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Comparative study of 5G waveform candidates for below 6GHz air interface

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Table of Contents

1. Context and issues
2. Waveforms
   - 2.1 CP-OFDM & SC-FDMA
   - 2.2 Filter bank multicarrier (FBMC)
   - 2.3 Universal Filtered Multicarrier (UFMC)
   - 2.4 Generalized Frequency Division Multiplexing (GFDM)
3. Comparizon between waveforms
4. Multi-user access scenario
5. Conclusion

5G Context

- 4G massively rolled out but will soon reaches its limits
- RAN 5G Workshop 09/15 : New non backward compatible Radio Access Technology as part of 5G
- Aggregation of non contiguous network is considered
  - Spectrum agility : need to study alternative multicarrier waveforms
- Sporadic access & MTC
  - Strong traffic overhead (fast dormancy)
  - Massive number of devices : Use relaxed synchronism
- Several candidates have been independently introduced in the past few years
  - Classic CP-OFDM shows its limits : Spectral efficiency, frequency leakage, need of tight synchronisation
  - We propose a **comparative study of 5G waveform candidates for below 6GHz air interface**

Context and objectives

Considering several candidates for 5G physical layer

- Baseline for comparison : OFDM and SC-FDMA
- Filter bank multicarrier (FBMC) [3]
- Universal Filtered Multicarrier : UFMC (or UF-OFDM) [9]
- Generalized Frequency Division Multiplexing (GFDM) [6]

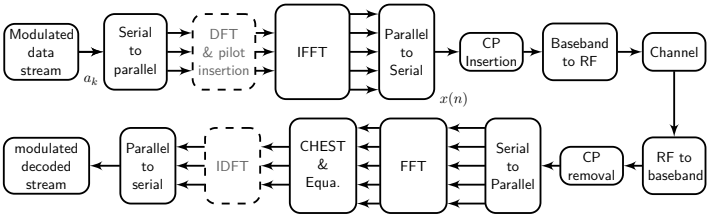
A fair comparison between waveforms in literature is lacking

Considering several metrics for comparison

- Spectral Efficiency (SE)
- Peak To Average Power Ratio (PAPR)
- Power spectral Density (PSD)

Also consider the asynchronous multi-user scenario [1, 11]

CP-OFDM & SC-FDMA

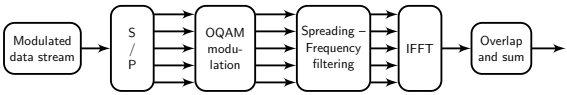


OFDM & SC-FDMA (additional stages in dash) transceiver scheme

- Multicarrier modulations, serves as physical layers for 3GPP-LTE or 802.11.a/g/n
- Efficient implementation (IFFT/FFT), simple equalization schemes
- Spectral efficiency loss due to Cyclic Prefix (CP) insertion to handle multipath channel
- For SC-FDMA : DFT/IDFT precoding stages to reduce PAPR (3GPP-LTE uplink : DFT-spread OFDM)

Filter bank multicarrier (FBMC)

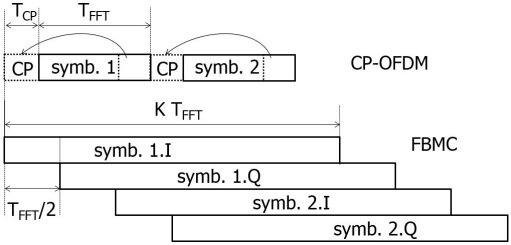
- Set of parallel data through bank of modulated filters
- Good spectral location, orthogonality and spectral efficiency kept with OQAM modulation



FBMC Tx stage

- Prototype filter in frequency domain (FS) [2]
  - Overlapping factor K
  - Filter defined in frequency domain (K=4)

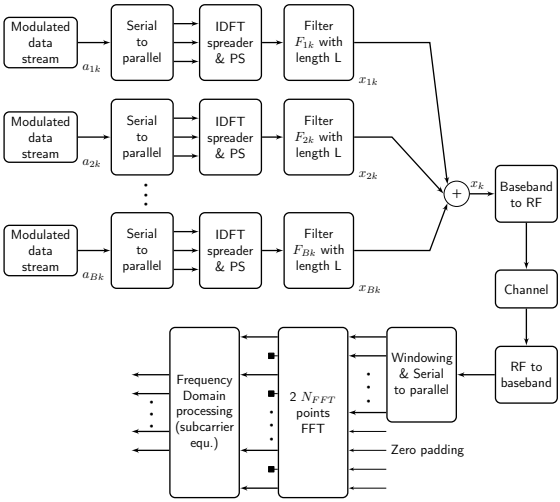
$$
\begin{aligned}
H_0 &= 1 \\
H_1 &= H_{-1} = 0.971960 \\
H_2 &= H_{-2} = \frac{\sqrt{2}}{2} \\
H_3 &= H_{-3} = \sqrt{1 - H_1^2}
\end{aligned}
$$



CP-OFDM (top) and FBMC (bottom) frames

Universal Filtered Multicarrier (UFMC)

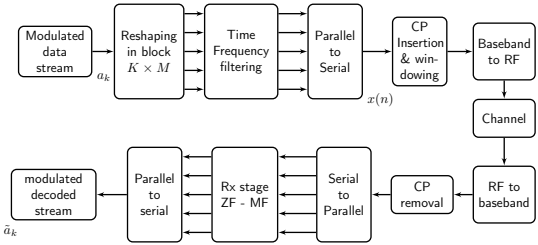
- Derivative of OFDM where a group of subcarriers (RB) is filtered with a Dolph-Chebyshev filter with length L and attenuation factor [9]
- B subbands are generated and combined
- On Rx side, Zero padding is applied before a $2N$ FFT
- Possibility to add a windowing process on the Rx side (asynchronous multi-user scenario)



UFMC transceiver

Generalized Frequency Division Multiplexing (GFDM)

- Based on time-frequency filtering of data blocks of size $P \times M$
- Shaping filter : Root Raised Cosine filter (RRC)
- Non orthogonal waveform : interference in time and frequency domains
- A CP is added at each symbols (P subsymbols)
- Possibility to add a windowing process to reduce the ACL
- Parametrized by P, M and roll-off factor α



GFDM transceiver

- On Rx side, different architectures : MF, ZF, MMSE [7]
- With MF, need to add Interference Cancellation (IC) scheme
- With ZF, no self-interference but noise enhancement

Simulation parameters & Spectral Efficiency

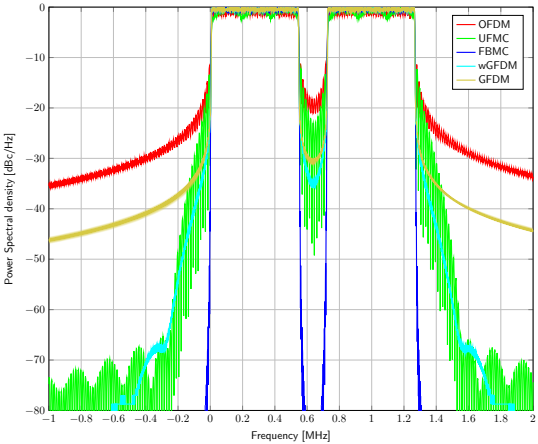
Overall parameters		
FFT size	N_{FFT}	1024
Bit per Symbol	m	2
Resource block size	N_{RB}	12
Number of active RBs	N_{Re}^1 N_{Re}^2	3 for User 1 9 for User 2
Sampling frequency	F_e	15.36 MHz
OFDM and SC-FDMA parameters		
Cyclic prefix	N_{CP}	72 samples
UFMC parameters		
Filter length	L	73
Stop band attenuation		40 dB
GFDM parameters		
Number of subsymbols	P	15
FFT size	M	1024
Roll Off factor	α	0.1
FBMC parameters		
Spreading factor	K	4
Asynchronous access parameters		
Guard carriers		[0, 1, 2, 5]
Timing Offset		[-0.25 :0.25]
Carrier Frequency Offset		0 ; 10%

- We consider 2 users for asynchronous multi-user access scheme [1]
  - 3 RBs for user 1 (12 carriers)
  - 9 RBs for user 2 (36 carriers)
- Same FFT size for all users : 1024
- Parameters are based on LTE 10MHz
- Length of UFMC filter has been set to have same Spectral Efficiency for UFMC and OFDM : $L = N_{CP} + 1$

Power Spectral Density

Power Spectral Density of waveforms :

- OFDM : high ACL due to sinc in freq. domain
- UFMC has lower ACL than GFDM (circular convolution)
- GFDM with windowing : Better OOB than GFDM and comparable to UFMC
- Best frequency location is obtained with FBMC



Power spectral density of waveforms

- 2 users of 3 RBs with 1 RB of guard carriers to better stress ACL impact

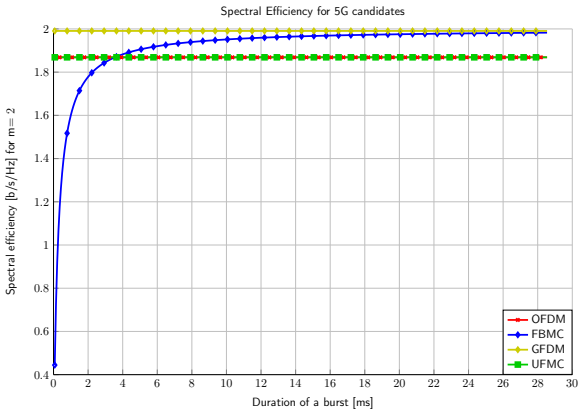
Spectral Efficiency

Spectral Efficiency for each waveform [bit/s/Hz]

- $\eta_{OFDM} = \frac{m \times N_{FFT}}{N_{FFT}+N_{CP}}$
- $\eta_{UFMC} = \frac{m \times N_{FFT}}{N_{FFT}+L-1}$
- $\eta_{GFDM} = \frac{m \times P \times M}{P \times M+N_{CP}}$
- $\eta_{FBMC} = \frac{m \times S}{S+K-\frac{1}{2}}$

UFMC and OFDM have same SE

GFDM SE depends on size block



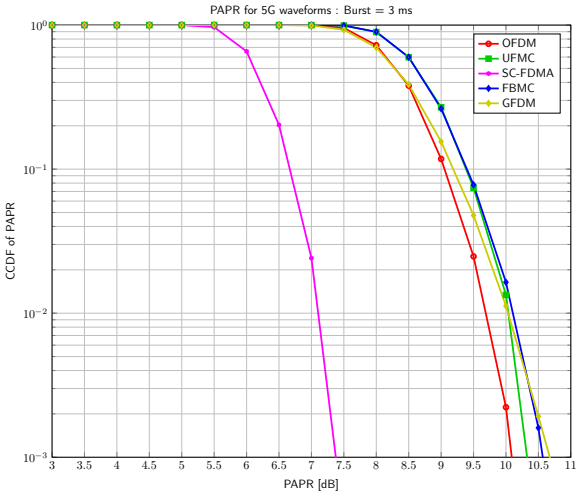
Comparaison between SE of waveforms

FBMC SE depends on burst duration : If burst duration $>$ 3ms, better SE than UFMC and OFDM

Peak to Average Ratio

PAPR computed on a 3ms burst :

- PAPR $= \frac{\max\left[|y[k]|^2\right]}{E[|y[k]|^2]}$
- We compute Complementary Cumulative Density Probability Function (CCDF)
- Low PAPR only obtained with SC-FDMA
- All multicarrier modulations have a comparable PAPR (gap around ~ 0.5 dB)

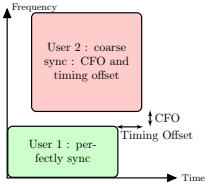


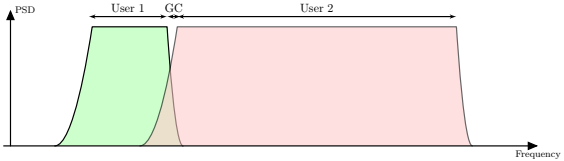
PAPR measured on 3ms burst

Multi-user access scenario

Comparison in a multi-user asynchronous access scenario between 2 users [1]

- First user is perfectly synchronised and second user interferes with the first one (due to time delay error and CFO)
- Performance measured in terms of Mean Squared Error (MSE), with different number of guard carriers (0, 1, 2 and 5)

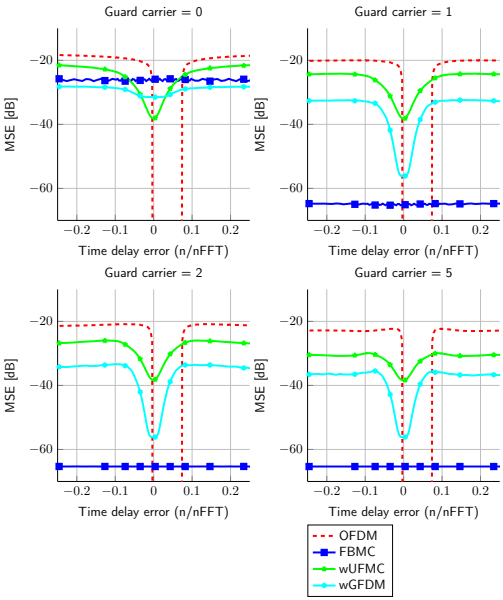




- Several 5G candidates with specific parametrisation (best case) :
  1. CP-OFDM (SC-FDMA has the same MSE)
  2. UFMC with windowing approach [10]
  3. GFDM with windowing [8] ; with MF receiver and IC [4]
  4. And FBMC

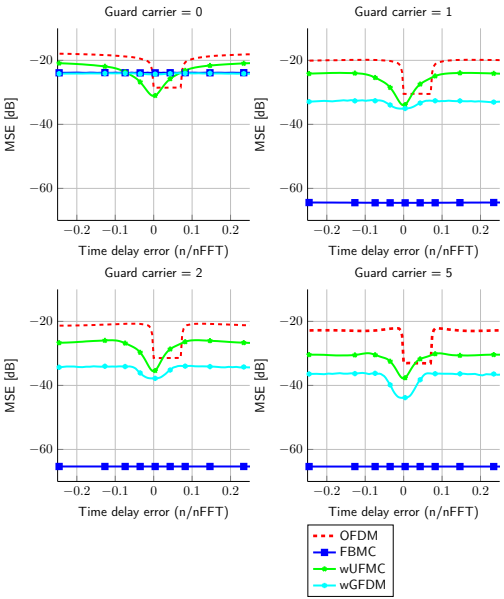
Multi-user access scenario : No CFO

- $0 <$ Delay error N_{CP} : no interference for OFDM
- No GC, GFDM with windowing has better performance
- No GC, Small delay value : UFMC with windowing has good performance
- wGFDM $>$ wUFMC if at least one GC
- At least one GC inserted : FBMC has the best performance : no interference (Phydyas filter + OQAM [5]) !



Multi-user access scenario : 10% CFO

- CFO breaks OFDM orthogonality and lowers performance for all waveforms
- No GC, wGFDM has same performance as FBMC
- No GC, Small delay value : UFMC with windowing has the best performance
- wGFDM > wUFMC if at least one GC is inserted but impact of CFO
- At least one GC inserted : FBMC has the best performance : no interference



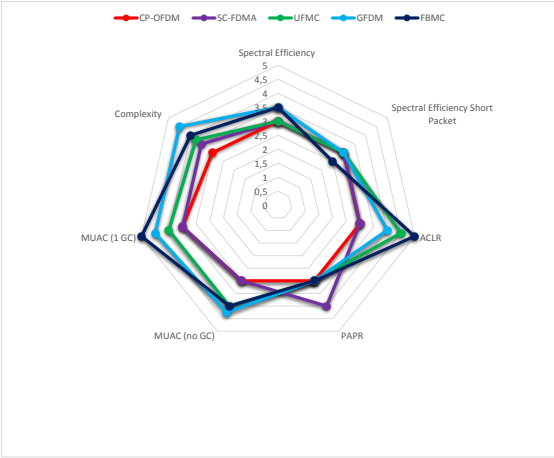
Conclusion

Fair comparison for several representative criteria :

- Spectral Efficiency, PAPR, PSD comparison
- Mean Square Error in multi-user access scenario

Comparison between 5G waveform candidates that outperform CP-OFDM :

- UFMC offers LTE backward compatibility
- GFDM and FBMC go further
  BUT still open questions : short packet, MIMO, ...



Comparison between waveforms

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