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FFT-Domain Signal Processing for Transparent Spectrum Enhancement in 5G New Radio

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Outline

- Transparent waveform processing in 5G New Radio (NR)
- Spectrum confinement for mixed numerology and asynchronous operation
- Filtered OFDM waveforms
- Fast-convolution (FC) for waveform processing
- FC-filtered OFDM
- Examples of FC-based transparent solutions

5G New Radio – Basic Waveform

- 3GPP TR 38.802 states that the baseline assumption of the waveform for below 52.6 GHz communications is CP-OFDM …

5G New Radio - Transparent waveform processing

- 3GPP TR 38.802 states that the baseline assumption of the waveform for below 52.6 GHz communications is CP-OFDM and that the TX processing for spectrum confinement (e.g. filtering or windowing) has to be transparent to the RX.
  - ➢ Any additional signal processing on top of the commonly agreed baseline CP-OFDM waveform, e.g., time domain windowing or subband/bandwidth part filtering performed in the TX, is not signaled to the RX.
- Spectrum confinement techniques may be applied also on the RX side, but this will be unknown to the TX.

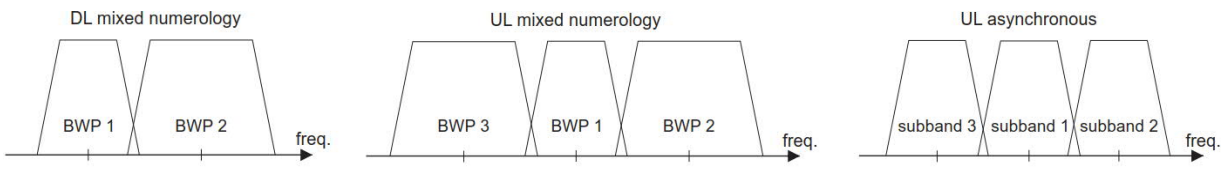
Need for improved spectrum confinment

- The spectral utilization of LTE is 90 % (e.g. 9 MHz active band in 10 MHz channel)
- 5G NR targets are considerably higer utilization, up to 99 %.
- 5G NR supports mixed numerology, i.e., different subcarrier spacings in different subbands (or bandwidth parts)
  - ➢ Orthogonality of subcarriers is lost due to high sidelobes of CP-OFDM.
- Also asynchronous uplink operation is considered, e.g., for massive MTC devices, in order ot reduce the synchronization overhead for low-rate devices.
  - ➢ Orthogonality is lost also in this case.

➢ The spectrum localization of CP-OFDM needs to be improved at carrier and subband levels!

Mixed numerology and asynchronocity

- Subband: Waveform processing (windowing, filtering) is applied at subband level
- Bandwidth part (BWP): One or more contiguous subbands (and contiguous PRBs) using the same numerology
- Examples:



Transparent waveform processing in 5G New Radio

- On the Tx side, the target of additional signal processing is to suppress the out-of-band emissions and in-band interference leakage to achieve defined emission masks, and good spectral efficiency in mixed numerology and asynchronous cases.
- On the Rx side, the additional processing is used to improve adjacent-channel-selectivity, reducing the interference from a nearby interferer using different numerology or transmission link direction or operating asynchronously.
- The mixed numerology in-band emission masks considered for UL are a new aspect for 5G NR to allow in-channel mixing of different services using different numerologies and thus possibly different waveform processing within a carrier.

Transparent waveform processing in 5G New Radio

Matched processing cases:

- Reference TX – Reference RX
- Agnostic TX – Agnostic RX
  - Using the same scheme

Non-matched cases:

- Reference TX – Agnostic RX
- Agnostic TX – Reference RX
- Agnostic TX – Agnostic RX
  - Using different schemes

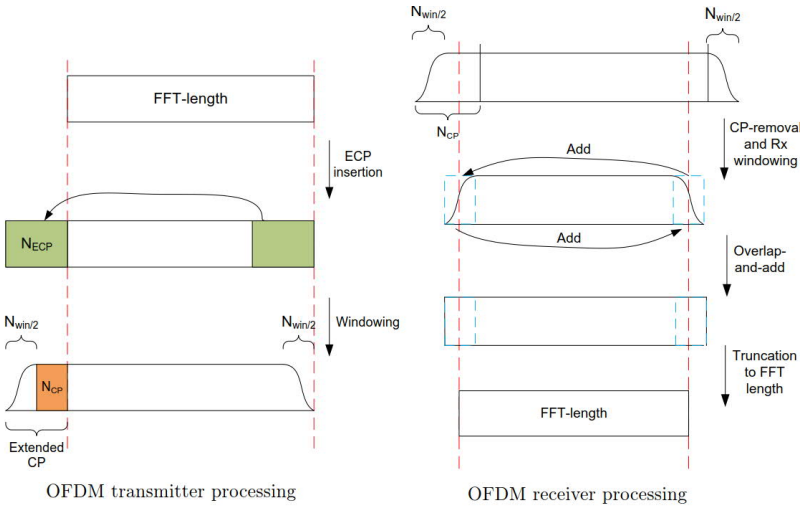
- Agnostic TX/RX: A device that is using spectrum confinement techniques without knowledge of the processing used on the other side.

Transparent waveform processing in 5G New Radio

Benefits:

- In standardization, hard exclusive decisions on the supported processing techniques can be avoided => Vendors can select different schemes for their implementations
- Allows fast time-to-market for the first 5G products
- Initially, additional frequency isolation can be achieved by introducing additional guard bands through deactivated OFDM subcarriers or physical PRBs in scheduling.
- When the implementation techniques are improved, additional waveform signal processing can be applied separately at the network and the UE sides, in a fully backward compatible manner, without negative impacts on the existing devices.

Spectrum confinement techniques - WOLA



Weighted ovarlap and add

- Low-complexity time-domain windowing technique on both RX and TX sides
- Limited confinement effect when targeting at low overhead
- No ”in-subband” distortion

Spectrum confinement techniques – Subband filtering

- Various time-domain filtering schemes proposed with specific filter designs
  - Universal Filtered OFDM (UF-OFDM, UFMC), *Schaich, Wild, Globecom 2013*
  - Resource Block Filtered OFDM (RB-F-OFDM), *Li et al., ICT 2013*
  - Filtered OFDM (f-OFDM), *J. Abdoli et al., SPAWC 2015*
- Fast-Convolution Filtered OFDM (FC-F-OFDM)
  - Basic scheme: *Renfors et al., Globecom 2015*
  - Matched processing: *Yli-Kaakinen et al., IEEE JSAC, June 2017*
  - Transparent processing: *Levanen et al., accepted to IEEE Wireless Comm. Mag.*

Fast-convolution (FC) filtering

$$\mathbf{y} = \mathrm{IFFT}\left(\mathbf{d} \times \mathrm{FFT}(\mathbf{x})\right)$$

precomputed FFT of filter impulse response

Input sequence

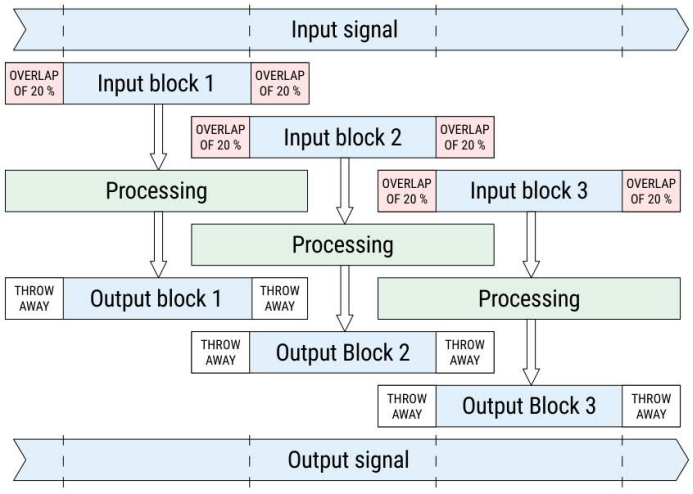
- For long/continuous input sequences, overlap-save or overlap-add processing is applied.

Fast-convolution (FC) filtering

$$\mathbf{y} = \mathrm{IFFT}\left(\mathbf{d} \times \mathrm{FFT}(\mathbf{x})\right)$$

- Fast convolution processing is an efficient implementation of high-order time-domain filters in frequency domain.
  - Replace time-domain convolution with frequency-domain multiplication
  - Overlapped processing is used with long sequences
- Exact representation possible, but not optimal from computational complexity – performance trade-off perspective.
  - Implementation complexity can be fine tuned by relaxing the correspondence between the time-domain and frequency-domain models
  - Reduced overlap makes the processing more effective, but causes in-band and out-of-band interference
  - Analytical signal models are essential for effectively evaluting the interferences in optimization.

Fast-convolution – Overlap-save processing flow



- Symmetric overlap model is natural, because symmetric (linear-phase) FIR filters are used.
- Here the overlap is 40 %.

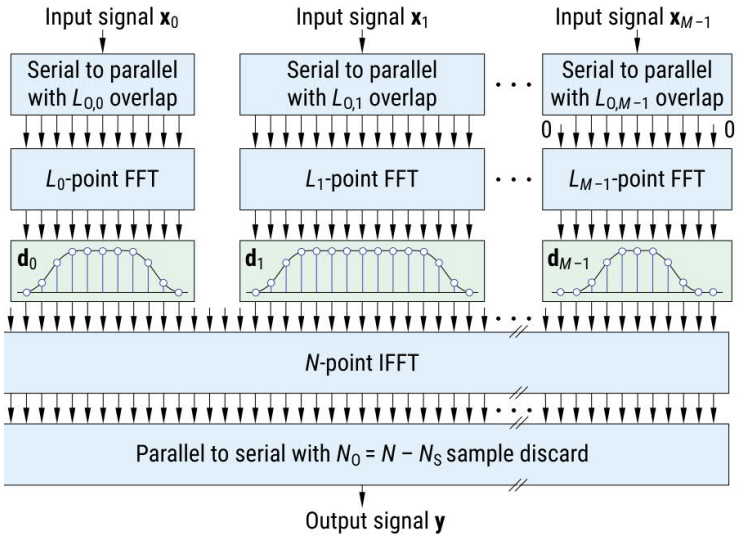
Fast-convolution - Parametrization

- The main constraint for FC parameterization is that overlapping and non-overlapping parts have to be expressed as an integer number of samples on both sides of FC processing block.



- In case of filtered CP-OFDM, the overall symbol duration ($L+L_{CP}$) should be an integer number of samples
  - In LTE and 5G NR numerology, the shortest possible short transform length is $L_{\min} = 128$.
  - Breaking this size limitation is one future research topic!

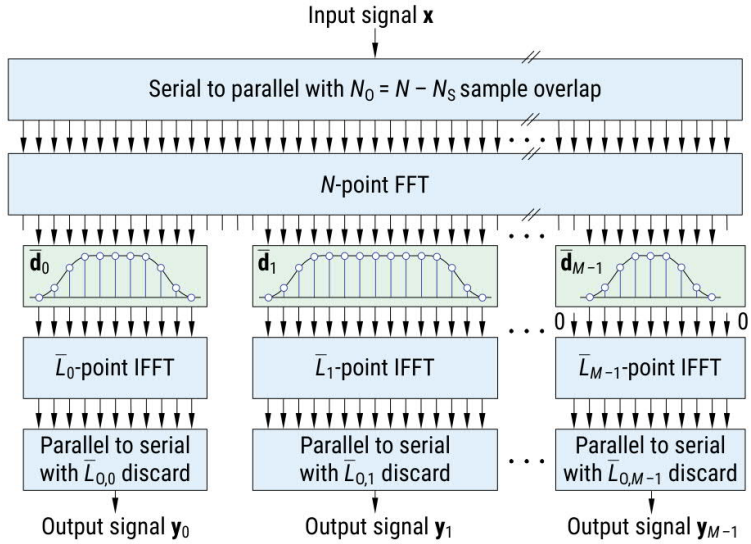
Fast-convolution - Synthesis filter bank



- Overlap-save used here
- Low-rate narrowband subchannels are combined into a high-rate wideband channel
- The bandwidth and shape of each subchannel can be adjusted individually by modifying the weight masks, $\mathbf{d_m}$
- The oversampling ratio is the ratio between transform lengths
  $R_m = N/L_m$

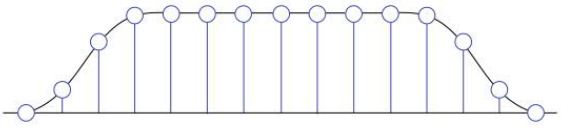
➢ Quite effective and very flexible!

Fast-convolution - Analysis filter bank

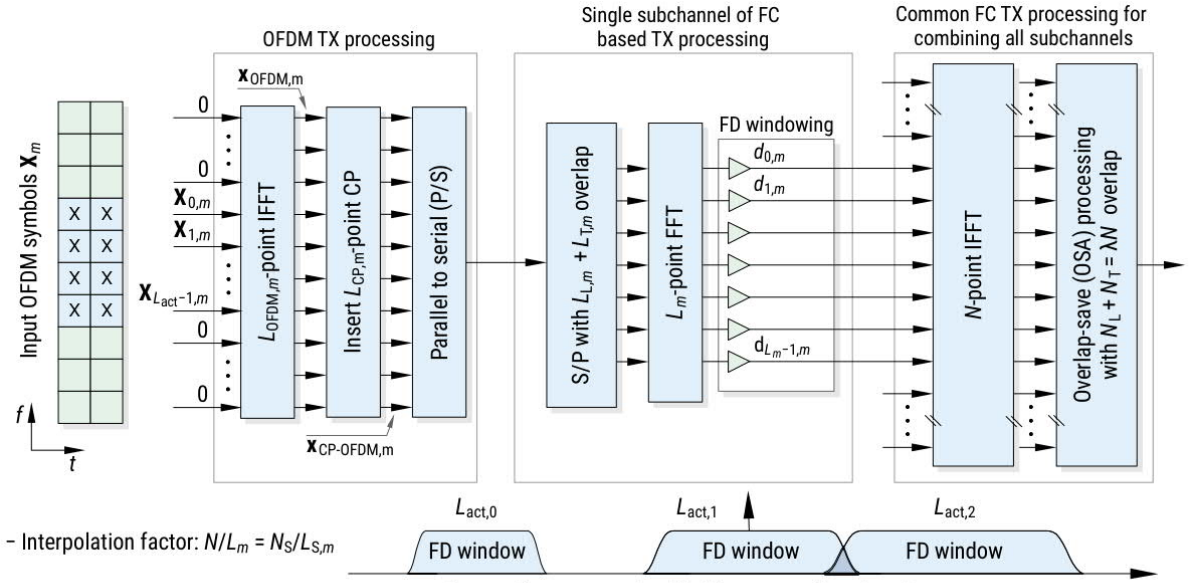


Fast-convolution - Optimization

- In our approach FC filter design is done in frequency-domain by optimizing the weight coefficients $\mathbf{d}_m$.
  - All passband weights are 1
  - All stopband weights are 0
  - Two symmetric transition bands with non-trivial weights
    - Very low memory requirements
    - Only few parameters to optimize



Fast-convolution filtered OFDM



FC-F-OFDM – Examples of full-band filtered OFDM

Optimization based on minimizing the inband MSE (or EVM) given the attenuation target at the end of transition band

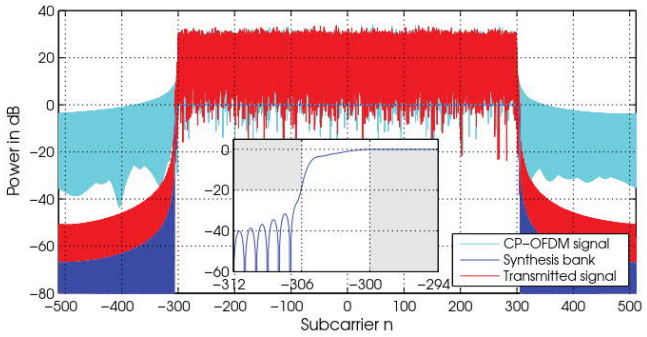


Figure: 20-dB attenuation target

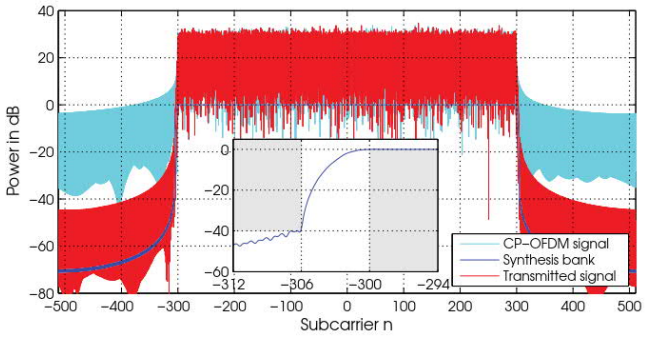


Figure: 40-dB attenuation target

FC-F-OFDM – Examples of subband filtered OFDM

Supports flexible spectrum allocations and adjustable subcarrier spacings

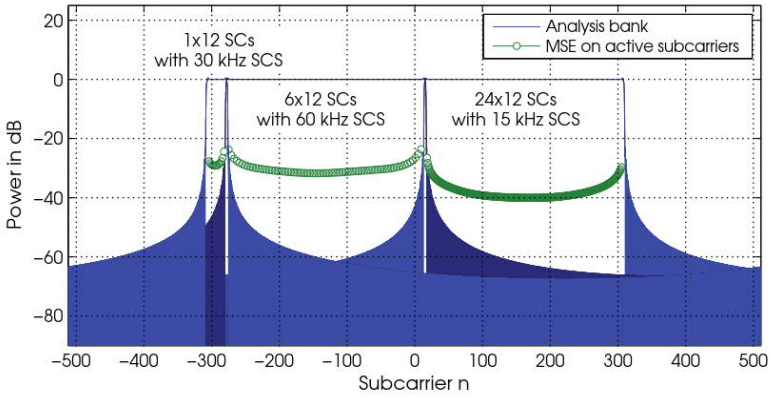


Figure: Three BWPs of N_{act} = {12, 72, 288} active subcarriers with subcarrier spacings of {30, 60, 15} kHz, respectively.

FC-F-OFDM – Performance vs. transition bandwidth

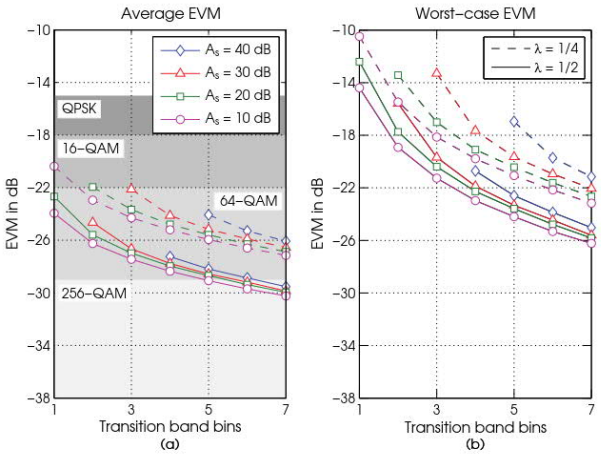


Figure: Wideband transmitted CP-OFDM signal, Rx filtering only

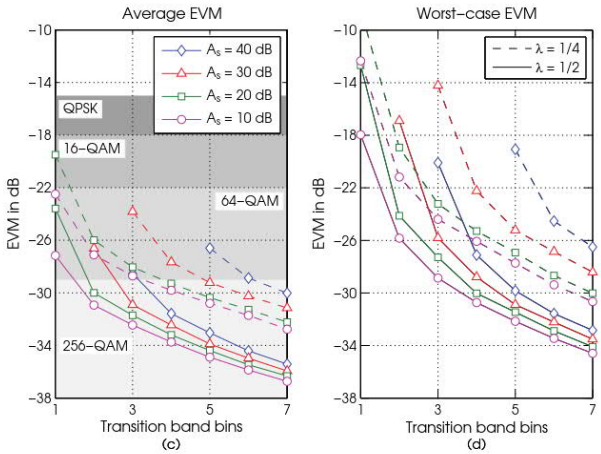
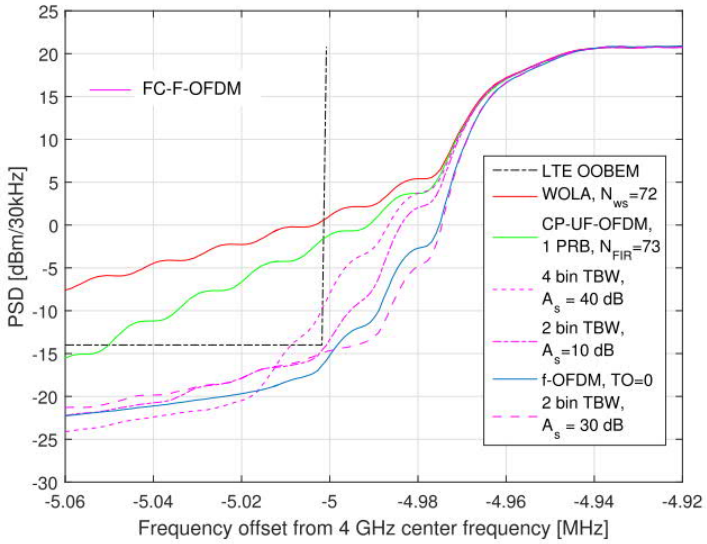


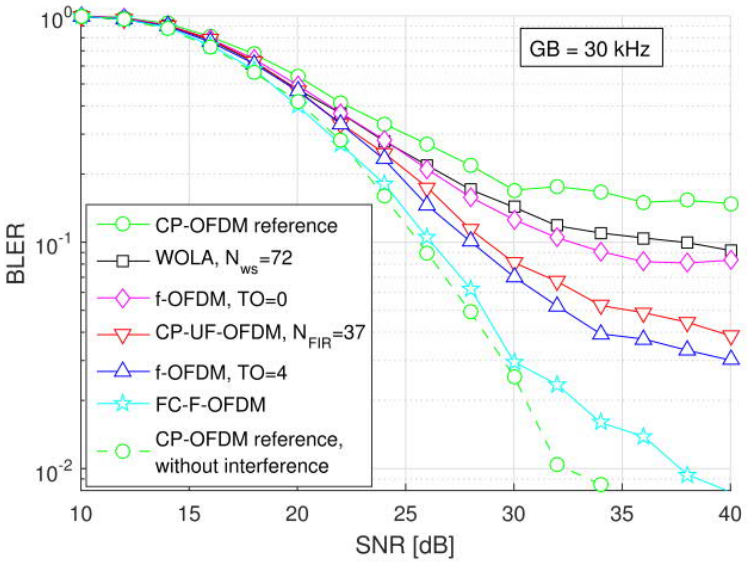
Figure: Isolated group of 4 PRBs with both Tx and Rx filtering

Comparisons – 10 MHz full-band case, 55 PRB's



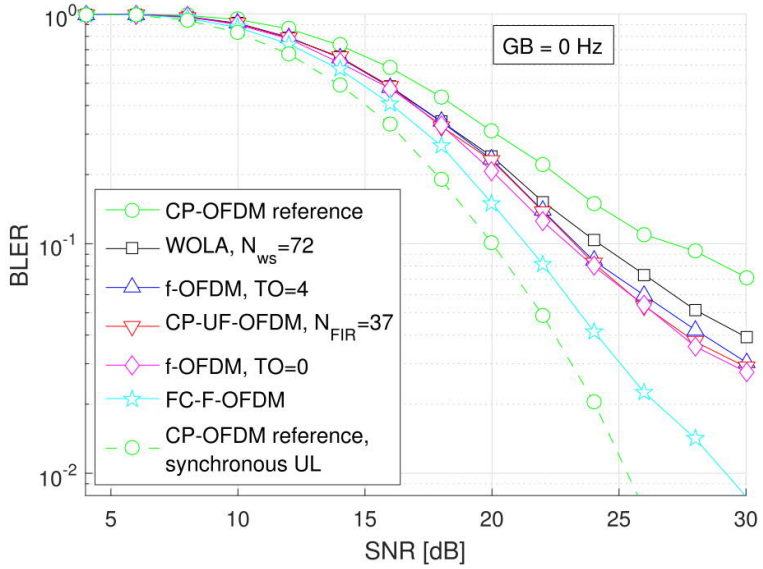
Average EVM
- WOLA: 0.5 %
- FC-F-OFDM: 0.7 %
- f-OFDM: 1 %

Comparisons – Mixed-numerology downlink case



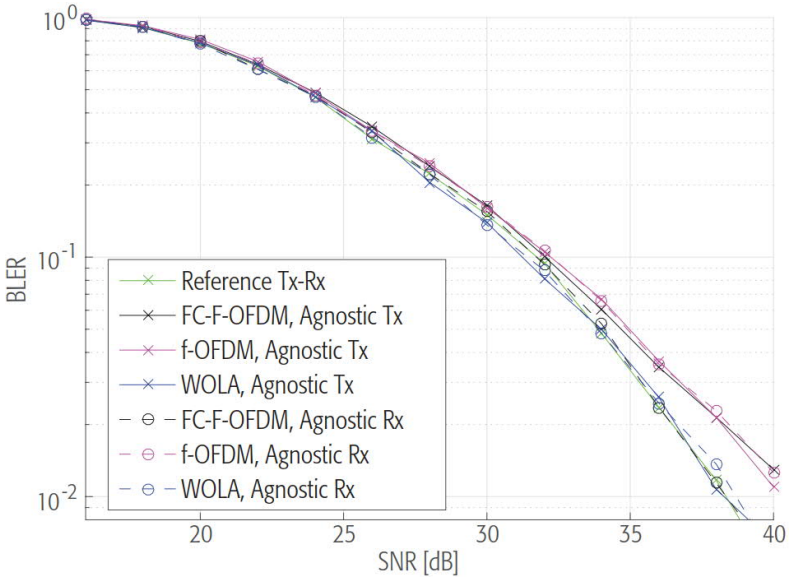
- Matched TX and RX processing
- Target: 15 kHz SCS, 4 PRBs
- Interferer: 30 kHz SCS, 2 PRBs
- MCS: 64QAM, R=3/4
- Guardband: 30 kHz
- Transition bandwidth: 30 kHz
- TDL-C 1000 ns channel

Comparisons – Mixed-numerology uplink case



- Matched TX and RX processing
- Target: 15 kHz SCS, 4 PRBs
- Interferer: 30 kHz SCS, 2 PRBs
- MCS: 64QAM, R=1/2
- Guardband: 0
- Transition bandwidth: 30 kHz
- TDL-C 1000 ns channel

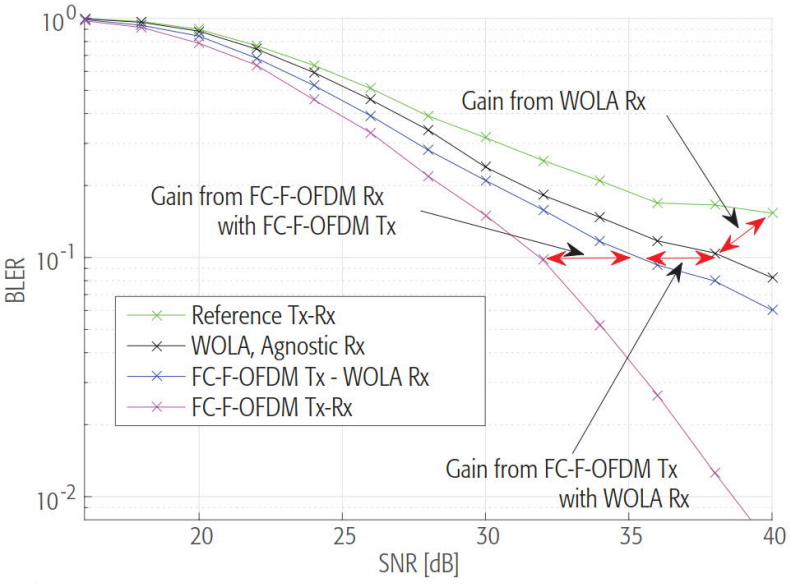
Transparent processing – DL performance



- Interference-free case
  Target: 15 kHz SCS, 4 PRBs
- Reference
  TX: Channel filtered CP-OFDM
  RX: CP-OFDM
- MCS: 256QAM, R=4/5
- Guardband: 180 kHz
- TDL-C 300 ns channel

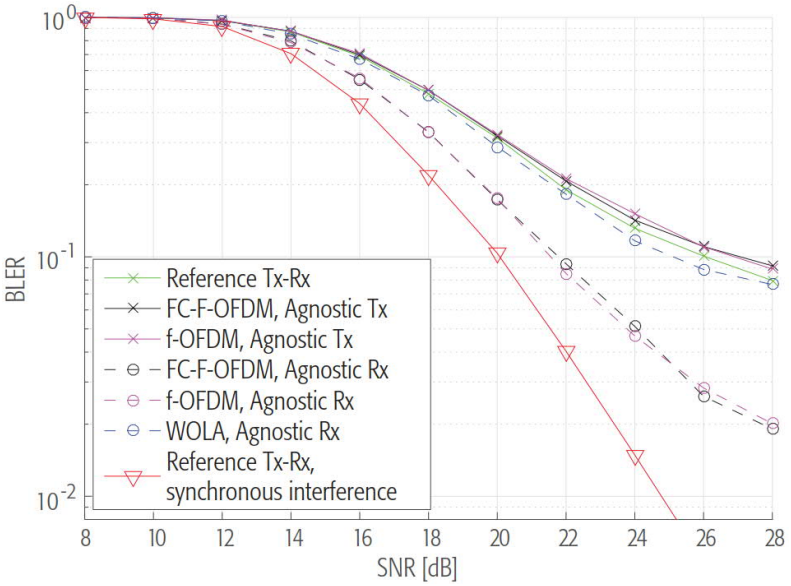
Minor effects on performance due to agnostic TX or RX with all spectrum confinement schemes

Transparent processing – Possible DL evolution



- Mixed-numerology case
  - Target: 15 kHz SCS, 4 PRBs
  - Interferer: 30 kHz SCS, 4 PRBs
- Reference
  - TX: Channel filtered CP-OFDM
  - RX: CP-OFDM
- MCS: 256QAM, R=4/5
- Guardband: 180 kHz
- TDL-C 300 ns channel
- Matched FC-F-OFDM reaches the interference-free reference link performance

Transparent processing – UL performance



- Asynchronous case
  - Target: 15 kHz SCS, 4 PRBs
  - Interferer: 15 kHz SCS, 4 PRBs half-symbol timing offset
- Reference
  - TX: WOLA
  - RX: Channel filtered CP-OFDM
- MCS: 64QAM, R=3/4
- Guardband: 30 kHz
- TDL-C 1000 ns channel
- Clear gain from RX filtering

Spectrum confinement schemes - Complexity

Allocation size	FC-F-OFDM		WOLA		f-OFDM	
	Complexity		Complexity		Complexity	
	Muls/ act. SC	Relative to OFDM	Muls/ act. SC	Relative to OFDM	Muls/ act. SC	Relative to OFDM
1 PRB	1417.3	×2.4	600.7	≈ ×1.0	1139.0	×1.9
4 PRBs	354.3	×2.4	150.2	≈ ×1.0	284.8	×1.9
50 PRBs	63.2	×5.3	12.0	≈ ×1.0	954.5	×79.9
12 × 4 PRBs	60.8	×4.9	12.5	≈ ×1.0	284.8	×22.9
25 + 12 PRBs	58.4	×4.8	22.8	×1.9	638.4	×26.5

- WOLA has low complexity, but it is less effective than than the subband filtering schemes.
- FC-F-OFDM has realistic complexity in all considered scenarios.
- Time-domain filtering is effective for one/few narrow subbands, but it has high complexity with many or wide subbands.

Concluding remarks

- Different waveform signal processing techniques can be flexibly mixed, making it possible to separately optimize complexity-performance trade-offs for transmitter and receiver implementations, and separate evolution paths for base-stations and user equipment.
- Fast-convolution filtered OFDM has flexibility and real-time configurability to support a wide range of subband consigurations with reasonable computational complexity.

Acknowledgements

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  - TUT: Juha Yli-Kaakinen, Toni Levanen, AlaaEddin Loulou, Sami Valkonen, Markku Renfors, Mikko Valkama
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