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5G Waveform & Multiple Access Techniques

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Outline

Executive summary

Executive Summary

- 5G will support diverse use cases
  - Enhanced mobile broadband, wide area IoT, and high-reliability services
- OFDM family is well suited for mobile broadband and beyond
  - Efficient MIMO spatial multiplexing for higher spectral efficiency
  - Scalable to wide bandwidth with lower complexity receivers
- CP-OFDM/OFDMA for 5G downlink
  - CP-OFDM with windowing/filtering delivers higher spectral efficiency with comparable out-of-band emission performance and lower complexity than alternative multi-carrier waveforms under realistic implementations
  - Co-exist with other waveform & multiple access options for additional use cases and deployment scenarios
- SC-FDM/SC-FDMA for scenarios requiring high energy efficiency (e.g. macro uplink)
- Resource Spread Multiple Access (RSMA) for use cases requiring asynchronous and grant-less access (e.g. IoT)

OFDM-based waveform & multiple access are recommended for 5G

Additional waveform & multiple access options are included to support specific scenarios

Downlink recommendation (for all use cases):

- Waveform: OFDM[1]
- Multiple access: OFDMA

eMBB for Sub-6GHz

- Licensed macro uplink
  - Waveform: OFDM, SC-FDM
  - Multiple access: OFDMA, SC-FDMA, RSMA
- Unlicensed and small cell uplink
  - Waveform: OFDM
  - Multiple access: OFDMA

Wide Area IoT

- Uplink:
  - Waveform: SC-FDE
  - Multiple access: RSMA

mmWave

- Uplink:
  - Waveform: OFDM, SC-FDM
  - Multiple access: OFDMA, SC-FDMA

High-Reliability Services[2]

- Uplink
  - Waveform: OFDM, SC-FDM
  - Multiple access: OFDMA, SC-FDMA, RSMA

1. OFDM waveform in this slide refers to OFDM with cyclic prefix and windowing. 2. with scaled frame numerology to meet tighter timeline for high-reliability services

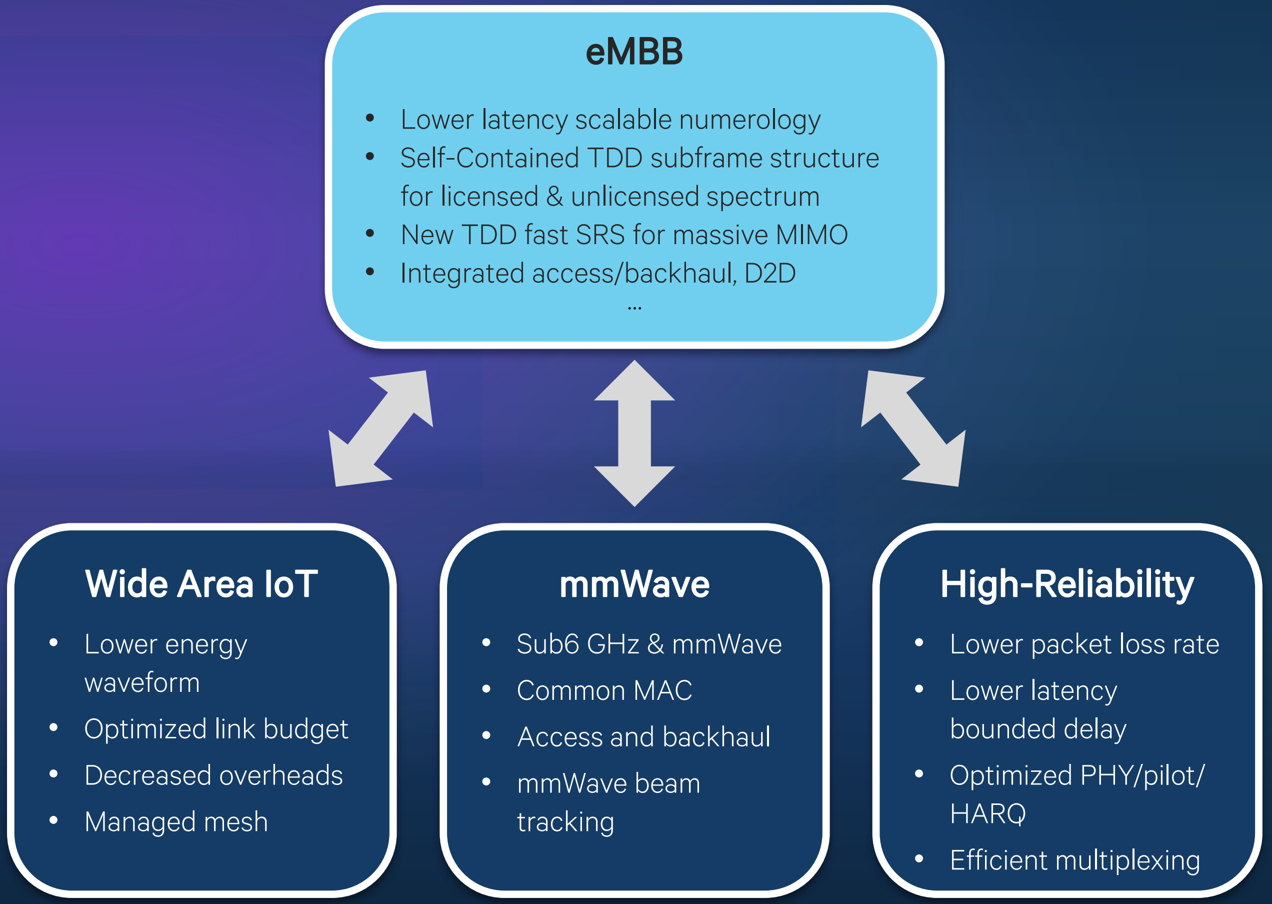
Waveform & multiple access techniques evaluation and recommendations

5G design across services

Motivations of waveform & multi-access design

- Support wide range of use cases:
  - eMBB: higher throughput / higher spectral efficiency
  - Wide area IoT: massive number of low-power small-data-burst devices with limited link budget
  - Higher-reliability: services with extremely lower latency and higher reliability requirements
- Accommodate different numerologies optimized for specific deployment scenarios and use cases
- Minimize signaling and control overhead to improve efficiency

Enhanced Mobile Broadband (eMBB) is the anchor technology on to which other 5G services are derived



Key design targets for physical layer waveform

Key design targets	Additional details
Higher spectral efficiency	• Ability to efficiently support MIMO • Multipath robustness
Lower in-band and out-of-band emissions	• Reduce interference among users within allocated band • Reduce interference among neighbor operators, e.g. achieve low ACLR
Enables asynchronous multiple access	• Support a higher number of small cell data burst devices with minimal scheduling overhead through asynchronous operations • Enables lower power operation
Lower power consumption	• Requires low PA backoff leading to high PA efficiency
Lower implementation complexity	• Reasonable transmitter and receiver complexity • Additional complexity must be justified by significant performance improvements

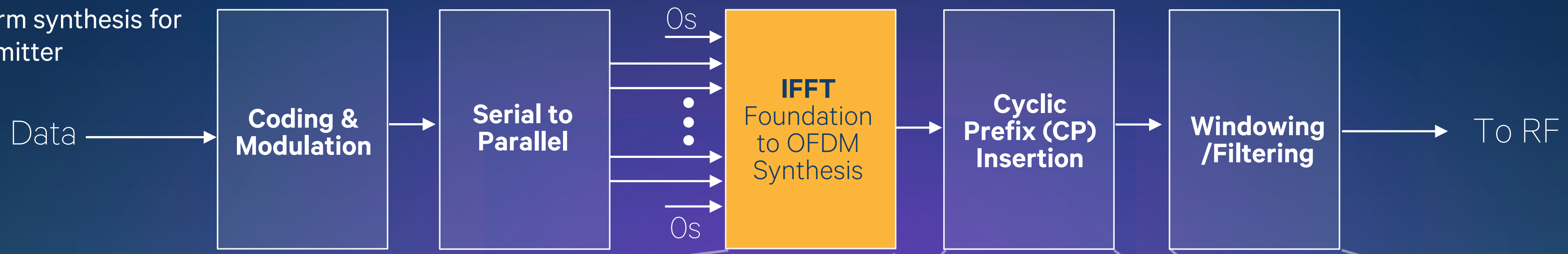
Key design targets for multiple access technique

Key design targets	Additional details
Higher network spectral efficiency	• Maximize spectral efficiency across users and base stations • Enable MU-MIMO
Link budget and capacity trade off	• Maximize link budget and capacity taking into consideration their trade off as well as the target use case requirements
Lower overhead	• Minimize protocol overhead to improve scalability, reduce power consumption, and increase capacity • Lower control overhead

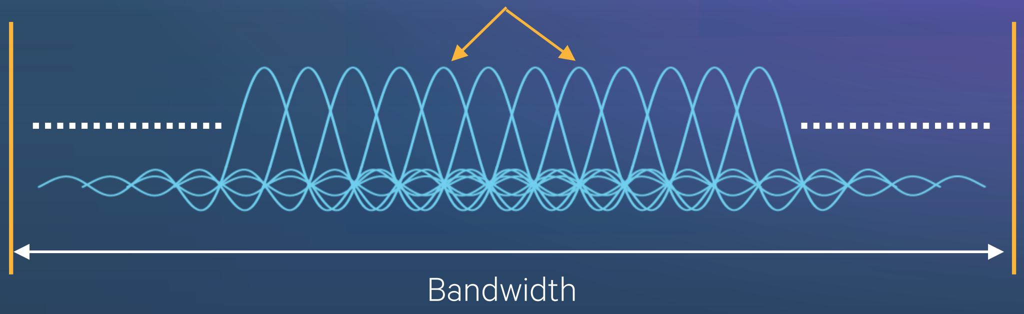
Quick refresh on OFDM

Orthogonal Frequency Division Multiplexing

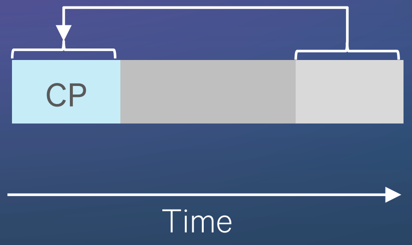
Simplified OFDM waveform synthesis for a transmitter



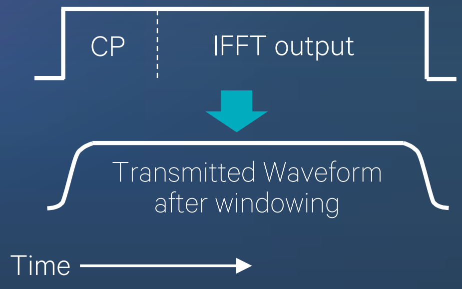
Data transmitted via closely-spaced, narrowband subcarriers – IFFT operation ensures subcarriers do not interfere with each other



Helps maintain orthogonality despite multipath fading



Windowing reduces out-of-band emissions



OFDM-based waveforms are the foundations for LTE and Wi-Fi systems today

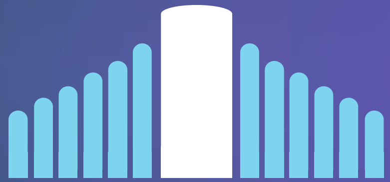
OFDM family well suited to meet the evolving requirements

Additional waveform & multiple access options can complement OFDM to enable more use cases

Higher spectral efficiency

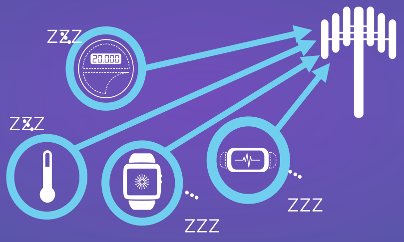
Efficiently support MIMO spatial multiplexing with wide bandwidths and larger array sizes

Lower out-of-band emissions



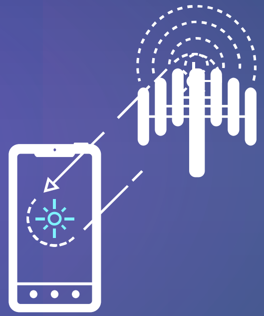
Windowing effectively enhances frequency localization

Asynchronous multiplexing



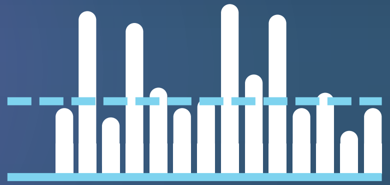
Can co-exist with other waveform/multi-access within the same framework to support wide area IoT

Lower complexity



Lower complexity receivers even when scaling to wide bandwidths with frequency selectivity

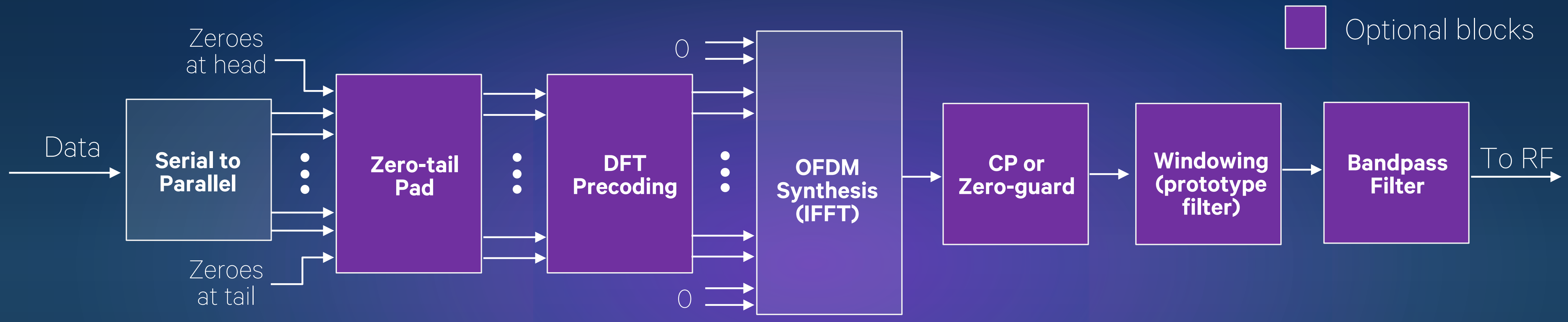
Lower power consumption



Single-carrier OFDM waveform for scenarios with higher power efficiency requirements

Numerous OFDM-based waveforms considered

Different implementation options and optimizations



Waveforms	A	B	IFFT	C	D	E	
CP-OFDM + WOLA[1]			√	CP	√		LTE DL
SC-FDM + WOLA		√	√	CP	√		LTE UL
UFMC			√	ZG		√	
FBMC			√		√		
Zero-tail SC-FDM	√	√	√				

[1] Weighted OverLap and Add (WOLA) – Windowing technique popular in 4G LTE systems today

Summary of single-carrier waveforms

Waveforms	Pros	Cons
Constant envelope (e.g., GMSK in GSM and Bluetooth LE; MSK in Zigbee)	• 0dB PAPR • Allow asynchronous multiplexing • Good side lobe suppression (GMSK)	• Lower spectral efficiency
SC-QAM (in EV-DO, UMTS)	• Low PAPR at low spectral efficiency • Allow asynchronous multiplexing • Simple waveform synthesis	• Limited flexibility in spectral assignment • Non-trivial support for MIMO
SC-FDE	• Equivalent to SC-QAM with CP • Allow FDE processing	• Similar as SC-QAM • ACLR similar to DFT-spread OFDM
SC-FDM[1] (in LTE uplink)	• Flexible bandwidth assignment • Allow FDE processing	• Higher PAPR and worse ACLR than SC-QAM • Need synchronous multiplexing
Zero-tail SC-FDM[2]	• Flexible bandwidth assignment • No CP, but flexible inter-symbol guard • Better OOB suppression than SC-FDM without WOLA	• Need synchronous multiplexing • Need extra control signaling • Lack of CP makes multiplexing with CP-OFDM less flexible

1. Also referred to as SC DFT-spread OFDM. 2. Also referred to as Zero-tail SC DFT-spread OFDM

Summary of OFDM-based multi-carrier waveforms

Waveforms	Pros	Cons
CP-OFDM (in LTE spec. but existing implementations typically include WOLA to meet performance requirements)	• Flexible frequency assignment • Easy integration with MIMO	• High ACLR – side lobe decays slowly • Need synchronous multiplexing
CP-OFDM with WOLA (in existing LTE implementations)	• All pros from CP-OFDM • Better OOB suppression then CP-OFDM • Simple WOLA processing	
UFMC	• Better OOB leakage suppression than CP-OFDM (but not better than CP-OFDM with WOLA)	• ISI from multipath fading (no CP) • Higher Tx complexity than CP-OFDM • Higher Rx complexity (2x FFT size) than CP-OFDM
FBMC	• Better than CP-OFDM with WOLA (but the improvement is reduced with PA nonlinearity)	• High Tx/Rx complexity due to OQAM (waveform is synthesized per RB) • Integration with MIMO is nontrivial • Subject to ISI under non-flat channels
GFDM	• Same leakage suppression as CP-OFDM with WOLA	• Complicated receiver to handle ISI/ICI • Higher block processing latency (no pipelining) • Multiplex with eMBB requires large guard band

Summary of multiple access techniques

Multiple access	Pros	Cons
SC-FDMA (in LTE uplink)	• With PAPR/coverage • Multiplexing with OFDMA	• Need synchronous multiplexing • Link budget loss for large number of simultaneous users
OFDMA (in LTE downlink)	• No intra-cell interference • higher spectral efficiency and MIMO	• Need synchronous multiplexing • Link budget loss for large number of simultaneous users
Single-carrier RSMA	• Allow asynchronous multiplexing • Grantless Tx with minimal signaling overhead • Link budget gain	• Not suitable for higher spectral efficiency
OFDM-based RSMA	• Grantless Tx with minimal signaling overhead	• Need synchronous multiplexing
LDS-CDMA/SCMA	• Allow lower complexity iterative message passing multiuser detection (when there are small number of users)	• Higher PAPR than SC RSMA • Need synchronous multiplexing • Lack of scalability/flexibility to users requiring different spreading factors • Not exploiting full diversity
MUSA	• Similar to LDS-CDMA with SIC	• Higher PAPR

Waveform comparison

Waveforms	SC-QAM	SC-FDM/ SC-FDE	Zero-tail SC-FDM	CP-OFDM with WOLA	UFMC	FBMC	GFDM
Higher spectral efficiency with efficient MIMO integration				✓	✓		
Lower in-band and OOB emissions	✓	✓	✓	✓	✓	✓	✓
Enables asyn. multiple access	✓	✓					
Lower power consumption	✓	✓	✓				
Lower implementation complexity	✓	✓	✓	✓			

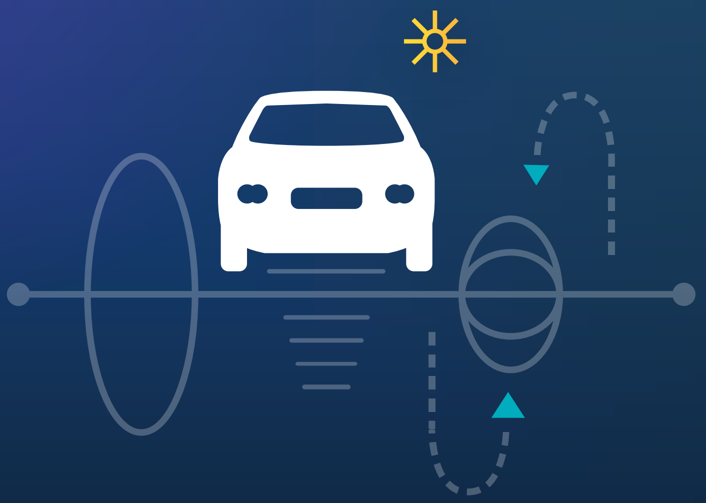
- CP-OFDM with WOLA offers higher spectral efficiency and low implementation complexity, and is suitable for the downlink where energy efficiency requirement is more relaxed
- Other waveform and multiple access options can co-exist with CP-OFDM within the same framework to support additional scenarios:
  - SC-FDM with orthogonal multiple access on macro uplink for better PA efficiency
  - SC-FDM with RSMA for use cases requiring grant-less asynchronous access

Summary of recommendations

Use cases		Key requirements	Recommended waveform / multiple access
eMBB	Uplink	• Macro cell: low PAPR as devices are power-limited	• Macro cell: SC-FDM / SC-FDMA
		• Small cell/unlicensed: higher spectral efficiency due to transmit power limitation	• Small cell/unlicensed: CP-OFDM with WOLA / OFDMA
	Downlink	• Higher peak spectral efficiency • Fully leverage spatial multiplexing	• CP-OFDM with WOLA / OFDMA
Wide area IoT	Uplink	• Support short data bursts • Long device battery life • Deep coverage	• SC-FDE / RSMA
	Downlink		• CP-OFDM with WOLA / OFDMA[1]
Higher-reliability services	Uplink	• Lower latency • Lower packet loss rate	• Macro cell: SC-FDM / SC-FDMA or RSMA[2] • Small cell and unlicensed: CP-OFDM with WOLA / OFDMA[2]
	Downlink		• CP-OFDM with WOLA / OFDMA[1,2]

1. For IoT and high-reliability downlink, PAPR is not the most critical constraint, and synchronization among user is not a concern. Therefore it is desirable to use the same waveform and multi-access as nominal traffic
2. The numerology for subframe and HARQ timeline may need to be condensed to provide very high reliability in a shorter time span.

Additional information on physical layer waveforms



Potential waveform options

Single-carrier waveform

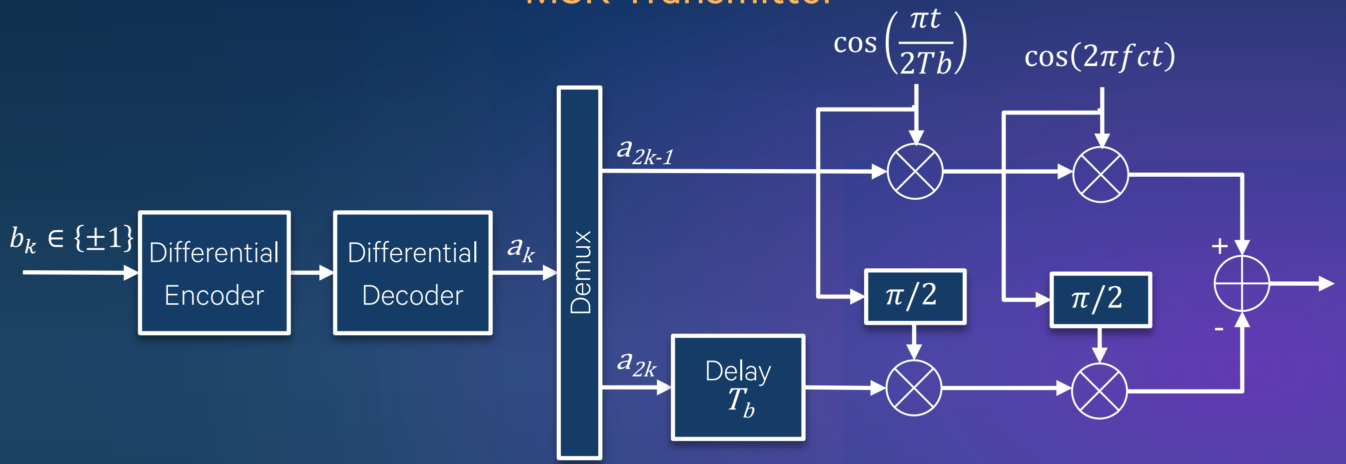
- Time domain symbol sequencing:
  - Typically lower PAPR leading to high PA efficiency and extended battery life
  - Equalizer is needed to achieve high spectral efficiency in the presence of multipath
- Example waveforms:
  - Constant envelops waveform, such as:
    - MSK (adopted by IEEE 802.15.4)
    - GMSK (adopted by GSM and Bluetooth)
  - SC-QAM (adopted by EV-DO and UMTS)
  - SC-FDE (adopted by IEEE 802.11ad)
  - SC-FDM (adopted by LTE uplink)
  - Zero-tail SC-FDM

OFDM-based multi-carrier waveform

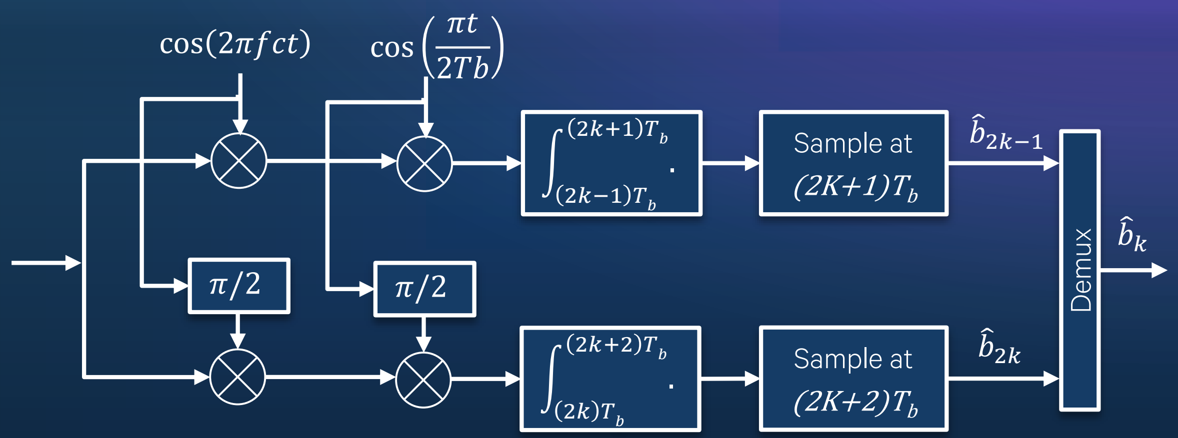
- Frequency domain symbol sequencing
  - Support multiple orthogonal sub-carriers within a given carrier bandwidth
  - Typically easy integration with MIMO leading to improved spectral efficiency
- Example waveforms:
  - CP-OFDM (adopted by LTE spec)
  - CP-OFDM w/ WOLA (existing LTE implementation)
  - UFMC
  - FBMC
  - GFDM

Constant envelope waveforms

MSK Transmitter



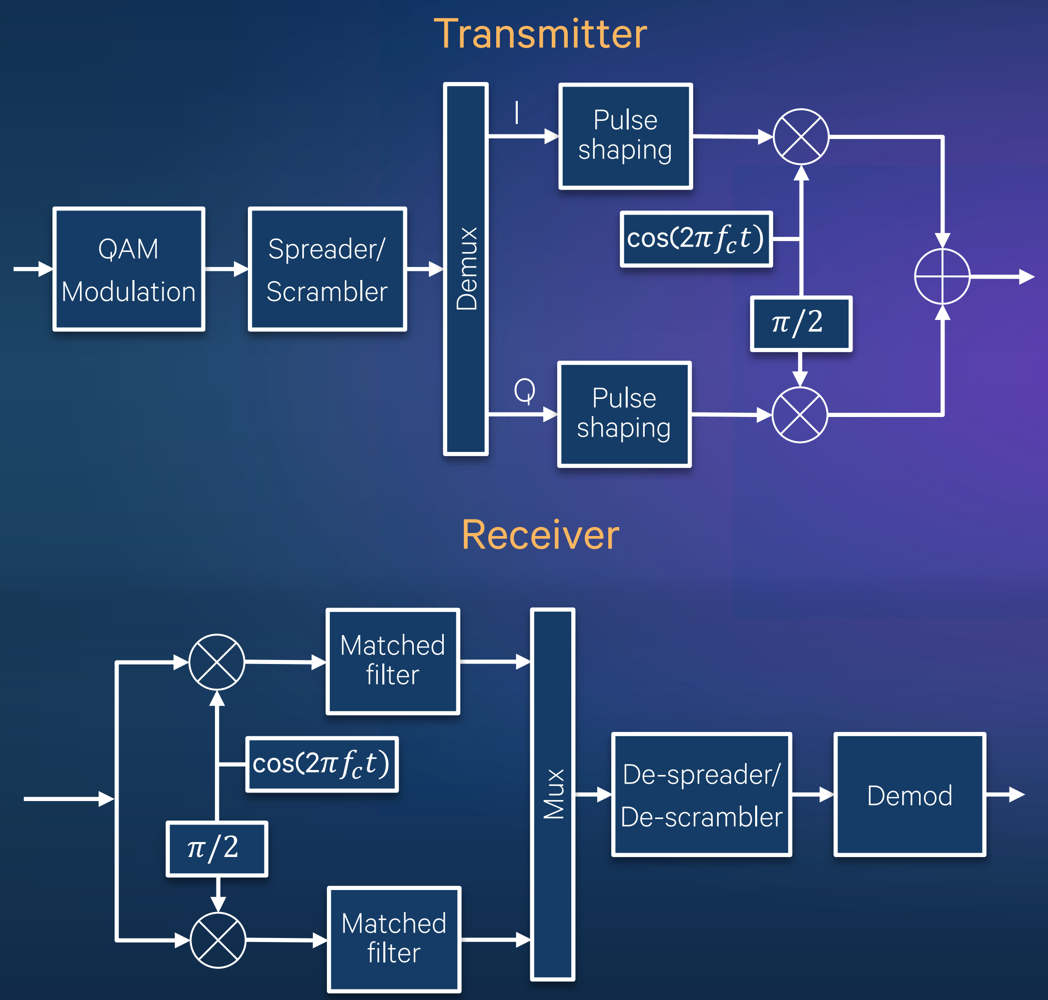
MSK Receiver



Key characteristics

- Pros:
  - Higher transmit efficiency:
    - Constant transmit carrier power: 0dB PAPR
    - Allow PA to run at saturation point
  - Good side lobe suppression (e.g. GMSK)
  - Allow asynchronous multiplexing
  - Reasonable receiver complexity
- Cons:
  - Lower spectral efficiency
- Example applications:
  - MSK (adopted by Zigbee and IEEE 802.15.4)
  - GMSK (adopted by GSM and Bluetooth LE)

Single carrier QAM

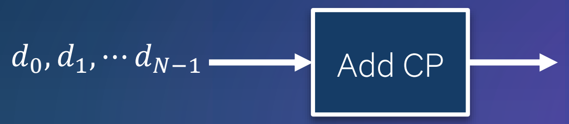


Key characteristics

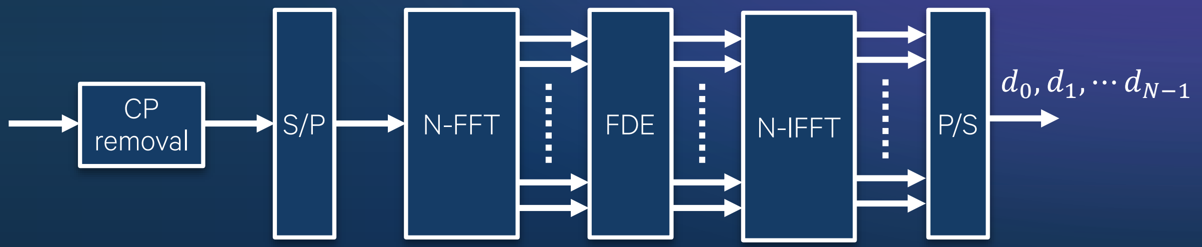
- Pros:
  - Lower PAPR at low spectral efficiency
  - Lower ACLR with the use of pulse shaping filter
  - Allow asynchronous multiplexing
  - Simple waveform synthesis
  - Higher spectral efficiency then constant envelope waveform using a single carrier
- Cons:
  - Limited flexibility in spectral assignment
  - Non-trivial support for MIMO
  - Equalization algorithm for improving spectral efficiency increases receiver complexity
- Example applications:
  - UMTS, CDMA2000, 1xEVDO

Single carrier frequency domain equalization (SC-FDE)

Transmitter



Receiver

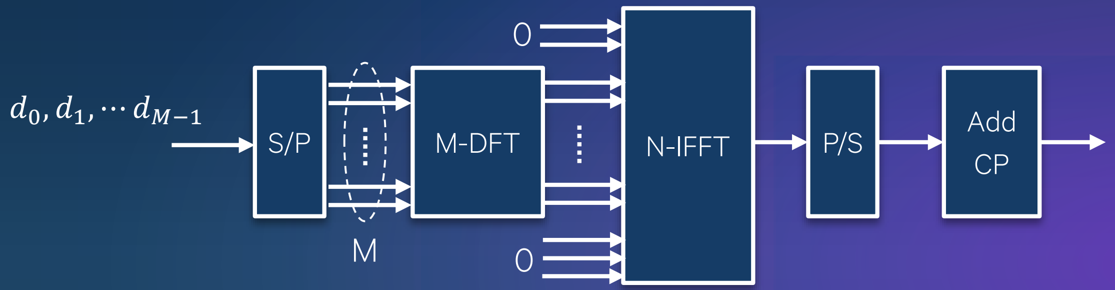


Key characteristics

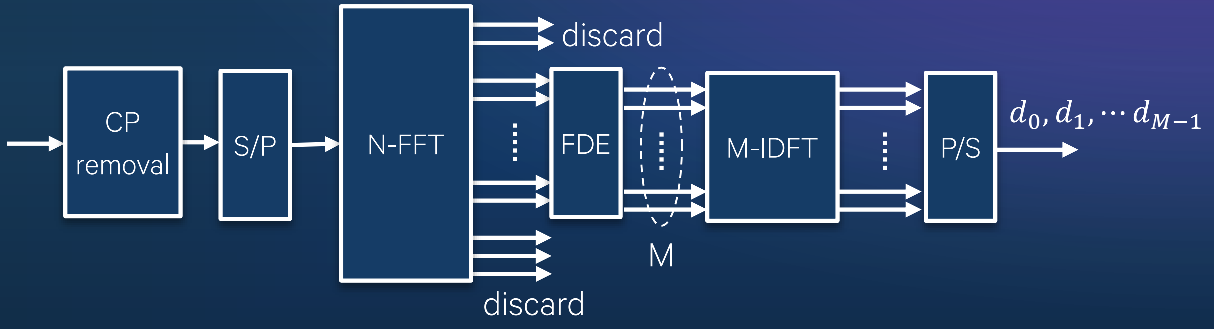
- Equivalent to SC-QAM with CP
- Pros:
  - Enable simple FDE implementation for single carrier waveform to Improve spectral efficiency under multipath fading
- Cons:
  - Slight spectral efficiency degradation due to the added Cyclic Prefix (CP)
  - Higher ACLR than SC-QAM

Single Carrier FDM

Transmitter



Receiver



Key characteristics

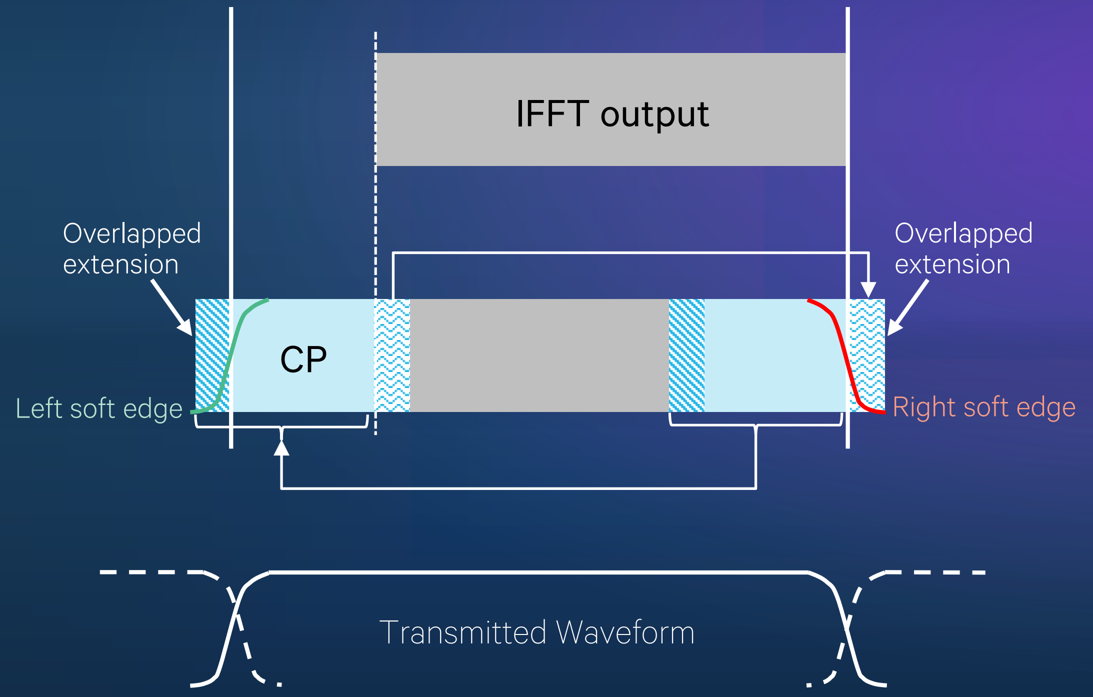
- Pros:
  - Support dynamic bandwidth allocation
    - Flexibility in allocating different bandwidth to multiple users through frequency multiplexing (referred to as SC-FDMA)
  - Mitigate multipath degradation with FDE
- Cons:
  - Higher PAPR than SC-QAM
  - Higher ACLR than SC-QAM
  - Need synchronous multiplexing
- Example applications:
  - LTE uplink

Weighted Overlap and Add (WOLA)

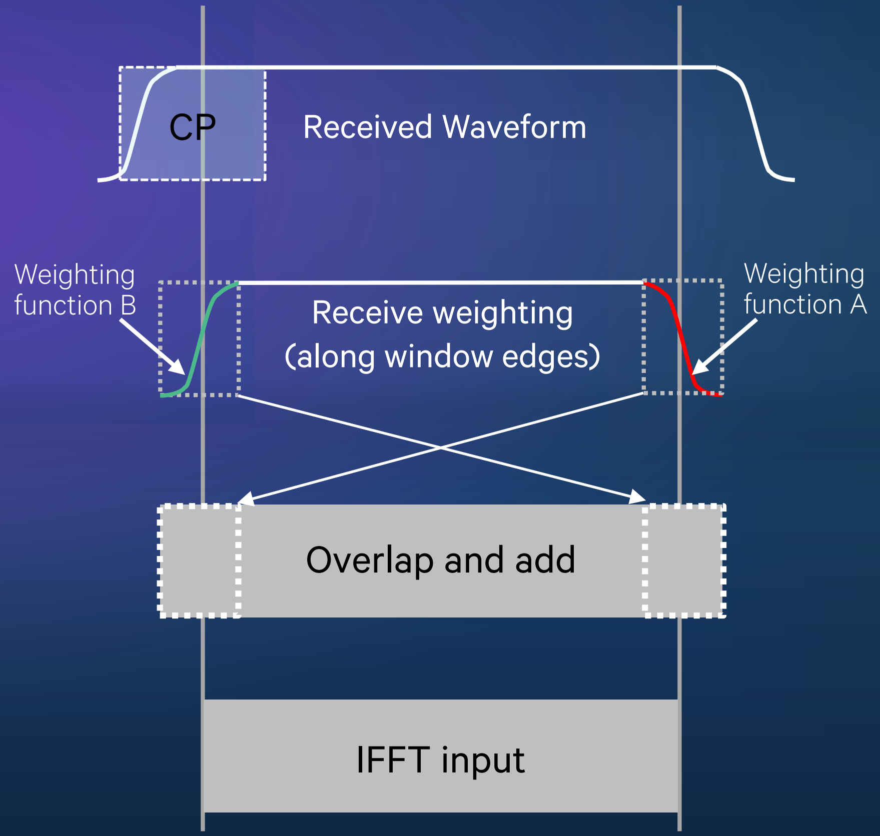
Significant improvement to out-of-band and in-band asynchronous user interference suppression

Practical implementations using time domain windowing

WOLA processing at Transmitter (Tx-WOLA)

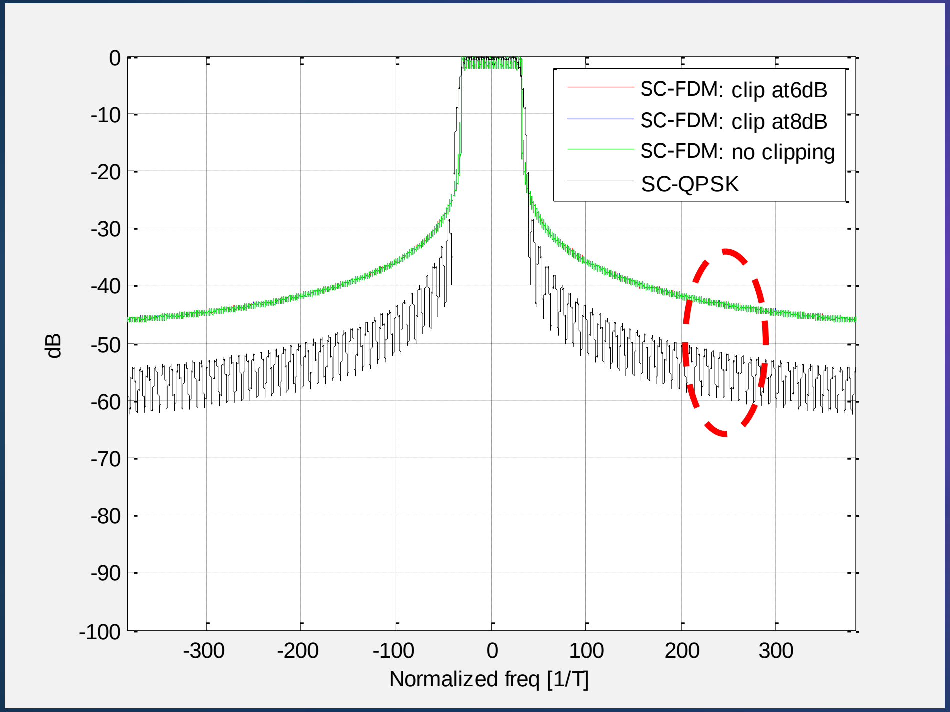


WOLA processing at Receiver (Rx-WOLA)



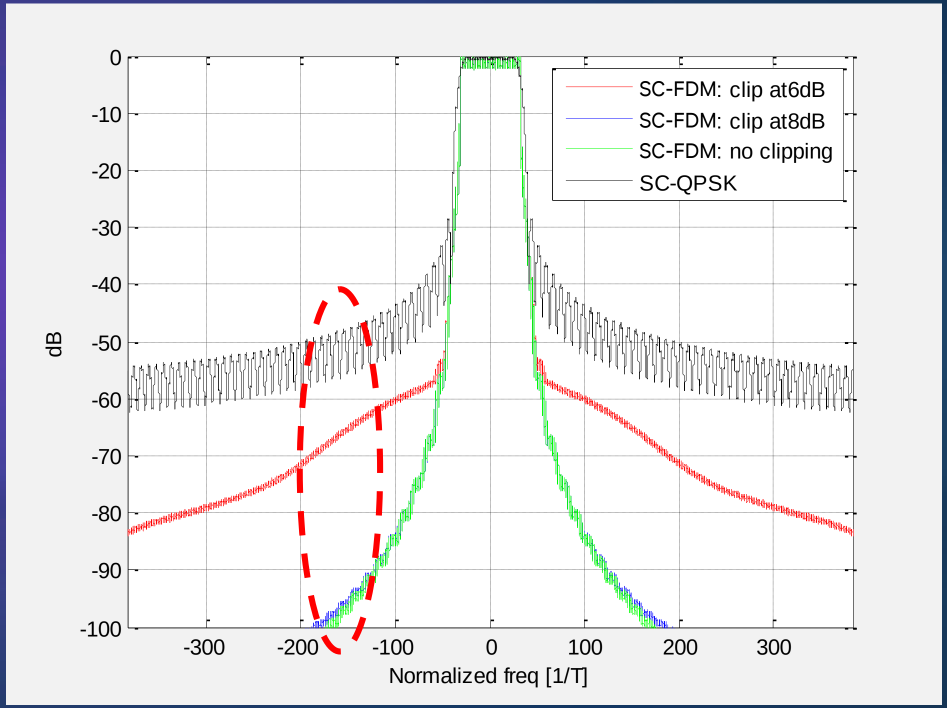
Improved OOB performance with WOLA

PSD of SC-FDM without WOLA



Higher OOB leakage than SC-QPSK due to discontinuities between OFDM transmission blocks

PSD of SC-FDM with WOLA

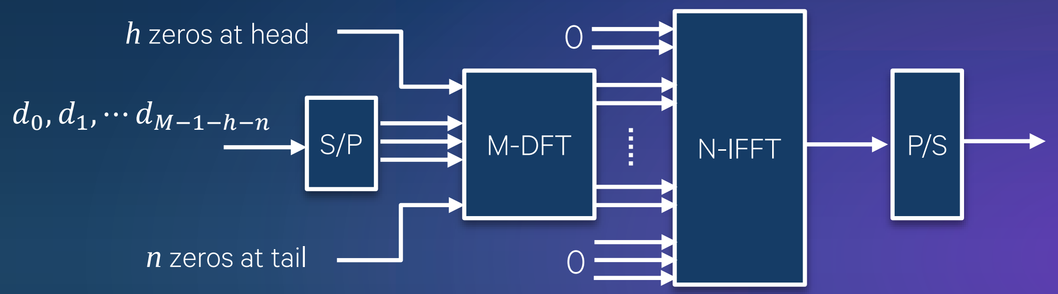


Significant improvement to OOB leakage performance using time-domain windowing (WOLA)

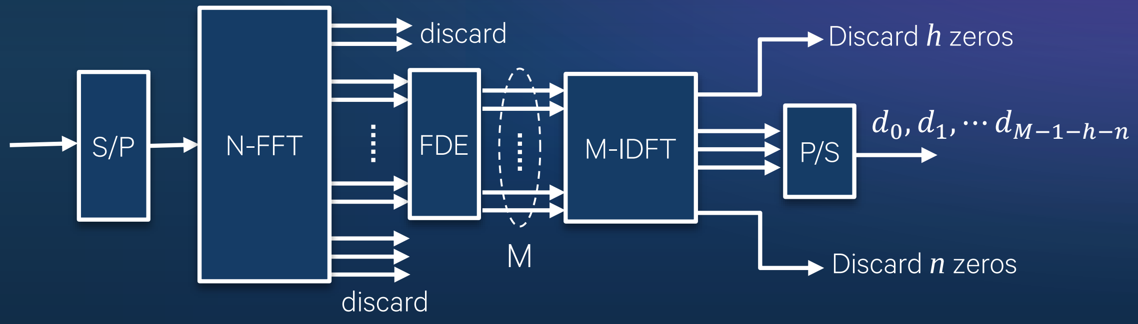
Assumptions: SC-FDM: 60 symbols per run, 1000 runs. CP length is set to be roughly 10% of the OFDM symbol length. For Tx-WOLA, raised-cosine edge with rolloff α≈0.64 is used.

Zero-Tail SC-FDM

Transmitter



Receiver

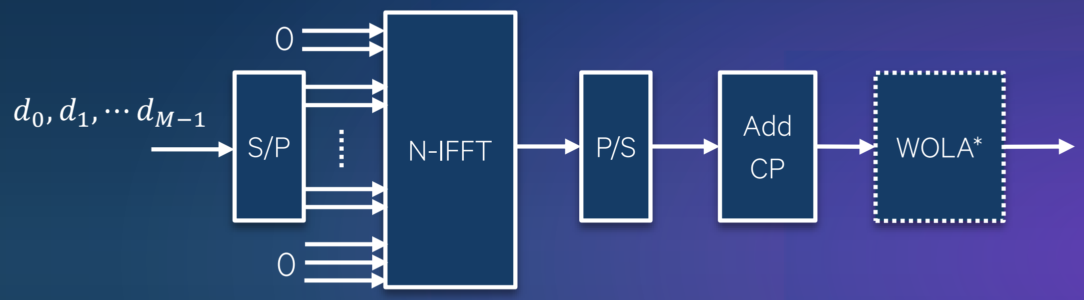


Key characteristics

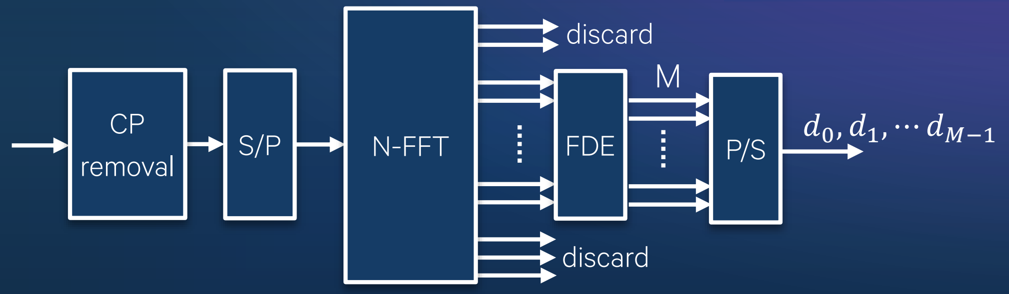
- Pros:
  - Flexible bandwidth assignment
  - No CP but support variable zero tail length, based on channel delay spread on a per-user basis
  - Improved spectral efficiency for some users – up to 7% due to removal of CP
  - Better OOB suppression than DFT-spread OFDM but worse than DFT-spread OFDM with WOLA
- Cons:
  - Need synchronous multiplexing
  - Extra signaling overhead to configure zero-tail
  - Lack of CP makes multiplexing with OFDM less flexible due to different symbol size

CP-OFDM waveform

Transmitter



Receiver



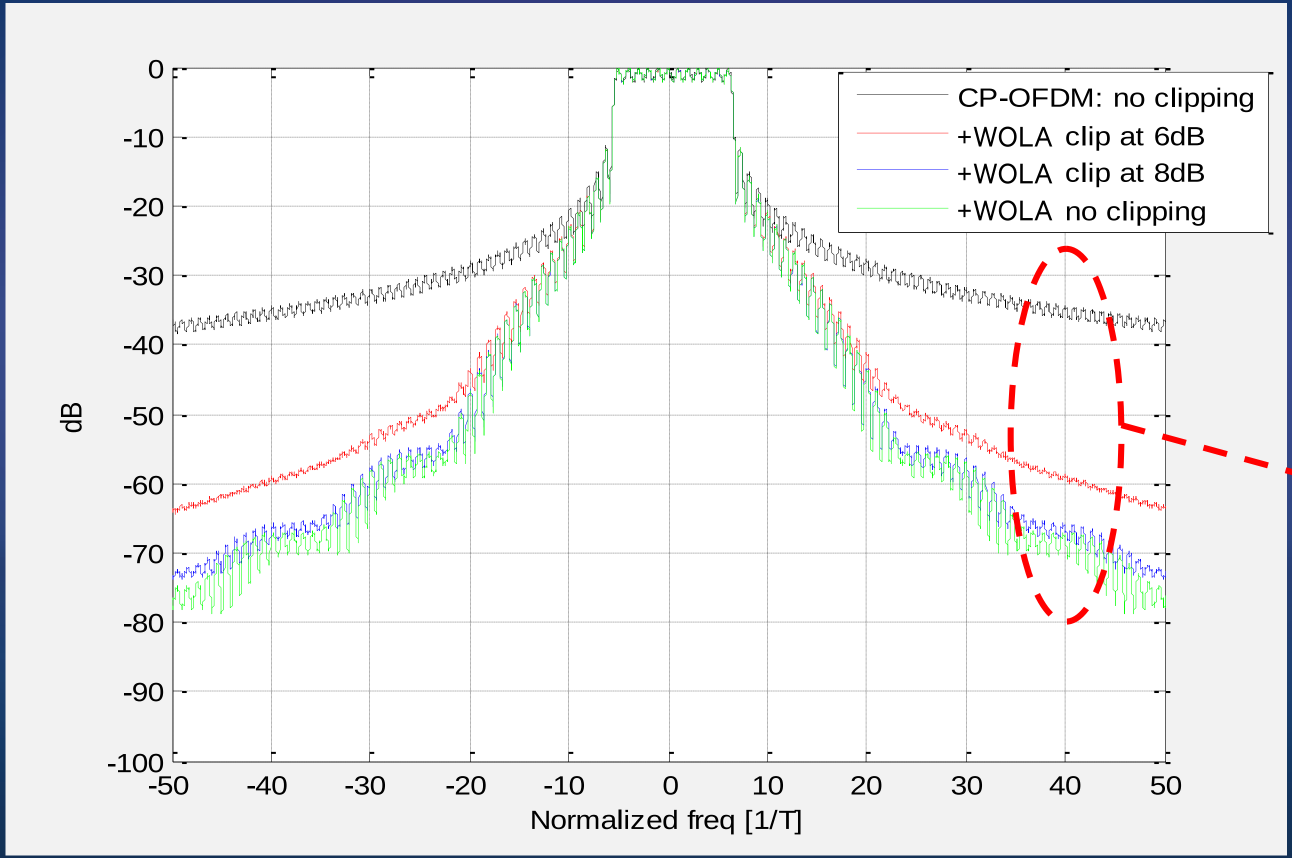
Key characteristics

- Pros:
  - Efficient implementation using FFT/IFFT
  - Flexible spectrum allocation to different users
  - Straight-forward application of MIMO technology:
    - Flexible signal and data multiplexing, e.g. placement of pilot across the frequency-time grid for channel estimation
  - Simple FDE for multipath interference mitigation
- Cons:
  - Poor frequency localization due to the rectangular prototype filter (without WOLA)
    - Can be significantly improved using WOLA
- Example applications:
  - CP-OFDM with WOLA is used in LTE downlink

* WOLA is not in LTE spec. but existing implementations typically include WOLA to meet performance requirements

WOLA substantially improves OOB performance

PSD of CP-OFDM with WOLA at the transmitter

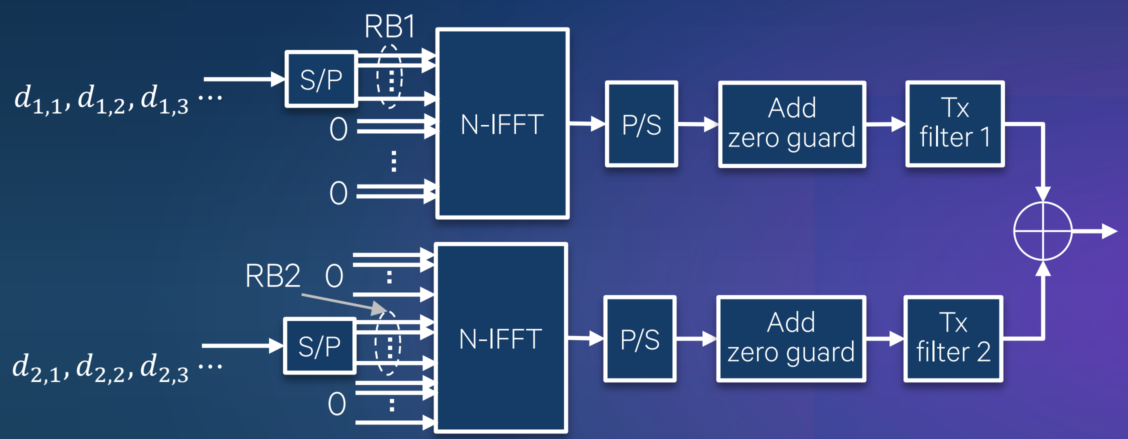


WOLA substantially improves CP-OFDM OOB leakage performance

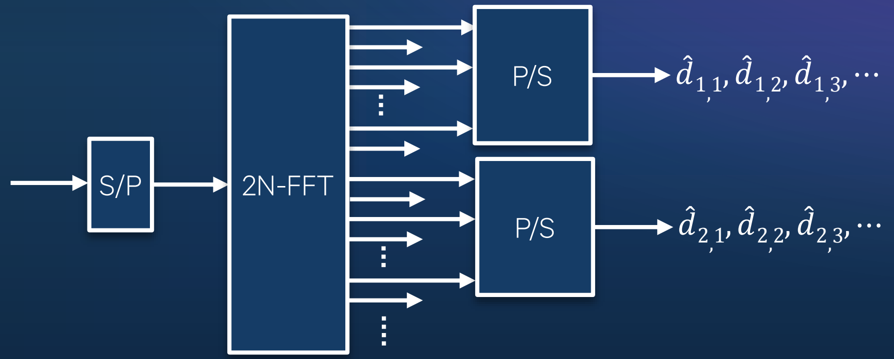
Assumptions: 12 contiguous data tones, 60 symbols per run, 1000 runs. CP length is set to be roughly 10% of the OFDM symbol length. For Tx-WOLA, raised-cosine edge with rolloff α≈0.8 is used.

Universal-Filtered Multi-Carrier (UFMC)

Transmitter



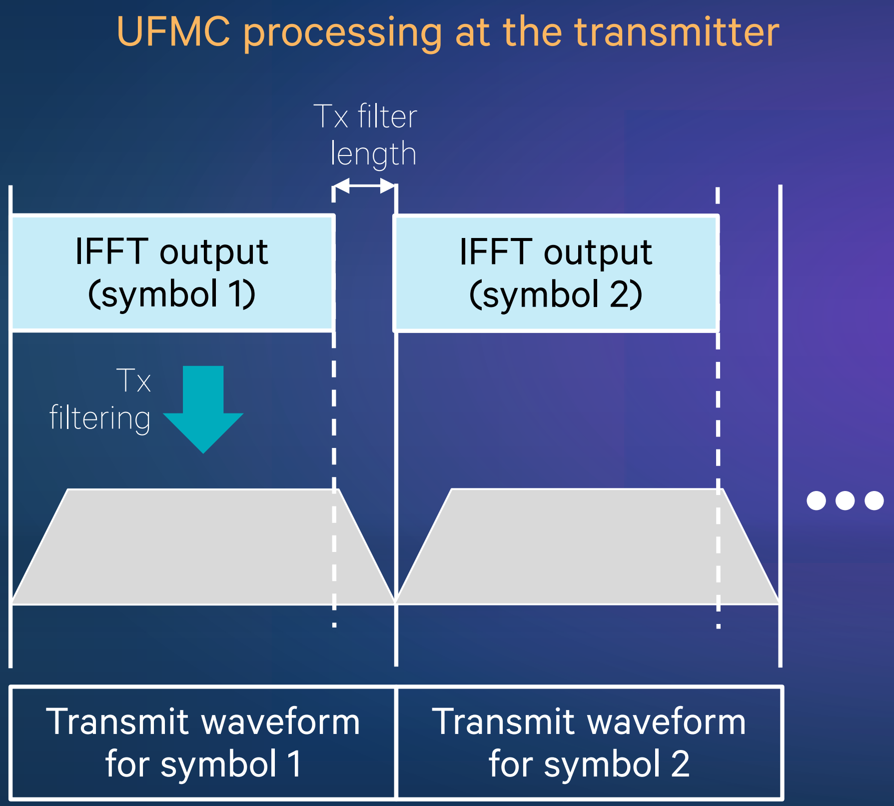
Receiver

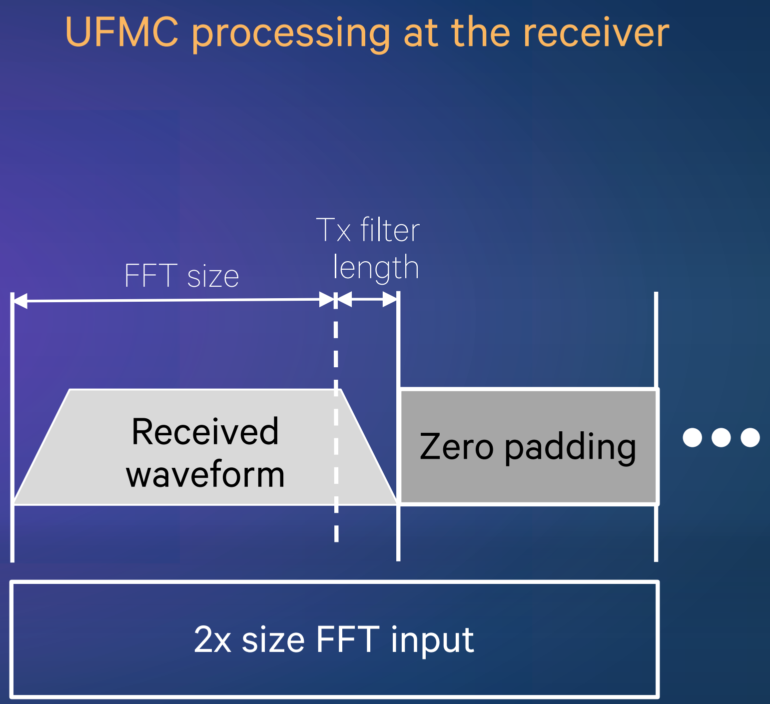


Key characteristics

- Use band-pass Tx filter to suppress OOB leakage:
  - Each Resource Block (RB) has a corresponding Tx filter, which is designed to only passes the assigned RB
  - A guard interval of zeros is added between successive IFFT symbols to prevent ISI due to Tx filter delay
- Pros:
  - Similar OOB performance as CP-OFDM with WOLA
  - Can be used to multiplex user with different numerologies (similar to CP-OFDM with WOLA)
- Cons:
  - More complex transmitter/receiver design
  - Subject to ISI due to the lack of CP

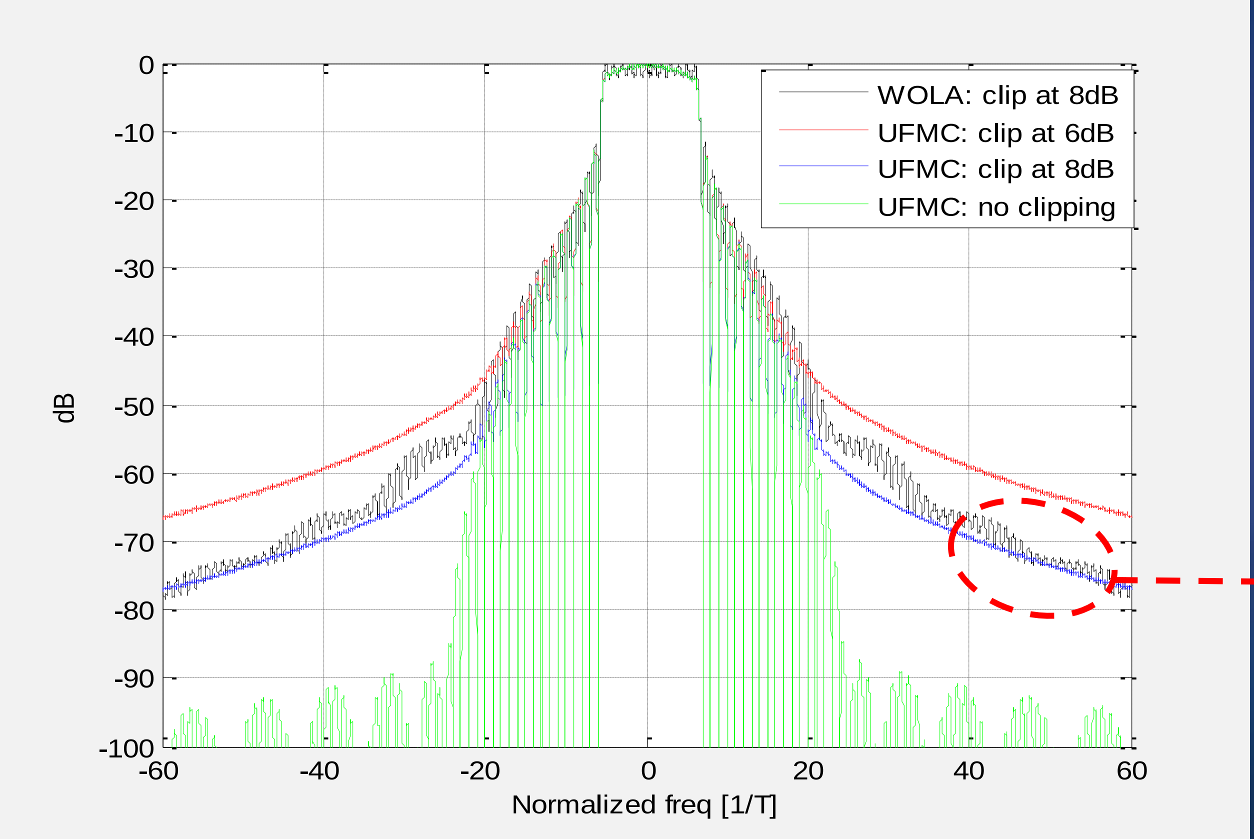
Additional details on UFMC transmitter/receiver processing





UFMC has comparable OOB performance as CP-OFDM+WOLA

PSD of UFMC at the transmitter



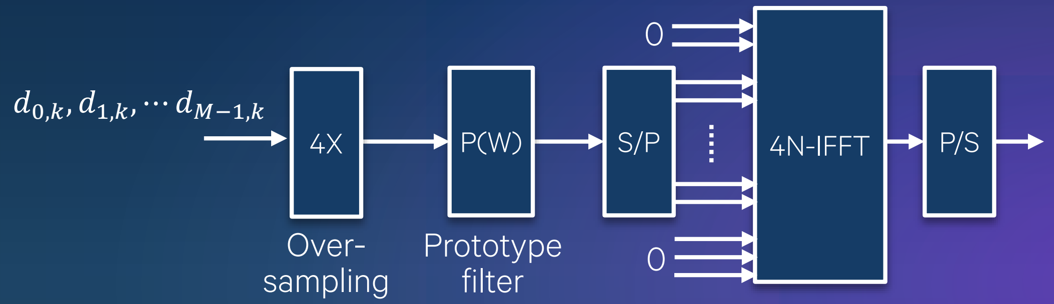
Comparable OOB leakage performance as CP-OFDM+WOLA

Note: WOLA refers to CP-OFDM with WOLA

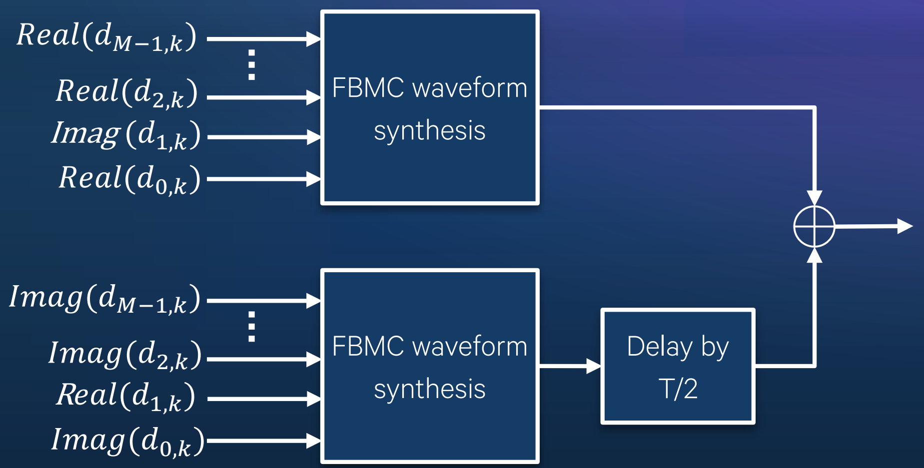
Assumptions: 12 contiguous data tones, 60 symbols per run, 1000 runs. Chebyshev filter is used for the tx filter. FFT and RB sizes are set to be 1024 and 12 respectively. Chebyshev filter has 102 taps, which corresponds to 10% CP, and has 60 dB of relative side-lobe attenuation

Filter bank multi-carrier (FBMC)

FBMC waveform synthesis



FBMC/OQAM Transmitter



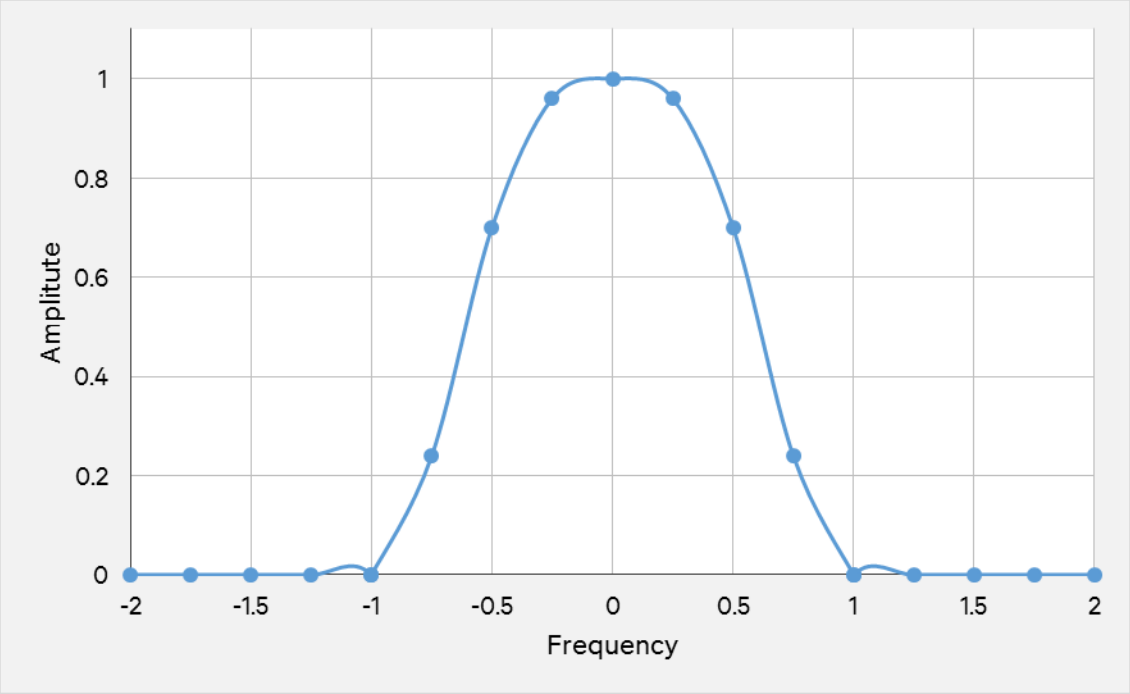
Key characteristics

- Improve spectral property using prototype filter with frequency domain over-sampling:
  - Prototype filter spans multiple symbol periods, T
  - Adjacent symbols are overlapped & added in time with offset T to maintain spectral efficiency
  - Overlap-and-add leads to potential ISI and ICI:
    - Use half-Nyquist prototype filter to mitigate ISI
    - Use “Offset-QAM” (OQAM) modulation to remove ICI
- Pros:
  - Superior side-lobe decay than other MC waveforms but the benefit reduces with PA non-linearity
- Cons:
  - Complicated receiver design due to OQAM
  - Subject to ISI under non-flat channel
  - More complex MIMO integration than OFDM

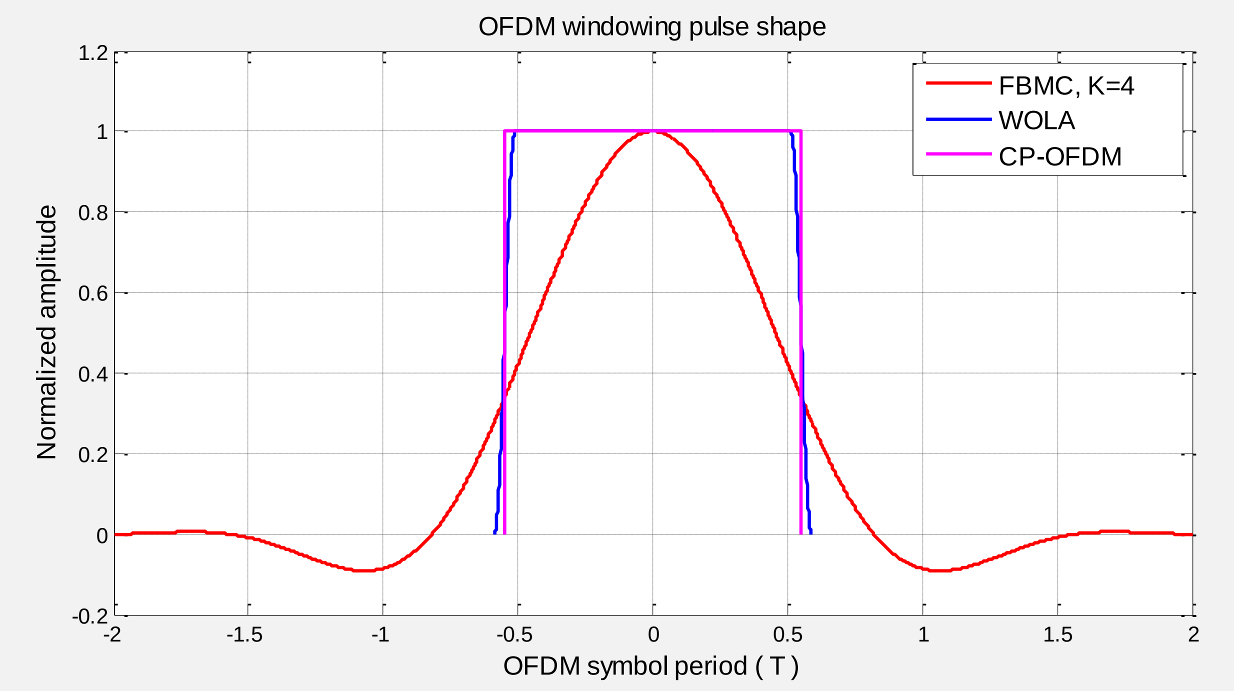
FBMC prototype filter

Improve spectral property using prototype filter with frequency domain over-sampling

Frequency-domain response with oversampling factor *K*=4
(frequency between samples: 1/4T)



Time-domain response
(spanning multiple symbol periods *T*)



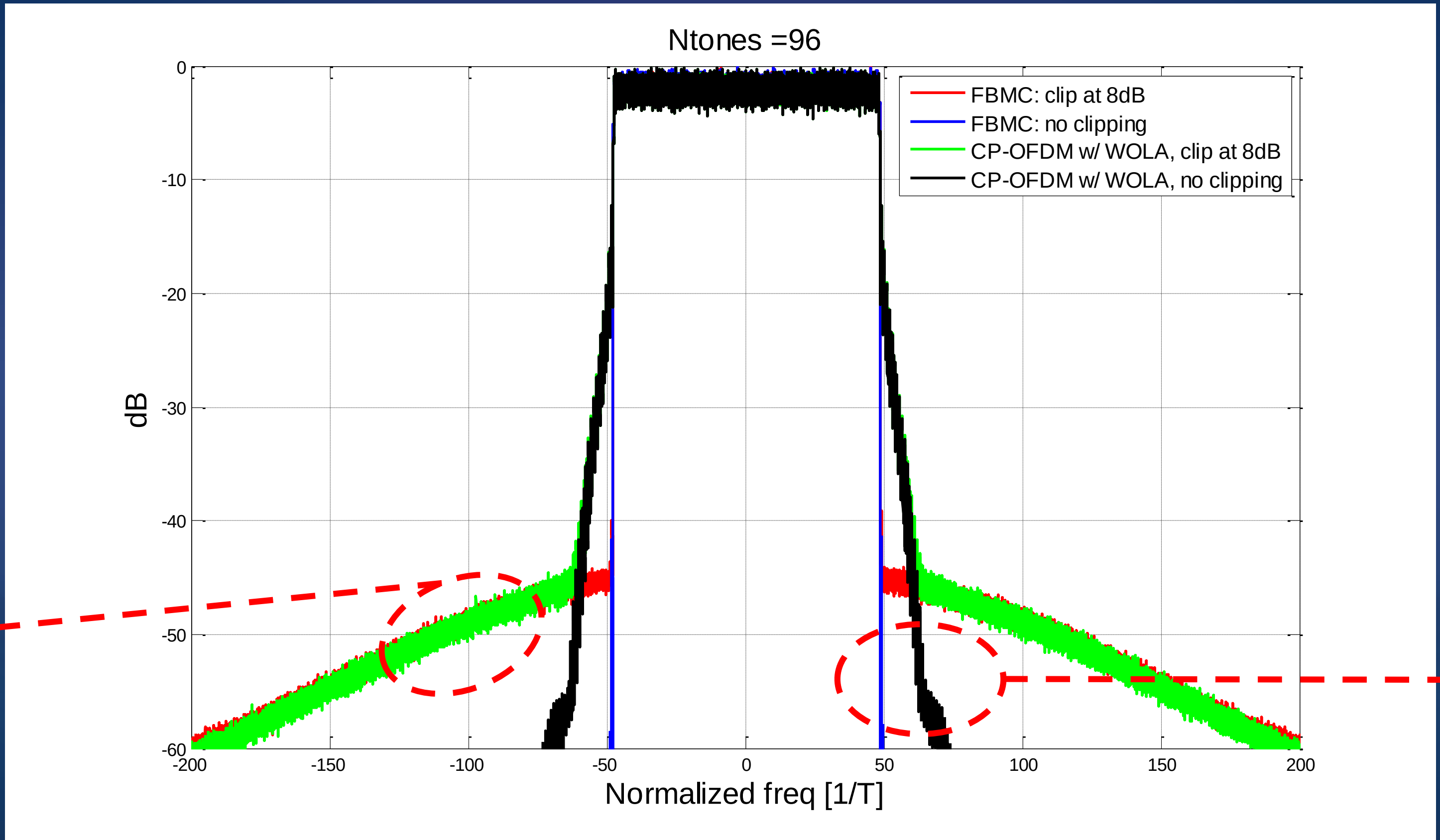
Increased block processing latency can remove the benefits of asynchronous transmission

Note: WOLA refers to CP-OFDM with WOLA

FBMC's OOB performance degrades with PA non-linearity

PSD of FBMC at the transmitter

OOB leakage suppression performance reduces with PA clipping

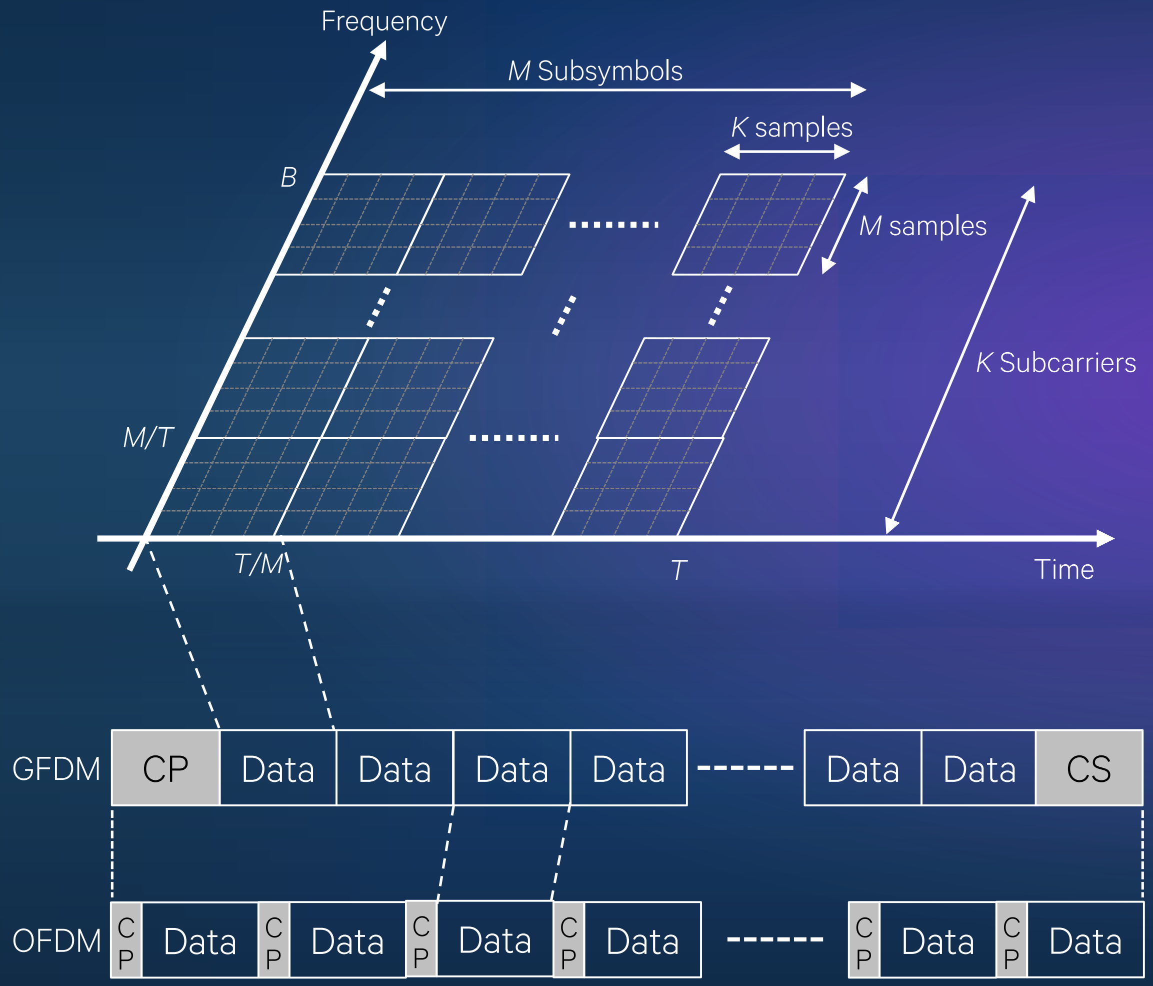


FBMC side-lobe decays faster than CP-OFDM+WOLA with no PA clipping

Downlink transmissions are synchronized and additional improvement in OOB emission performance at the expense of added implementation complexity and less-efficient MIMO support is not preferred

Assumptions: FBMC has 24 tones, 60 symbols per run, 1000 runs. For a fair comparison to other multi-carrier waveforms, the overall FBMC symbol duration is normalized to T, which is the same as the CP-OFDM symbol duration.

Generalized frequency division multiplexing (GFDM)

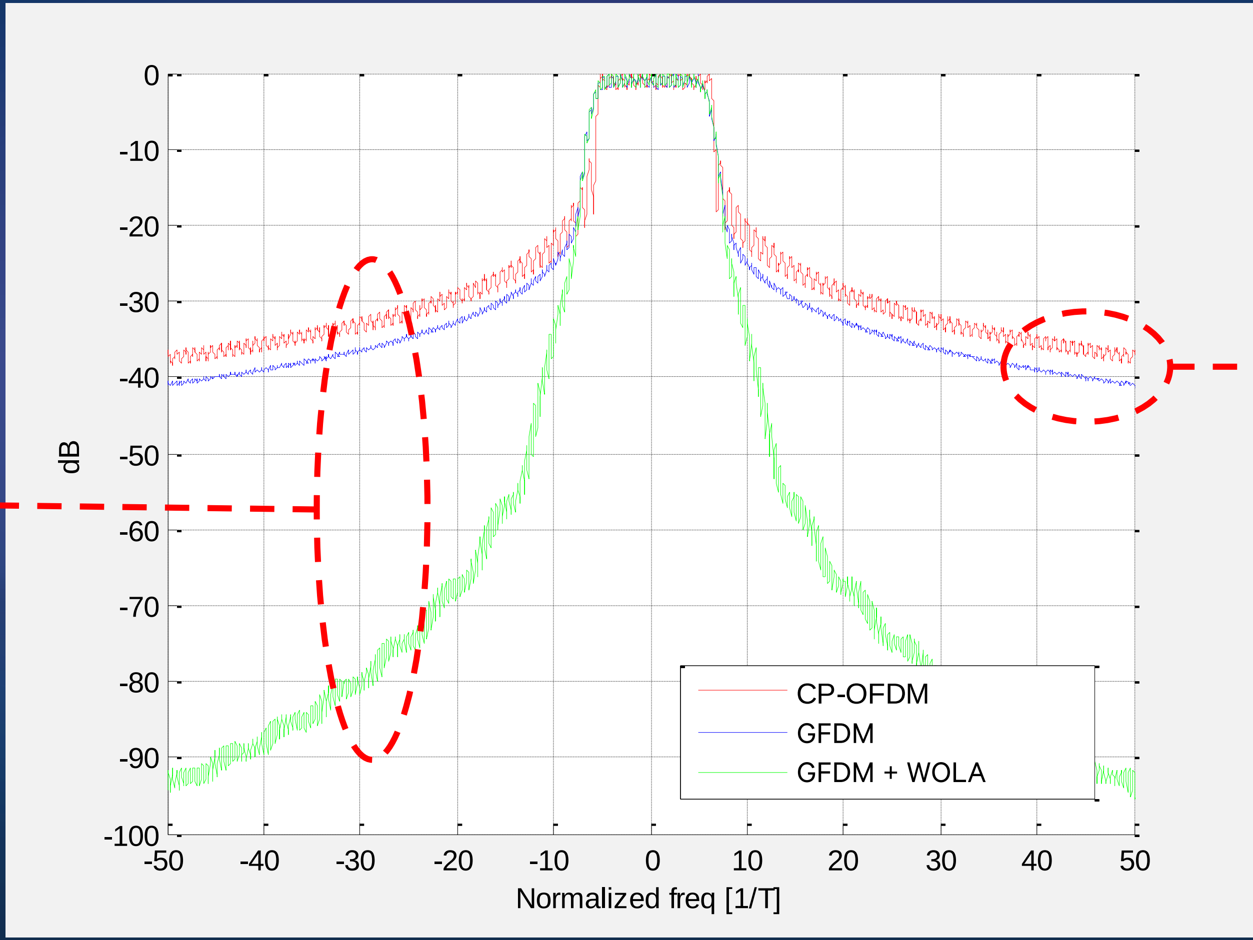


Key characteristics

- Similar to FBMC where prototype filter is used to suppress OOB leakage. However, for GFDM:
  - Multiple OFDM symbols are grouped into a block, with a CP added to the block
  - Within a block, the prototype filter is "cyclic-shift" in time, for different OFDM symbols
- Pros:
  - Better OOB leakage suppression than CP-OFDM (same as CP-OFDM with WOLA)
- Cons:
  - Complicated receiver to handle ISI/ICI
    - Prototype filter may require more complicated modulation/receiver, e.g. OQAM as in FBMC
  - Higher block processing latency (no pipelining)
  - Multiplexing with CP-OFDM requires large guard band

GFMD has comparable OOB performance as CP-OFDM

PSD of GFMD at the transmitter

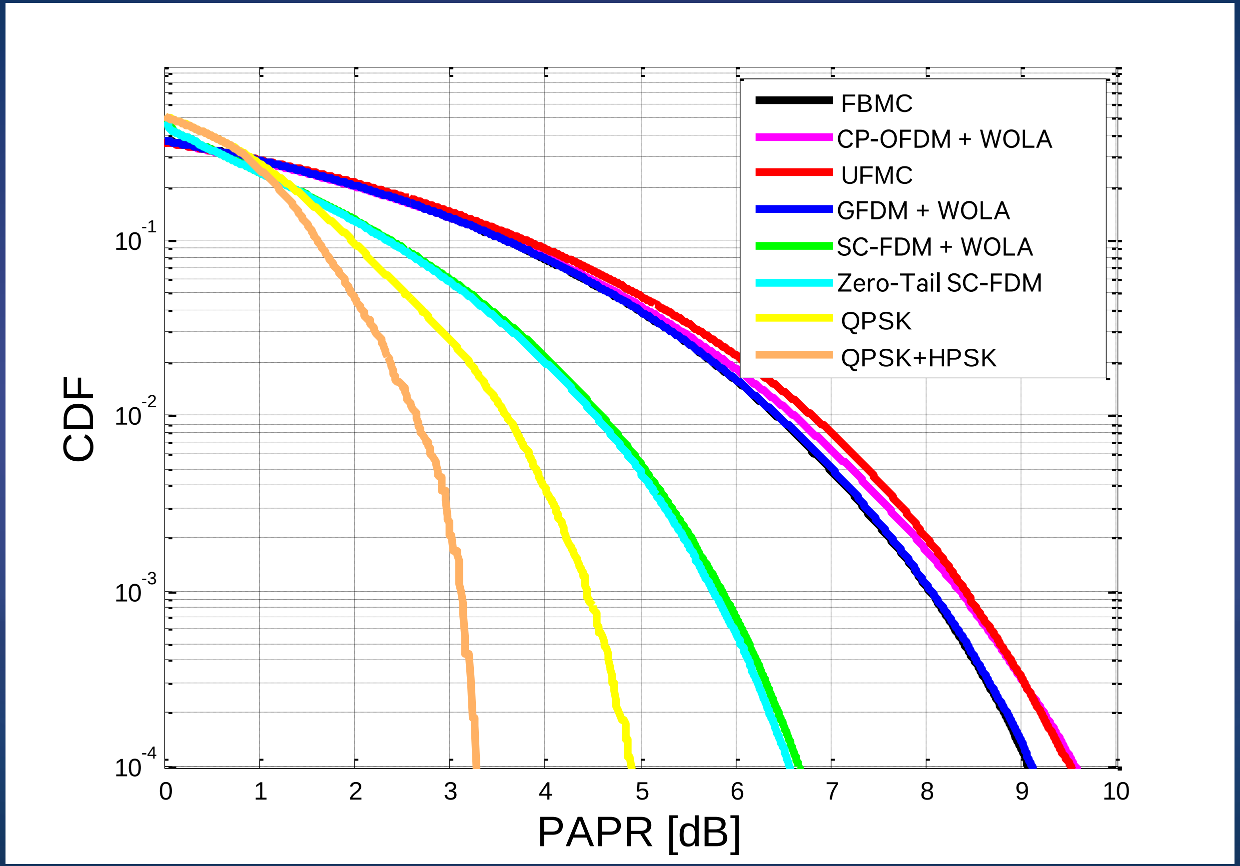


Time-domain windowing (like WOLA) significantly reduces OOB leakage

Comparable OOB leakage performance as legacy CP-OFDM

Assumptions: 3 tones, 9 sub-symbols, 6 symbols per run, 1000runs. CP length is set to be roughly 10% of the OFDM symbol length. For Tx-WOLA, raised-cosine edge with rolloff α≈0.8 is used.

Single-carrier waveform has comparatively lower PAPR

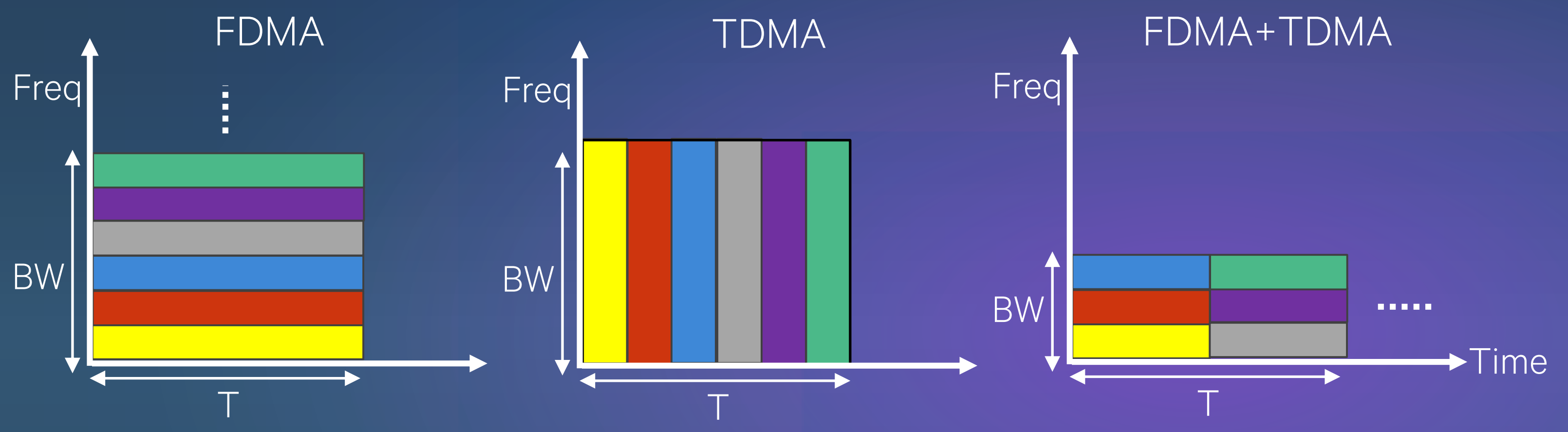


OFDM-based multi-carrier waveform delivers higher spectral efficiency and is suitable for downlink where energy efficiency requirement is more relaxed. Single carrier waveform can be used for other scenarios requiring high energy efficiency.

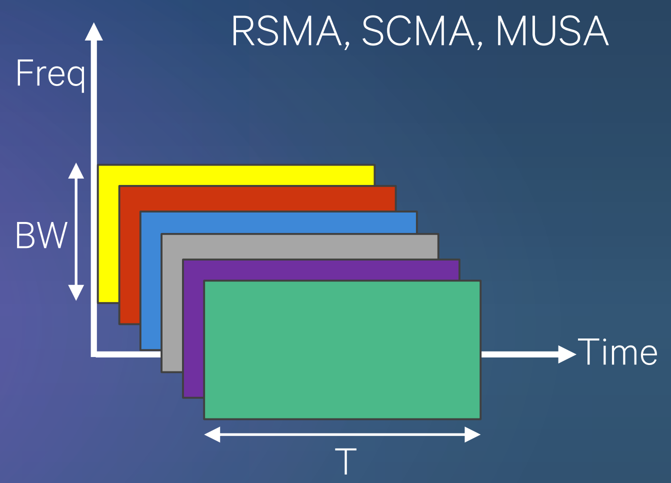
Additional information on multiple access techniques

Potential multiple access schemes

Orthogonal multiple access



Non-orthogonal multiple access



Example comparison of orthogonal and non-orthogonal multiple access techniques*

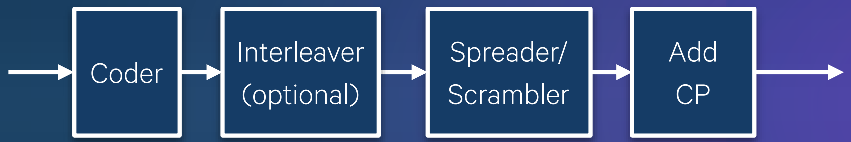
Multiple access techniques:	Non-orthogonal	FDMA	FDMA+TDMA (1RB/user)
Effective Rate (kbps)	50	50	100
EbNo** (dB)	-1.52	-0.73	-0.73
Link budget (dB)	146.1	145.3	142.3

* Assumptions: 12 users, 500 bits/10ms over 1 MHz bandwidth, 2Rx, an RB = 180kHz. **Derived using Shannon formula.

Resource Spread Multiple Access (RSMA)

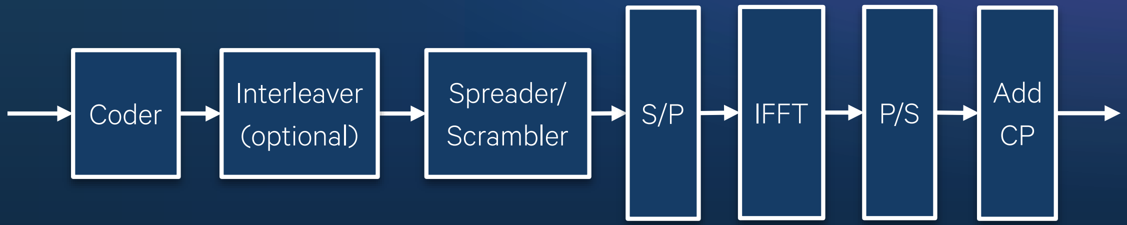
Single carrier RSMA

Deliver better PA efficiency and has no synchronization requirement



Multi-carrier RSMA

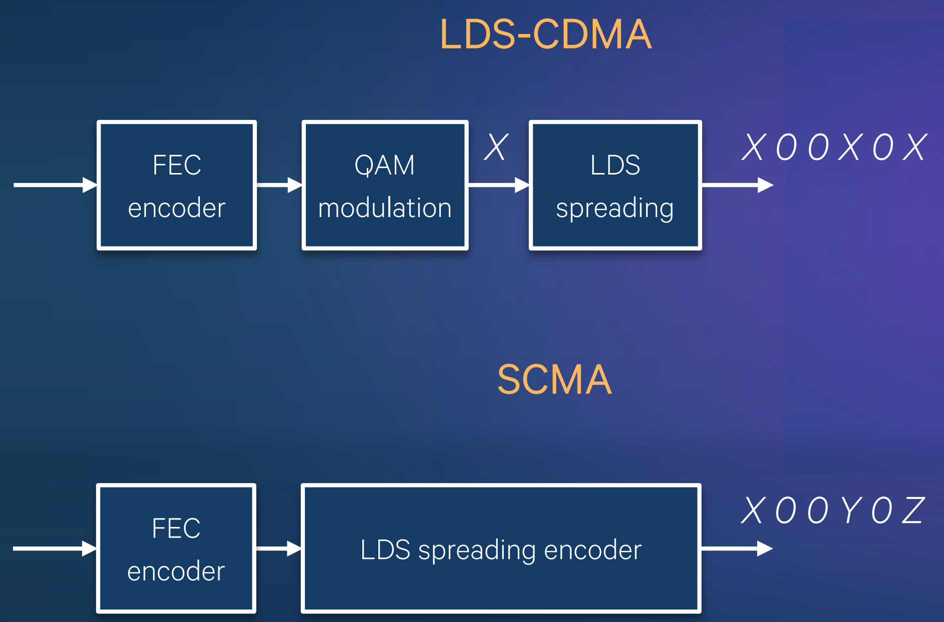
Exploit wider bandwidth to achieve lower latency for less power-constrained applications



Key characteristics

- Spread user signal across time and/or frequency resources:
  - Use lower rate channel coding to spread signal across time/frequency to achieve lower spectral efficiency
  - Users' signals can be recovered simultaneously even in the presence of mutual interference
- RSMA is more robust:
  - Coding gain provides EbNo efficiency compared with orthogonal spreading or simple repetition
  - More powerful codes can be employed than simple repetition combined with low rate convolution codes

Sparse code multiple access (SCMA)



Key characteristics

- SCMA is based on Low Density Signature (LDS) CDMA
  - Lower-density spreading
  - Only partially uses the available time/frequency resources
- But unlike LDS-CDMA, SCMA uses multi-dimensional constellations:
  - Each user has a unique codebook which maps each of M codewords to a length N constellation
  - The length N constellation is extended to length L by inserting L-N zeros.
- Requires iterative multiuser joint detection

Appendix

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List of Abbreviations

Abbreviation	Definition
ACLR	Adjacent Channel Leakage Ratio
CDMA	Code Division Multiple Access
CP	Cyclic prefix
CP-OFDM	OFDM with Cyclic Prefix
D2D	Device-to-Device Communication
DFT	Discrete Fourier Transform
DL	Downlink
eMBB	Enhanced Mobile Broadband
EVDO	Evolution-Data Optimized
FBMC	Filter Bank Multi-Carrier
FDE	Frequency Domain Equalization
FDM	Frequency Division Multiplexing
FDMA	Frequency Division Multiple Access
FEC	Forward Error Correction
FFT	Fast Fourier Transform
GFDM	Generalized Frequency Division Multiplexing
GMSK	Gaussian Minimum Shift Keying
GSM	Global System for Mobile Communications
HARQ	Hybrid Automatic Repeat Request
IAB	Integrated Access and Backhaul
IFFT	Inverse Fast Fourier Transform
IoT	Internet of Things
LE	Low Energy
ICI	Inter Carrier Interference
ISI	Inter Symbol Interference
LDS-CDMA	Low Density Signature CDMA
LTE	Long Term Evolution
MAC	Multiple Access Control Layer
MC	Multi-Carrier
MIMO	Multiple-Input Multiple-Output

Abbreviation	Definition
mmWave	Millimeter Wave
MSK	Minimum Shift Keying
MUSA	Multi-User Shared Access
MU-MIMO	Multiuser MIMO
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
OOB	Out of Band Emissions
OQAM	Offset-QAM
PA	Power Amplifier
PAPR	Peak-to-Average Power Ratio
PHY	Physical Layer
P/S	Parallel-to-Serial
PSD	Power Spectral Density
QAM	Quadrature Amplitude Modulation
RB	Radio Block
RSMA	Resource Spread Multiple Access
RX	Receiver
SC-DFT-Spread OFDM	Single Carrier Discrete Fourier Transform Spread OFDM
SC-FDE	Single Carrier Frequency Domain Equalization
SC-FDM	Single Carrier Frequency Division Multiplexing
SCMA	Sparse Code Multiple Access
S/P	Serial-to-Parallel
SRS	Sounding Reference Signal
TDD	Time Division Duplexing
TDMA	Time Division Multiple Access
TX	Transmitter
UFMC	Universal Filter Multi-Carrier
UL	Uplink
UMTS	Universal Mobile Telecommunications System
WOLA	Weighted Overlap and Add filtering
ZT-SC-DFT-Spread OFDM	Zero-Tail Single Carrier DFT Spread OFDM

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