Optimized Fast Convolution Based Filtered-OFDM Processing for 5G

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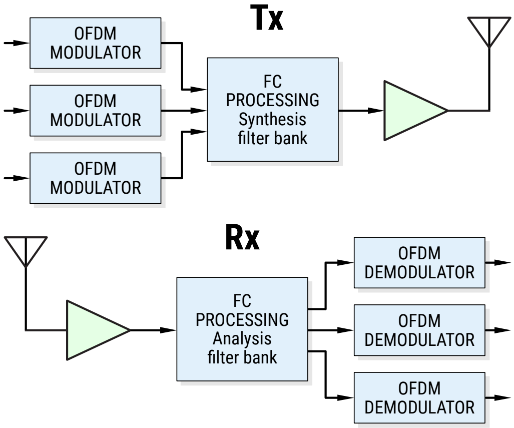
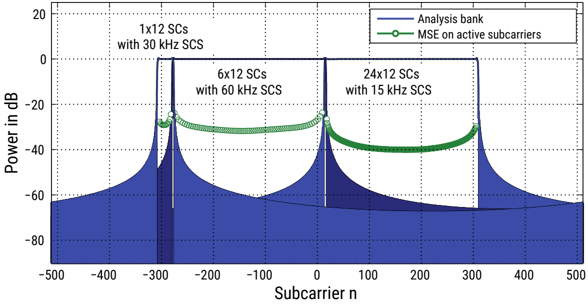
Fast-convolution (FC) filtering schemes provide flexible and effective waveform generation and processing in the fifth generation (5G) systems

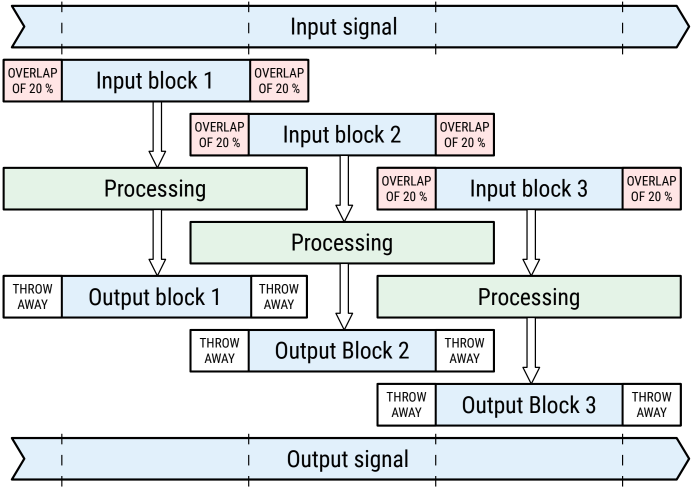




Fast Convolution

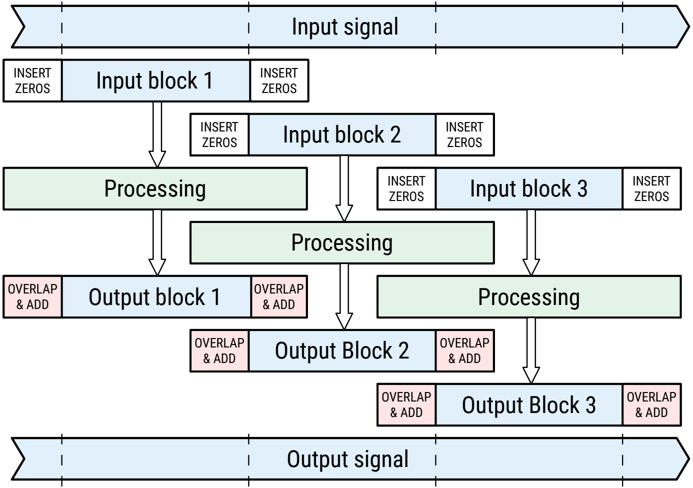
- Fast convolution processing is an efficient implementation of high-order time-domain filters in frequency domain
  - Replace time-domain convolution with frequency-domain multiplication
  - Overlap-and-save (OSA) processing is used with long sequences
- Implementation complexity can be fine tuned by relaxing the correspondence between the time-domain and frequency-domain models
  - Exact representation possible, but not optimal from computational complexity – performance trade-off perspective

Fast Convolution – Overlap-and-Save Processing



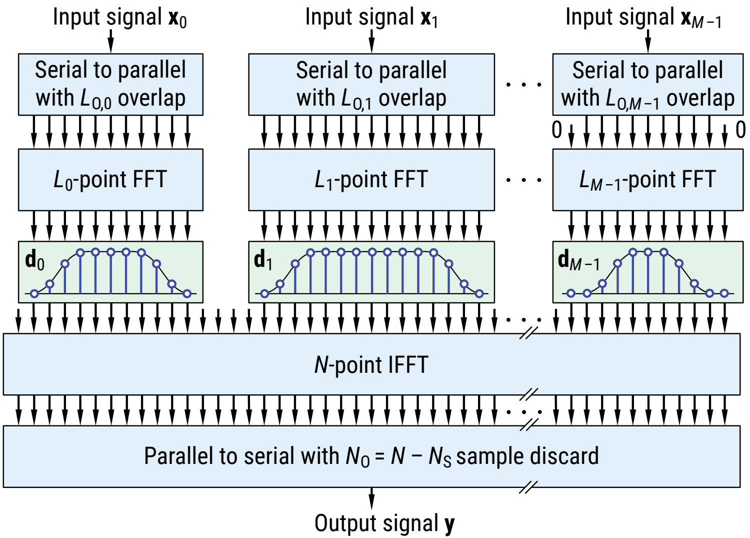
- Input signal is divided into overlapping blocks (e.g. with 40% overlap)
- Blocks are transformed to frequency-domain for processing (filter)
- Processed blocks are transformed back to time-domain for concatenation

Fast Convolution – Overlap-and-Add Processing



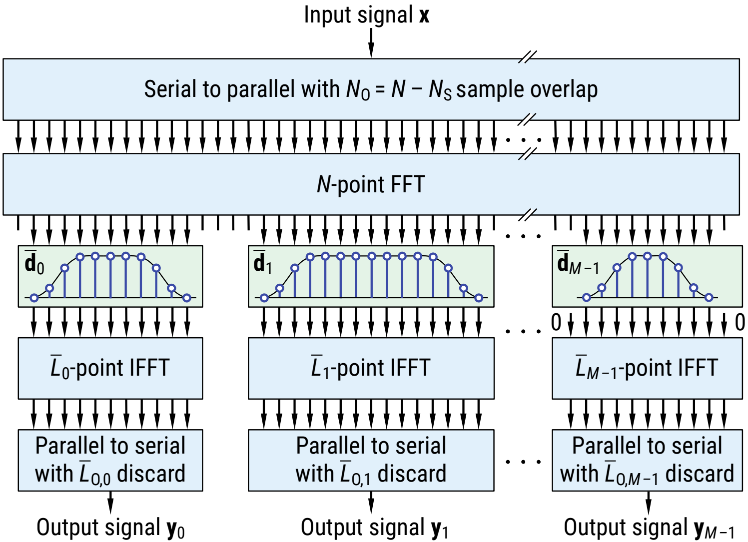
- We use the overlap-and-save because of its better properties in finite wordlength implementation
- This is due to the possible transients at the beginning and end of each overlap-add processing block

Fast Convolution – Synthesis Filterbank Tx Processing



- Low-rate narrowband subchannels are combined into a high-rate wideband channel
- The bandwidth and the shape of the subchannels can be adjusted by modifying the weight masks d_m's
- Subband signals are detectable with basic OFDM receiver

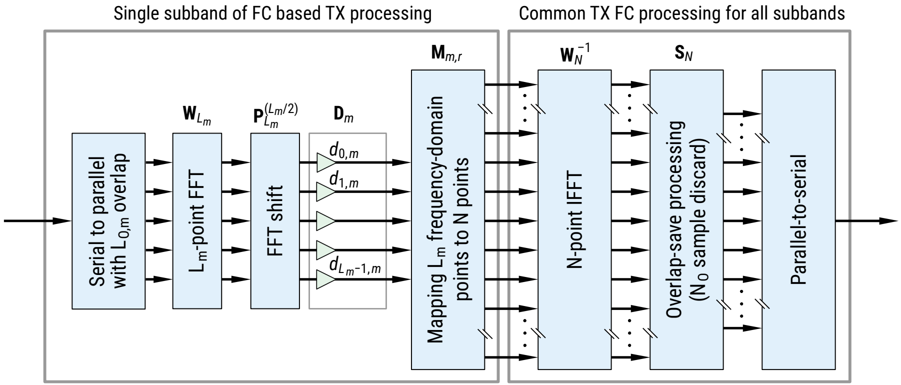
Fast Convolution – Analysis Filterbank Rx Processing



- High-rate wideband channel is divided into low-rate narrowband subchannels
- N in synthesis and analysis filterbanks don't have to be equal
- The subcarrier-wise channel equalizer coefficients can be combined with the weight masks $\bar{\mathbf{d}}_m$'s

Matrix Model for FC Processing – Synthesis Filterbank

$$\mathbf{F}_{m,r} = \mathbf{S}_N \mathbf{W}_N^{-1} \mathbf{M}_{m,r} \mathbf{D}_m \mathbf{P}_{L_m}^{(L_m/2)} \mathbf{W}_{L_m}$$



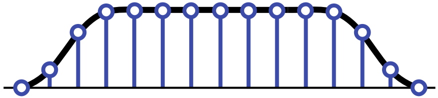
Matrix Model for FC Processing – Analysis Filterbank

Similarly for analysis filterbank

$$\mathbf{G}_{m,r} = \mathbf{S}_{\bar{L}_m} \mathbf{W}_{\bar{L}_m}^{-1} \mathbf{P}_N^{(N/2)} \mathbf{D}_m \mathbf{M}_{m,r}^{\mathsf{T}} \mathbf{W}_N$$

In our approach FC design is done in frequency-domain by optimizing the weight coefficients embedded in $\mathbf{D}_m$

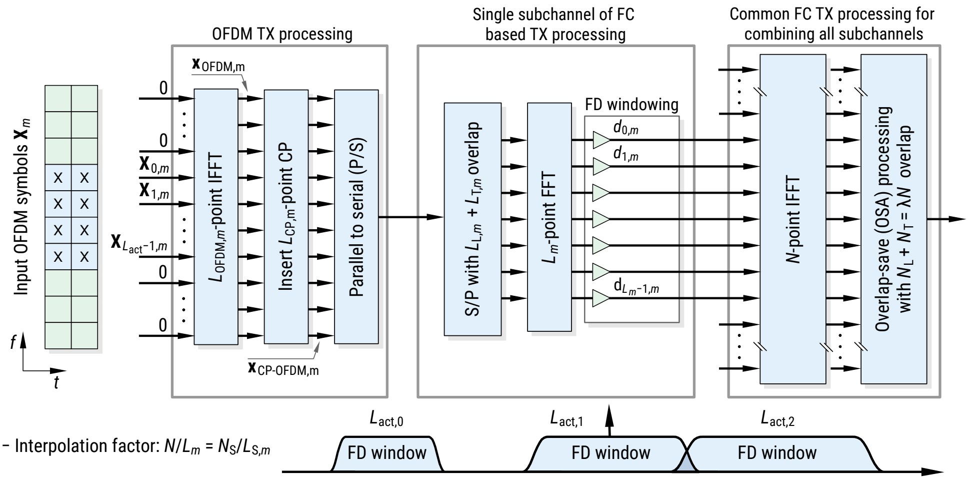
- Two symmetric transition bands with non-trivial weights (very low memory requirement)
- All passband weights are 1
- All stopband weights are 0



FC-F-OFDM

- FC filtered CP-OFDM/DFTs-OFDM (FC-F-OFDM) is a scheme where the FC processing is used to implement *highly adjustable* and *computationally efficient* subband filtering for CP-OFDM or DFTs-OFDM signals

FC-F-OFDM (processing structure for one filtered group of PRBs)



– Interpolation factor: $N/L_m = N_S/L_{S,m}$

Discrete frequency axis with N frequency-domain points.
The number of active subcarrier $L_{\mathrm{act},m}$ can be different for each subband.

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

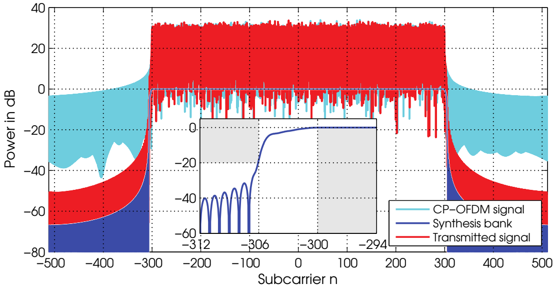


Figure: 20-dB attenuation target

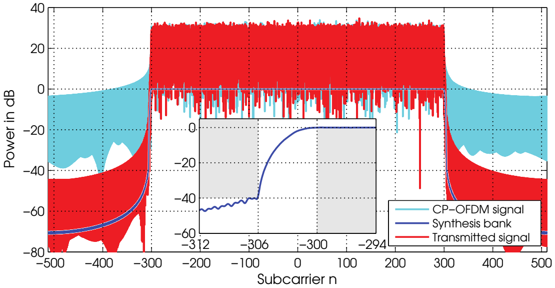


Figure: 40-dB attenuation target

FC-F-OFDM – PSDs of Filtered Groups of PRBs

Supports flexible spectrum allocations and adjustable subcarrier spacings

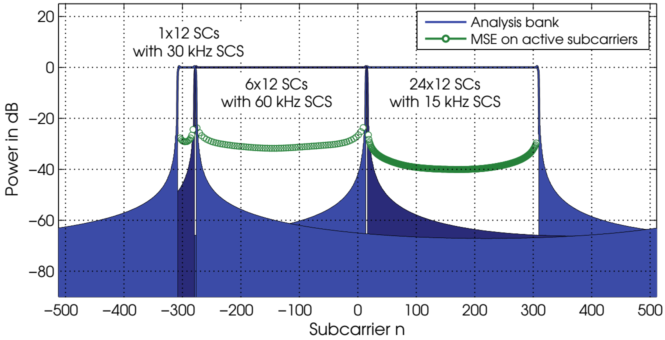


Figure: Three RBGs of N_{act} = {12, 72, 288} active subcarriers with subcarrier spacing of {30, 60, 15} kHz, respectively.

Performance with optimized transition band weights

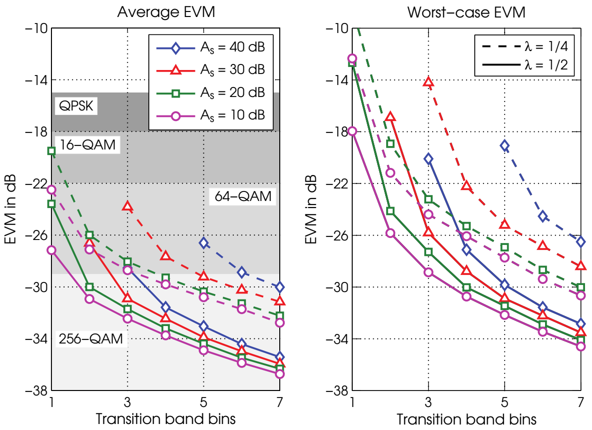


Figure: Isolated group of 4 PRBs with both Tx and Rx filtering

FC-F-OFDM Complexity

Table: Rx MSE versus complexity

No. active subcarriers	Overlap factor λ	Rx complexity (muls/MC-symbol)	Rx complexity (muls/symbol)	Rx complexity relative to OFDM
4 PRBs	1/2 1/4	17 302 11 758	360.46 244.96	$\times$2.41 $\times$1.64
50 PRBs	1/2 1/4	38 468 28 131	64.11 46.89	$\times$5.36 $\times$3.92
12 $\times$ 4 PRBs	1/2 1/4	35 430 25 774	61.51 44.75	$\times$4.94 $\times$3.59

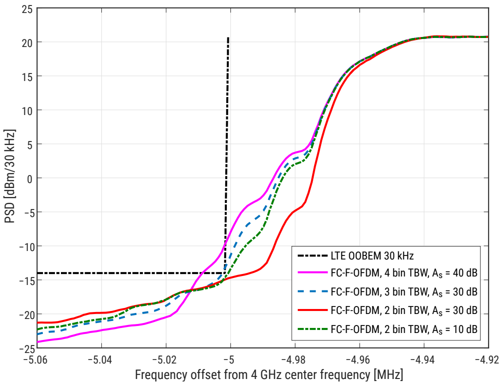
Table: Corresponding FIR realization complexity for the 50 PRB case

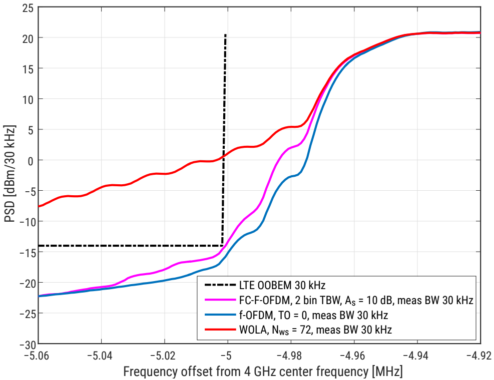
FIR filter length	Rx complexity (muls/MC-symbol)	Rx complexity relative to OFDM
50	51 200	$\times$7.14
100	102 400	$\times$14.28
150	153 600	$\times$21.42

- The FC filtering complexity is defined by the number of FC processing blocks, subband bandwidth, and number of filtered subbands.
- To minimize complexity
  - reducing overlap reduces the number of FC processing blocks
  - minimizing small transform size with respect to the subband size reduces related complexity

Performance Comparison

Case 1a, 55 PRBs in 10 MHz channel, spectral localization example

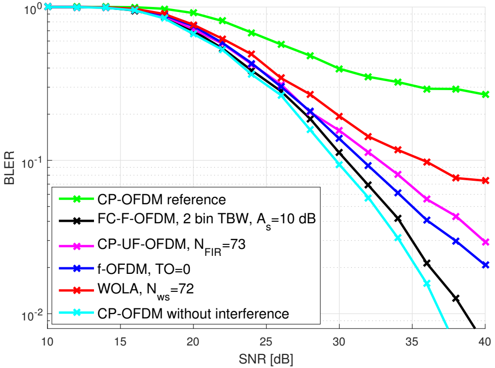




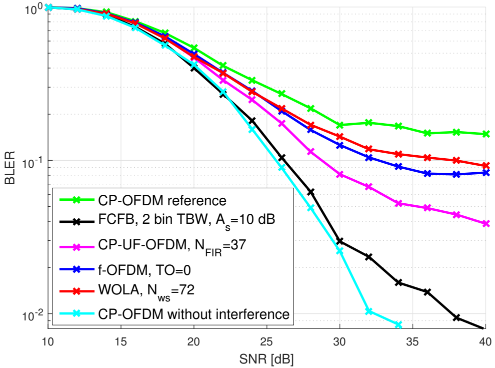
EVM: FC-F-OFDM 0.8 %, f-OFDM 1.1 %, and WOLA 0.7 %

Performance Comparison

Case 2, mixed numerology DL, victim 15 kHz SCS, aggressor 30 kHz SCS GB = 30 kHz

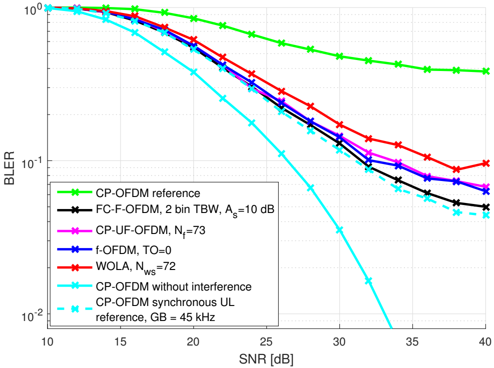


TDL-C 300 ns, 256-QAM, $R = 3/4$

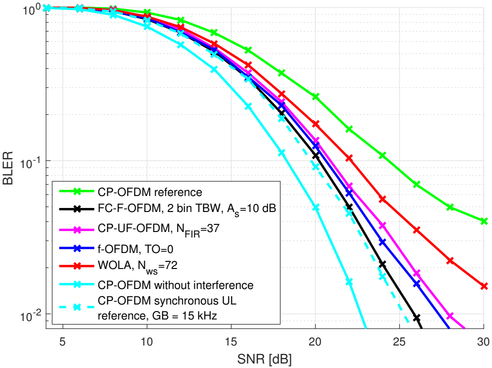


TDL-C 1000 ns, 64-QAM, $R = 3/4$

Case 3, asynchronous UL



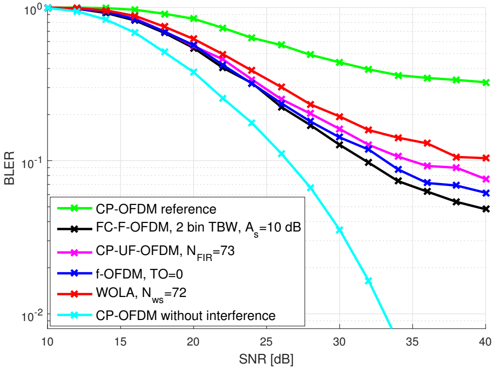
TDL-C 300 ns, 64-QAM, $R = 3/4$, GB $= 45$ kHz



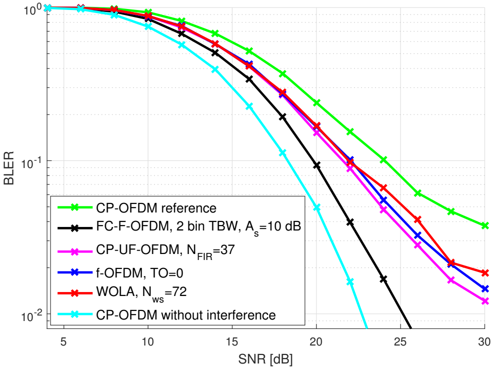
TDL-C 1000 ns, 64-QAM, $R = 1/2$, GB $= 15$ kHz

Performance Comparison

Case 4, mixed numerology UL, victim 15 kHz SCS, aggressor 30 kHz SCS



TDL-C 300 ns, 64-QAM, $R = 3/4$, GB $=$ 45 kHz



TDL-C 1000 ns, 64-QAM, $R = 1/2$, GB $=$ 15 kHz

Conclusions

- FC processing provides a computationally efficient, flexible, and highly selective subband filtering engine
- Can be used with CP-OFDM, DFTs-OFDM, ZT-DFTs-OFDM, and single carrier waveforms
- Given the number of transition-band bins, the performance can be optimized for adjusting the trade-off between the in-band MSE and the spectral containment
- For more complete description and performance analysis, see J. Yli-Kaakinen *et al.* "Efficient fast-convolution based waveform processing for 5G physical layer," *IEEE Journal on Selected Areas in Communications*, vol. 35, no. 6, pp. 1309–1326, 2017.

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