Multi-services and flexible air-interface: Waveforms for 5G

Robin Gerzaguet, Jean-Baptiste Doré
1. Introduction and context

2. From 1G to 4G: the path of history for communication

3. 5G: Unified framework and flexibility

4. Waveforms for 5G: the candidates

5. Conclusion & perspectives
1. Introduction and context

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5. Conclusion & perspectives
CEA Institute founded in 1967

Director: Dr Marie-Noëlle Semeria

1,800 collaborators
1,270 permanent staff
250 PhD + 40 post doc, 37% foreign students

2800 patents
311 registered in 2014
40% under licensing
680 publications per year

Budget: 318 M€
CapEx: 39 M€
80% from external revenue

8,500 m² clean rooms
For 200 and 300 mm wafer fab, operated 24/7
• 16 000 collaborators
  - 10 % PhD and post-doc
• 10 research centres
Serving a variety of wireless applications

Mobile communications
- Challenges: increasing data rate, future cellular systems, 4G any rate anytime anywhere affordable, reduction of communication energy footprint (GreenCom), monitoring interference and service coverage, heterogeneous networks - HetNets, small cells
- Spectrum efficiency, cooperative communications, HetNets, Femto / Macro RRM, Cognitive radio, Flexible radio systems...

Intelligent Transportation
- Challenges: traffic management, car-centric services (maintenance, routing), Electric Car services, infotainment / entertainment
- QoS system, mobility management, privacy and security, entertainment communication systems, propagation and adaptable antenna systems...

Advanced manufacturing
- Challenges: factory of the future, increasing competitiveness, new production and management communication systems, robust communication systems (coexistence, interference management), supply chain management
- Wireless sensor network, robust communication, M2M, RFID/NFC, indoor localization...

Health
- Challenges: hospital equipments management and supply chain support, no emission wireless communication systems (clean wireless), smart implants, teledicine, health monitoring, ambient assisted living...
- Body Area Network, Visible Light Communication, in vivo integration, contactless autonomous systems, indoor localisation, very high data rate communication systems, privacy, security...

Smart cities, Smart grid
- Challenges: infrastructure monitoring, city infotainment services, utility supply chain management, waste collection and management systems, citizen mobility assistance, urban smart transportation systems
- Long range sensor network, robust communication, M2M, security and privacy...
Key technical challenges

- High data rate, coverage
- HetNets, cooperative Nwks
- M2M, scalability, security, privacy, WSN
- Targets 1 Gbps in wide area (Peak data rate ~ 10 Gbps)
- Ad hoc deployment, dynamic spectrum access, white spaces, shared spectrum, fragmented spectrum

INSA lecture

R. Gerzaguet

October 17th
Communication system studies and specifications lab.

**LESC**

- **Field of expertise**
  - Wireless digital communication systems
  - Information theory and digital signal processing
  - Wireless protocols

- **Know how**
  - Modulation, channel coding, equalization, MIMO systems, ...
  - Information theory, cooperative communications, network coding
  - Access protocols (MAC, RRM), interference management
  - Localization and tracking algorithms
  - Link level and system level simulations
  - Wireless solution specifications

- **Specific equipment**
  - Computer grid for intensive simulations
  - 23 computation mini-servers, 104 processors, 416 Go memory
Wireless solutions and prototyping lab.

- **Field of expertise**
  - Hardware and embedded software architectures for digital communication systems
  - Prototype specification and design for advanced proof of concepts
  - Algorithmic / architectural adequation
  - Security for wireless systems

- **Know how**
  - Specification and design of wireless digital systems (HW,SW)
  - Hardware / software partitioning for real-time wireless systems
  - Optimized design with various figure of merit (power consumption, data rate,...)
  - Multi-mode / multi-standards flexible radio systems
  - Security solutions for wireless systems

- **Specific equipment**
  - Lab equipment for prototyping and realtime measurement and analysis
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A cellular network is controlled by base stations (BS)

Different types of cellular networks
- Macro: up to 10 km, 40W (46dBm), High Point localization
- Micro: up to 100m, 10W (40dBm), Roof localization
- Pico: Micro with limited power, 0.25 to 5 W (24 to 37 dBm), indoor, hot spot (airports, malls...)
- Femto: up to 10m, 20dBm, indoor office, Set Top Box...
Definitions

Cellular network architecture

- **User Equipment** (UE): mobile phone, Wireless stick...
- **Access Network** (RAN): Radio access network. Infrastructure, operator equipment
- **Core Network** (CN): Infrastructure, operator equipment

Radio link:

- **Downlink** (DL): BS to UE
- **Uplink** (UL): UE to BS
Early 1980

- AMPS (Advanced Mobile Phone System), US
- TACS (Total Access Communication System), Japan and UK
- NMT (Nordic Mobile Telephone), Nordic countries
- Radiocom2000, France
- C-NETZ, Germany

- Analog modulation using FDMA, capacity few calls per BS

- Compatibility issues!!

- Conclusion: An International standardized system is necessary!
1990’

- GSM (Global System for Mobile communications), Europe, GMSK modulation + TDMA and FDMA
- PDC (Personal Digital Communications), Japan, $\pi/4$-DQPSK + TDMA and FDMA
- IS-95 (Interim Standard), US, CDMA (introduced by Qualcomm)

Services: Voice call + SMS (a revolution) + Low rate data (EDGE 240Kbps)

- GSM was a success (worldwide deployment, success for Europe: Nokia, Ericsson, Alcatel...), but cell capacity is limited and new use cases have motivated the definition of the 3G
UMTS (Universal Mobile Telecommunications System) and CDMA2000

First international standard!

Objectives: Increase celle capacity and offer data services

W-CDMA WideBand CDMA (release 99) + two majors evolutions HSxPA (release 5 (2002), release 6 (2005))
  - Turbo codes
  - QPSK and 16-QAM
  - HARQ (Hybrid Automatic Response reQuest)

DL up to 14.4 Mbit/s, UL up to 5.8 Mbit/s (5MHz BW)

New use cases require more capacity (smartphone introduction)
HARQ de type CC (Chase combining)

- Retransmission du même paquet (codage à répétition)
- Combinaison de tous les paquets reçus (diversité et SNR cumulé plus grand)
- Décodage du paquet

Hybrid Automatic Response reQuest principle (Chase Combining) [4]
HARQ de type IR (Incremental Redundancy)

- Transmission du paquet fraction par fraction, en commençant par la partie “données”
- Assemblage à la réception et décodage commun

Hybrid Automatic Response reQuest principle (Incremental redundancy) [4]
HSPDA+ - Releases 7 (2007) and 8 (2008)

- DL: 64-QAM, UL: 16-QAM
- DC-HSDPA: Dual Carrier – HSDPA, bandwidth $\times 2$
- Introduction of MIMO scheme for DL
- Architecture optimization: decreasing latency
Why a new standard?

- Capacity and throughput should be increased to support new usages
- Latency: 3G 70ms. Decrease latency is a requirement addressed by LTE
- Spectrum agility: 3G 5MHz BW. Worldwide adaption difficult. A flexible BW allocation is required
- Network maintenance: Costly and hand-made! Automated network configuration management for 4G

Industrial and Economic context: IEEE introduced WiMAX (IEEE 802.16e), a serious competing standard for historical cellular companies! There’s a chance for a new deal. 3G market is dominated by few companies (patents!!). The definition of a new technology with less IP has motivated the introduction of 4G!

1. Introduction and context

2. From 1G to 4G: the path of history for communication

3. 5G: Unified framework and flexibility
   3.1 What will be 5G?
   3.2 Use-cases: the need of flexibility
   3.3 Consequence on physical layer and flexible air interface
   3.4 KPIs for waveforms
   3.5 Conclusion on 5G framework

4. Waveforms for 5G: the candidates

5. Conclusion & perspectives
5G will emerge use cases with a high variety of applications and variability of their performance [3]
5G Roadmap

Expected 5G roadmap [1]
KPIs and framework: the need of flexibility

- Many Use-cases and KPIs: flexibility is the key to address the challenges

- Let’s have a look on 5G use-cases
5G will emerging use cases with a high variety of applications and variability of their performance.
5G will emerging use cases with a **high variety** of applications and variability of their **performance**
Associated to **fully connected society**
- Provide connection to thousand people per km$^2$

Some challenging use-cases:
- **Persuasive Video**: Massive video between groups and persons: high data rates and low latency
- **Smart Office**: Massive number of devices wirelessly connected: ultra high data rates, bandwidth and latency
- **Operator Cloud services**: Full mobile, smart life experience: QoE in question, reliability
- **Stadium, open air gathering**: Sharing video/photo in massive events: high connection density, data rate, latency
- **Covering urban, suburban and rural area**
  - Provide connection to thousand people per km²

- **Some challenging use-cases**
  - **50 Mbps+ Everywhere**: minimum user data rate, even cell edge: Coverage, QoE
  - **Ultra low cost networks**: Deployment everywhere needs low cost equipment/network
5G will emerging use cases with a high variety of applications and variability of their performance.
Growing demand on mobility service such as train and aircrafts!

- Also demand for communication **between** vehicles
- Really challenging for the physical layer and the waveform part
Some challenging use-cases

- **High speed train**: Expect speed greater than 500km/h, with 1000 persons

- **Remote computing**: Industry will rely on remote processing for maintenance: low latencies with very robust communications and availability

- **Moving hot-spots**: moving vehicles and crowds [bicycle!]: capacity variation

- **3 dimensional connectivity**: aircrafts
5G will emerging use cases with a high variety of applications and variability of their performance
Connecting devices, Machine to Machine (M2M) and Machine Type Communication (MTC)

Some challenging use-cases

- **Smart wearables**: Low power, waterproof sensors for clothes and health sensors

- **Sensors networks**: humidity, temperature, monitoring buildings, ... Low power, long battery life

- **Mobile Network surveillance**: reliable, security, battery life
5G will emerging use cases with a **high variety** of applications and variability of their **performance**
Extreme real time communications

- Associated to **Real time communications and interactions**

- Some challenging use-cases
  - **Tactile Internet**: Software running in the cloud, high data rates sent to mobile: high data rates, latency
Ensure network and communications in natural disasters

- Several types of communications (text, voice, ...)

- Also metadata (position, health ...)

- Reliability, Efficiency, energy consumption
5G will emerging use cases with a **high variety** of applications and variability of their **performance**
Related to automotive, health and assisted living communications

Some challenging use-cases

- **Automated traffic and driving**: Ultra low latency and reliability for control signal. High Data rate depending on type of signal (video . . . )

- **Collaborative robots**: Underlying network with very low latency and good reliability

- **eHealth**: Health sensors and monitoring: prioritisation, security, privacy, identity

- **Remote object manipulation**: remote surgery example: latency, reliability, security
- 5G will emerging use cases with a high variety of applications and variability of their performance
Typical downlink massive transmission to end-users

Some challenging use-cases

- **News and Informations**: sharing sending information when happens.

- **Local/Regional/National broadcast services**: Associated to events, with variety of area range: Density, data rate, coverage
5G will emerging use cases with a **high variety** of applications and variability of their **performance**
Conclusion on use-cases

5G view from Ericsson
A new air-interface is needed to address the 5G challenges
  - Improving Spectral efficiency
  - Reducing OOB leakage
  - Enable low latency for critical applications
  - Flexibility is required

We focus on the **waveform part**
  - How to evaluate the waveform ?
  - Which **Key Performance Indicator** ?
Key Performance Indicator

1. User Data Rate in DL // UL
2. Connection Density
3. Traffic Density
4. Mobility
5. Availability
6. Reliability
7. Latency

Uses-cases are mapped to KPIs

BUT that doesn’t really help for waveform parametrisation

Cannot meet requirements without **Flexibility** in frame structure
Flexible and efficient use of all available non-contiguous spectrums and different network deployment scenarios: one big challenge for 5G.

The 5G air interface technologies will need to be flexible and capable of mapping various services.

Need to provide uniform service experience to users

Concept of the **unified frame structure for 5G**
Example of proposed Unified frame structure for 5G [13]
6 different planes, with different associated Time Transmission Interval

- **PRACH**: UE timing synchronisation process (connection request)
- **Non sync. plane**: MTC and M2M: sporadic communication
- **Data plane**: for sending data
- **Control plane**: normal control plane containing allocation information, modulation, coding scheme information (LTE compatibility)
- **Low latency data** and **Low latency control**: Shorter TTI and strict synchronisation for low latency communications.

- Need to revisit orthogonality and synchronisation for 5G
Several indicators are important for waveform parametrisation

1. Spectral Efficiency
2. Out of Band Emission [ACLR]
3. Peak To Average Power Ratio [PAPR]
4. Transceiver complexity
5. MIMO compatibility
6. Asynchronous access
7. Robustness to Channel effect (fading, doppler, . . .)
8. Robustness against hardware impairments
Definition: information rate that can be transmitted over a given bandwidth in a specific communication system

- Expressed both for time and frequency domains in \( \text{bit/s/Hz} \)
- Depends on waveform parametrisation (Time-Frequency grid) and also on modulation order (constellation) and Channel/source coding (linked to channel capacity)

Spectral Efficiency vs SNR for fiber for different transmission distance [14]
Related to spectrum occupation and potential interference between users

Associated to side lobe decay of the waveform in the **frequency** domain

Important for fragmented spectrum access and to fulfill mask requirements

Is also associated to **Adjacent Channel Leakage Ratio**
Define the amplitude variation of the signal

Mathematical expression of PAPR

\[ PAPR = \left( \frac{\max(|y[k]|^2)}{E[|y[k]|^2]} \right) \]

Linked to physical constraints on Power Amplifier (PA) on the transmission chain

For LTE-uplink, SC-FDMA has been chosen instead of OFDM to reduce PAPR

Often Complementary Cumulative Density Function (CCDF) is studied instead of PAPR

\[ CCDF(\gamma) = Pr \left( \frac{|y[k]|^2}{E[|y[k]|^2]} > \gamma \right) \]
Example of PAPR measure (burst 3ms) for 5G waveform candidates
- complexity is a key problem for low cost devices

- Take into account Tx // Rx architecture, waveform, hardware involved

- **Trade-Off** between complexity and flexibility

- Algorithm optimisation + hardware implementation
- Multiple Input Multiple Output [MIMO] compatibility
- Use multiple antenna to improve received SNR using *spatial diversity*

Massive MIMO principle (Beamforming) [8]
Improving capacity of channel using multiple antenna techniques

Capacity versus SNR, for several configurations [22]
- Sporadic traffic, M2M communications, need to relax synchronism

- In current OFDM systems, sync. is done with dedicated channels (PRACH,...), that leads to important synchronisation overhead

- New waveform can handle asynchronous access to spectrum
Multi-user access scenario: several users share the same bandwidth, and should be aligned in both time and frequency domains.

If it is not the case, interference between users.

Interference can be limited with the addition of guard bands but it reduces the spectral efficiency.

Asynchronous access scheme principle.
Carrier Mean Square Error for OFDM without Guard Carrier and without CFO
Channel can be time-frequency dispersive

Multipath channel in time domain: Frequency selectivity with notion of Coherence bandwidth

Channel may vary in time: Coherence time of channel

Waveform choice is particularly important when facing channel effect. CHEST should handle double-dispersive channel with low complexity.

Time-Frequency channel estimation [OFDM waveform, USPR N-210]
Impairments and pollution introduced by the transceiver itself

Analog pollution due to leakage, coupling, imperfections

Can severally degrade the overall link performance

Several RF/Hardware impairments sources
  - Carrier Frequency Offset
  - Phase noise
  - IQ-Mismatch
  - ...

To limit the effect of HW impairments
  - Design constraints to fulfill performance mask
  - Active cancellation techniques (filtering / signal processing)
Impact of hardware impairments on QPSK constellation (w/o channel and noise) [18]
Hardware impairments

Classical FDD-ZIF architecture [18]
This impairment is due to imperfections of oscillator (in both Tx and Rx stage)

Classical **Zero Intermediate Frequency** Transceiver use complex orthogonality to multiplex 2 paths [using cosine / sine base]

**The transmitted signal is**

\[ s_{\text{HF}}^{\text{Tx}}(t) = s_{\text{TxI}}(t) \cos(2\pi f_{\text{Tx}}t) - s_{\text{TxQ}}(t) \sin(2\pi f_{\text{Tx}}t) , \]

Using complex formalism (analytic signal)

\[
\begin{align*}
    s_{\text{Tx}}(t) &= s_{\text{TxI}}(t) + js_{\text{TxQ}}(t) , \\
    s_{\text{HF}}^{\text{Tx}}(t) &= \text{Re} \left\{ s_{\text{Tx}}(t)e^{2j\pi f_{\text{Tx}}t} \right\} ,
\end{align*}
\]
The oscillator on Rx path uses 2 branches:

\[ s_{I}^{OL}(t) = 2 \cos(2\pi f_{Rx}t) \]
\[ s_{Q}^{OL}(t) = 2 \cos \left( 2\pi f_{Rx}t + \frac{\pi}{2} \right) = -2 \sin(2\pi f_{Rx}t) \]

**IQ-Mismatch** : Gain and phase error

\[ s_{I}^{OL}(t) = g_{I} \cos(2\pi f_{Rx}t + \phi_{I}) \]
\[ s_{Q}^{OL}(t) = -g_{Q} \sin(2\pi f_{Rx}t + \phi_{Q}) \]
**Consequence:** Signal cannot be properly recover: We get a mixture of I and Q paths in each path

Model [29]

\[
D(n) = \begin{bmatrix}
g_I \cos(\phi_I) & g_I \sin(\phi_I) \\
-g_Q \sin(\phi_Q) & g_Q \cos(\phi_Q)
\end{bmatrix}
\times \begin{bmatrix}
x_I(n) \\
x_Q(n)
\end{bmatrix}
\]

Model (complex formulation) [30]

\[
d(n) = K_1 x(n) + K_2 x^*(n),
\]

with \((\cdot)^*\) denotes complex conjugate and \(K_1\) and \(K_2\) are IQ mismatch constants expressed as

\[
K_1 = \frac{1}{2} \left[ g_I e^{-j\phi_I} + g_Q e^{-j\phi_Q} \right] \quad K_2 = \frac{1}{2} \left[ g_I e^{j\phi_I} - g_Q e^{j\phi_Q} \right].
\]
IQ-Mismatch: Origin & Model

Impact of Mismatch on QPSK constellation (OFDM)
How to limit or compensate IQ Mismatch?

- **Calibration** techniques: Assuming that gains and phases are slowly varying, uses link between Tx and Rx to estimate the gain and phase.

- **Reference signal** techniques: Using pilots or reference signal to estimate and recalibrate the oscillator.

- Also **Active techniques**: using digital signal processing techniques in the **Digital Front End**

Blind Source Separation Estimation for IQ Mismatch compensation [18]
This impairment is due to imperfections of oscillator (in both Tx and Rx stage)

Due to time-varying phase component in oscillator

Consequence: Spread the bandwidth of frequency components

Influence of Phase noise on pure sinusoid component
- Particularly detrimental for millimeter wave transmissions, for multi-carrier waveforms
- Phase noise is defined in Frequency domain
- For many 5G waveform candidates, Phase noise and Phase Noise compensation is under investigation

<table>
<thead>
<tr>
<th>Paramètres</th>
<th>Valeur</th>
<th>Unité</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_0$</td>
<td>-95</td>
<td>dBc/Hz</td>
</tr>
<tr>
<td>$f_{\text{corner}}$</td>
<td>1</td>
<td>kHz</td>
</tr>
<tr>
<td>$B_{\text{PLL}}$</td>
<td>100</td>
<td>kHz</td>
</tr>
<tr>
<td>$L_{\text{Floor}}$</td>
<td>-150</td>
<td>dBc/Hz</td>
</tr>
</tbody>
</table>
### Timing jitter and Carrier frequency offset
- This impairment is due to imperfections of oscillator (in both Tx and Rx stage)
- Consequence depends on used waveform (SC: constellation rotation)
- Use feedback (Tx/RX or BS/UE) to estimate these impairments

### Non linearity of power amplifier
- Due to PA in Tx stage that is not perfectly linear
- Influence of non linearity can be modeled with Saleh model [25] or Taylor/Volterra series [33]
- Can partially breaks frequency localisation of the waveform and introduce interference (orthogonality broken)
- Possible to use pre-coding scheme to limit effect of non linearity

### Additive spurious content
- Pure tone at specific frequency due to leakage of clocks or PLL
- Introduces intermodulation products or saturation at leakage frequency
Hardware impairments must be studied and take into account in 5G systems.

Due to strong design constraints and multiplicity of use-cases, Joint channel estimation / Hardware compensation / waveform parametrisation should be done.

Dirty RF paradigm [17] can be a strong help in the design and the specification of 5G physical layer.
5G: Fragmentation of Use-cases and scenarios: many varieties of applications,

Need to investigate for flexible waveforms that can handle different services

Several indicators have been set to evaluate waveforms:
- Data rates (Spectral Efficiency, MIMO),
- Implementation (PAPR, complexity, resistance against hardware impairments)
- Time-frequency plan and propagation (resistance against channel effects, asynchronous access, out of band emission)

Which candidates for 5G physical layer?
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4. Waveforms for 5G: the candidates
   4.1 CP-OFDM & SC-FDMA: the reference
   4.2 UF-OFDM: The Alcatel-Lucent proposition
   4.3 FBMC: Flexible single carrier parallelization
   4.4 GFDM: a non-orthogonal waveform

5. Conclusion & perspectives
Focus here on **multicarrier** waveforms

Different waveform, all based on time-frequency partition

- **CP-OFDM**: Cyclic Prefix Orthogonal Frequency Division Multiplexing
- **UFMC**: Universal Filtered MultiCarrier (or UF-OFDM)
- **GFDM**: Generalized Frequency Division Multiplexing
- **FBMC**: Filter Bank Multicarrier
CP-OFDM is currently the most used multicarrier modulation

- IEE.802.11, LTE, ...

Some advantages: low complexity, simple equalisation scheme, MIMO compatibility,

- Easy implementation with IFFT/FFT process
- One tap per subcarrier for estimation
- Resistance against channel with delay spread lower than the Cyclic prefix length
- Frequency diversity and space diversity in MIMO techniques

PAPR is huge, SC-FDMA for LTE uplink mode to reduce it (Precoding)
Transmit $N_c$ in parallel (using $N_c$ sub-channels), each with duration $T = N_c T_e$ [$T_e$ is Elementary time]

Each channel has carrier frequency $f_c = f_0 + \Delta_f$ of width $W_c = W_s / N_c$

Equalisation is simple as it is based on each channel: less fluctuations over $W_c$ (if coherence bandwidth is large enough)

Channel must be constant over a symbol: importance of the coherence time!
FDM approach: separate each band in frequency domain \textbf{BUT} loss of Spectral Efficiency

- Possibility to allow overlapping in frequency domain without interference between carriers (ICI): maintain \textbf{Orthogonality}: that’s OFDM!

- We denote the base functions $\Psi^k(t) = e^{2j\pi k\Delta f t}$.

- The orthogonality is maintained if

$$<\Psi^k(t), \Psi^m(t)>_T = \delta(k, m)$$

That leads to
FDM approach: separate each band in frequency domain **BUT** loss of Spectral Efficiency

- Possibility to allow overlapping in frequency domain without interference between carriers (**ICI**): maintain **Orthogonality**: that’s OFDM!

- We denote the base functions $\Psi^k(t) = e^{2j\pi k \Delta f t}$.

- The orthogonality is maintained if

$$< \Psi^k(t), \Psi^m(t) >_T = \delta(k, m)$$

That leads to

$$< \Psi^k(t), \Psi^m(t) >_T = \frac{1}{T} \int_0^T (e^{2j\pi k \Delta f t})(e^{2j\pi m \Delta f t})^* dt$$

$$= \frac{1}{T} \int_0^T (e^{2j\pi k \Delta f t})(e^{-2j\pi m \Delta f t}) dt$$

$$< \Psi^k(t), \Psi^m(t) >_T = \frac{1}{T} \int_0^T e^{2j\pi (k-m) \Delta f t} dt$$
For $k \neq m$, the orthogonality condition is then

\[
(e^{2j\pi(k-m)\Delta fT} - 1) = 0
\]

\[
e^{2j\pi(k-m)\Delta fT} = 1
\]

\[
2\pi(k - m)\Delta fT = 2\pi K \text{ avec } K \in \mathbb{Z}
\]

\[
\Delta f = \frac{K}{T}
\]

Maximal spectral Efficiency is obtained with

\[
\Delta f = \frac{1}{T} \quad (1)
\]
Practical OFDM implementation: Tx stage

- Modulation in frequency domain is done with an Inverse Fast Fourier Transform (equivalent to direct mapping)
- Insertion of Cyclic Prefix (CP): end of symbol is appended on the beginning to ensure circularity of OFDM signal
Insertion of Cyclic Prefix: eliminate ISI (Intersymbol interference) and prevent ICI (Inter carrier interference)
Receiver stage: drop cyclic prefix (loss of spectral efficiency)

Channel equalisation using preamble or scattered pilots

CHEST is done in the frequency domain
An OFDM symbol can be expressed as

\[ x_k = r_{N,N_c} \times F_N^H \times A_k \]

- \( F_N \) is the discrete Fourier Matrix

\[
F_N = \frac{1}{\sqrt{N}} \begin{bmatrix}
1 & 1 & 1 & \ldots & 1 \\
1 & w_N & w_N^2 & \ldots & w_N^{N-1} \\
\vdots & \vdots & \vdots & \ddots & \vdots \\
1 & w_N^{N-1} & w_N^{2(N-1)} & \ldots & w_N^{(N-1)(N-1)}
\end{bmatrix}
\]

- with \( a_k \) is the \( k^{th} \) symbol to transmit,
- \( N_c \) the length of the cyclic prefix and
- and \( r_{N,N_c} \) the CP insertion matrix of size \( N + N_c \times N \), defined as

\[
r_{N,N_c} = \begin{bmatrix}
0_{N_c,N-N_c} & 1_{N_c} \\
1_N & 1_N
\end{bmatrix}
\]

where \( 0_{N_c,N-N_c} \) is the zero-matrix of size \( N_c \times N - N_c \) and \( 1_N \) is the unitary matrix of size \( N \times N \).
- Mathematical model of channel impact
- Received signal without synchronisation

\[ r(p) = \begin{bmatrix}
  r_1(p) \\
  \vdots \\
  r_N(p) \\
  \tilde{r}_{N+\Delta}(p)
\end{bmatrix} = \begin{bmatrix}
  \tilde{r}_{\Delta+1}(p) \\
  \vdots \\
  \tilde{r}_{N+\Delta}(p)
\end{bmatrix} = \begin{bmatrix}
  h_{L_1-1} & \cdots & h_0 & 0 & \cdots & 0 \\
  0 & \ddots & \vdots & \ddots & \vdots & \ddots \\
  \vdots & \ddots & 0 & h_{L_1-1} & \cdots & h_0 \\
  \tilde{s}_{\Delta-L+1}(p) \\
  \vdots \\
  \tilde{s}_{N+\Delta}(p)
\end{bmatrix}_{N \times (N+L_1)} \begin{bmatrix}
  s_{\Delta-L+1}(p) \\
  \vdots \\
  s_{N+\Delta}(p)
\end{bmatrix}_{N+L_1} \]
Channel equalisation

- Mathematical model of channel impact
- Getting synchronisation (channel in the cyclic prefix)

$$r(p) = \begin{bmatrix}
    h_0 & 0 & \ldots & 0 & h_{L_t-1} & \ldots & h_1 \\
    h_1 & \ddots & & \ddots & & & \vdots \\
    \vdots & & \ddots & & \ddots & & \vdots \\
    h_{L_t-1} & \ddots & & \ddots & & \ddots & h_1 \\
    0 & \ddots & & \ddots & & \ddots & \vdots \\
    \vdots & & \ddots & & \ddots & & \ddots \\
    0 & \ldots & 0 & h_{L_t-1} & \ldots & h_1 & h_0
\end{bmatrix} \begin{bmatrix}
    s_1(p) \\
    \vdots \\
    \vdots \\
    s_N(p)
\end{bmatrix}$$
On Rx side, the received signal is

\[ y(p) = \mathbf{FHF}^H \mathbf{x}(p) \]

- With \( H \) circular matrix composed of channel submatrix
- In Fourier domain, decomposition of Fourier Matrix is diagonal

\[
y(p) = \begin{bmatrix}
H_1 & 0 & 0 & 0 \\
0 & \ddots & \ddots & \vdots \\
\vdots & \ddots & \ddots & 0 \\
0 & 0 & \ldots & H_N
\end{bmatrix} \times x(p)
\]

- One tap per subcarrier
OFDM is the waveform used in 4G, why not for 5G?

Let’s have a look on the KPIs

1. Spectral Efficiency
2. Out of Band Emission [ACLR]
3. Peak To Average Power Ratio [PAPR]
4. Transceiver complexity
5. MIMO compatibility
6. Asynchronous access
7. Resistance to Channel effect (fading, doppler, . . .)
8. Resistance against hardware impairments
OFDM for 5G

- OFDM is the waveform used in 4G, why not for 5G?
- Let’s have a look on the KPIs

1. Spectral Efficiency  ✗
2. Out of Band Emission [ACLR]  ✗
3. Peak To Average Power Ratio [PAPR]  ✗
4. Transceiver complexity  ✓
5. MIMO compatibility  ✓
6. Asynchronous access  ✗
7. Resistance to Channel effect (fading, Doppler, . . .)  ✓
8. Resistance against hardware impairments ( ✗, ✓)
- Spectral efficiency loss due to CP insertion

- Raw spectral efficiency expression

\[ \eta_{OFDM} = \]

- \( n \): modulation order (bit per symbol)
- \( N_{Re} \): Number of enable carriers (Ressource Elements)
- Maximal SE when \( N_{Re} = N_{FFT} \): loss due to CP insertion
Spectral efficiency

- Spectral efficiency loss due to CP insertion

- Raw spectral efficiency expression

\[ \eta_{OFDM} = \frac{n \times N_{Re}}{N_{FFT} + N_{CP}} \]

- \( n \): modulation order (bit per symbol)
- \( N_{Re} \): Number of enable carriers (Resource Elements)
- Maximal SE when \( N_{Re} = N_{FFT} \): loss due to CP insertion
Out of Band Emission

- OOB is parametrized by the waveform pulse shape
- For OFDM, pulse shape is sinc in frequency domain
- OFDM is perfectly localised in time domain, and thus poorly localized in frequency domain
OFDM is a multicarrier waveform with strong PAPR

Assuming $N_{Re}$ active subcarriers, with the same complex symbol transmitted ($a_k = 1, \forall k$), the max of the signal can be expressed as:

$$\max[x(t)x^*(t)] = \max \left[ \sum_{k=0}^{N_{Re}-1} a_k e^{\frac{2j\pi k}{T}} \times \sum_{k=0}^{N_{Re}-1} a_k^* e^{\frac{-2j\pi k}{T}} \right]$$

$$= \max \left[ \sum_{k=0}^{N_{Re}-1} \sum_{k=0}^{N_{Re}-1} |a_k|^2 e^{\frac{2j\pi k}{T} e^{\frac{-2j\pi k}{T}}} \right]$$

$$= N_{Re}^2$$

while the expectancy is

$$E[x(t)x^*(t)] = E \left[ \sum_{k=0}^{N_{Re}-1} \sum_{k=0}^{N_{Re}-1} |a_k|^2 e^{\frac{2j\pi k}{T} e^{\frac{-2j\pi k}{T}}} \right] = N_{Re}$$

For OFDM, PAPR can be approximated to $N_{Re}$ [802.11.ad : 17 dB !]. CCDF is more appropriate to evaluate the PAPR.
High PAPR is a real problem for low cost devices as it requires strong Power Amplifier.

For LTE-Uplink, an alternative has been used with Single Carrier Frequency Division Multiplexing.

Adding a precoding scheme in Tx to limit the PAPR in order to change the OFDM signal into a quasi single carrier one.
High PAPR is a real problem for low cost devices as it requires strong Power Amplifier.

For LTE-Uplink, an alternative has been used with Single Carrier Frequency Division Multiplexing.

Adding a precoding scheme in Tx to limit the PAPR in order to change the OFDM signal into a quasi single carrier one.
Influence of precoding on SC-FDMA

PAPR for 5G waveforms: Burst = 3 ms

PAPR for OFDM and SC-FDMA
What happens if several users use the same bandwidth without proper synchronisation access?

As OFDM uses sinc. in frequency domain, interference is preserved between 2 users perfectly synchronized. But interference is strong when it occurs!

Considering a certain use case [used in 5G project 5G-Now [2]]

- 2 users, one perfectly synchronized and a second not synchronized (in time and frequency domain)
- 3 RB for user 1, 9 RB for user 2
- There is a **Time offset** and a **Frequency offset** for user 2
Asynchronous Access

Power spectral density of the 2 users
Carrier MSE for OFDM with GC = 0 and CFO= 0%

Performance without guard carrier
Asynchronous Access

Carrier MSE for OFDM with GC = 1 and CFO = 0%

Performance with one guard carrier
CHEST in OFDM is simple, as one tap per subcarrier is possible

- Insertion of pilots with preamble or scattered pilot insertion

- Different CHEST architecture, Zero-Forcing (noise ampl.), Mean Square Error (MSE)
Considering a slow fading channel

Channel use-case in frequency domain (magnitude)
Impact on constellation without equalisation: only gain+phase (complex gain) influence
The CHEST here is one tap per subcarrier, with a Zero-Forcing equalisation: noise is enhanced in some carriers.

Constellation with CHEST
OFDM is a very well known multicarrier modulation

Main advantages
- Simplicity and low complexity with the IFFT/FFT implementation
- Simple equalisation model with CP insertion and one tap per subcarrier CHEST
- Easy MIMO compatibility
- Also, compatibility with existing standards, such as LTE

Main drawbacks
- Poor Frequency localisation (need additional guard carriers, and poor performance in asynchronous access)
- Spectral efficiency is lowered by the insertion of the CP
- High PAPR (addressed in the SC-FDMA mode)
- Potential weakness against hardware impairments
Derivation of CP-OFDM where a group of subcarrier is filtered in time domain

Introduced by Alcatel Lucent, based on the Resource Block (RB) filtering [28, 32, 31]

- In LTE, the smallest frequency element is not the carrier but the RB (i.e. 12 subcarriers)
- The filtering in time domain allows better localisation in frequency domain
- There is no Cyclic Prefix, but smooth transitions, still lower performance for multipath channel (orthogonality is not preserved)
UF-OFDM Transceiver

Modulated data stream $a_{1k}$
- Serial to parallel
- IDFT spreader & PS
- Filter $F_{1k}$ with length $L$

Modulated data stream $a_{2k}$
- Serial to parallel
- IDFT spreader & PS
- Filter $F_{2k}$ with length $L$

... (pattern repeated)

Modulated data stream $a_{Bk}$
- Serial to parallel
- IDFT spreader & PS
- Filter $F_{Bk}$ with length $L$

$x_k$ (sum of all filtered signals)
- Baseband to RF
- Channel
- RF to baseband

Frequency Domain processing (subcarrier equ.)
- 2 $N_{FFT}$ points IFFT
- Windowing & Serial to parallel
- Zero padding

UF-OFDM Transceiver
**Tx block**

- We consider $B$ group of subband (for example $B$ users in uplink).
- On each block is applied an IFFT of size $N$ and then filter in frequency domain.
- The $B$ bandpass signals are then added.

**Rx Block**

- The first operation is optional: Windowing effect.
- The received signal is length $N + L - 1$ due to filter of length $L$ so a $2N$ FFT is done on the receiver.
- The obtained signal is then decimated with a factor 2 to recover $N$ FFT points.
- CHEST is done after (similar to CP-OFDM).
The UF-OFDM signal can be expressed as

\[ x_k = \sum_{i=1}^{B} F_{i,k} \times V_{i,k} \times S_{i,k} , \]

- \( S_{i,k} \) is the data vector for the block \( i \),
- \( V_{i,k} \) is the IFFT matrix of size \( N_{FFT} \times n_i \) with appropriate frequency mapping
- \( F_{i,k} \) is the filtering matrix of size \( (N_{FFT} + L - 1) \times N_{FFT} \)

- The transmitted signal is then longer due to transient state of filtering BUT without CP insertion
- Convenient to have \( L = N_{CP} + 1 \)
- Need to add pre-distortion stage in Tx or Rx to limit the filter effect
Filter in time domain: Dolph-Chebyshev filter (low-pass) with parametrized size and rejection factor

UF-OFDM shaping filter

UF-OFDM Dolph Chebyshev filter

Filtering operation
Filter is applied both in Tx and Rx (matched filter)

After Tx filter: OOB is reduced

Power spectral density of RB for UF-OFDM and OFDM (source: [26])
- No CP but transient state of filter between consecutive symbol
- Orthogonality is not preserved but low interference as signal has low level in the transient shape
Spectral Efficiency depends on the filter length

\[ \eta_{UFMC} = \]

- \( n \) : modulation order (bit per symbol)
- \( N_{Re} \) : Number of enable carriers (Resource Elements)
- Comparable to OFDM
Spectral Efficiency depends on the filter length

\[ \eta_{UFMC} = \frac{n \times N_{Re}}{N_{FFT} + L} \]

- \( n \): modulation order (bit per symbol)
- \( N_{Re} \): Number of enable carriers (Resource Elements)
- Comparable to OFDM
The waveform is well localized in frequency domain so better performance on case of multi-user scenario ([2]).
Mean performance (MSE) in the same scenario

Performance versus time delay error

Performance of multiuser case for UF-OFDM and OFDM
Mean performance (MSE) in the same scenario

Performance versus time delay error

Performance of multiuser case for UF-OFDM and OFDM
Mean performance (MSE) in the same scenario

Performance versus time delay error

- OFDM: guard carrier = 5
- UFMC: guard carrier = 5

Performance of multiuser case for UF-OFDM and OFDM
Mean performance (MSE) in the same scenario

Performance versus time delay error

Performance of multiuser case for UF-OFDM and OFDM
If we have a look again on the UFMC transceiver

- Can help to separate contiguous users on the Rx side: particularly useful in the multi-user context
Performance in multi-user case for UFMC (no GC)
Additionnal Windowing

Carrier MSE for wUFMC with GC = 0 and CFO= 0%

Performance in multi-user case for UFMC (no GC)
Windowing helps to separate contiguous users for UFMC

Performance are better in multi-user asynchronous scheme

If the delay error is small, performance is not improved

- Windowing introduces self-interference between carriers, so if delay is small, self-interference is predominant
UF-OFDM addresses the poor frequency localisation of OFDM

- Let’s have a look on the KPIs

1. Spectral Efficiency
2. Out of Band Emission [ACLR]
3. Peak To Average Power Ratio [PAPR]
4. Transceiver complexity
5. MIMO compatibility
6. Asynchronous access
7. Resistance to Channel effect (fading, Doppler, ...)
8. Resistance against hardware impairments
UF-OFDM addresses the poor frequency localisation of OFDM

Let’s have a look on the KPIs

1. Spectral Efficiency ✗
2. Out of Band Emission [ACLR] ✓
3. Peak To Average Power Ratio [PAPR] ✗
4. Transceiver complexity ✓
5. MIMO compatibility ✓
6. Asynchronous access ✓
7. Resistance to Channel effect (fading, Doppler, . . .)  ✓ ✓
8. Resistance against hardware impairments ?
UF-OFDM is a promising candidate for 5G waveform

**Main advantages**
- The RB filtering allow better behaviour in frequency domain and still offer very good compatibility with OFDM
- The transceiver is more complex but the enhancement is reasonable (compared to some other candidates)
- The multi-user access scenario performance are better, and can be improved with Windowing in reception

**Main drawbacks**
- Orthogonality is not preserved so lower performance is expected in case of selective channels
- Resistance to hardware impairments (and compensation) need to be investigate
- Same Spectral efficiency as OFDM
- High PAPR
FBMC principle

- Based on the **parallelization** of single carrier paths
- Each path is shaped by a shaping filter, frequency translation of a **prototype** filter
- Frequency location and frequency spreading of each path (or carrier) can be controlled and optimized
- The data is not block-based but **contiguous**
- Classic implementation: **Polyphase Network PPN**
Each path is first oversampled, filtered by the prototype filter and then frequency translated at the carrier frequency.

The oversampling factor $K$ is defined within the filter.

Possible implementation of FBMC (source [9])
Polyphase Network Implementation

- Can be rephrased as a Polyphase Network Structure (PPN) with the use of IFFT scheme
- $Z$ represents the frequency shift in the frequency domain, with $M$ the oversampling factor, and the IFFT is on $MN$ samples

FBMC synthesis with PPN architecture [7]
- Analysis in the receiver with important complexity due to filter in oversampling mode
- The complete structure can be based on PPN architecture

FBMC analysis with PPN architecture [7]
Filters are based on **prototype** filters of length $KN$.

- Example for $N = 1024$, $K = 4$
In PPN, filter is defined in time domain and applied after IFFT.

An other approach is to directly consider filters in frequency domain, and see the oversampling+filtering (in time) as a spreading in frequency.

This approach is called **Frequency Spreading** FBMC [6, 5].

Replacing PPN by FS.
Final FFT is on $KN$ points, because each carrier is spread in the frequency domain.

The spreading factor $P = 2K - 1$ with $K$ the filter parameter (called overlapping factor).

The carriers then overlap in frequency domain.

The filter is now defined in the frequency domain by $2K - 1$ points.

- This taps will multiply in frequency domain the subcarriers.
- The taps values must satisfy some conditions [23].
For $K = 4$

\[
G_0 = 1 ; G_1 = 0.971960 = G_{-1} ; \\
G_2 = \frac{\sqrt{2}}{2} = G_{-2} ; G_3 = \sqrt{1 - \frac{G_1^2}{2}} = G_{-3}
\]

For $K = 3$:

\[
G_0 = 1 ; G_1 = 0.911438 = G_{-1} ; \\
G_2 = 0.411438 = G_{-2}
\]

and for $K = 2$:

\[
G_0 = 1 ; G_1 = \frac{\sqrt{2}}{2} = G_{-1}
\]

The impulse response of the prototype filter is given by:

\[
h(t) = G_0 + 2 \sum_{k=1}^{K-1} (-1)^k G_k \cos \left( \frac{2 \pi k}{KN} (t + 1) \right)
\]
FBMC filter in frequency domain (for 3 subcarriers) [5]
Each carrier is multiplied by the taps and then added in the frequency domain [6]

*Overlap and sum* operation as symbol overlap also in time domain

**FS-FBMC Transmitter stage**
FBMC symbol structure: need overlap and sum operation

FBMC symbols in time domain

- The overlapping in time domain depends on overlapping factor $K$
On receiver side $KN$ FFT is applied and matched filter approach

**FS-FBMC receiver [5]**
FS-FBMC Mathematical model using matrix formulation

\[ x(n) = F_{KN}^HGA_n + \sum_{p=1}^{P-1} \left( Q_{\frac{PN}{2}} F_{KN}^HGA_{n-p} + Q_{N-\frac{PN}{2}} F_{KN}^HGA_{n+p} \right) \]

- \( G \) is the prototype matrix \( KN \times N \)
- \( A_n \): data to transmit
- \( F_{KN} \): DFT matrix of size \( KN \times KN \)
- \( Q_x \): delay matrix to apply overlap and sum
Filters overlap in both time and frequency domains: FBMC with QAM modulation is non orthogonal.

This issue can be handled by the replacement of OQAM with another system that guarantees orthogonality.

As the filter is well localized in the frequency domain, only consecutive neighbours will interfere.

The filter is real so interference will be real. The solution is to use the complex field to recover orthogonality [27].
OQAM modulation: alternation of pure real and pure imaginary samples in the time frequency lattice

Time $T_s$ between 2 symbols is divided by 2
Incorporation of OQAM in FBMC modulation

- QAM to OQAM transformation is a complex to real with additional delay
- Considering only real symbols with an additional phase rotation to apply OQAM

OQAM modulation | OQAM demodulation
Include FBMC-OQAM in FBMC Tx-Rx scheme

FBMC-OQAM transceiver [15]
- OQAM with FBMC guarantees orthogonality and same spectral efficiency as QAM

- However, the prototype filter must be adequate

- **Transmultiplexer** matrix: time-frequency interference matrix, based on Tx and Rx stages

![Transmultiplexer matrix for Phydias filter $K = 4$](image)
Overlapping in time domain

- Each OQAM symbol is filtered by the prototype filter and has a length $K \times N$
- A complex symbol is of size:
- $S$ QAM-symbols duration last:
Overlapping in time domain

- Each OQAM symbol is filtered by the prototype filter and has a length $K \times N$
- A complex symbol is of size: $KN + N/2$
- $S$ QAM-symbols duration last: $\frac{N}{2} \times (2S - 1) + KN$
FBMC is the parallelization of single carrier paths, that overlap in time and frequency domain.

Each carrier is shaped in frequency domain with the translation of a prototype filter.

The implementation can be done with a Polyphase Network architecture, or in Frequency domain with the **Frequency Spreading** architecture.

The **prototype filter** is defined in frequency domain by its non-null points that characterizes the frequency domain overlapping.

The orthogonality is preserved with an appropriate prototype filter with the use of **OQAM** modulation (alternation in time-frequency lattice).
- FBMC spectral efficiency is the same for QAM and OQAM modulation
- SE is number of bits per second per hertz
FBMC spectral efficiency is the same for QAM and OQAM modulation.

- SE is number of bits per second per hertz.

- Number of bits

\[ N = n \times N_{Re} \times S \]

- Length of FBMC signal

\[ T = \left( \frac{N}{2} \times (2S - 1) + KN \right) \times T_e \]

- Bandwidth

\[ B = 1/T_e \]

- Final Spectral Efficiency

\[ \eta_{FBMC} = \frac{n \times N_{Re} \times S}{\frac{N}{2} \times (2S - 1) + KN} \]
Comparison between spectral efficiency of FBMC and OFDM/UFMC

Spectral Efficiency comparison between UFMC/OFDM and FBMC
Power spectral density of FBMC filter $K = 4$
Power spectral density of FBMC filter $K = \{2, 3, 4\}$
Channel estimation is not easy in FBMC as scattered pilot insertion is not straightforward due to OQAM modulation.

Need to use some preamble frame structure to estimate channel and to perform synchronisation.

Preamble system for FBMC-OQAM [11]
With the use of FBMC-OQAM with FS architecture, CHEST is done in the frequency domain.

More resilient against long delay spread channel
CHEST is done in the frequency domain with FS-FBMC

Need however longer FFT ($K \cdot N$) and memory
FS-FBMC can resist against long delay spread channels

Bit Error Rate versus delay spread of the channel [12]
FBMC is perfectly localised in frequency domain: with the use of OQAM modulation, it is possible to totally reject the interference at the price of one guard carrier insertion.

Carrier MSE for FBMC with GC = 0 and CFO= 0%
FBMC is perfectly localised in frequency domain: with the use of OQAM modulation, it is possible to totally reject the interference at the price of one guard carrier insertion.
Considering PAPR for a 3ms burst for OFDM, SC-FDMA, UFMC and FBMC

PAPR for several 5G candidates
FBMC: perfect frequency location

Let’s have a look on the KPIs

1. Spectral Efficiency
2. Out of Band Emission [ACLR]
3. Peak To Average Power Ratio [PAPR]
4. Transceiver complexity
5. MIMO compatibility
6. Asynchronous access
7. Resistance to Channel effect (fading, Doppler, . . .)
8. Resistance against hardware impairments
FBMC: perfect frequency location

Let’s have a look on the KPIs

1. Spectral Efficiency ✓
2. Out of Band Emission [ACLR] ✓
3. Peak To Average Power Ratio [PAPR] ❌
4. Transceiver complexity ❌
5. MIMO compatibility ❌
6. Asynchronous access ✓
7. Resistance to Channel effect (fading, Doppler, …) ✓
8. Resistance against hardware impairments ?
FBMC-OQAM is well suited for 5G

**Main advantages**
- Perfect frequency localisation, very low OOB leakage due to filter optimisation
- Spectral efficiency is very good. The longer the burst the better
- Very good performance in case of long delay spread channel with the FS architecture

**Main drawbacks**
- OQAM should be used to preserve orthogonality: non straightforward compatibility with LTE
- Long burst mode due to the $KN$ IFFT (can be parametrized)
- Due to QOAM, MIMO is not easy to implement, still an open question
- Complexity
- High PAPR
GFDM principle

- Generalized Frequency Division Multiplexing introduced by Gerhard Fettweis [16]

- Can be seen a generalisation of CP-OFDM and Single carrier modes with \(2\) dimensions: addition of time domain in the shaping

Basic principle

- Data stream is reshaped in matrix form: \(d_k[m]\) : symbol sent from \(k^{th}\) subcarrier at time index \(m\) : \(M\) element in \(K\) subcarriers.

- Filtering each time slot of each subcarrier with a time and frequency shifted version of a prototype filter \(g(n)\)

- Superposition of all transmit symbols (on \(K\) subcarriers and \(M\) slots) to have the transmitted sequence \(x(n), N = 0 \ldots N - 1\)

- Addition of a CP
Each element of the obtained matrix is filtered by a **shaping filter** constructed from a **Prototype filter**

- Each shaping filter is a time-frequency translation of the prototype filter
- Due to the time-frequency grid, the filters overlap in both time and frequency domain
- GFDM is a **non orthogonal** waveform
GFDM principle (source [21])

- $g(n)$ can be a RRC, SRRC, 1st Xia, 4th Xia ([21])
GFDM formulation using matrix computation [20]

Transmitted signal is expressed as:

\[ x = \text{Diag} \left( G_{Tx} S^M_N D (S^N_M)^T F^H_{MN} \right) \]

- \( S^M_N \): Upsampling matrix (zero insertion) (N to MN)
- \( G_{Tx} \): pulse shape matrix
- \( D \): matrix of data symbols
GFDM formulation using matrix computation [20]

Received signal can be obtained through

- **Matched filter approach**: Inverse filtering is done, interference occurs

- **Zero Forcing approach**: inversion of transmultiplexer matrix: no self-interference but depends on matrix conditioning
Classic GFDM architecture is based on MF filtering

- Interference between subsymbols and carriers is strong
- Interference cancellation can be applied to improve the performance [10]

Decoded constellation with and without Interference cancellation
GFDM is **Generalized**: lot of parameters!

- Filter type
- Filter length (number of subsymbols per symbols)
- CP length
- Presence of windowing
- Type of Rx architecture

Performance can severally depends on these parameters
Considering different size of shaping filters (RRC filter)

Influence of filter size for GFDM
Considering different roll-off factor for GFDM

![BER vs Eb/No for GFDM with FEC = 0.75](image)

Influence of Roll-Off factor for GFDM
Example of GFDM configuration

BER vs Eb/No for GFDM with FEC = 0.75, α = 0.1, M=15

GFDM performance with appropriate configuration
What is GFDM spectral efficiency?

\[
\eta_{GFDM} = \frac{n \times N_{Re} \times M}{N_{FFT} \times M + N_{CP}}
\]

- \(n\): modulation order (bit per symbol)
- \(N_{Re}\): Number of enable carriers (Ressource Elements)
- \(M\): the number of subsymbol per symbols
- Maximal SE when \(N_{Re} = N_{FFT}\): loss due to CP insertion

2 choices

- Frequency resolution is same as OFDM (\(N_{Re}^{OFDM} = N_{Re}^{GFDM}\) and \(M > 1\)): GFDM SE is **higher** than OFDM (GFDM subsymbol \(\approx\) OFDM symbol) as there is one CP per symbol (M times less CP)
- Data block are identical (\(N_{Re}^{OFDM} = M \times N_{Re}^{GFDM}\)), GFDM and OFDM SE are **identical** (GFDM symbol \(\approx\) OFDM symbol)
- GFDM is based on pulse shape filtering: good spectral location?
  - Contrary to UFMC, filtering has no transient state as *circular convolution* is used instead.
  - It has consequence on OOB leakage

![Power Spectral Density Graph](https://via.placeholder.com/150)

- Frequency [MHz]
- Power Spectral density [dBc/Hz]

---

**Comparison of OOB leakage**

- OFDM
- UFMC
- GFDM
To improve the ALC, possibility to use windowing

- Window is applied after pulse shaping
- It introduces interference between carriers that can be handled by the IC scheme
Performance versus time delay error with CFO of 0

-10
-20
-30
-40
-50
-60
-70
-0.25 -0.2 -0.15 -0.1 -5 \cdot 10^{-2} 0 5 \cdot 10^{-2} 0.1 0.15 0.2 0.25

Time delay error (n/nFFT)

MSE [dB]

- GFDM : guard carrier = 0
- wGFDM : guard carrier = 0
- GFDM : guard carrier = 1
- wGFDM : guard carrier = 1
- GFDM : guard carrier = 2
- wGFDM : guard carrier = 2
- GFDM : guard carrier = 5
- wGFDM : guard carrier = 5

performance in multi-user access scheme for GFDM and weighted GFDM
Multiuser scenario

- GFDM is better with windowing
- GFDM performance is better than UFMC
- But, with a GC, lower performance compared to FBMC

performance in multi-user access scheme
Space time encoding system possible with classical OFDM derived Alamouti scheme

- Under the assumption that coherence time is longer than 2 consecutive GFDM symbols (longer than OFDM ones)

Space Time Encoding (STE) transmitter and receiver [2]
GFDM is the generalisation of SC and CP-OFDM

Let’s have a look on the KPIs

1. Spectral Efficiency ✓
2. Out of Band Emission [ACLR] ✓
3. Peak To Average Power Ratio [PAPR] ✗
4. Transceiver complexity ✗
5. MIMO compatibility ✓
6. Asynchronous access ✓
7. Resistance to Channel effect (fading, Doppler, ...) ✗
8. Resistance against hardware impairments ?
GFDM is a new candidate for 5G

**Main advantages**
- With windowing, the carrier filtering allows good performance in frequency domain with low OOB
- The compatibility with LTE is quite straightforward for MIMO and as GFDM can be parametrized to become CP-OFDM
- Parametrisation can help to fulfill different KPI

**Main drawbacks**
- Orthogonality is not preserved: poor performance, need IC but still better performance for other waveforms
- Complexity
- Some instabilities has been shown depending on parametrisation
- Many freedom degrees
- High PAPR
Summary

1. Introduction and context

2. From 1G to 4G: the path of history for communication

3. 5G: Unified framework and flexibility

4. Waveforms for 5G: the candidates

5. Conclusion & perspectives
5G framework need flexibility as it addresses many different use-case:
Flexible air interface and maybe unified frame structure

Strong investigations on 5G physical layer and on waveforms

KPIs help to adress 5G challenges
1. Spectral Efficiency
2. Out of Band Emission [ACLR]
3. Peak To Average Ratio [PAPR]
4. Transceiver complexity
5. MIMO compatibility
6. Asynchronous access
7. Resistance to Channel effect (fading, Doppler, . . .)
8. Resistance against hardware impairments
▶ There is no an **ideal** candidate for 5G waveform

▶ Many fields are under investigation in PHY
  ▶ MIMO compatibility and LTE retro-compat
  ▶ Hardware impairments resistance and investigation on compensation structure
  ▶ Specific millimeter-wave environment
  ▶ Frame structure, numerology, channel code . . .
  ▶ . . .

▶ Difficult but necessary to study and compare waveforms in realistic configuration
## Comparison between waveforms

- **Statement of KPIs and waveforms**

<table>
<thead>
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<th></th>
<th>OFDM</th>
<th>SC-FDMA</th>
<th>UFMC</th>
<th>FBMC-OQAM</th>
<th>GFDM</th>
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<tbody>
<tr>
<td>Spectral Efficiency</td>
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<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Complexity.</td>
<td>✓ ✓</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
<td>✗ ✓</td>
</tr>
<tr>
<td>MIMO</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✗</td>
<td>✓</td>
</tr>
<tr>
<td>Async.</td>
<td>✗</td>
<td>✗</td>
<td>✓</td>
<td>✓ ✓</td>
<td>✓</td>
</tr>
<tr>
<td>Channel</td>
<td>✓</td>
<td>✓</td>
<td>✓ ✓</td>
<td>✓</td>
<td>✓ ✓</td>
</tr>
<tr>
<td>Impairments</td>
<td>✗ (✓)</td>
<td>✗ (✓)</td>
<td>?</td>
<td>?</td>
<td>?</td>
</tr>
</tbody>
</table>
Example of waveform comparison

Comparison between waveforms [19]
3GPP Meeting in August 2016

- For the phase 1 of 5G (New Radio Work Item) should be specification transparent, i.e. the receiver does not need to know the filtering/windowing used at transmitter.
- Rx Stage should be FFT based!

OFDM seems to be still the best candidate!

- Not for all use case/scenarios
- For some use-cases, additional filtering operation should be done

FBMC cannot fulfill this requirement

- Still good ideas though!

Mixing waveform to optimize performance? Idea of BF-OFDM (CEA-Leti proposal)

- Internship open next semester!
Etude, portage et interfaçage d’une pile protocolaire OpenAirInterface avec un modem 5G

- Dimitri Ktenas [dimitri.ktenas@cea.fr]
- Define Hardware / Software partitionning for a 5G solution: Scheduling algorithm (MAC layer)
- With the use of Air Interface

Compétences:

- Domaines de spécialité requis : télécommunications, informatique & logiciel embarqué, électronique, protocole
- Moyens informatiques mis en oeuvre
  - Langages : C/C++, Matlab, VHDL
  - Logiciels : Linux, Eclipse, Matlab, Vivado
  - Niveau souhaité : Bac +5
  - Durée du stage : 6 mois
- Formation souhaitée : Ingénieur/Master2
Etude hardware et implémentation d’un opérateur FFT avec contrôle de flux

- Marc Laugeois [marc.laugeois@cea.fr]
- Etude et implémentation d’un opérateur FFT
- Evaluation performance + intégration dans une chaine matérielle

Compétences:

- Domaines de spécialité requis : Traitement du signal, architecture numérique
- Moyens informatiques mis en œuvre
  - Langages : MATLAB, VHDL
  - Logiciels : MATLAB, Xilinx VIVADO
  - Niveau souhaité : Bac + 4/5
- Formation souhaitée : Ingénieur/Master
Mise en œuvre d’une liaison 5G multiservice et expérimentation en condition réelle

- Jean-Baptiste Doré [jean-baptise.dore@cea.fr] et Robin Gerzaguet [robin.gerzaguet@cea.fr]
- Mise en place d’une couche physique en Hardware in the Loop (allocation, synchronisation, . . .)
- Mise en œuvre sur le campus du CEA, transmission en conditions réelles

Compétences:

- Domaines de spécialité requis : Traitement du signal, communication numérique (OFDM, MIMO, Synchronisation), couche physique
- Moyens informatiques mis en œuvre
  - VHDL, C C++, Matlab
  - Des notions en ingénierie radio (antennes, propagations) est un plus
- Formation souhaitée: élève en dernière année d’école d’ingénieur ou Master2.
References


Thank you for your attention
Any questions?

Multi-services and flexible air-interface:
Waveforms for 5G
Robin Gerzaguet, Jean-Baptiste Doré
End of presentation