau}}-\frac{nk}{N_{S,\nu}}\right)} \quad (1)$$

One fundamental difference with respect to OFDM is that an OTFS PRB usually spans a much larger region of the time-frequency plane, i.e. it is spread across larger parts of time and frequency domain. This allows OTFS to effectively capture most and sometimes all the diversity in the channel. Figure 2 provides an illustration of the corresponding time-frequency footprint of an OTFS PRB, where the OTFS PRB is defined along one Doppler dimension.

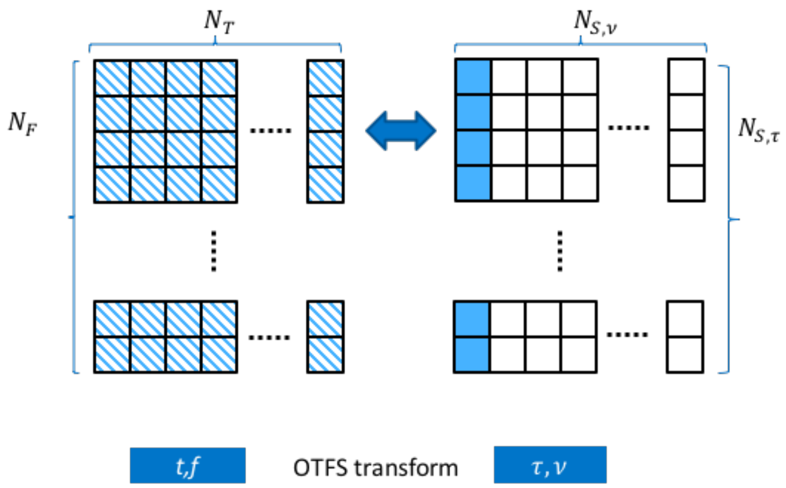

Figure 2. Example of time-frequency footprint of an OTFS PRB.

3. OTFS Uplink Resource Allocation Scheme

UEs may be allocated to disjoint Doppler slices of the delay-Doppler plane. An example is provided in Figure 3.

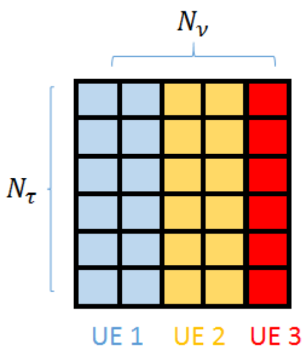

Figure 3: Example of OTFS allocation scheme in Delay Spread and Doppler Domain.

To modulate data, UEs first place a sequence of QAM symbols on their assigned resource elements, in the region of the delay-Doppler plane corresponding to their PRB allocation. Next, the UEs perform an OTFS tranform to convert their data from delay-Doppler domains to time-frequency domains. Finally, the standard OFDM zero-padded IFFT generates a time series. This process which takes place in the transmitter can be seen in Figure **4**.

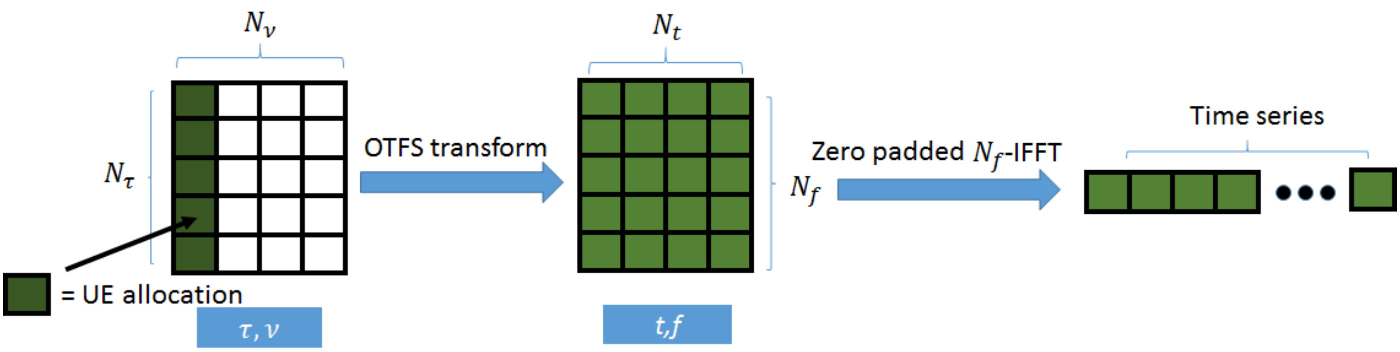

Figure 4: OTFS allocation in the Delay Spread and Doppler domain and mapping to time-frequency domain via OTFS transform.

The proposed uplink scheme has two key benefits:

- For small packets the PAPR of the time series is low (equivalent to SC-FDMA).
- Packets can be spread across all of time and frequency thus achieving the full diversity of the channel yielding in higher reliability and enhanced link margins.

In the following section we elaborate on these fundamental OTFS advantages.

3.1 PAPR For Small Packets

We now explain why OTFS has low PAPR for small packets sizes.

Assuming that a UE is allocated the first Doppler bin, then the transmitted OTFS satisfies

$$x[k,l] = 0, \forall\, k \neq 0$$

As a result, equation (1) simplifies to

$$X[n,m] = \frac{1}{N_{S,\tau} N_{S,\nu}} \sum_{l=0}^{N_{S,\tau}-1} x[0,l]\, e^{-j2\pi\left(\frac{ml}{N_{S,\tau}}\right)}$$

Therefore, for any OFDM symbol n within the TTI, the signal in the frequency domain is the result of applying a DFT to the delay domain symbols, which is equivalent to the operation done by SC-FDMA. As a result, for symbol n, the OTFS waveform is equivalent to a DFT-spread waveform (i.e. SC-FDMA), multiplied by a constant phase, which for this example is 0. Therefore, in terms of PAPR, OTFS also enjoys the benefits observed in SC-FDMA.

3.2 Frequency Diversity

The OTFS modulation can spread each QAM symbol into different bandwidths (even over the full bandwidth) and TTI durations. Typically, this spreading in frequency and time is larger than the one of OFDM and so often achieves the full diversity of the channel. In contrast, for small packets, SC-FDMA only transmits over a narrow bandwidth. The concept is illustrated in Figure 5.

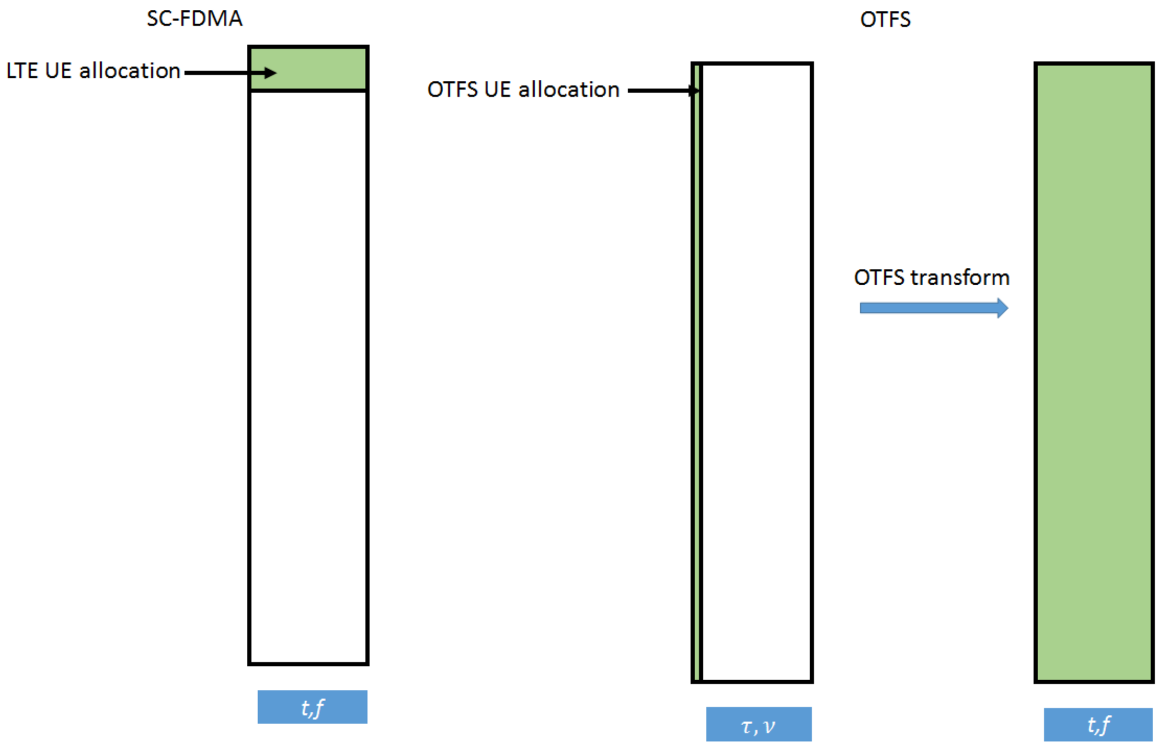

Figure 5: OTFS allocation scheme in Uplink.

SC-FDMA cannot spread their allocation across frequency without always paying a penalty in pilot overhead (for the case of evenly spreading data across frequency) or increasing PAPR (for the case of unevenly spreading across frequency), whilst these effects can eventually be avoided by OTFS.

More details on OTFS technology can be found in [9], [10]. OTFS performance superiority over OFDM has been shown in [11], [12], while for small packets OTFS and SC-FDMA have equal PAPR.

While both OTFS and SC-FDMA keep the PAPR at low levels, OTFS inherent frequency and time diversity extraction and the lack of such in SC-FDMA translates to performance superiority expressed as enhanced link budget and higher reliability of payload delivery.

4. Simulation Results

We evaluated the packet error rate (PER) of OTFS and SC-FDMA under the simulation assumptions reported in Table 1. A potential cell edge situation, with a small Transport Block size of 3 PRB, was considered. Both UMi and RMa channel models were simulated, with a UE speed of 30 kph (since the resilience of OTFS to higher Doppler was reported in RAN1#86 in [12], in these simulations we omit higher UE speeds). For a fair comparison, both OTFS and SC-FDMA were evaluated using an advanced turbo equalizer receiver. The effect of channel estimation was not accounted for, being the simulation carried out with perfect channel knowledge at the receiver. Results, shown in Figure 6 and Figure 7, confirm that the higher degree of diversity attained by OTFS results in remarkable performance advantages. Gains for a 10% target PER are summarized in Table 2.

Table 1. Evaluation Assumptions

Parameter	Value
Carrier frequency	4 GHz
System BW	10 MHz
TTI length	1 msec
Subcarrier spacing	15 kHz
Transport Block Size	3 PRB
Coding	LTE Turbo code
MCS	16-QAM, R=1/2; 64-QAM, R=1/2
Antenna Configuration	SISO
Receiver	Turbo equalizer (both OTFS and SC-FDMA)
Channel profile	Rural Macro (RMa), Urban Micro (UMi)
UE Speed	30 kph
Channel estimation	Ideal

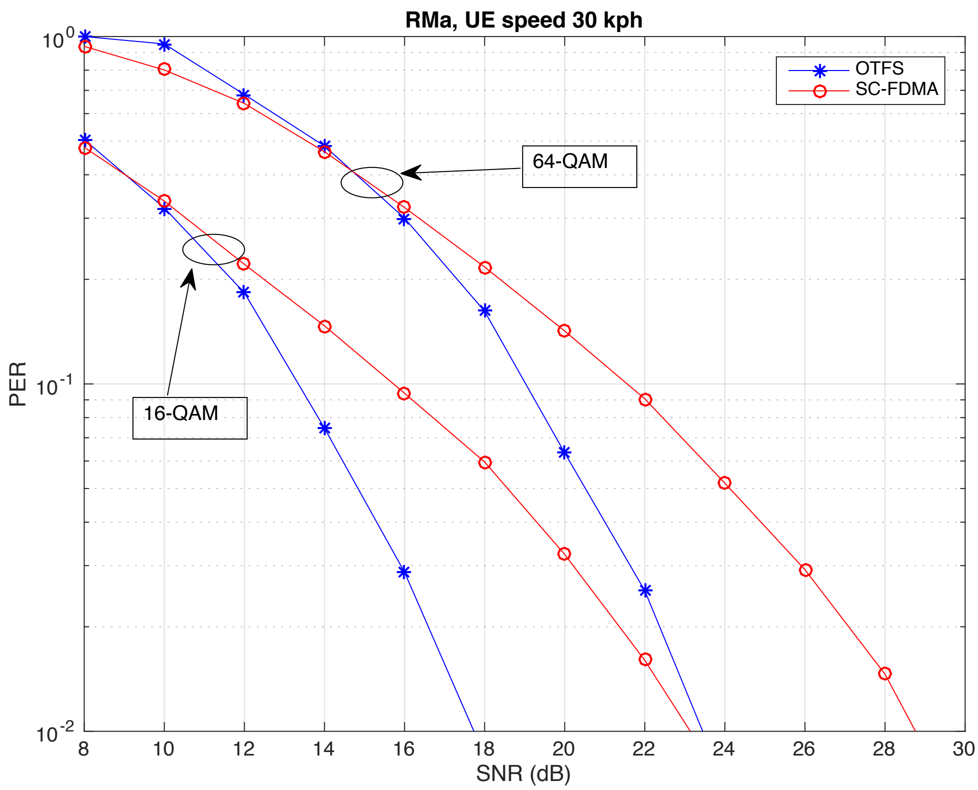

Figure 6. Packet Error Rate of OTFS and SC-FDMA at equal PAPR, Rural Macro channel.

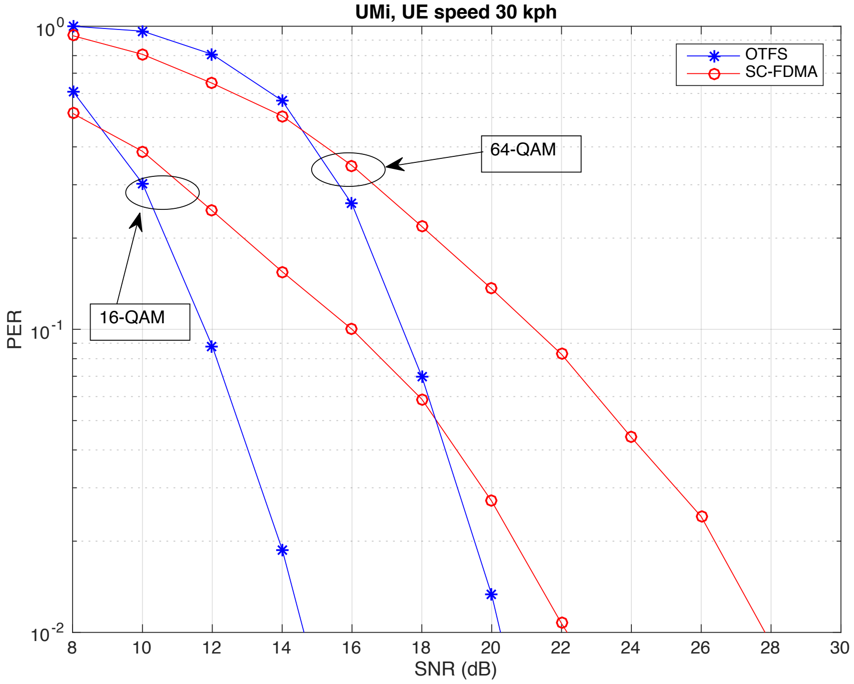

Figure 7. Packet Error Rate of OTFS and SC-FDMA at equal PAPR, Urban Micro channel.

Table 2. Performance Gain of OTFS Over SC-FDMA

	RMa	UMi
16-QAM	2.3 dB	4.2 dB
64-QAM	2.5 dB	3.7 dB

5. Conclusion

The analysis in this contribution indicates that OTFS outperforms SC-FDMA for small to medium packet size communication, offering enhanced link margins and higher reliability of payload delivery. OTFS exhibits low PAPR values for small number of PRBs that match the PAPR values of SC-FDMA, while OTFS benefits from higher diversity gains compared to SC-FDMA. Simulation results show performance gains of 2.3-2.5 dB for the Rural Macro channel and of 3.7-4.2 dB for the Urban Micro channel, at the 10% PER operating point.

6. References

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