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5G
The 1st 5G Algorithm
Innovation Competition
F-OFDM
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1st 5G Algorithm Innovation Competition-F-OFDM

Task	Description	Requirements
F-OFDM – Foundational waveform design of 5th generation wireless communications	Waveform modulation is the most foundational physical layer technologies of wireless communication. CP-OFDM has been widely adopted in 4G LTE, Wifi and other wireless communication systems, due to the advantages of high efficiency, simple for implementation and easy to combine with MIMO technology, etc. However, the traditional CP-OFDM system also has some weaknesses, such as out-of-band power leakage, rigorous requirement of synchronization and the entire bandwidth can be only configured with same waveform parameters, i.e., the subcarrier spacing, CP length and TTI length. Compared to 4G, 5G supports more diverse traffic scenarios. Considering the huge difference of different traffics (e.g., the traffic of vehicle to vehicle and the traffic of low cost machine), it is better to dynamically configure waveform parameters based on traffic scenarios, while still retain the benefits of the traditional CP-OFDM. Filtered-OFDM, by applying subband filtering on traditional CP-OFDM, can meet the needs of waveform for 5G. The system bandwidth is divided into sub-bands and filtered independently, then each sub-band can be configured with different waveform parameters set according to the actual traffic scenario. Through the filter configuration, each subband would achieve its own configuration, and the combined 5G waveforms would supports dynamic soft parameters configuration for air-interface according the traffic types. According to the above description of the basic principles of F-OFDM, design the basic F-OFDM downlink communication system, and verify the system performance.	**Requirements:** According to the description in the training materials about F-OFDM, design/implement/verify the simplified F-OFDM downlink multi-user communication system, focusing on how to develop the sub-band filter, and investigate/validate the performance of F-OFDM. **Works format:** 1. Complete the simplified F-OFDM downlink multi-user link design documents, especially the sub-band filter design. 2. Complete simplified F-OFDM downlink multi-user link Matlab simulation, and gives Out-Of-Band Emission (OOBE) performance, as well as receiver BLER (or PER) vs Eb / No waterfall curve. 3. Complete the simplified F-OFDM downlink multi-user link implementation on FPGA, test its performance (OOBE performance and a receiver waterfall curve (contrast with OFDM)) and provide processing latency and FPGA resource usage. **Delivery Material:** 1. F-OFDM downlink multi-user link design documentation, code and simulation results; 2. FPGA design specifications, code, and test results and test file. **Selection criteria in the First Round** 1. Finish the system design documents of the simplified F-OFDM downlink multi-user communication link, and properly understand F-OFDM systems. 2. Provide Matlab simulation results of OOBE performance, and BLER (or PER) vs Eb/No curves, the required performance gap between F-OFDM and OFDM should be less than 0.3dB at the point of 10% BLER. 3. Provide the architecture design and implementation method of F-OFDM system based on the provided FPGA platform . **Selection criteria in the Second Round** 1. Complete the FPGA logic design of F-OFDM downlink multi-user link. Correct decoding rate should be more than 90%. 2. The performance gap between FPGA system test performance curve (F-OFDM and OFDM) and the simulation curve should be less than 0.5dB. 3. Provide FPGA implemented algorithm design, data throughput, processing delays and FPGA chip resource use.

Reference to Read

OFDM Fundamental :

- R. Nee and R. Prasad, “OFDM for Wireless Multimedia Communications”. Artech House, Inc., 2000.
- A. Bahai, B. R. Saltzberg, and M. Ergen, “Multi-Carrier Digital Communications: Theory and Applications of OFDM”. Springer Science & Business Media, 2004.
- 3GPP, “Overview of 3GPP release 8 v0.3.3,” Tech. Rep., Sep. 2014.

Filter Design and Fast Filtering Implementation

- A. Antoniou, “Digital Filters: Analysis, Design, and Applications”, New York, NY: McGraw-Hill, 1993.
- Douglas L. Jones, "Fast Convolution", available online: https://inst.eecs.berkeley.edu/~ee123/sp15/docs/FastConv.pdf

Algorithm Design of F-OFDM

- “F-OFDM algorithm design”，attached in this document

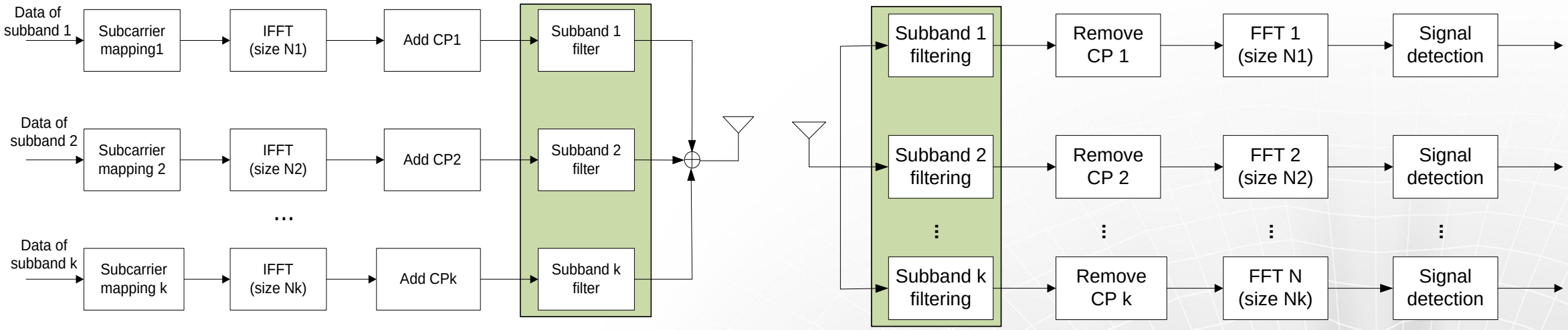
Outline

- What is F-OFDM?
- Why we need F-OFDM in 5G?
- How does F-OFDM work?
- What will you implement?

To have a gut feeling what is filtered OFDM

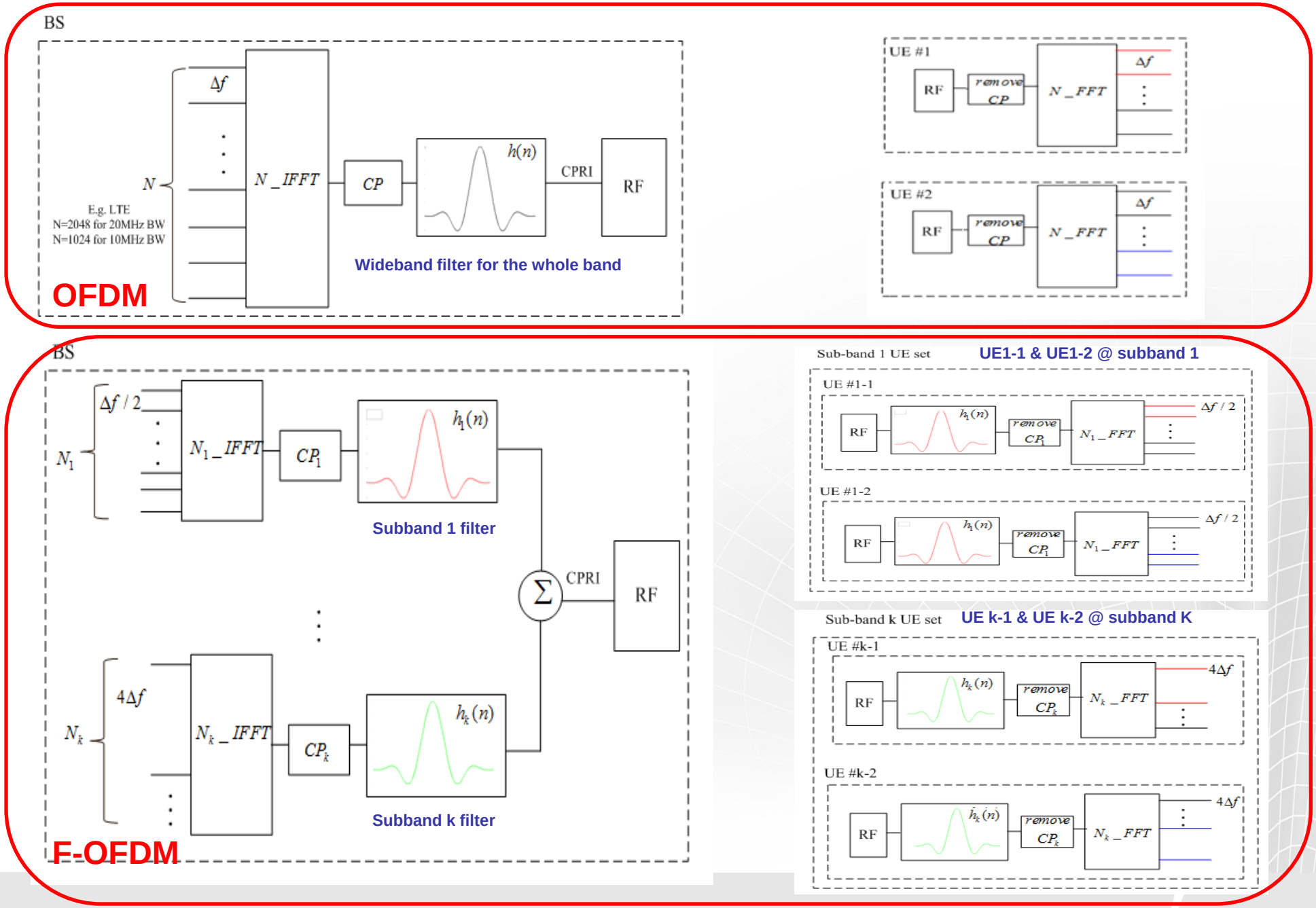
WHAT IS F-OFDM?

F-OFDM System Diagram



Key message

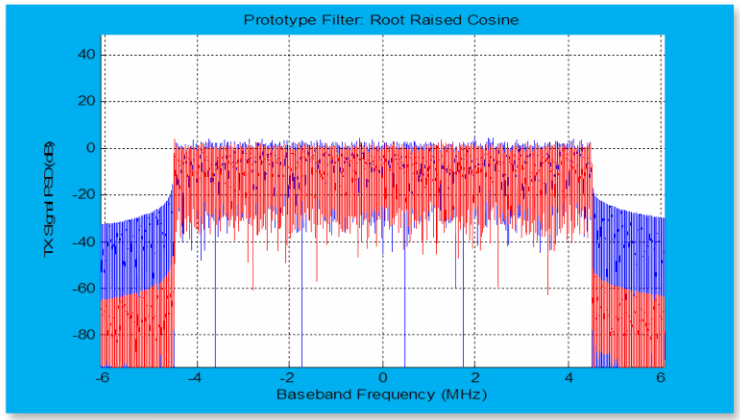
1. **Subband filter is added on top of CP-OFDM, without any change on existing CP-OFDM**
2. **Filtering for each subband (subband BW >= 1RB)**
3. **Independent Subcarrier spacing/ CP length/ TTI configuration for each subband**
4. **Rather low guard tone overhead between neighboring subband**
5. **Support asynchronous inter-band transmission due to perfect OOB performance**

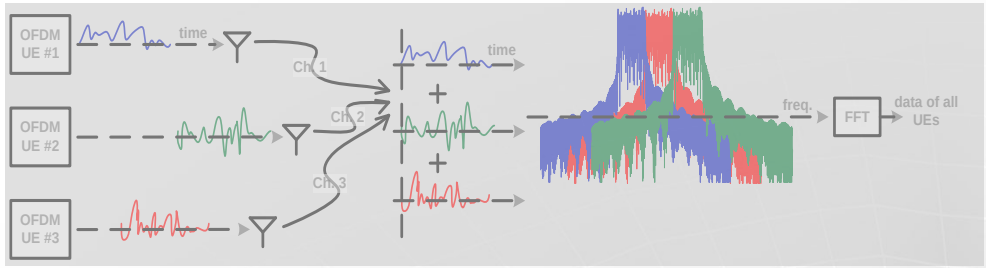

BS
Δf
N
N _IFFT
CP
h(n)
CPRI
RF
E.g. LTE
N=2048 for 20MHz BW
N=1024 for 10MHz BW
Wideband filter for the whole band
OFDM
UE #1
RF
remove CP
N _FFT
Δf
UE #2
RF
remove CP
N _FFT
Δf
BS
Δf / 2
N1
N1 _IFFT
CP1
h1(n)
Subband 1 filter
Σ
CPRI
RF
4Δf
Nk
Nk _IFFT
CPk
hk(n)
Subband k filter
F-OFDM
Sub-band 1 UE set
UE1-1 & UE1-2 @ subband 1
UE #1-1
RF
h1(n)
remove CP1
N1 _FFT
Δf / 2
UE #1-2
RF
h1(n)
remove CP1
N1 _FFT
Δf / 2
Sub-band k UE set
UE k-1 & UE k-2 @ subband K
UE #k-1
RF
hk(n)
remove CPk
Nk _FFT
4Δf
UE #k-2
RF
hk(n)
remove CPk
Nk _FFT
4Δf

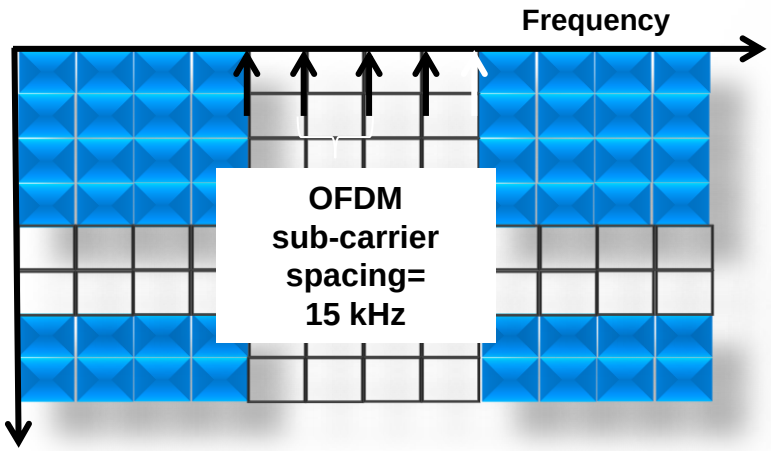
To know what role F-OFDM plays in 5G and what benefit it brings along

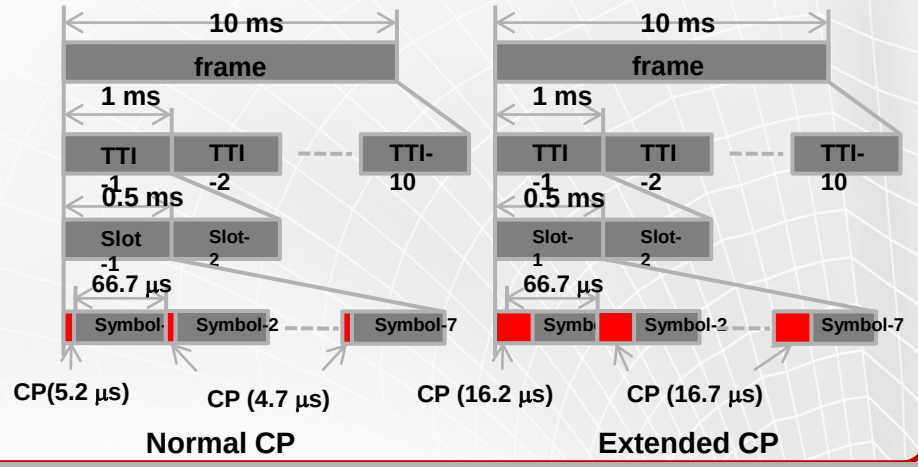
WHY WE NEED F-OFDM IN 5G?

Issues of Existing OFDM Waveform



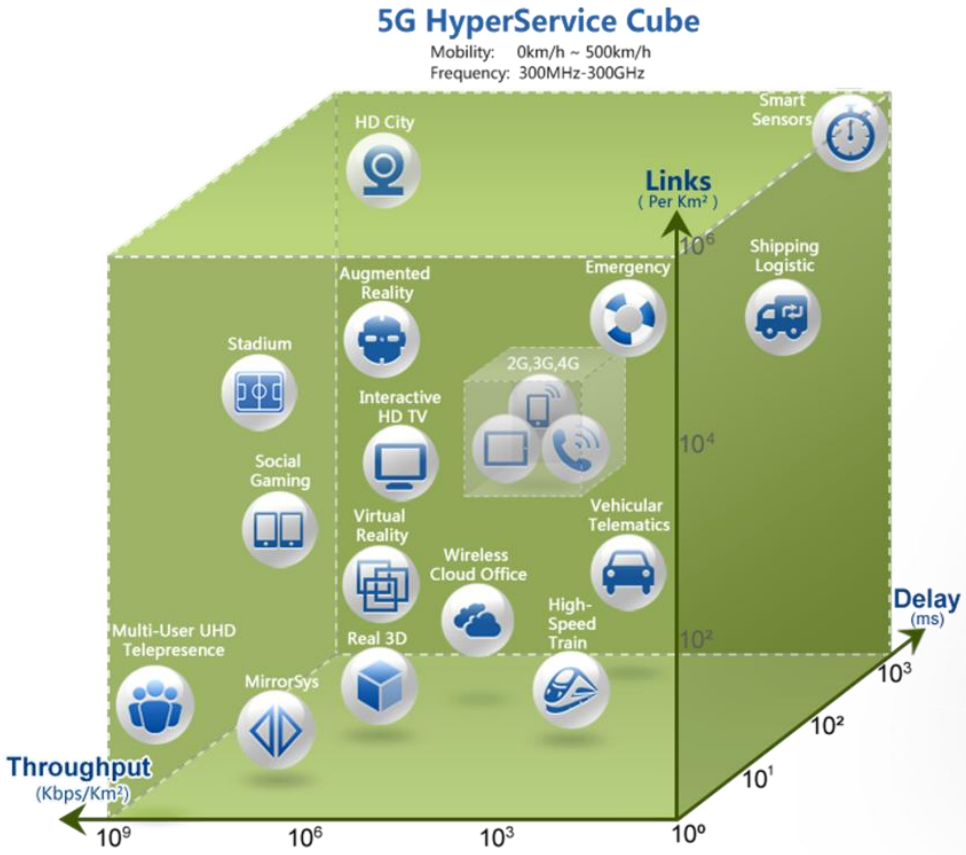






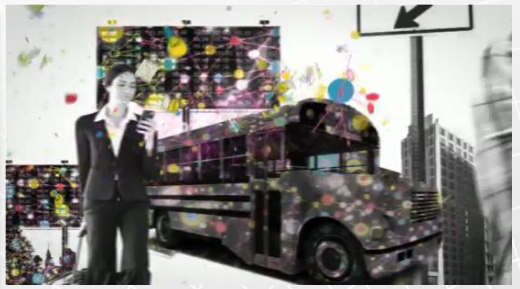
- OFDM waveform is not spectrum localized
  - 10% Guard band is needed in order to meet out-of-band leakage rejection requirement.
- OFDM waveform is not flexible
  - Fixed subcarrier spacing & limited number of cyclic CP
- OFDM waveform cannot support asynchronous operation
  - Timing adjustment is needed

5G Vision: Zero Distance Communications



Massive Capacity

Massive Connectivity



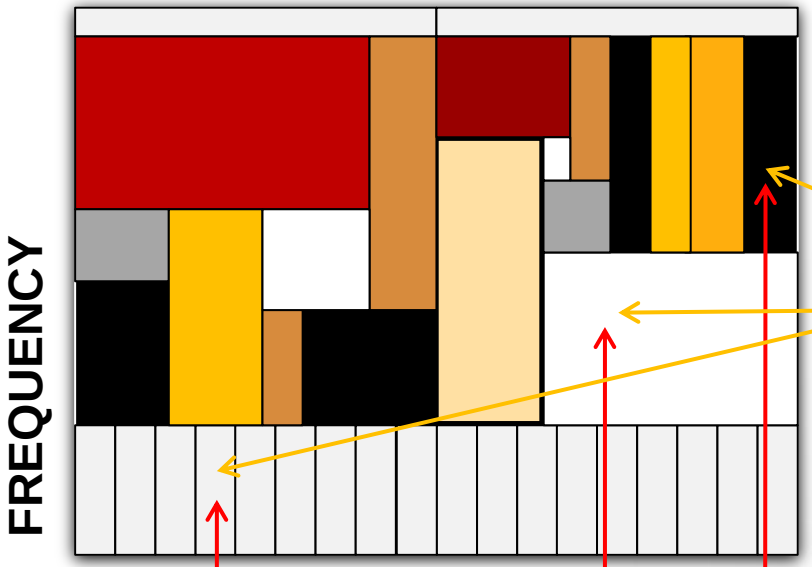
Zero Waiting

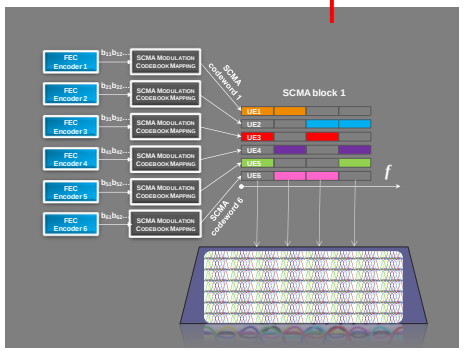
10^3 Times Traffic Flooding

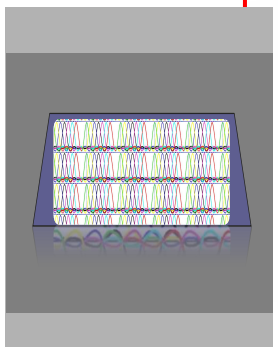
10^2 Billion Connections

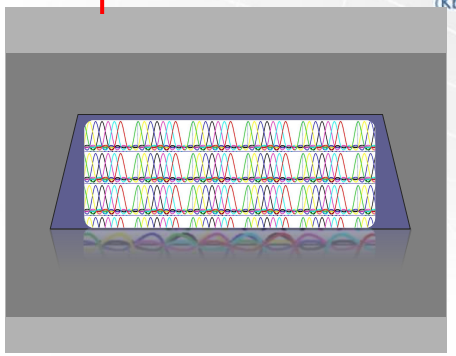
10^0 ms Delay Experience

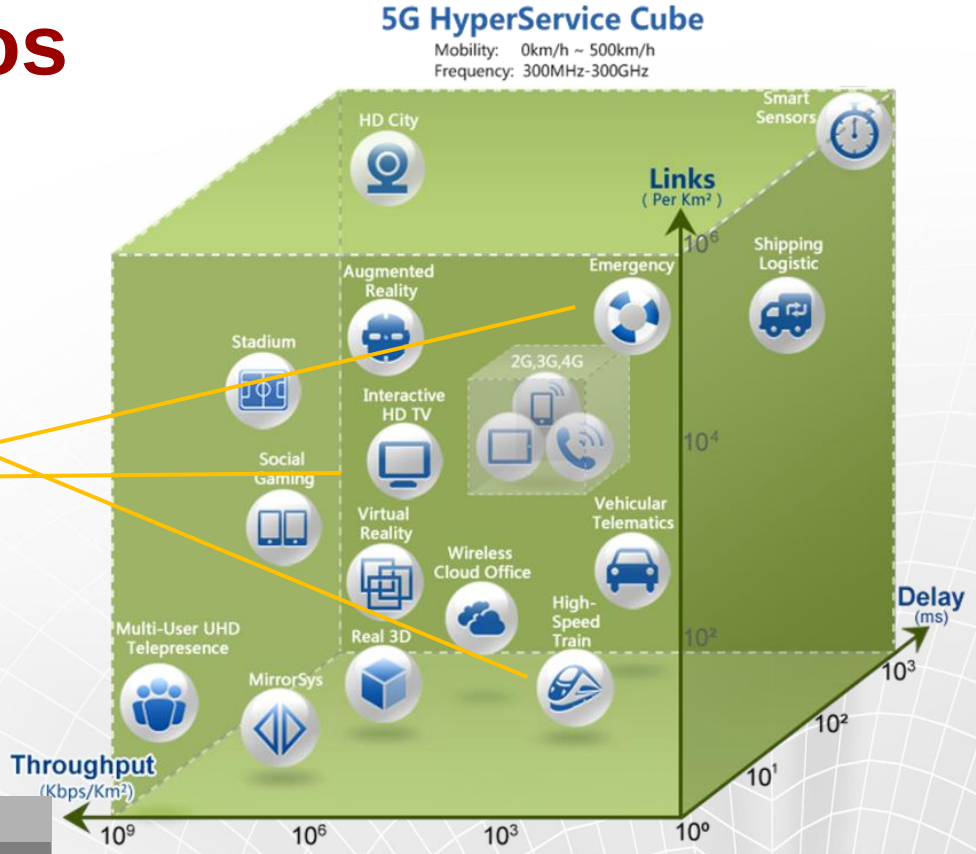
F-OFDM Application Scenarios





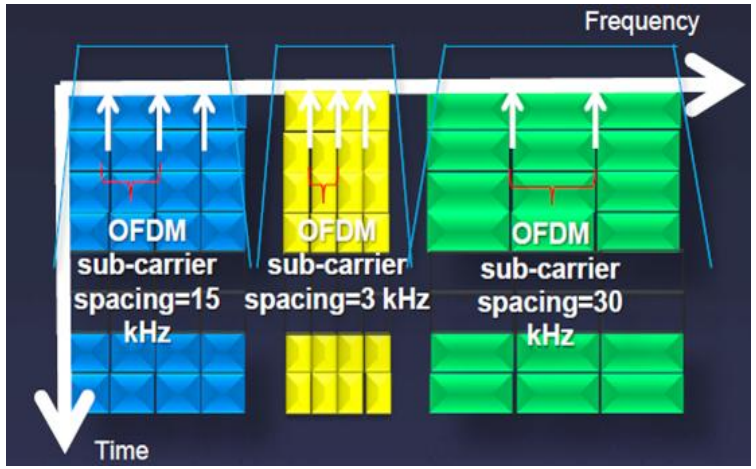




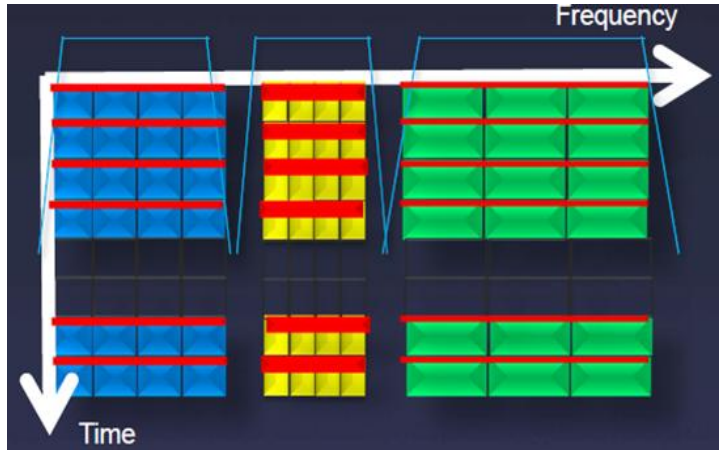


- F-OFDM as the basic 5G waveform, enables the flexible air interface to support co-existence of different waveform / multiple access schemes / flexible TTI configurations
- F-OFDM enables straightforward backward compatible & forward compatible

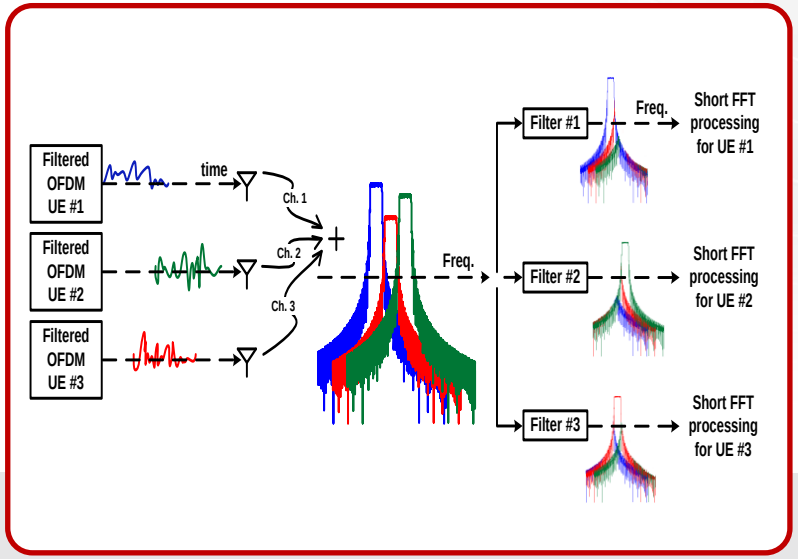
F-OFDM: advantages



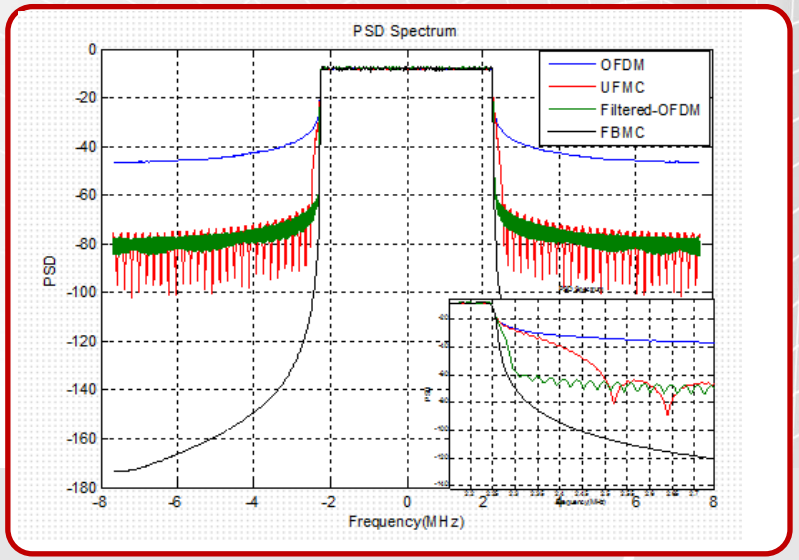
Co-existence of waveform with different OFDM primitive



Different Cyclic prefix for each specific sub-band

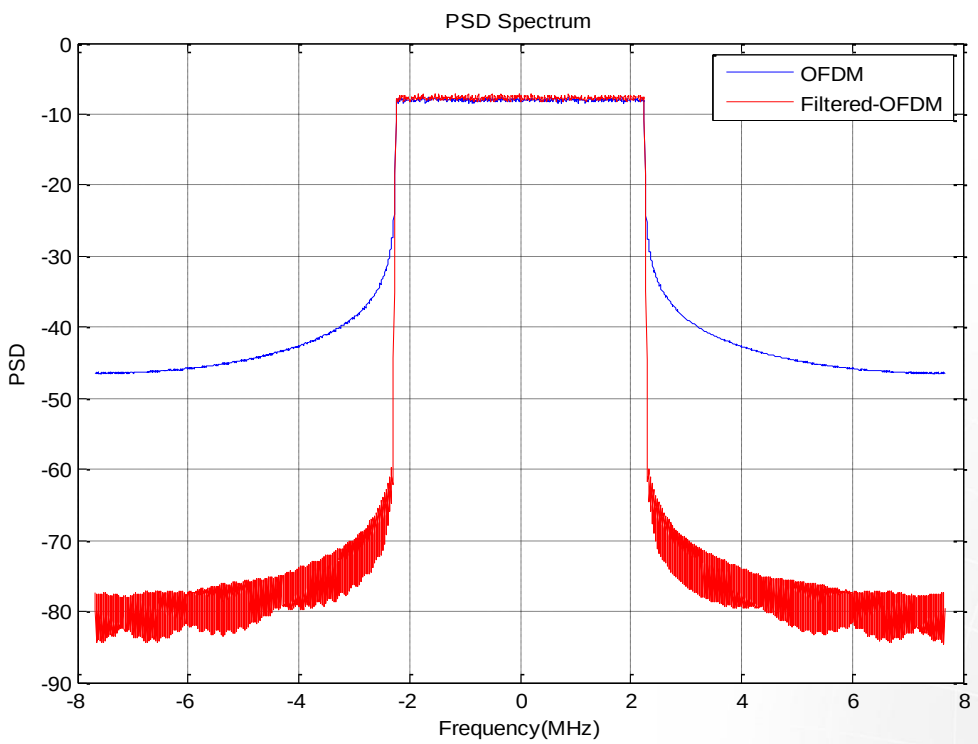


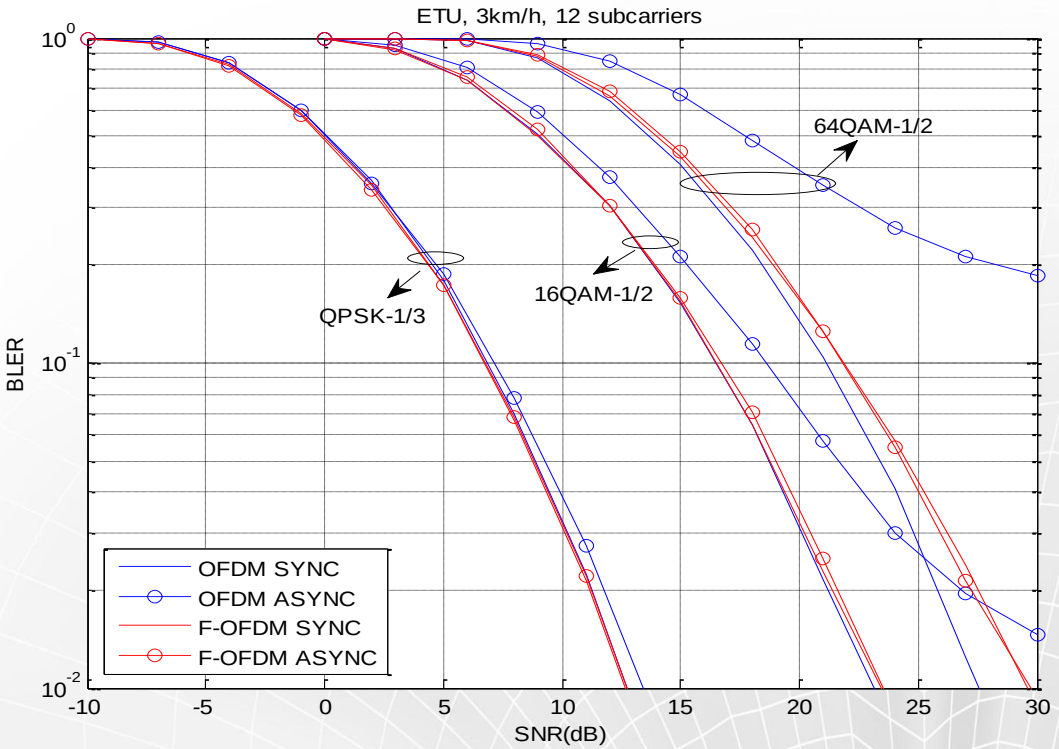
Support asynchronous OFDMA transmission



Good Out-of-band leakage rejection

F-OFDM: simulations(SISO)

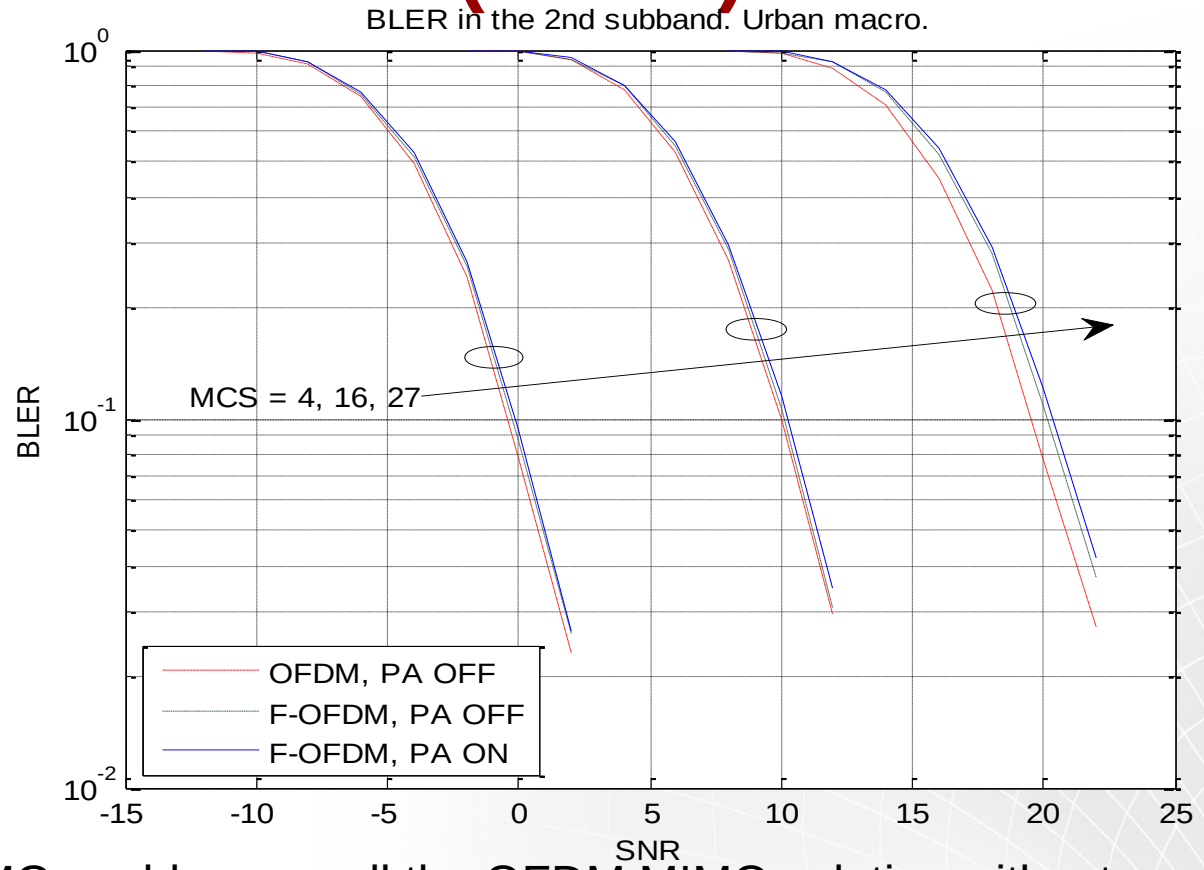




1. F-OFDM has rather low OOB leakage

2. With only 1 guard tone, F-OFDM could achieve the same performance as OFDM with neighbor band interference

F-OFDM: simulations(MIMO)



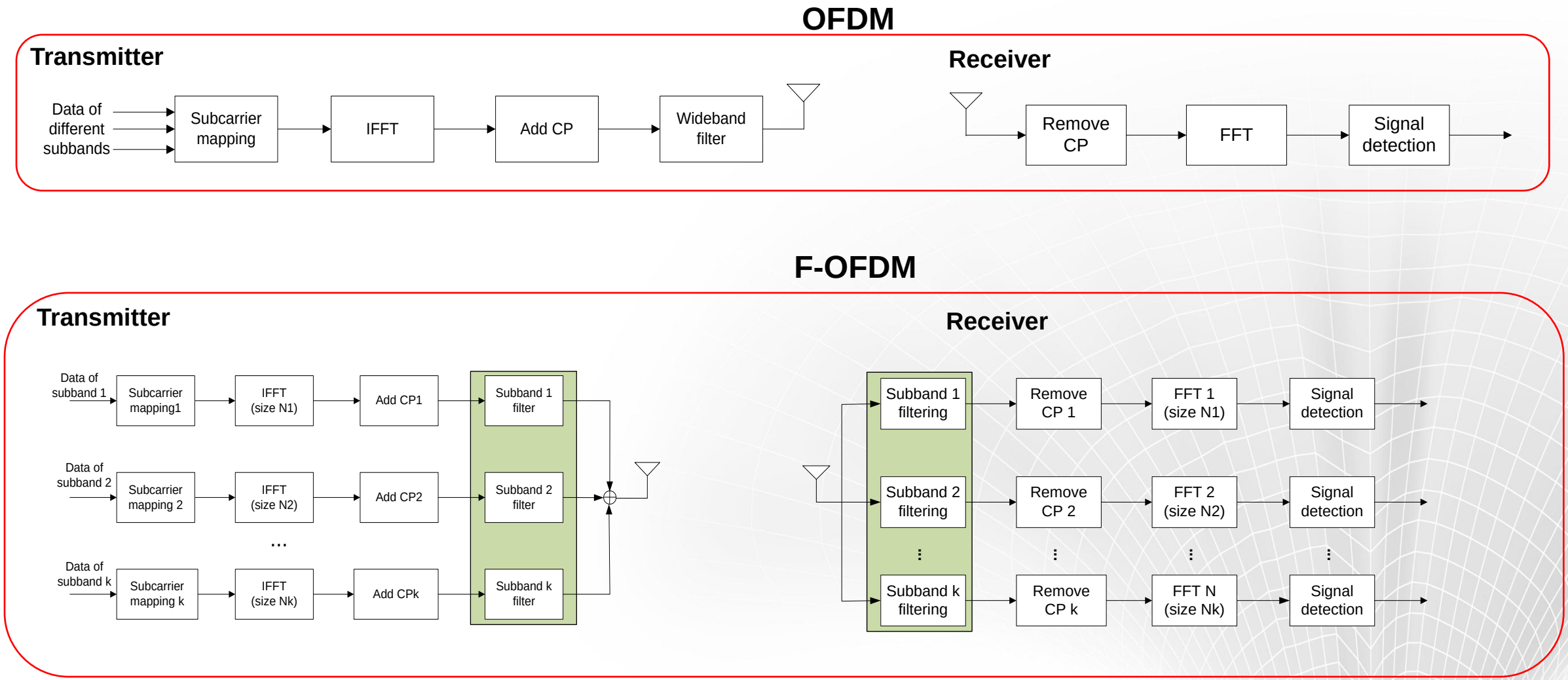
1. F-OFDM MIMO could re-use all the OFDM MIMO solution without any change

2. With only 1 guard tone, F-OFDM MIMO could achieve the same performance as OFDM MIMO with neighbor band interference

To have a gut feeling how F-OFDM will be implemented in the 5G wireless systems

HOW DOES F-OFDM WORK?

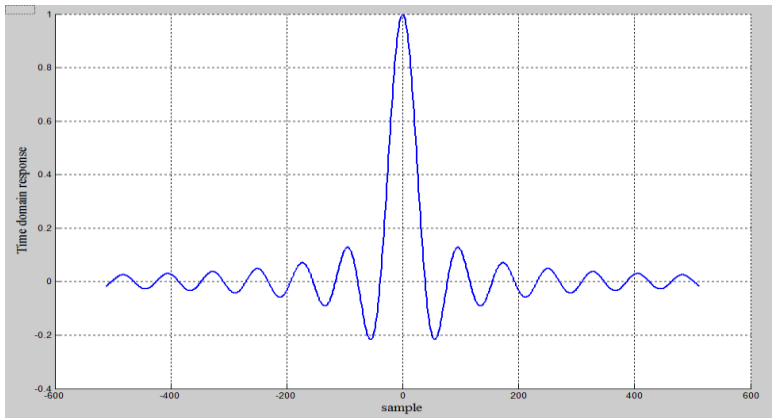
F-OFDM System Diagram



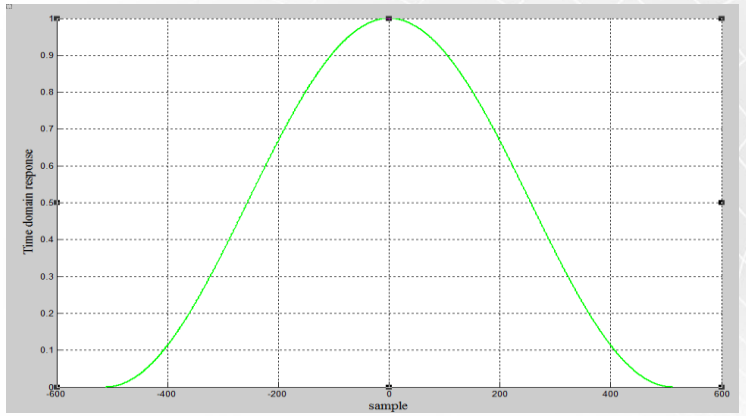
Filter design

- Soft truncated filter with specific window is recommended to achieve
  - Trade-off between time and frequency localization (that is ISI and ICI)
  - Easy implementation for flexible subband configuration
  - Small round-up error due to frequency domain fixed point implementation

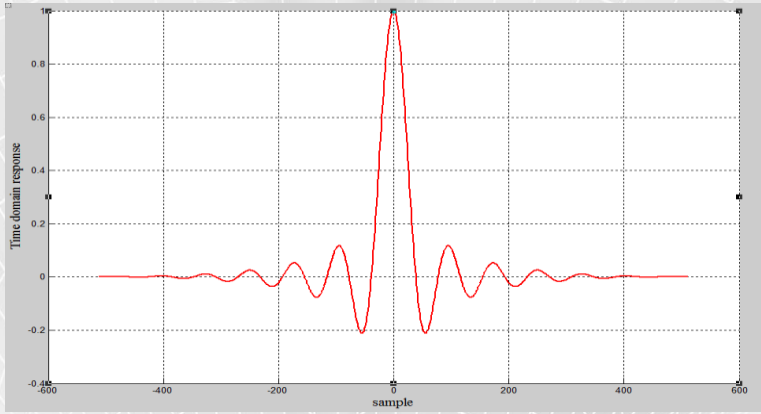
Time domain Sinc function:
Ideal filter with BW = subband BW + some guard tone



Time domain window (e.g. Hanning/Kaiser/RC…) :
to balance pass-band flatness & T/F localization



Final filter



$$W_{Sinc} \cdot W_{spec\_win} = W_{filter\_time}$$

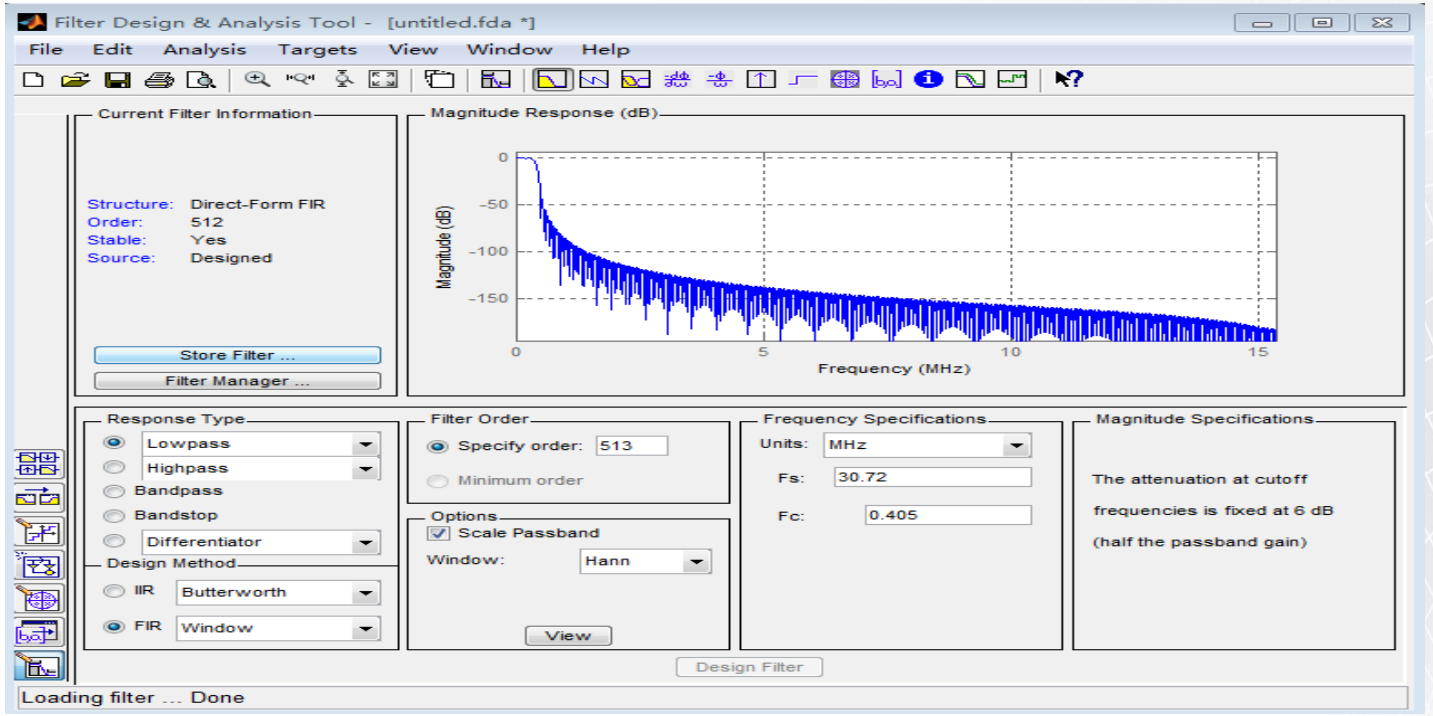
Example of filter

- **Example with Hanning window**
  - Subcarrier spacing = 15KHz
  - Subband = 720KHz
  - Fs = 30.72MHz (LTE baseband sampling rate)

$$W_{filter\_time} = W_{Sinc} \cdot W_{Hanning}$$

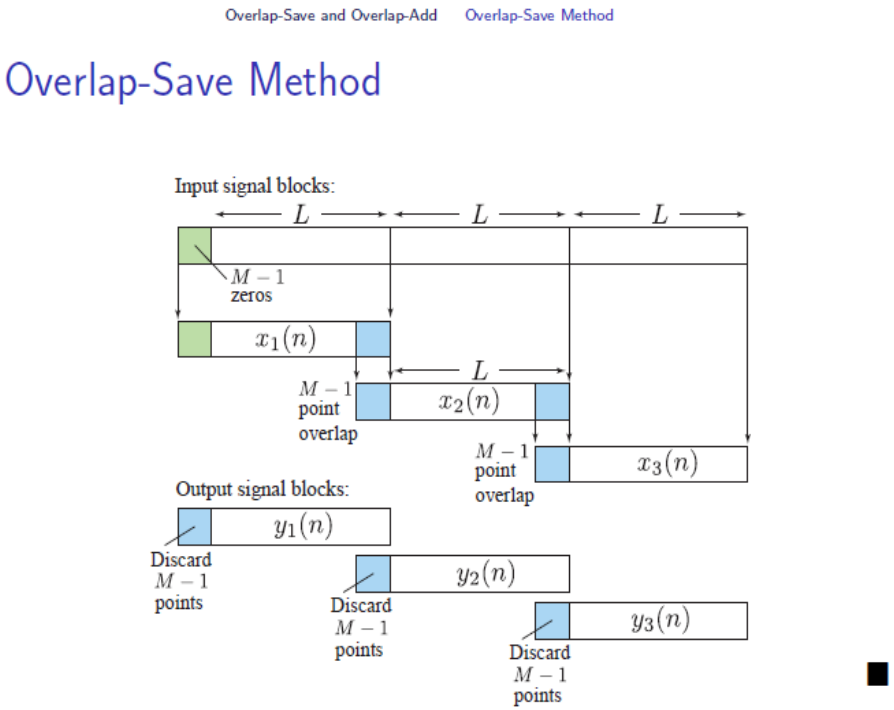
$$W_{Hanning}(n) = 0.5\left(1 - \cos\left(\frac{2\pi n}{N-1}\right)\right)$$

Matlab built-in filter tool to generate the soft truncated filter



Filter implementation

1. Conceptually, F-OFDM filtering operation is continuous filtering in time domain
2. However, frequency domain filtering operation is preferred for simple implementation[1]

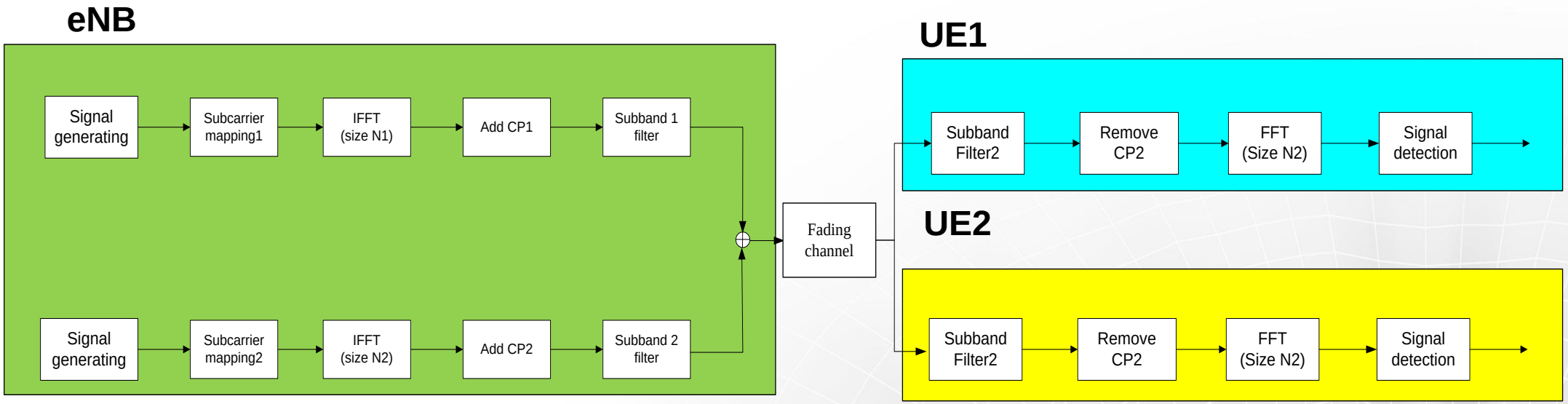


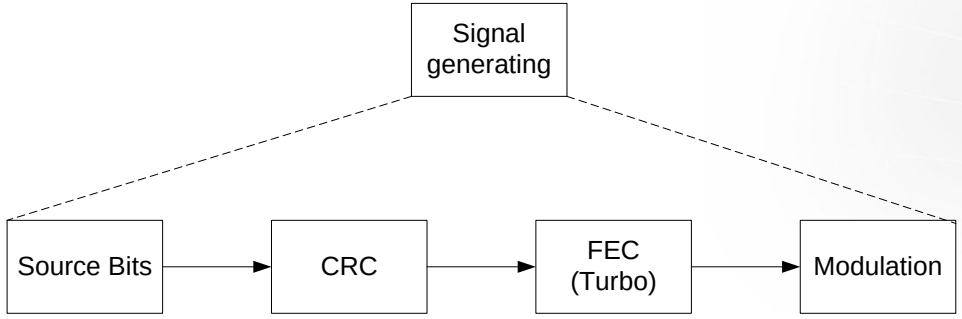
- For each FFT/IFFT based block filtering, we can filter a data block of size L.
- Filter time domain length is of size M.
- FFT size N = L + M – 1.
- Complexity is much less sensitive to the filter length.

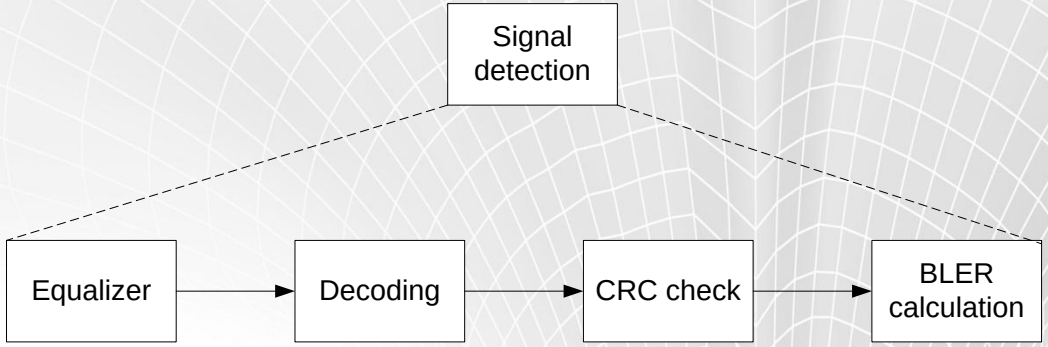
[1] *reference:* Douglas L. Jones, "Fast Convolution", available online: https://inst.eecs.berkeley.edu/~ee123/sp15/docs/FastConv.pdf

WHAT WILL YOU IMPLEMENT?

Simplified Downlink F-OFDM System to be Implemented







Link Parameters

Parameters	F_OFDM @ subband1	F-OFDM @subband2	
Duplex	FDD		
Antenna config.	SISO		
Sampling rate	30.72Mbps		
Subband BW	720KHz	720KHz	Configurable, two sub-bands can be different.
Subcarrier spacing	15KHz	30KHz	
FFT size	2048	1024	
Symbol duration	1/15K=66.67us	1/30K=33.33us	
TTI	1ms	0.2ms	
# symbol per TTI	14	5	
CP length	160 samples(5.2us) for symbol 1 144 samples(4.7us) for symbol 2~7	224 samples for symbol 1 200 samples for symbol 2~5	
Guard tone number	0/1/2/3		
CRC	24 bit		
Modulation	QPSK/16QAM/64QAM		Configurable, two sub-bands can be different.
Turbo coding rate	1/3,1/2, 3/4		Configurable, two sub-bands can be different.

How We Judge and Compete the Results

Description	Requirement	Deliverables
Implement two Filtered-OFDM links, wherein the subband filtering functions are switchable, i.e., when the filter functions are switched off, the links will be OFDM, otherwise they will be F-OFDM. The two links should have different OFDM parameters, including subcarrier spacing, CP length and TTI length. Moreover, adjacent frequency subbands should be used by the two links, and guard tones should be reserved between the two subbands. The performance gap between F-OFDM and OFDM should be observed by setting different number of guard tones, the performance metrics include: 1. The out-of-band emission of each link 2. The BLER/PER curves of each link	1. Design correctly, simulation results are right 2. The performance of F-OFDM meets requirement, includes: a. The OOBE is much better than OFDM b. The BLER/PER are similar to OFDM under the channel models of (a) ETU 3km/h, (b) EPA 3km/h, (c) AWGN 3. Low complexity, fine realizability 4. Optimized filter design	1. The design document of F-OFDM links 2. The maltab simulation program of F-OFDM links, and simulation report which should include the OOBE simulation results, the BLER/PER curves. 3. The FPGA implementation of F-OFDM links and test report which should include the OOBE and BLER performance.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