FBMC/OQAM transceivers for 5G mobile communication systems

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“Modulation”

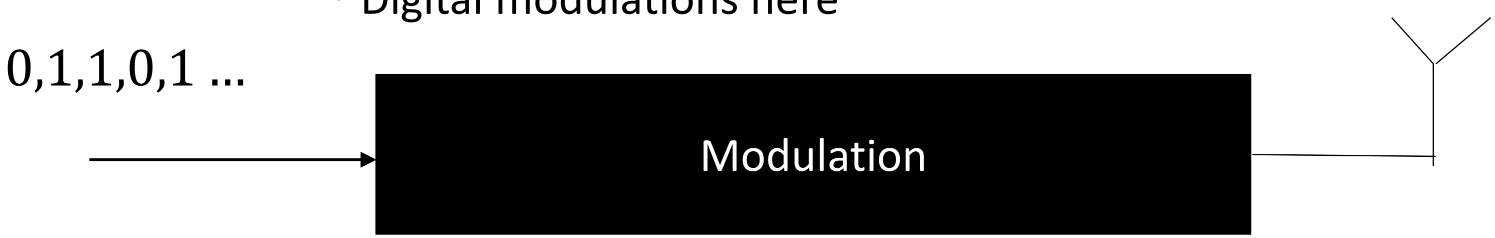
Wikipedia definition:

Process of varying one or more properties of a periodic waveform, called the carrier signal, with a modulating signal that typically contains information to be transmitted.

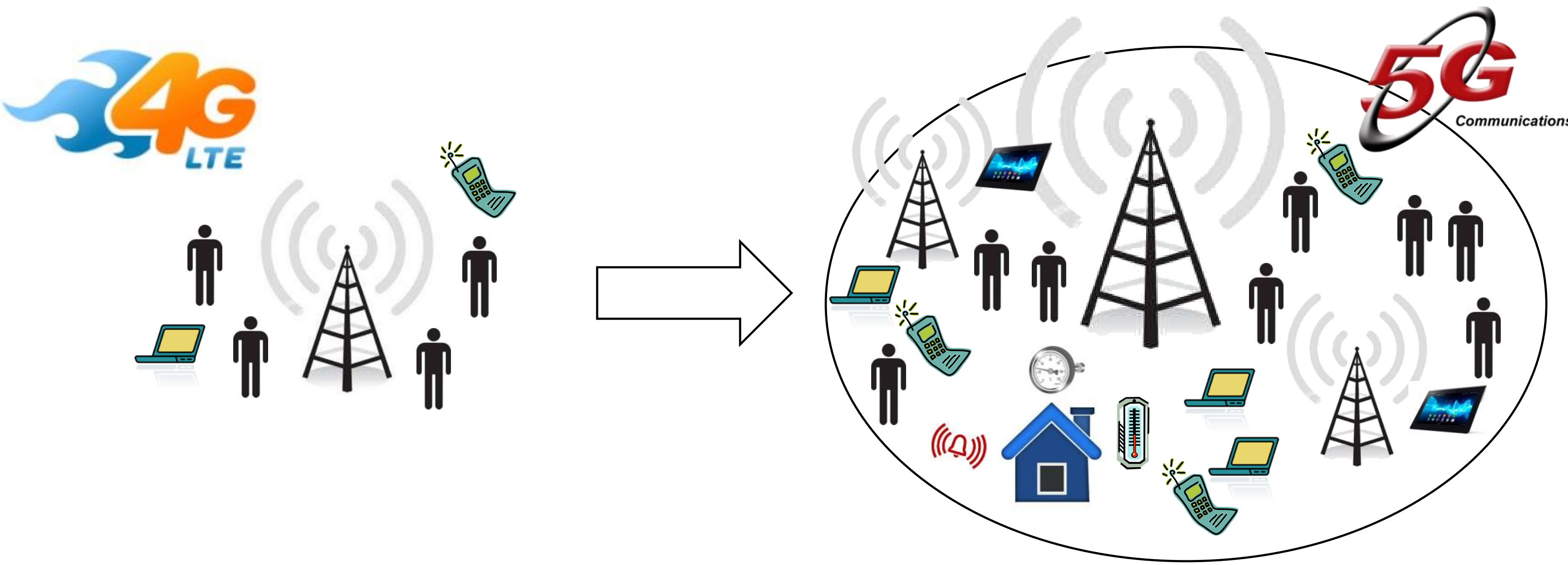
“Someone I know” definition:

Convert bits of information into an electromagnetic wave

Digital modulations here



Evolution of telecommunication standards



2010... 2030 | 2020... 2040

4G modulation format might not be the best to address 5G challenges

Outline

- Some basics
  - Single-carrier systems
  - Classical multicarrier systems
- FBMC-OQAM systems
  - Principle
  - Pros and cons
- My research

Outline “vulgarized”

Some basics “La télécom pour les nuls”

- Single-carrier systems “How are old systems working?”
- Classical multicarrier systems "4G-like systems"

FBMC-OQAM systems “The systems I study”

- Principle “How do they work?”
- Pros and cons “Why are they the best?”

My research “What am I doing?”

Outline

Some basics

- Single-carrier systems
- Classical multicarrier systems

FBMC-OQAM systems

- Principle
- Pros and cons

My research

Outline

Some basics

Single-carrier systems

"How are old systems working?"

Classical multicarrier systems

FBMC-OQAM systems

Principle

Pros and cons

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“Modulation”

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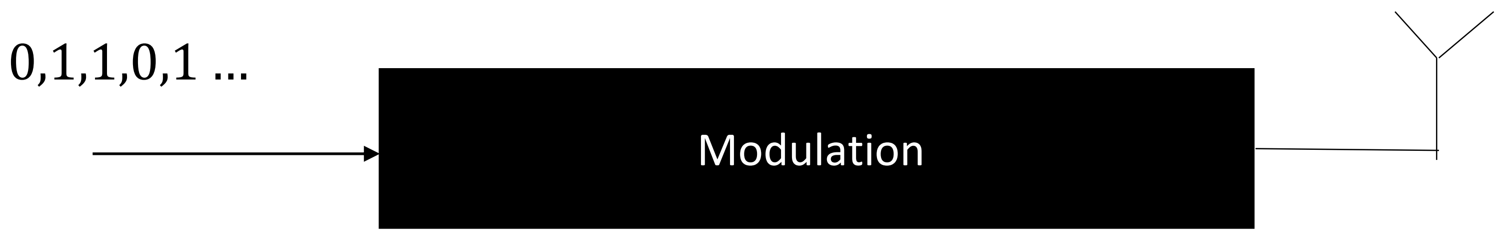
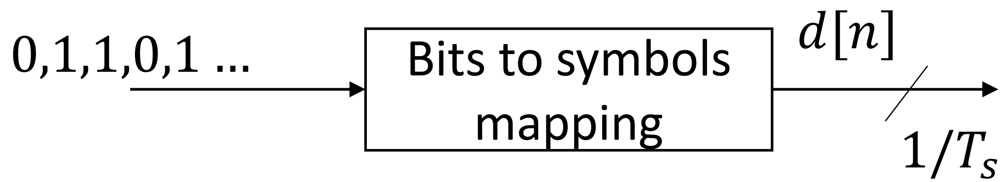


Bits to symbols mapping

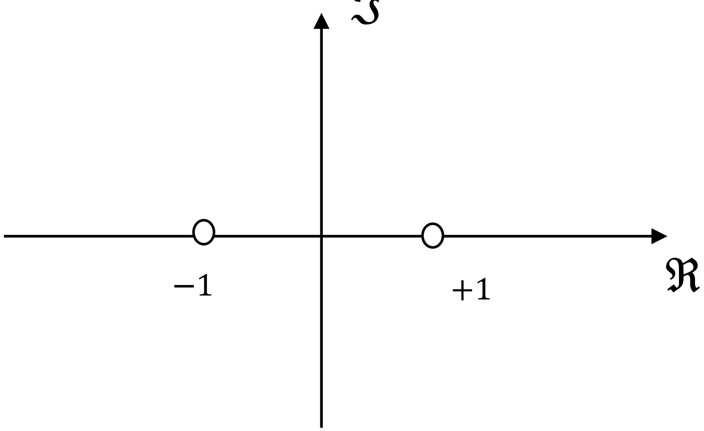


T_s is called the sampling period

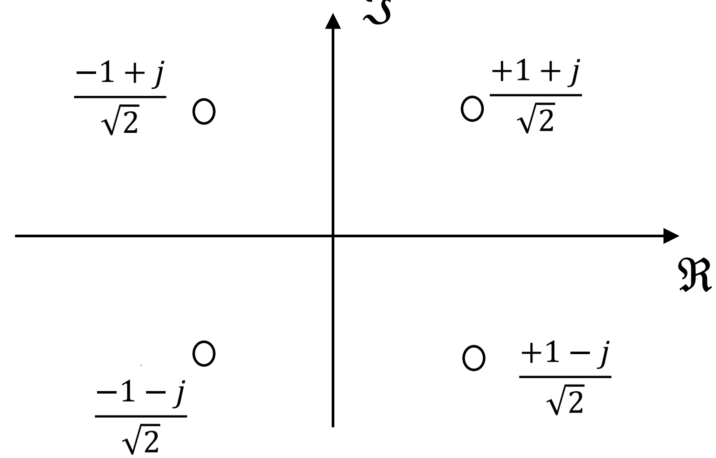
Symbols $\mathrm{d}[n]$ might be complex, contain one or more bits of information

Bits to symbols mapping

$d[n]$ might be complex, contain one or more bits of information



1 bit of information



2 bits of information

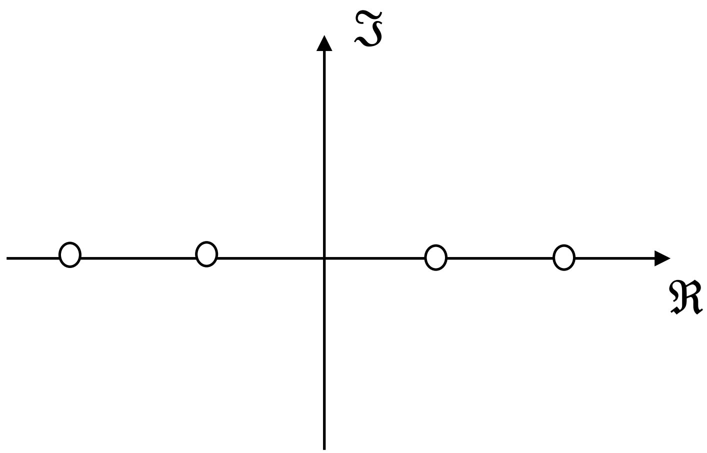
Incoming bits	Symbol $d[n]$
0	-1
1	+1

00	$\frac{-1-j}{\sqrt{2}}$
01	$\frac{-1+j}{\sqrt{2}}$

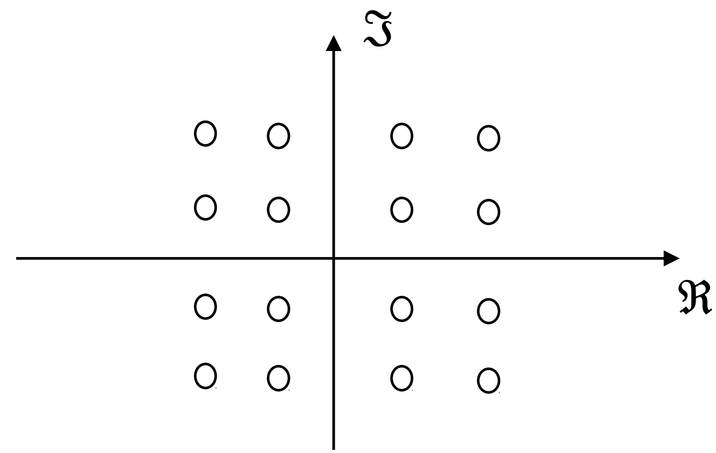
10	$\frac{+1-j}{\sqrt{2}}$
11	$\frac{+1+j}{\sqrt{2}}$

Bits to symbols mapping

$d[n]$ might be complex, contain one or more bits of information, depending on "link quality"…

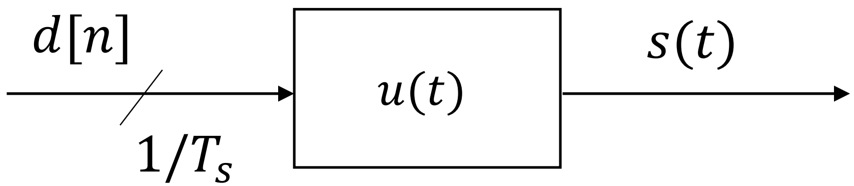


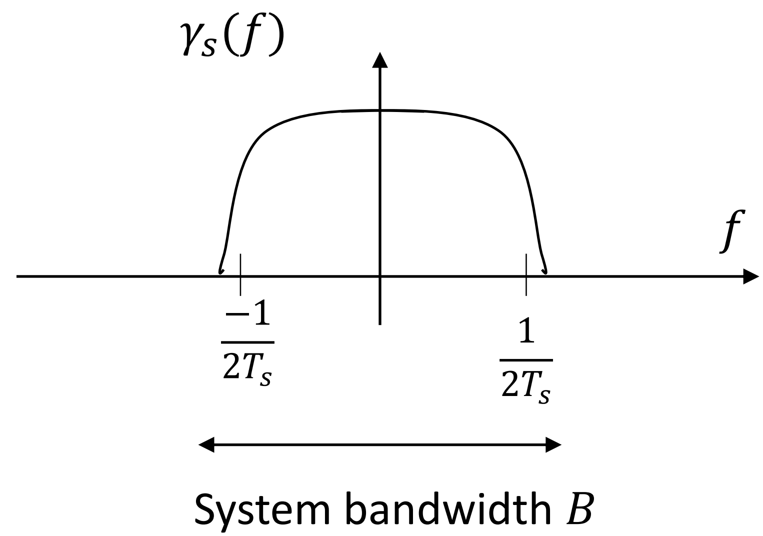
2 bits of information



4 bits of information

Digital to analog conversion (DAC)



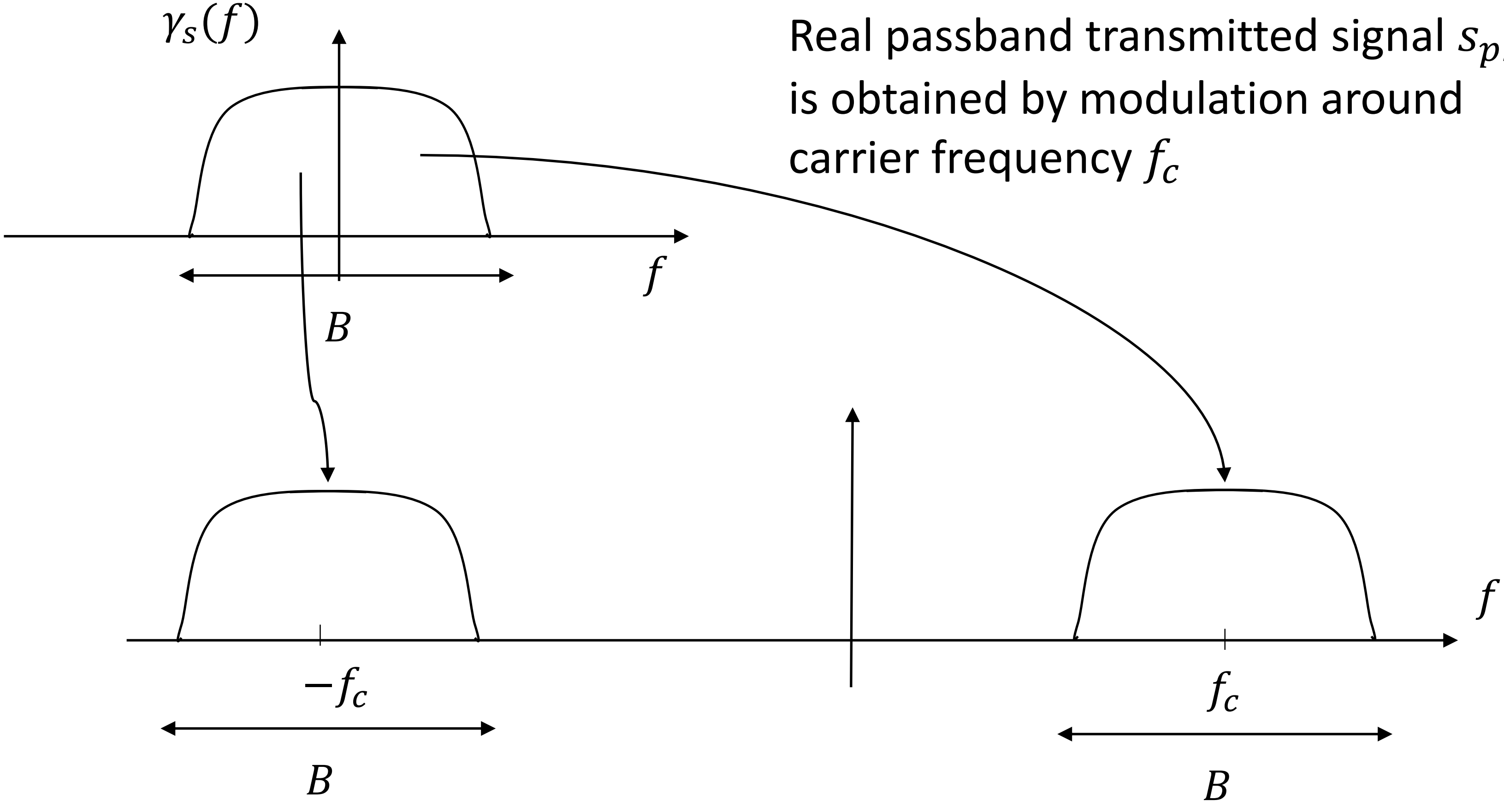


$$s(t) = \sum_n d[n]\delta(t - nT_s) \otimes u(t)$$

$$= \sum_n d[n]u(t - nT_s)$$

Wait… $s(t)$ complex?!

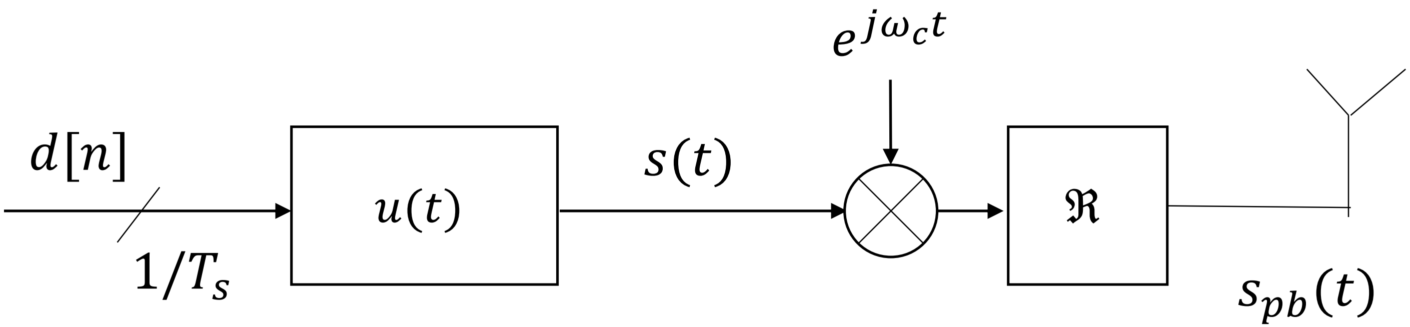
$s(t)$ is called the baseband equivalent of the transmitted signal



Real passband transmitted signal $s_{pb}(t)$ is obtained by modulation around carrier frequency f_c

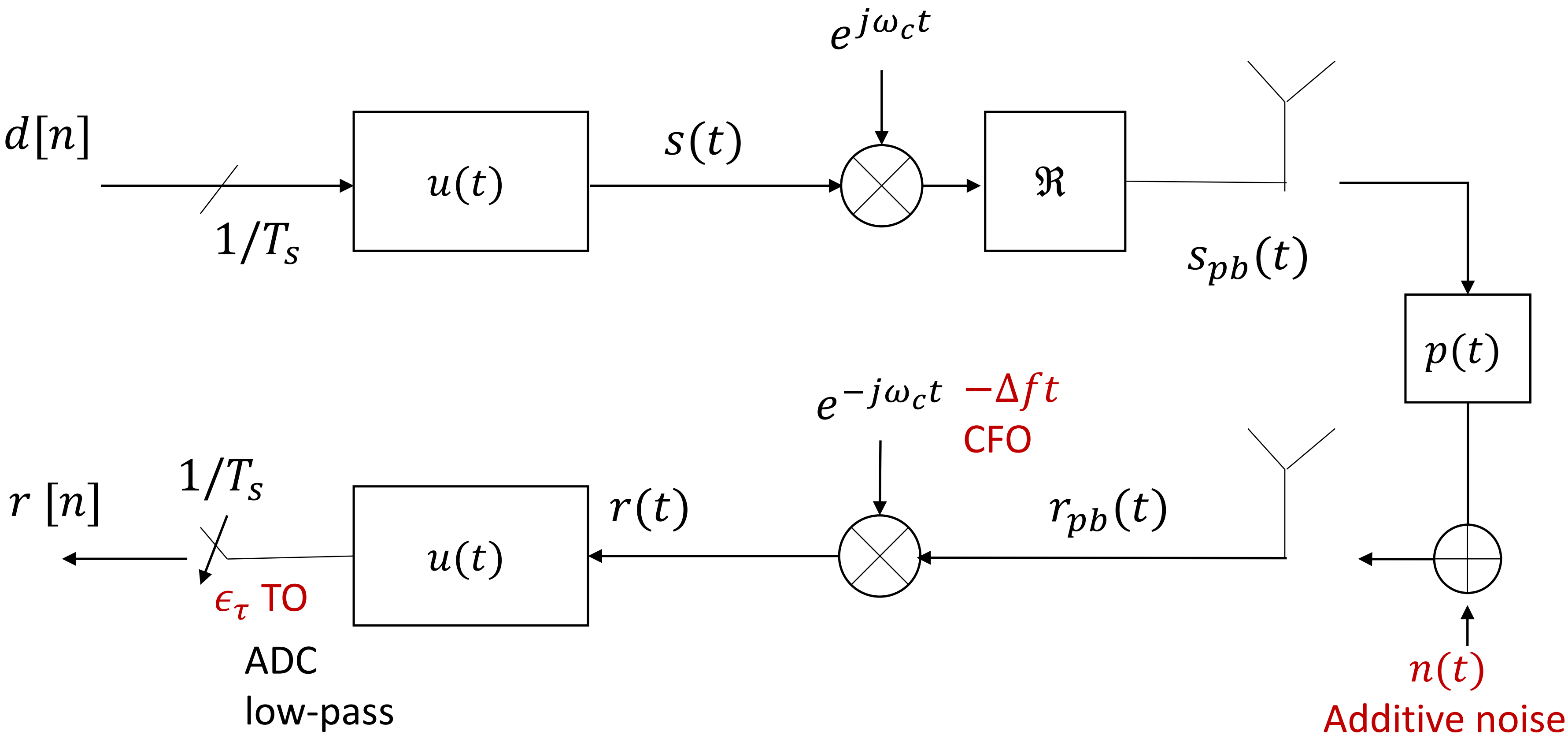
How in practice?

Analog mixer/oscillator/modulator…



$$s_{pb}(t) = \Re\left(s(t)e^{j\omega_c t}\right) = \Re\left(s(t)\right)\cos(\omega_c t) - \Im\left(s(t)\right)\sin(\omega_c t)$$

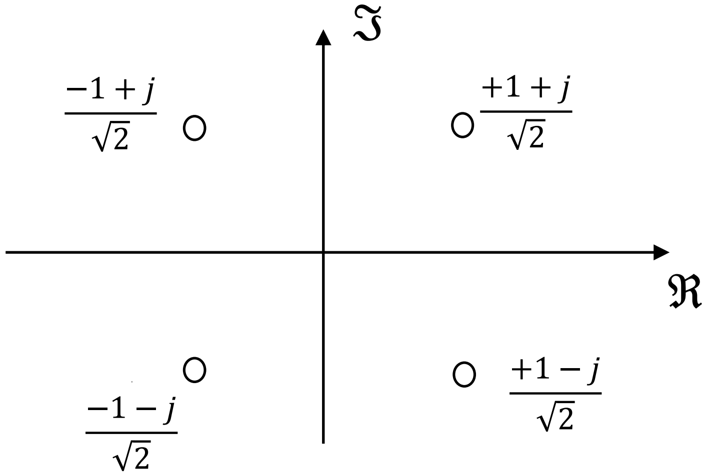
What about the receiver?



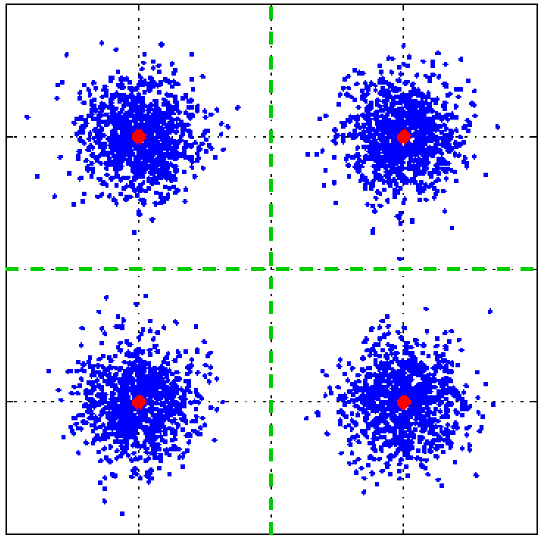
If $p(t) = \delta(t)$ and several conditions, we will have $r[n] = d[n]$. In practice, not really equality…

Noise and impairments

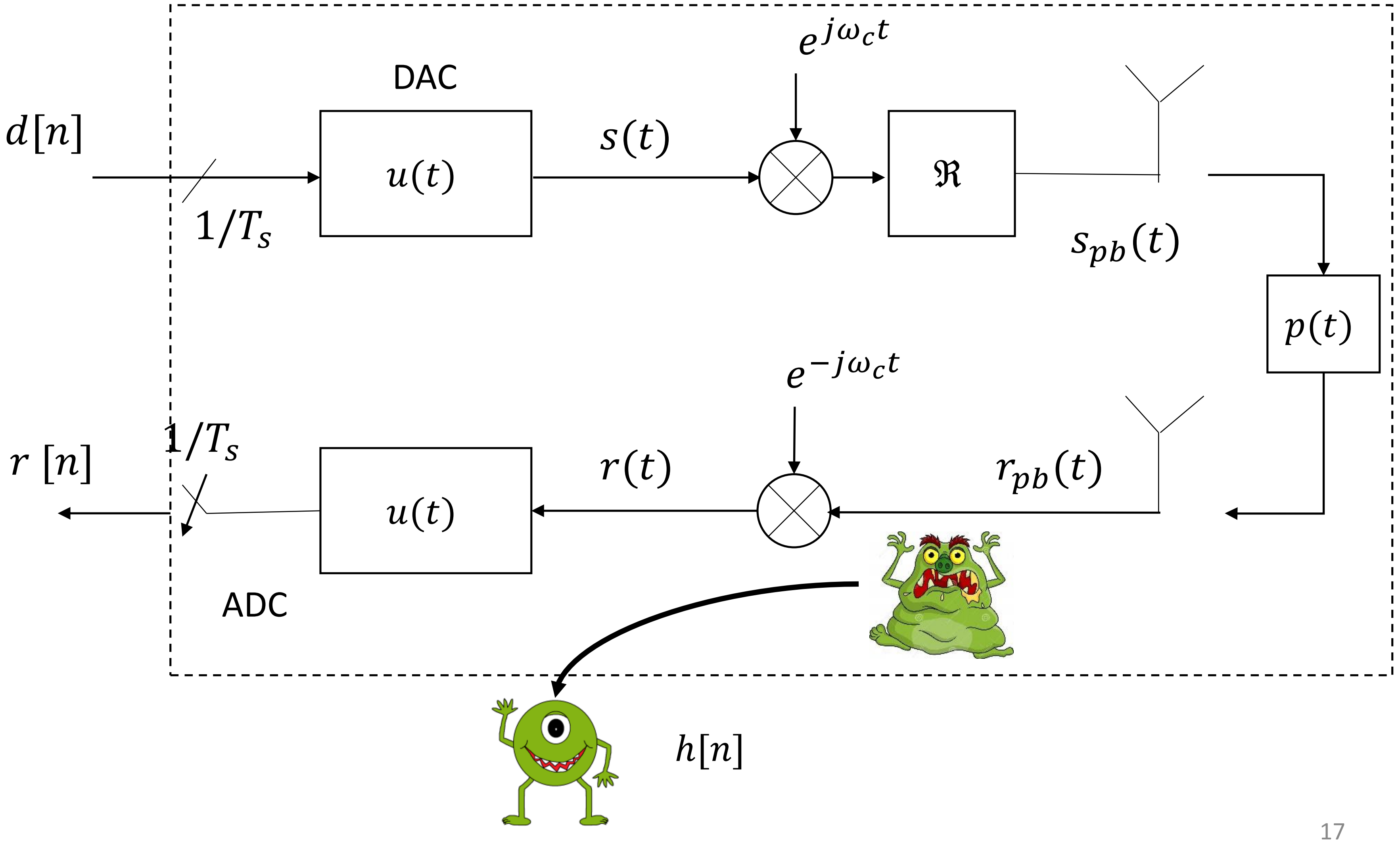
$d[n]$



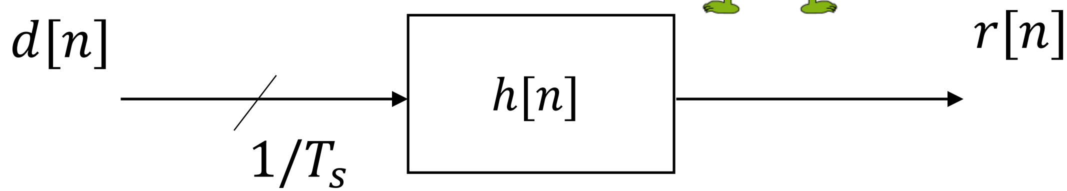
$r[n]$



Equivalent transmission chain



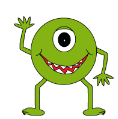
All discrete baseband equivalent model, why?



Abstraction model

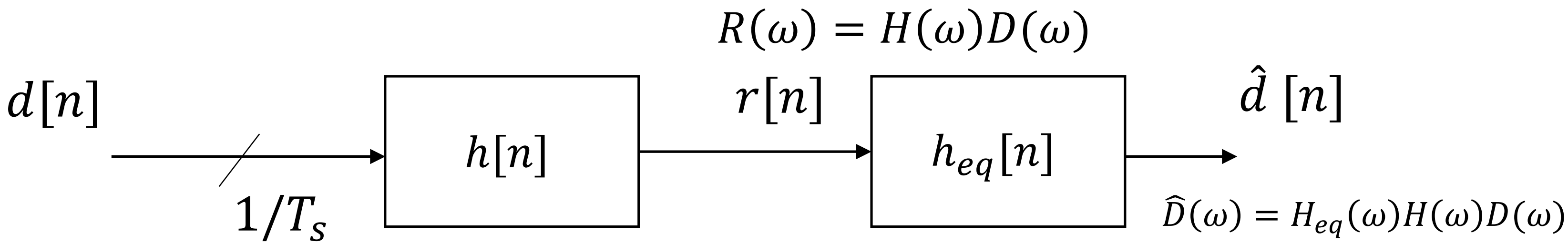
Easy to simulate

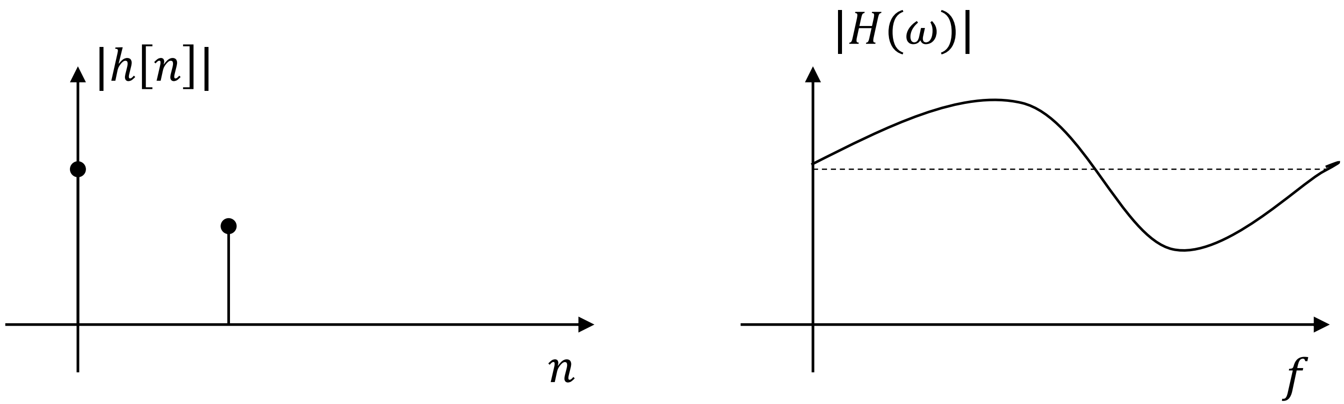
How it is done in practice

Easy to understand, more tractable 

Very accurate

What are the disadvantages of single-carrier systems?





In practice, multipath channel, intersymbol interference,

$$R(\omega) = H(\omega)D(\omega)$$

Need for channel « equalization », might require long filters…

$$H(\omega)H_{eq}(\omega) \approx 1 \leftrightarrow \widehat{D}(\omega) \approx D(\omega) \leftrightarrow \left(h \otimes h_{eq}\right)[n] \approx \delta[n]$$

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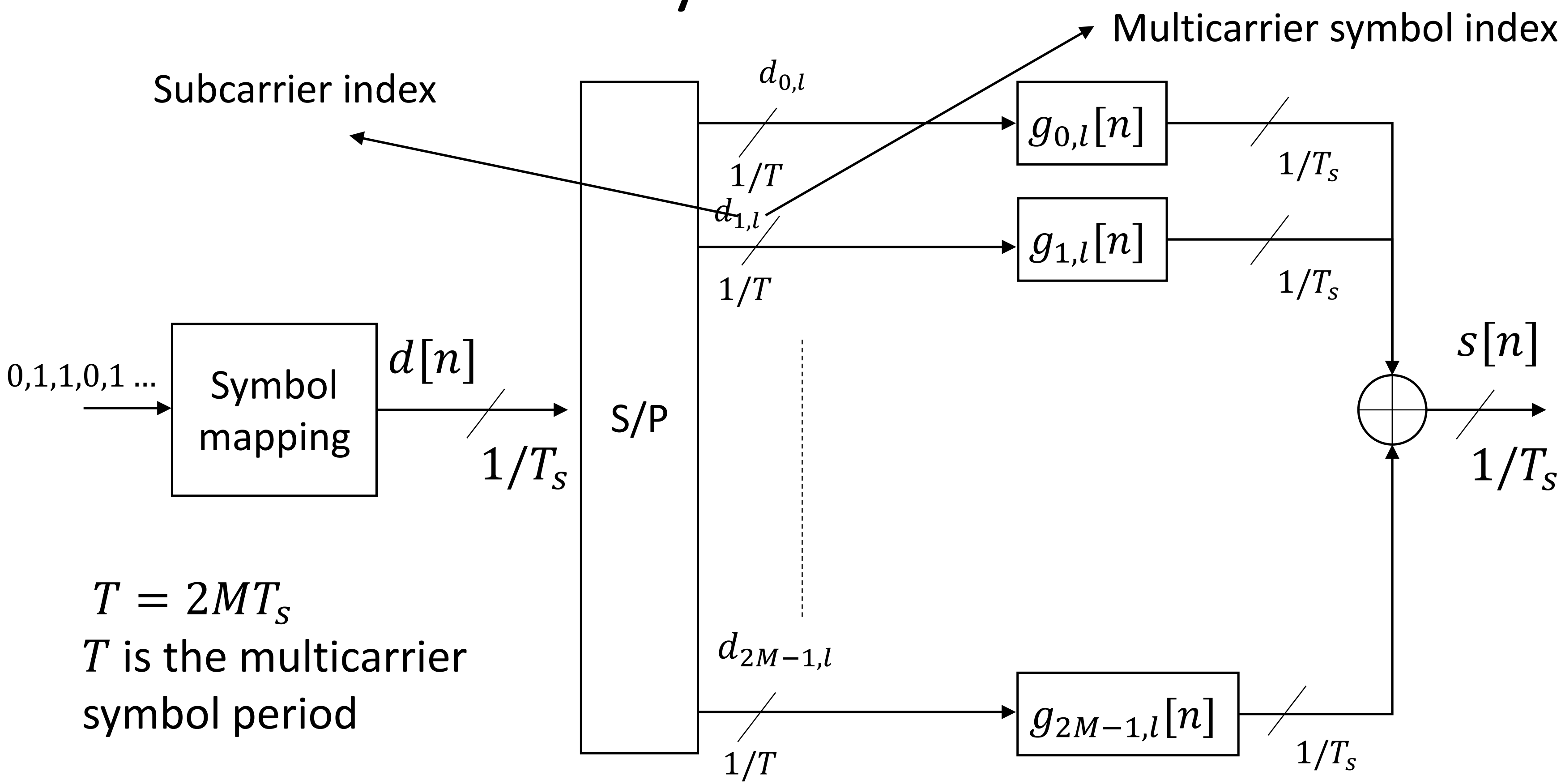
Multicarrier systems



$T = 2MT_s$
T is the multicarrier symbol period

$$g_{m,l}[n] = g[n - l2M]e^{\frac{j2\pi}{2M}mn}$$

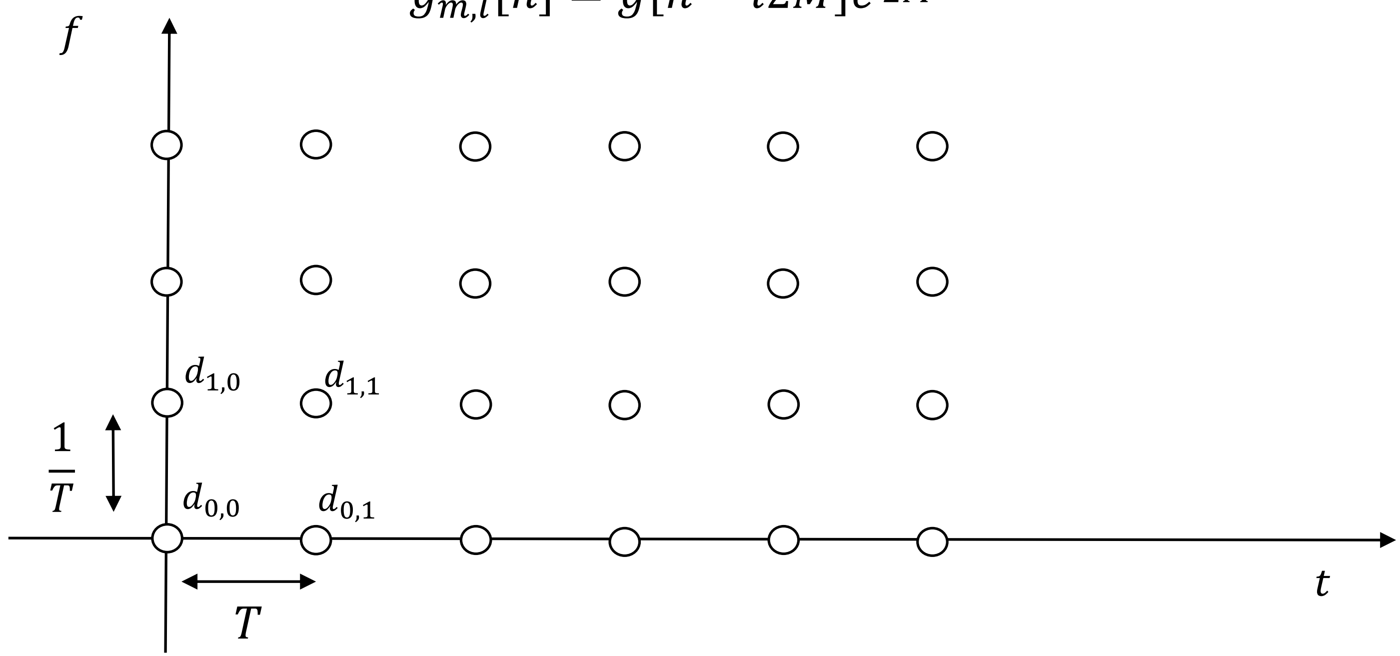
Baseband equivalent of the transmitted signal

$$s[n] = \sum_{m=0}^{2M-1} \sum_{l=-\infty}^{+\infty} d_{m,l}\, g_{m,l}[n]$$

Time-frequency lattice

$$s[n] = \sum_{m=0}^{2M-1} \sum_{l=-\infty}^{+\infty} d_{m,l}\, g_{m,l}[n]$$

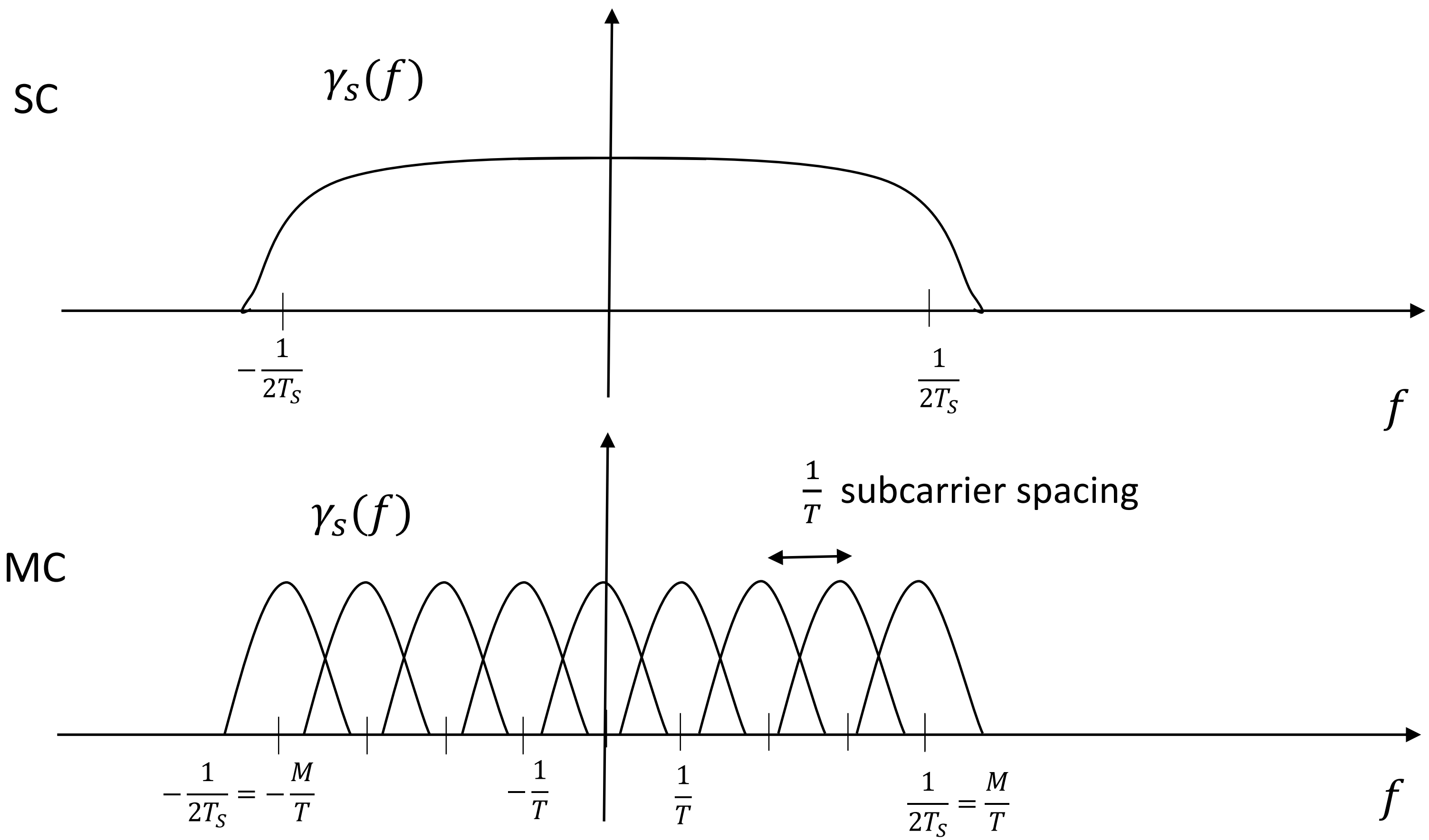
$$g_{m,l}[n] = g[n - l2M] e^{\frac{j2\pi}{2M} mn}$$



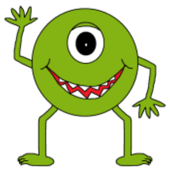
Lattice density: $\frac{1}{\Delta t \Delta f} = \frac{1}{\frac{1}{T}T}$ symbol per second per Hertz

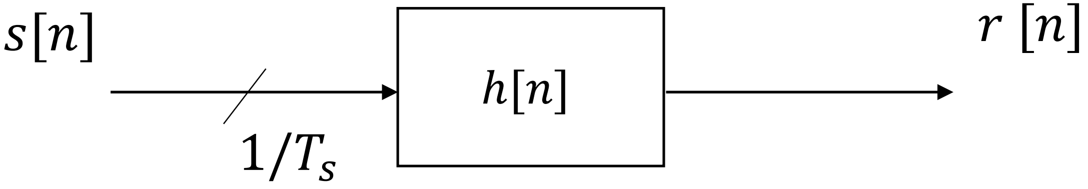
Exactly the same throughput rate as SC system $\frac{1}{T_s \frac{1}{T_s}} = 1$

Single-carrier baseband and multicarrier spectrum comparison



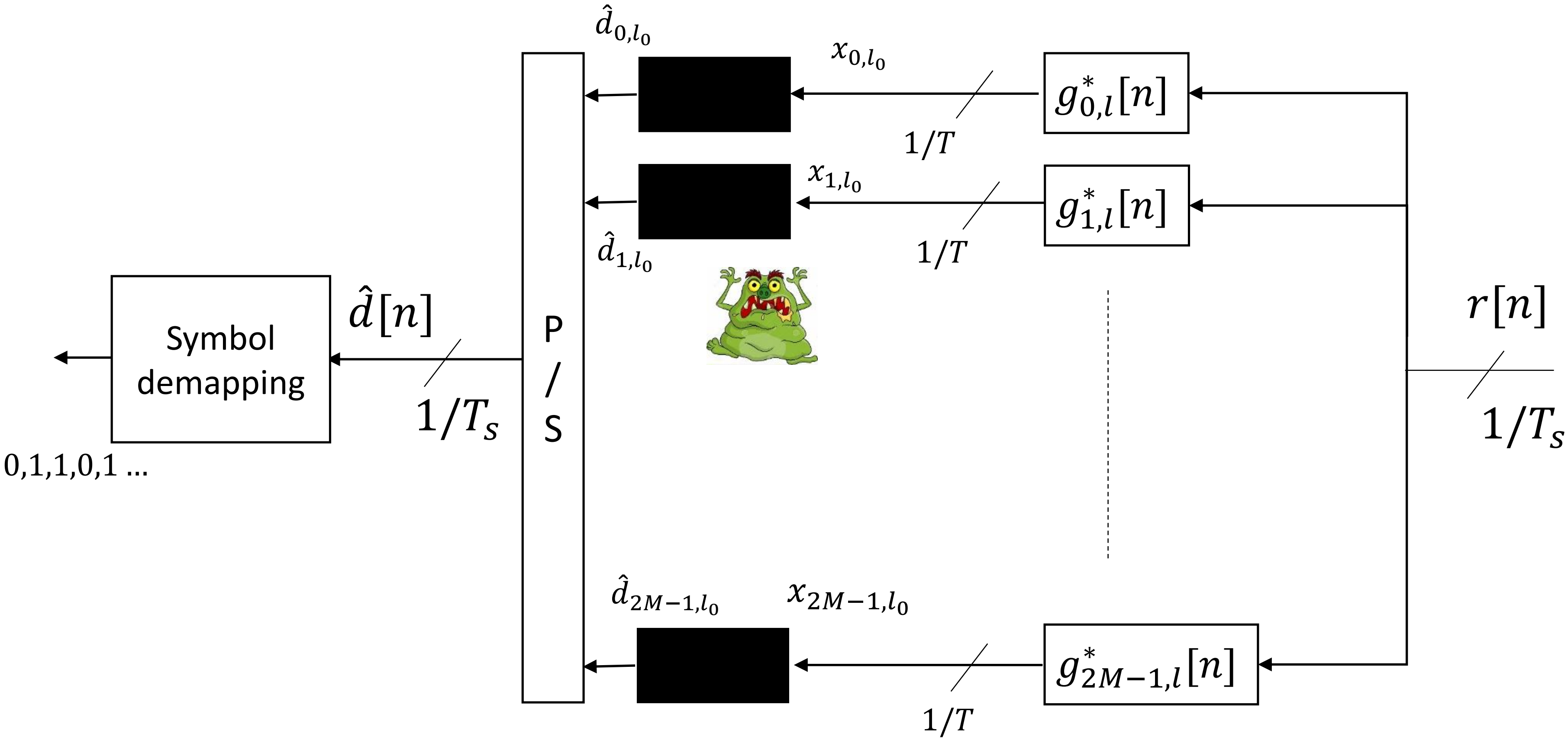
Channel





$$r[n] = (s \otimes h)[n]$$
$$R(\omega) = S(\omega)H(\omega)$$

Receiver



Demodulated symbol at subcarrier m_0 and multicarrier symbol l_0:

$$x_{m_0,l_0} =< r[n], g_{m_0,l_0}[n] > \sum_n r[n] g^*_{m_0,l_0}[n]$$

Orthogonality conditions

Assume ideal condition, $h[n] = \delta[n]$ and $r[n] = s[n]$

$$
\begin{aligned}
\hat{d}_{m_0,l_0} &=< s[n], g_{m_0,l_0}[n] > \\
&= \sum_{m=0}^{2M-1} \sum_{l=-\infty}^{+\infty} d_{m,l} < g_{m,l}[n], g_{m_0,l_0}[n] > \\
&= d_{m_0,l_0}
\end{aligned}
$$

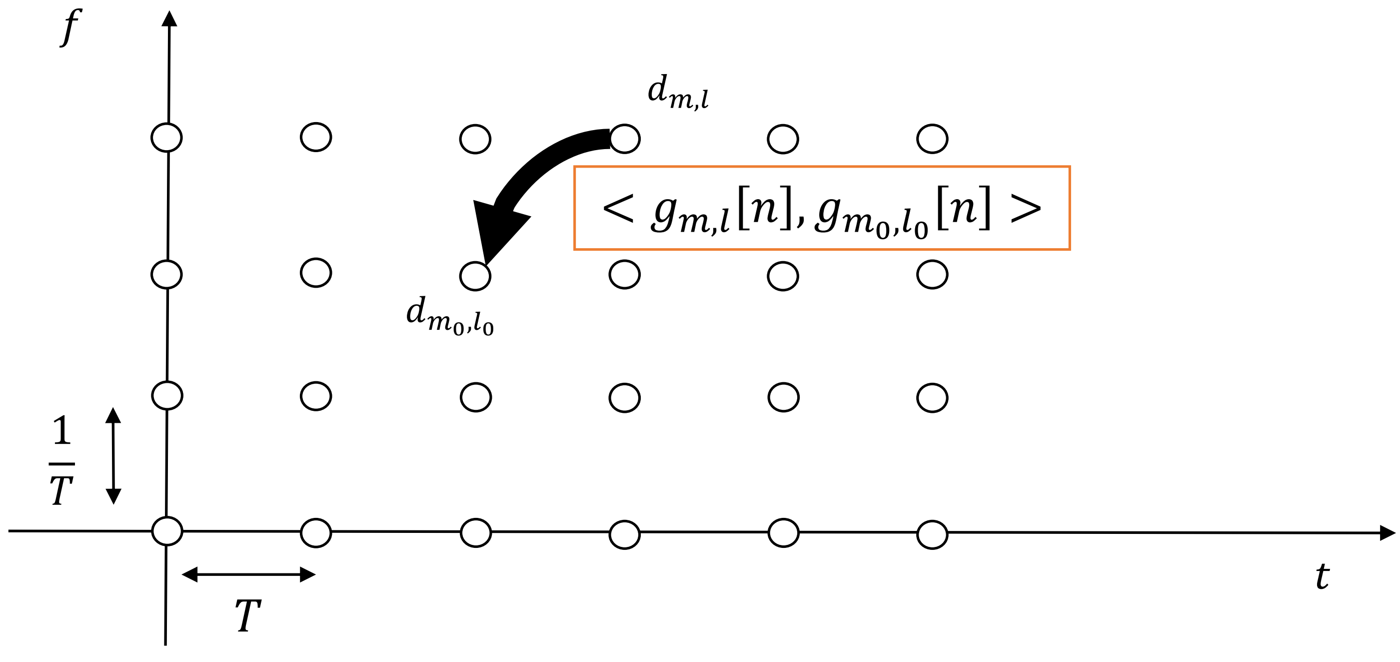
if **<u>« complex »</u>** orthogonality of the pulses is fullfilled, i.e.,

$$< g_{m,l}[n], g_{m_0,l_0}[n] >= \delta_{m-m_0,l-l_0}$$

for $m_0, m = 0, .., 2M-1$ and $\forall l, l_0$ (between symbols and subcarriers). “Generalized Nyquist constraint”.

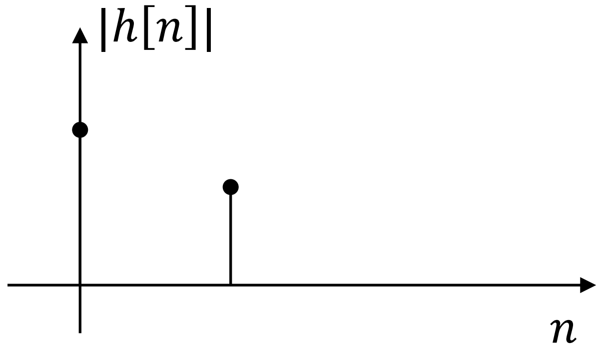
Generalized Nyquist constraint

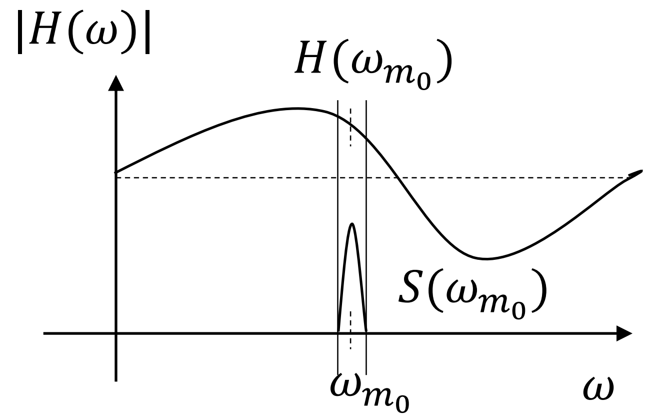
$$< g_{m,l}[n], g_{m_0,l_0}[n] >= \delta_{m-m_0,l-l_0}$$



Where is the gain of multicarrier systems?!

Practical channel conditions





Channel approximated as flat at the subcarrier level

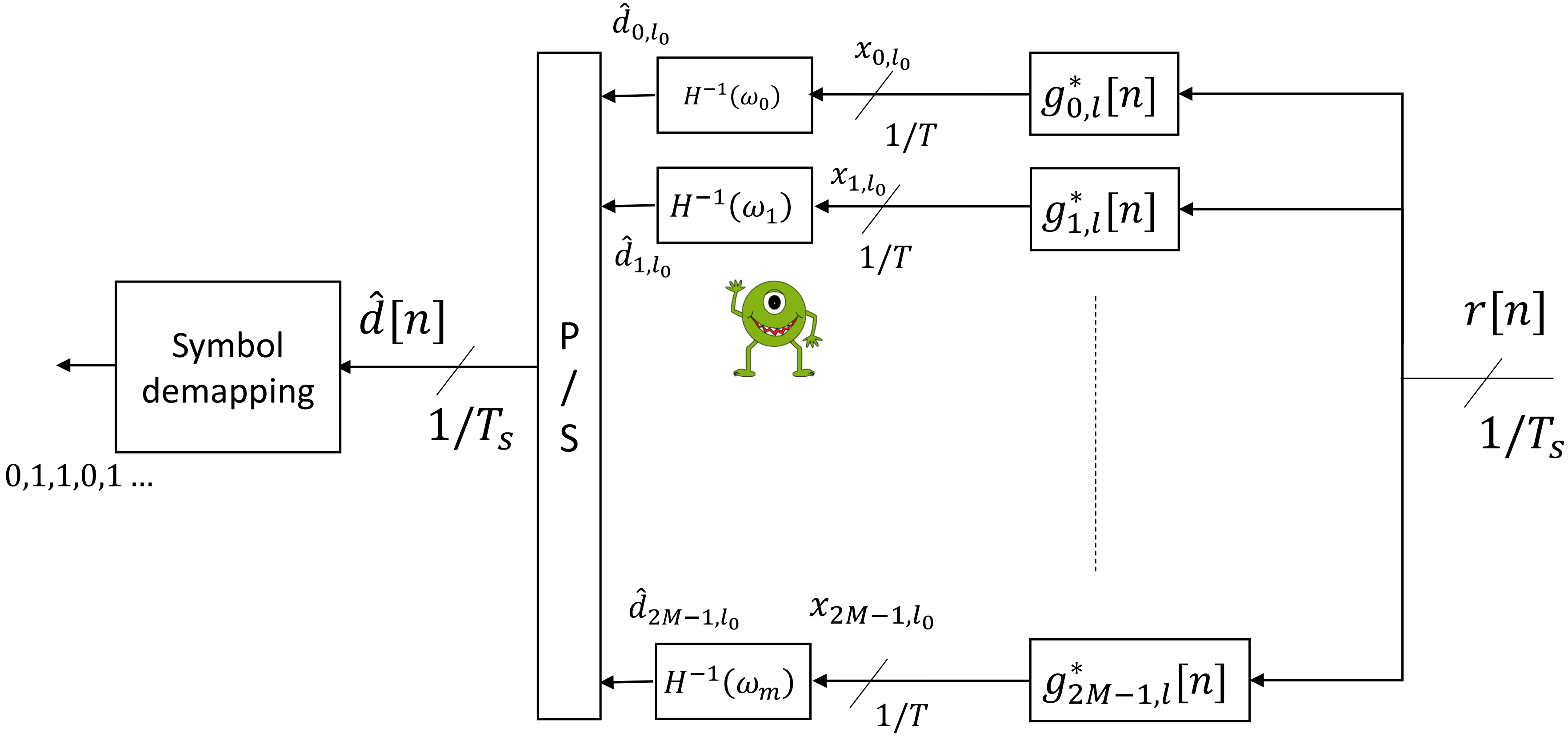
$$x_{m_0,l_0} = < r[n], g_{m_0,l_0}[n] > \approx H(\omega_{m_0}) d_{m_0,l_0}$$

and d_{m_0,l_0} is simply recovered by

$$\hat{d}_{m_0,l_0} = H^{-1}(\omega_{m_0}) x_{m_0,l_0} \approx d_{m_0,l_0}$$

⇨ Very simple channel "equalization"

Receiver



Demodulated symbol at subcarrier m_0 and multicarrier symbol l_0:

$$x_{m_0,l_0} =< r[n], g_{m_0,l_0}[n] > \sum_n r[n] g^*_{m_0,l_0}[n]$$

Multicarrier systems vs single-carrier systems?

<u>Easy channel equalization</u>

Frequency division multiplexing

Resource allocation

Robust … t

Sensitiv … equency offset
and channel variation in time

High peak-to-average power r

Used in most wireless communication standards ! Wi-Fi, DSL, LTE, DVB…

Disadvantages of classical multicarrier systems based on complex orthogonality

Suppose $g(t)$ is a square-integrable function on the real line and consider the Gabor system

$$g_{m,l}(t) = g(t - l\Delta t)e^{j2\pi m\Delta f t}$$

where $m, l \in \mathbb{Z}$. If $\Delta t\Delta f = 1$, the **<u>Balian-Low theorem</u>** states that, if

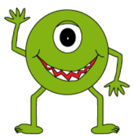
$$\{g_{m,l}(t), m, l \in \mathbb{Z}\}$$

is an orthonormal basis for the Hilbert space $L^2(\mathbb{R})$, then either

$$\int_{-\infty}^{+\infty} t^2|g(t)|^2 dt = \infty \text{ or } \int_{-\infty}^{+\infty} \omega^2|G(\omega)|^2 d\omega = \infty$$

where $G(\omega)$ is the Fourier transform of $g(t)$.

Limitations of classical multicarrier systems based on complex orthogonality?



In other words, if $\Delta t \Delta f = 1$ (1 symbol per s per Hz, full spectral efficiency, **high data rate**) and

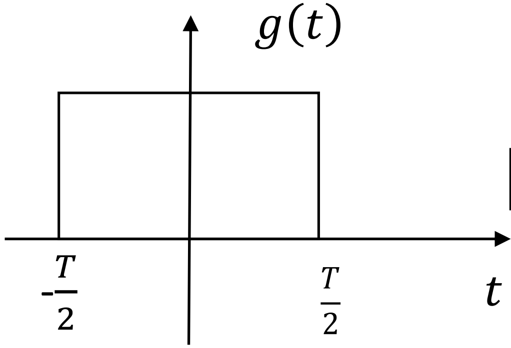
$< g_{m,l}, g_{m_0,l_0} > = \delta_{m-m_0,l-l_0}$ for all m, l (**complex orthogonality**),

the Balian-Low theorem tells us that the prototype filter/atom $g(t)$ cannot be well localized in time and frequency.

Bad for spectral efficiency, robustness, synchronization…

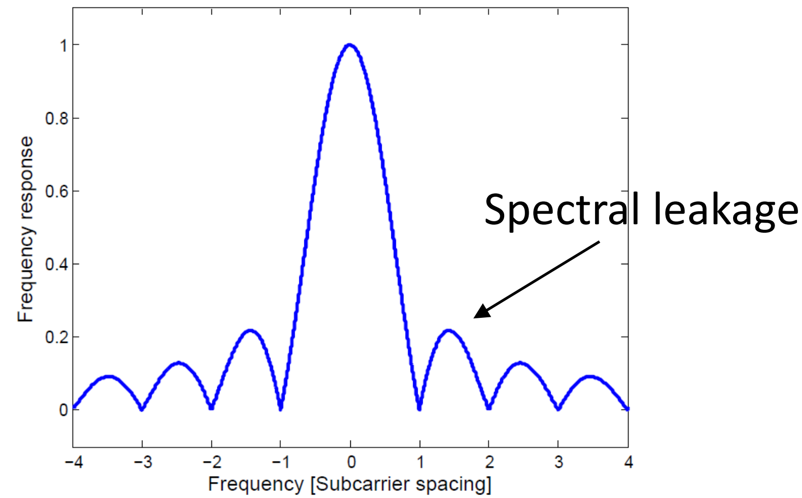
Wi-Fi, DSL, LTE, WiMAX, DVB…

OFDM leakage



$$\int_{-\infty}^{+\infty} t^2 |g(t)|^2 dt \leq \xi$$

$$|G(\omega)| = |\text{sinc}\,(\omega T)|$$

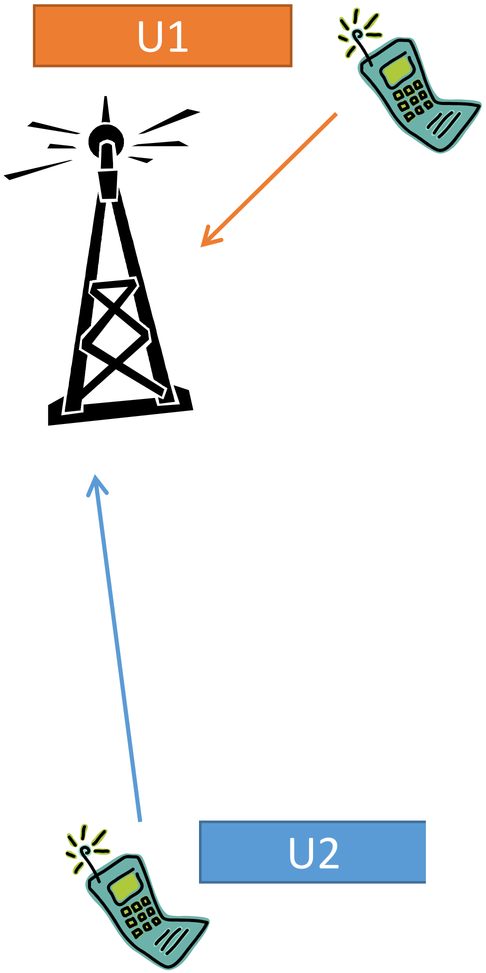


$$\int_{-\infty}^{+\infty} \omega^2 |G(\omega)|^2 d\omega = \infty$$

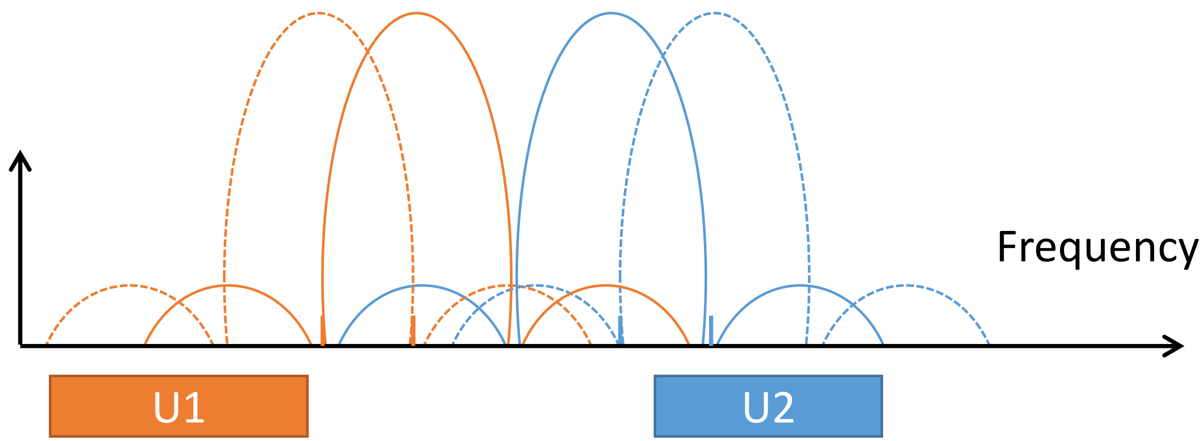
$\Delta t = T, \Delta f = \frac{1}{T}$ and complex orthogonality (easy to show)

$$< g_{m,l}, g_{m_0,l_0} > = \int_t g_{m,l}(t) g^*_{m_0,l_0}(t) dt = \delta_{m-m_0,l-l_0}$$

Spectral leakage leads to interference



Overlapping

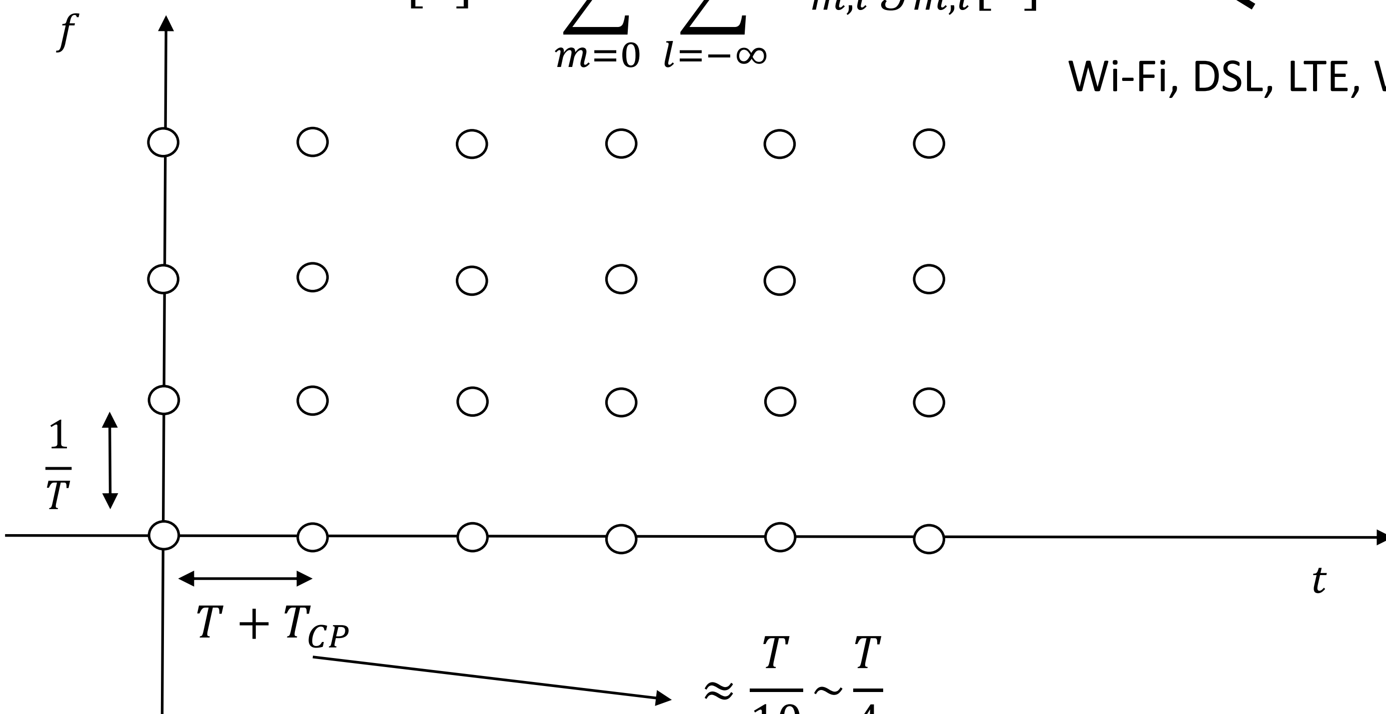


Synchronisation required to keep orthogonality

Time-frequency lattice of **CP**-OFDM

$$s[n] = \sum_{m=0}^{2M-1} \sum_{l=-\infty}^{+\infty} d_{m,l}\, g_{m,l}[n]$$

Wi-Fi, DSL, LTE, WiMAX, DVB…



$$\approx \frac{T}{10} \sim \frac{T}{4}$$

Undersampled lattice, loss in throughput rate

$$\frac{1}{(T + T_{CP})\frac{1}{T}} = \frac{T}{T + T_{CP}} < 1$$

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- Principle
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- Pros and cons

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FBMC-OQAM principle

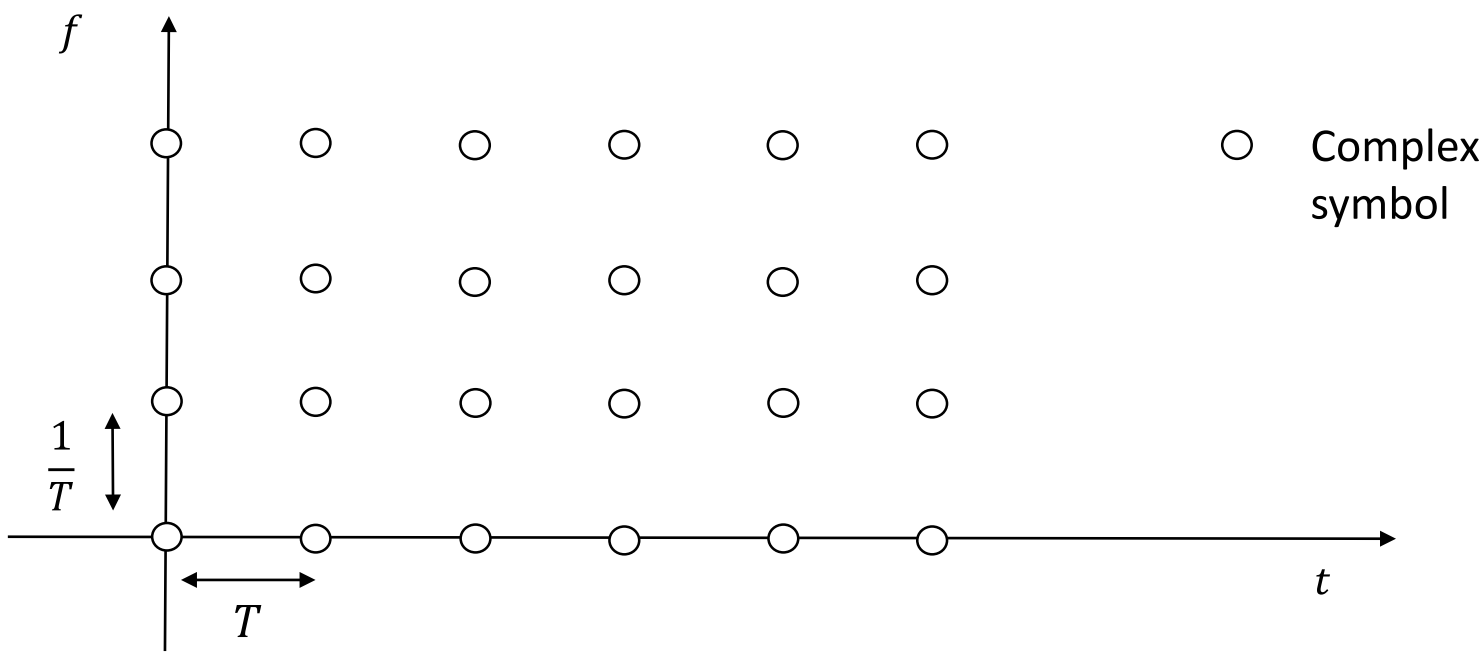
We want:

- Good time-frequency localization
- Full spectral efficiency

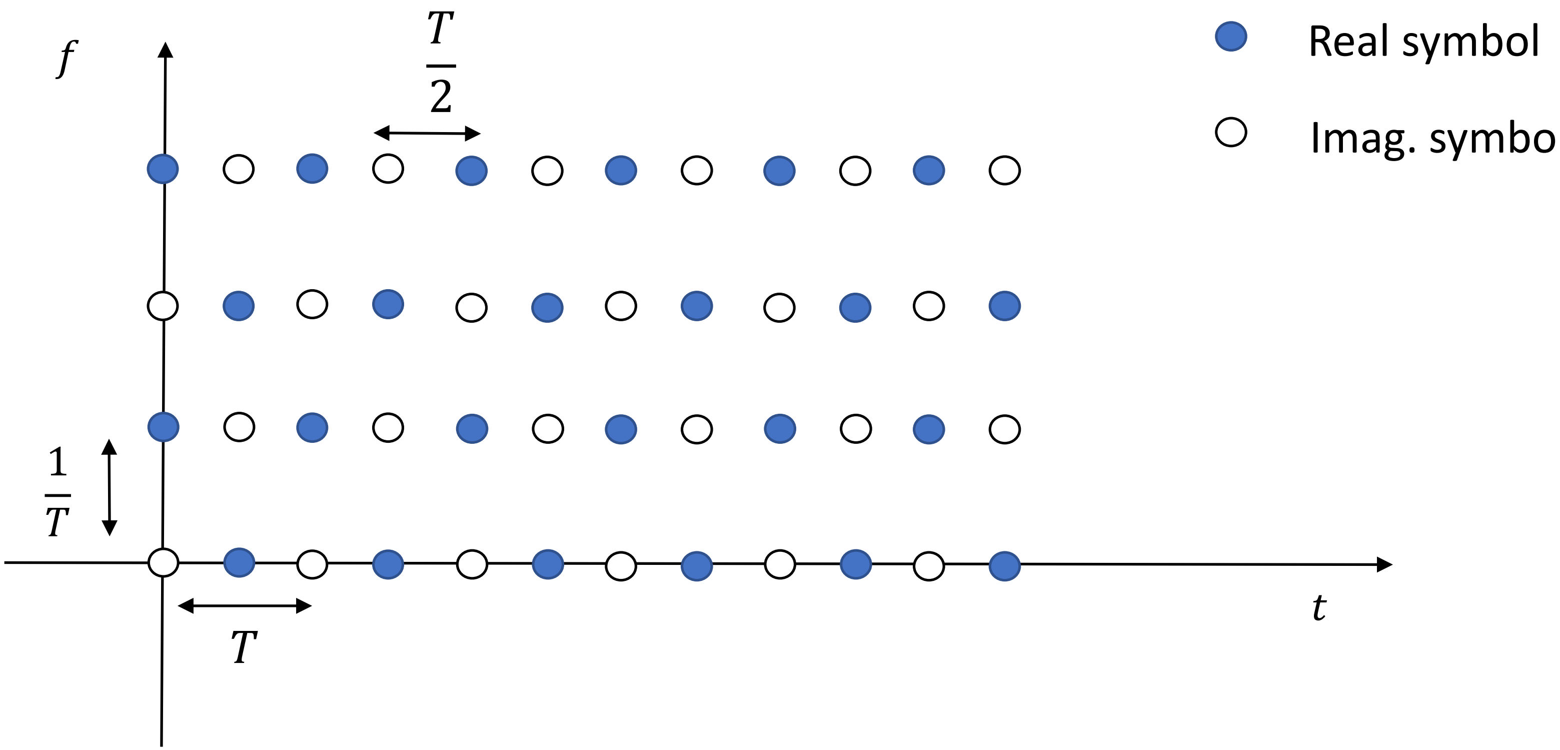
But how? Balian-Low…

⇒ Use staggered lattices to circumvent the Balian-Low theorem
Idea used by FBMC-OQAM modulations [Chang, 66], [Saltzberg, 67]
Link to Wilson bases.

Classical multicarrier lattice



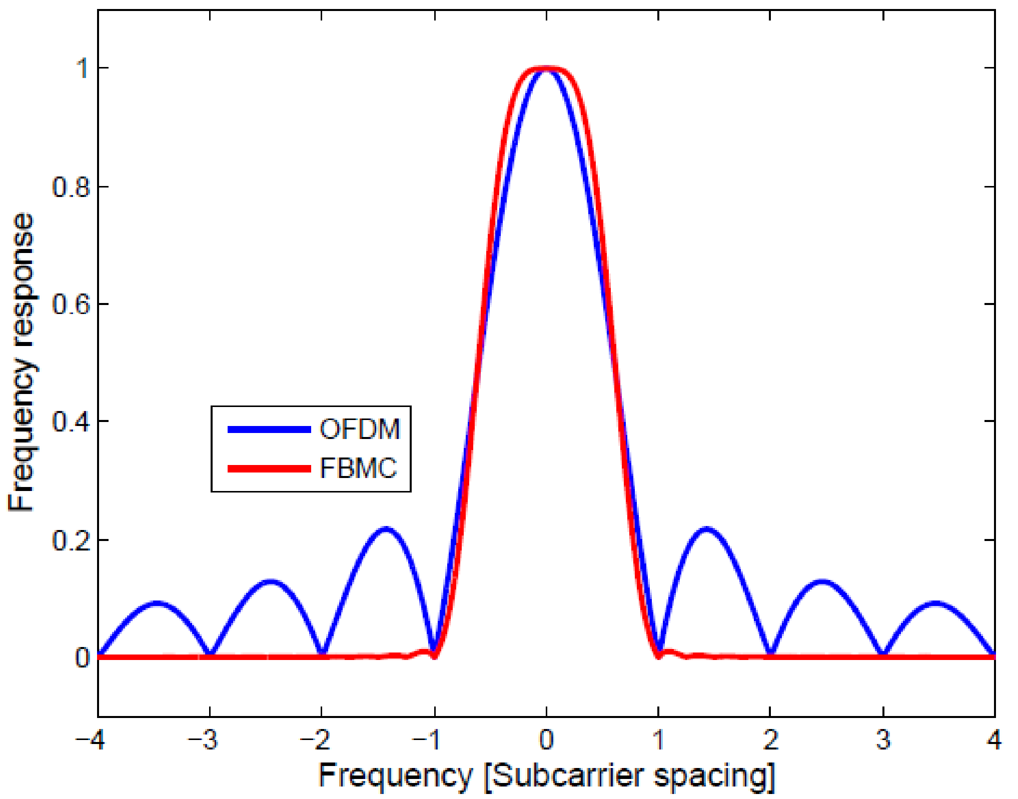
FBMC-OQAM lattice



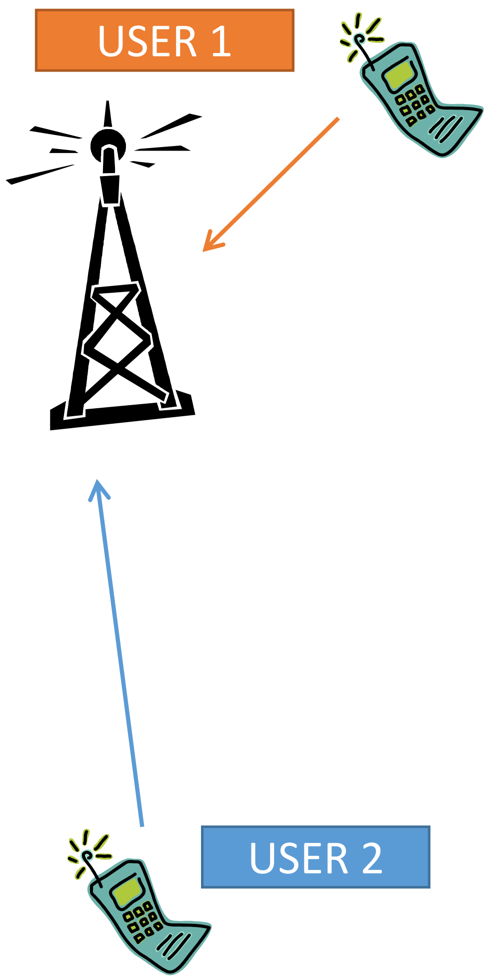
Lattice density $\frac{1}{\Delta t \Delta f} = \frac{1}{\frac{T}{2} 1/T} = 2$ real symbols per second per Hertz

Orthogonality satisfied only in the real domain

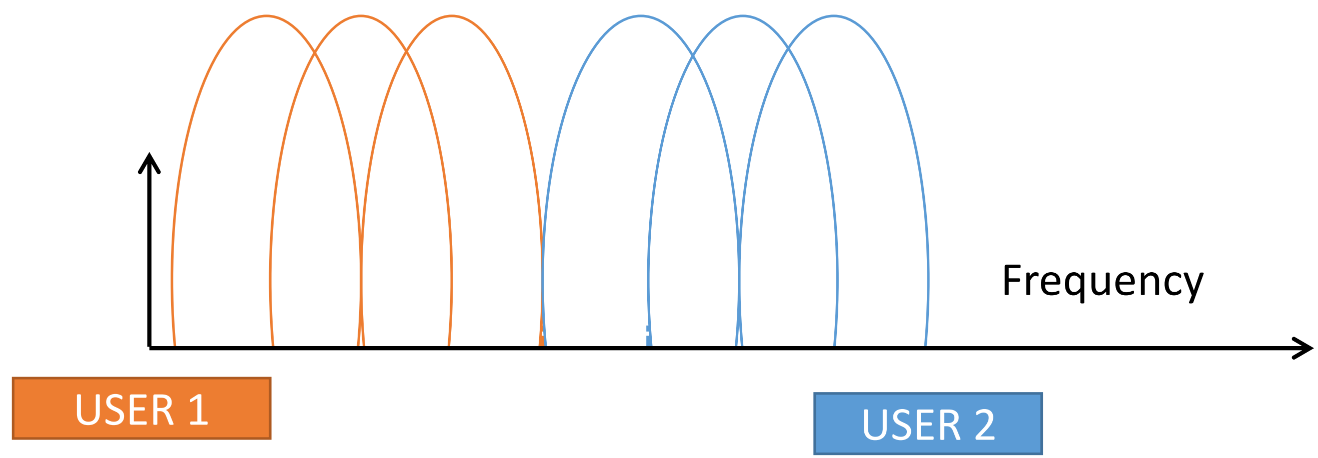
Good frequency localization



No need for synchronization of the users



No overlapping



FBMC-OQAM transmission model

Transmitted signal

$$s[n] = \sum_{m=0}^{2M-1} \sum_{l=-\infty}^{+\infty} d_{m,l}\, g_{m,l}[n]$$

Purely real now !

$\Re$-$\Im$ pattern

with $g_{m,l}[n] = \boldsymbol{j^{l+m}} g[n - \boldsymbol{lM}] e^{\frac{j2\pi}{2M}mn}$.

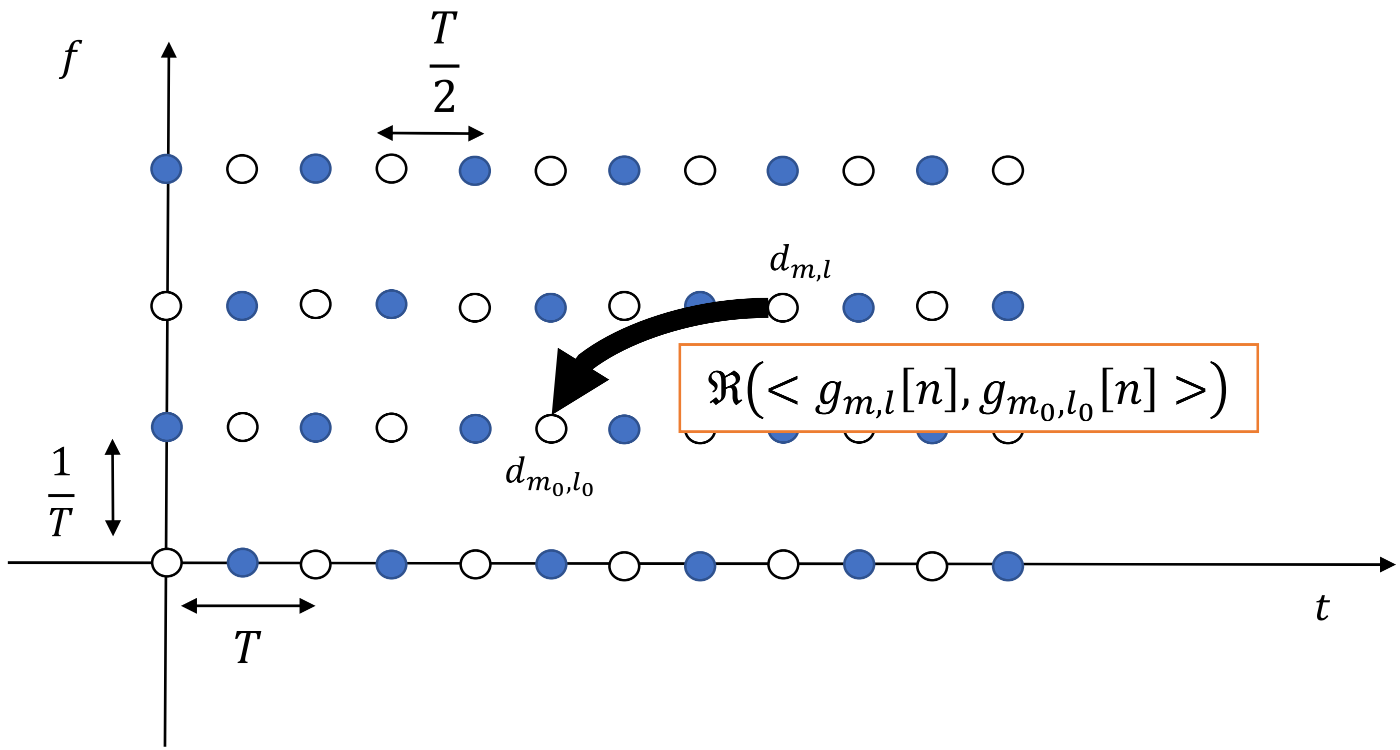
$-l\cancel{2}M$ symbols are closer in time

Assume ideal channel, i.e., $r[n] = s[n]$. The demodulated signal is

$$\begin{aligned} \hat{d}_{m_0,l_0} &= \Re\left(< s[n], g_{m_0,l_0}[n] >\right) \\ &= \textstyle\sum_{m=0}^{2M-1} \sum_{l=-\infty}^{+\infty} d_{m,l}\, \underbrace{\Re\left(< g_{m,l}[n], g_{m_0,l_0}[n] >\right)}_{\text{Interference from symbol } d_{m,l}} \\ &= d_{m_0,l_0} \end{aligned}$$

if, $\Re\left(< g_{m,l}[n], g_{m_0,l_0}[n] >\right) = \delta_{m-m_0,l-l_0} \forall m, m_0, l, l_0$.

FBMC-OQAM lattice



Real orthogonality conditions

$$< g_{m,l}[n], g_{m_0,l_0}[n] > = j^{\Delta m+\Delta l} \sum_n g[n-lM]g[n-l_0M]e^{\frac{j2\pi}{2M}\Delta\mathrm{m}n}$$

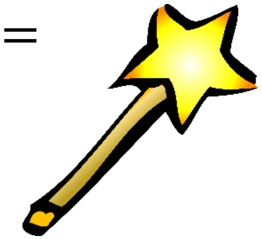
… (simple math. manipulations)

$$= j^{\Delta m+\Delta l+\Delta l\Delta m}(-1)^{\Delta m l_0} \sum_n \underbrace{g\left[n-\frac{\Delta l M}{2}\right] g\left[n+\frac{\Delta l M}{2}\right] e^{\frac{j2\pi}{2M}\Delta\mathrm{m}n}}$$

$\Delta m = m - m_0, \Delta l = l - l_0$

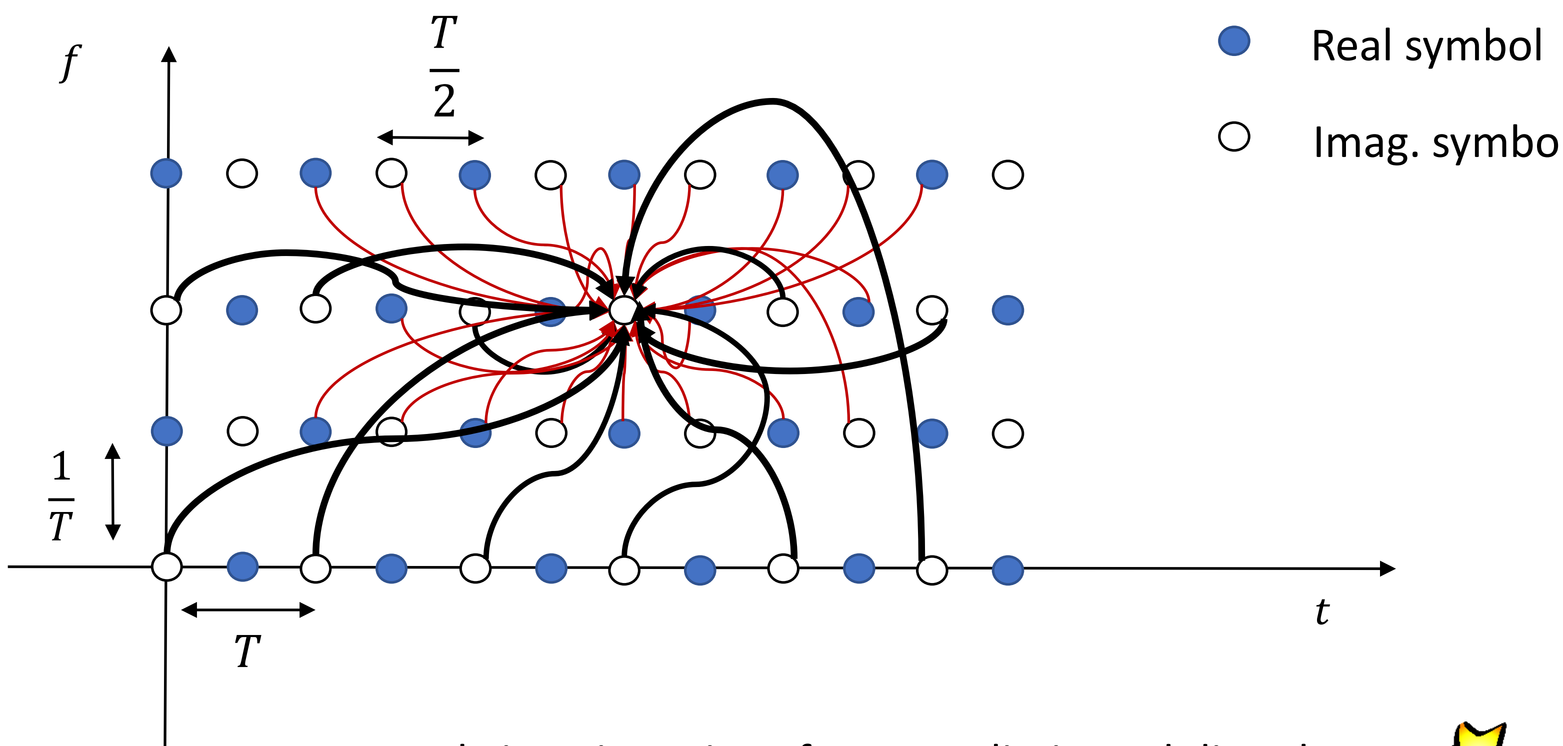
“Ambiguity function”: real for real and even pulse $g[n]$

$\Re(< g_{m,l}[n], g_{m_0,l_0}[n] >)$ is only non zero if $\Delta m + \Delta l + \Delta l \Delta m = 0 \bmod 2$, which only occurs when $\Delta m = \Delta l = 0 \bmod 2$.



Hence, $g[n]$ should be designed to cancel those terms.

FBMC-OQAM lattice



Purely imaginary interference, eliminated directly when $g[n]$ is even and real

Remaining interference, eliminated by filter design $\Delta m = \Delta l = 0 \bmod 2$

Outline

Some basics

- Single-carrier systems
- Classical multicarrier systems

FBMC-OQAM systems

- Principle
- Pros and cons "Why is it better?"

My research

Pros and Pros “Le beurre et l’argent du beurre”

Advantages of MC systems: easy channel equalization…

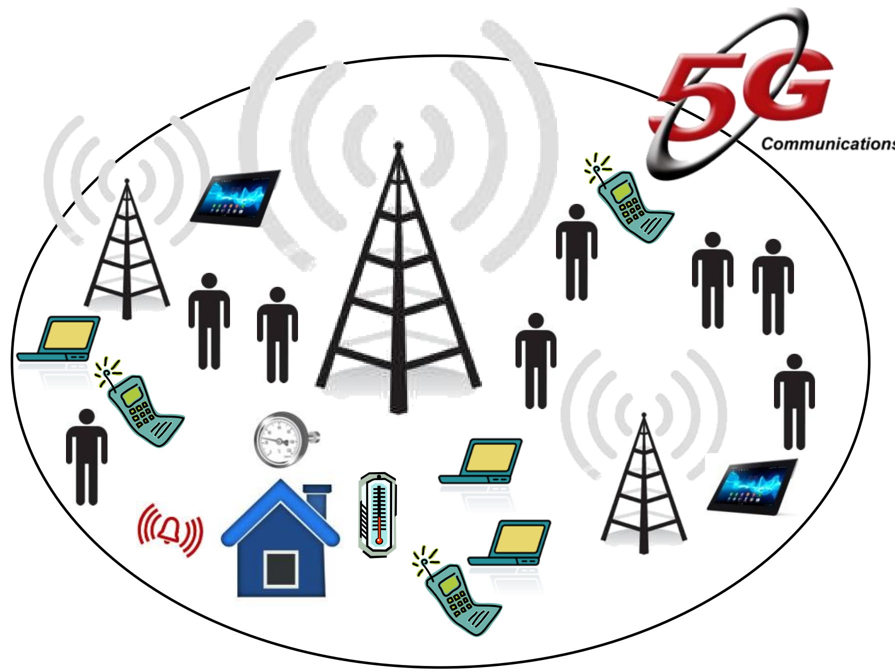
High data rate

Filter well time-frequency localized:

Higher complexity… especially in certain scenarios. Need for more investigation, many open issues.

Wait… Good for us ! We like complex things !
That means that there is still a lot to do !

Evolution of telecommunication standards



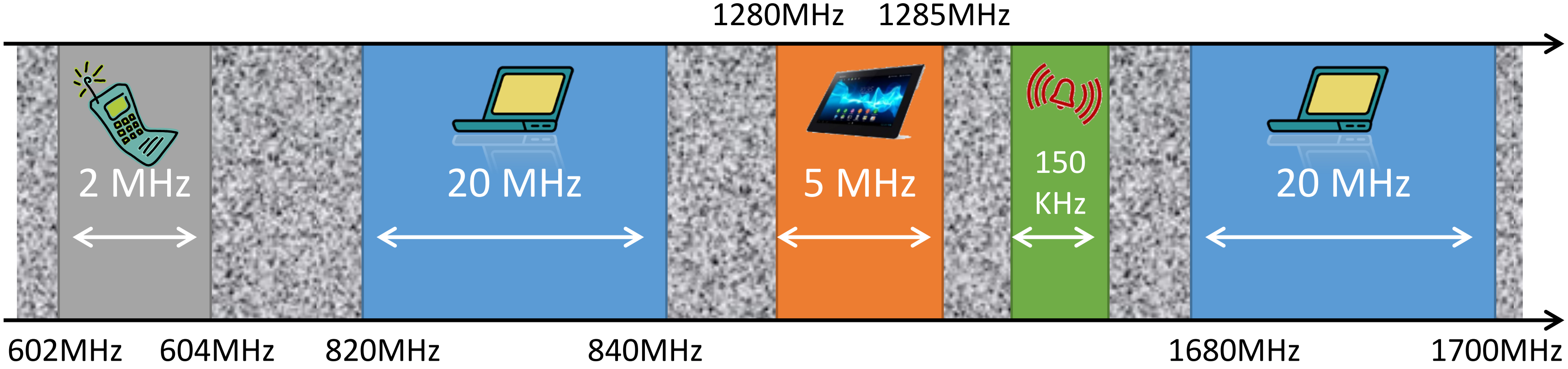
2010… 2030

2020… 2040

4G modulation format might not be the best to address 5G challenges

Flexible spectrum utilization in 5G

Fragmented spectrum



Outline

- Some basics
  - Single-carrier systems
  - Classical multicarrier systems
- FBMC-OQAM systems
  - Principle
  - Pros and cons
- My research “What am I doing?”

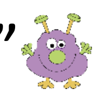
My research

Investigate the applicability of FBMC-OQAM modulations for 5G communication systems

-Channel estimation

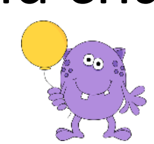
-MIMO “What if we use multiple antennas at transmitter and/or receiver?”

-Massive MIMO “What if the number of those antennas grows very large?”



-High speed scenario: “What if the channel changes quickly?”

-Application to optical fiber: other issues and challenges



I hope I convinced you !

We are note alone…