# DVB-T2 receiver

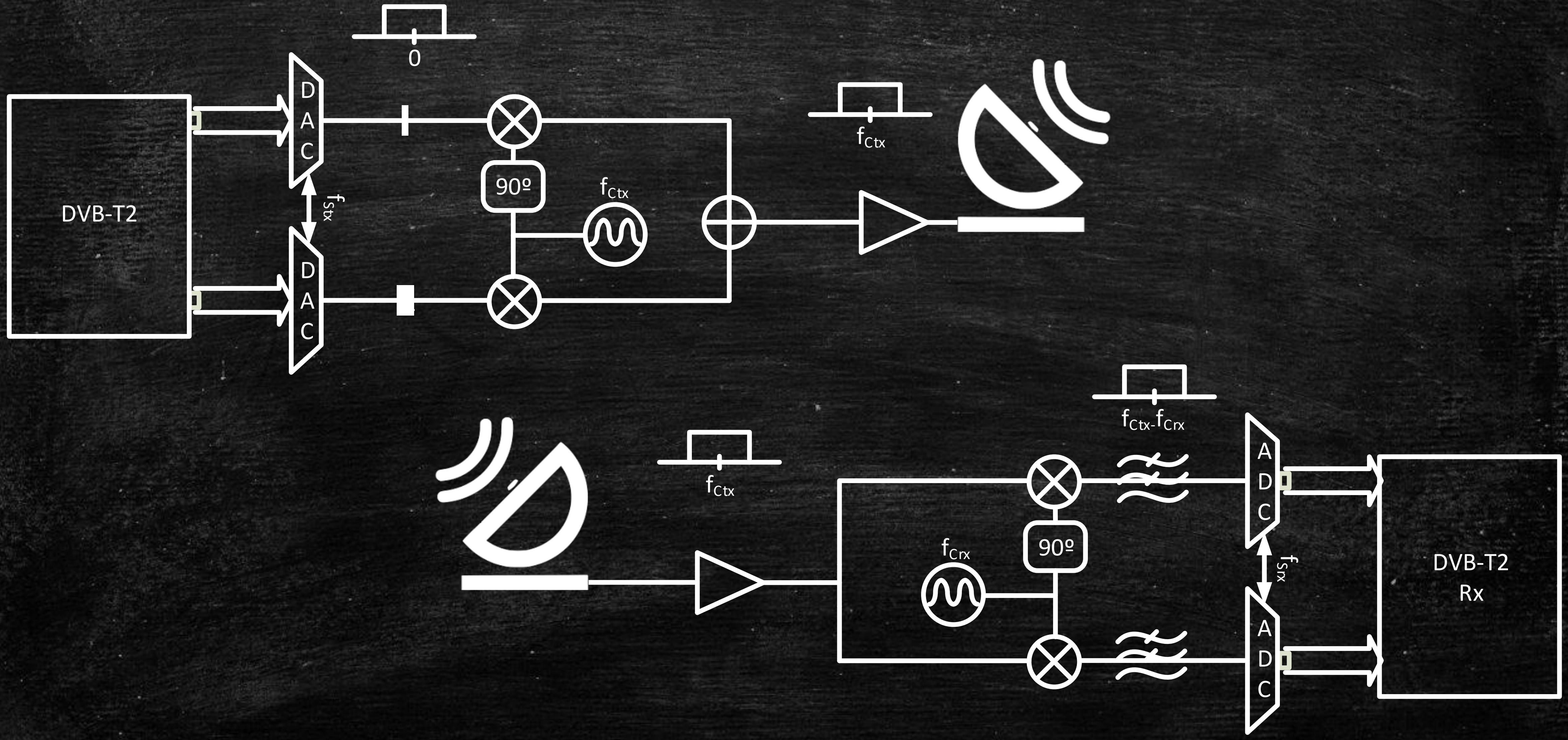
# Introduction

- The implementation of the receiver is not included in DVB-T2 standard
  - Only the transmitter is fully detailed

- However  the DVB Project provides as additional information the Implementation Guidelines
  - A guide to follow when implementing the receiver

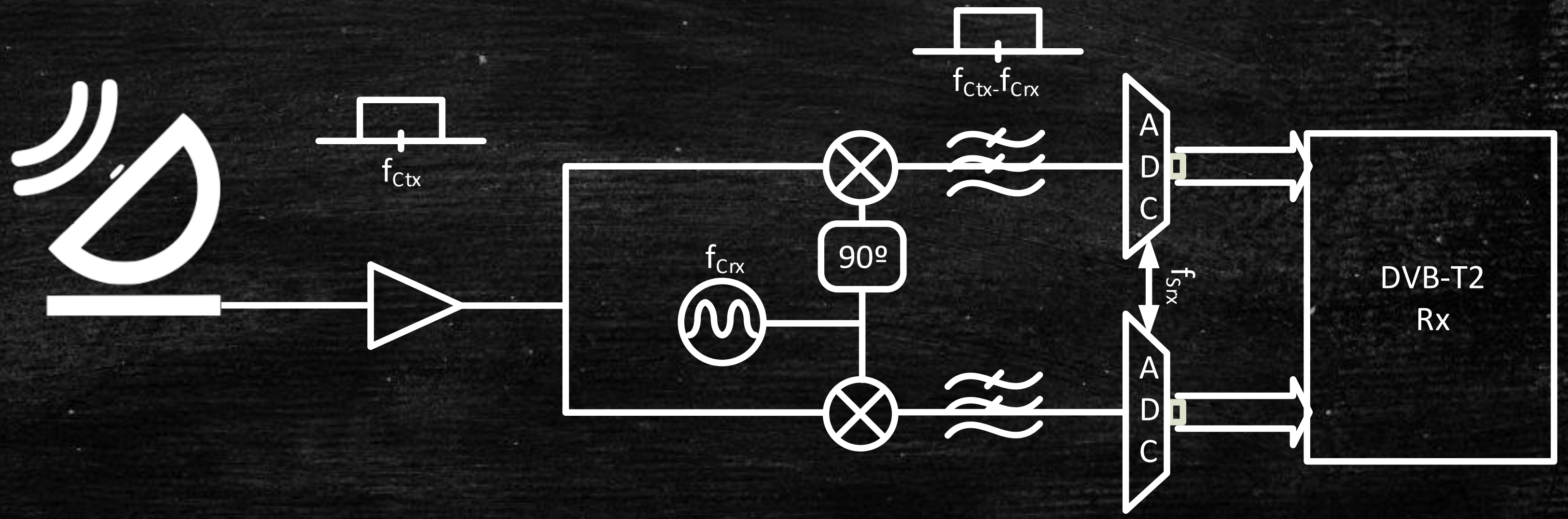
    https://dvb.org/?standard=implementation-guidelines-for-a-second-generation-digital-terrestrial-television-broadcasting-system-dvb-t2

- **After the digital blocks of the transmitter**



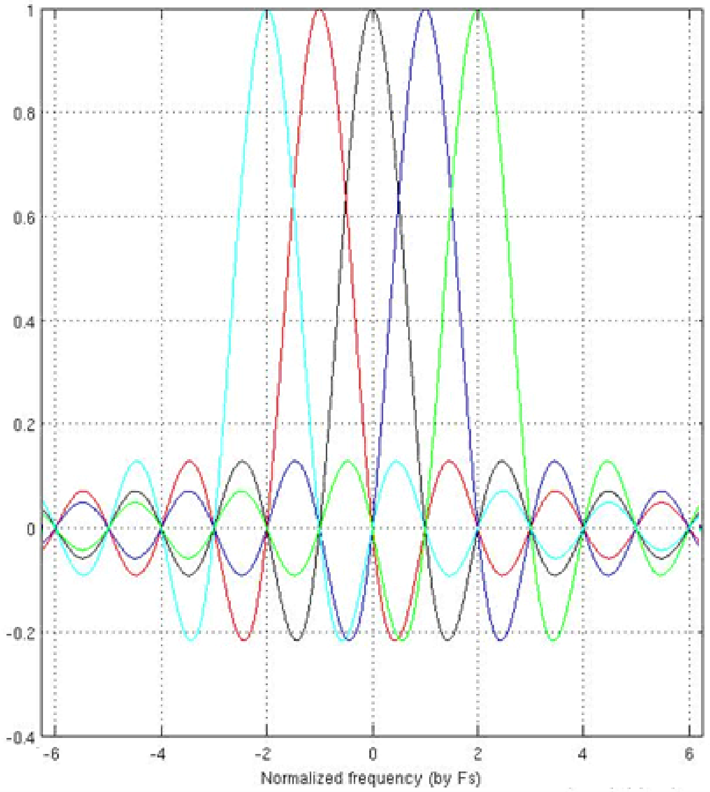
# Frequency offset

- **Due to the implementation derive, frequencies at the Tx and Rx may differ even being nominally the same**
  - **Frequency offset** $\Delta f = F_{Tx} - F_{Rx}$
  - **This can vary with the temperature (drift)**
  - **Makes necessary a tracking**

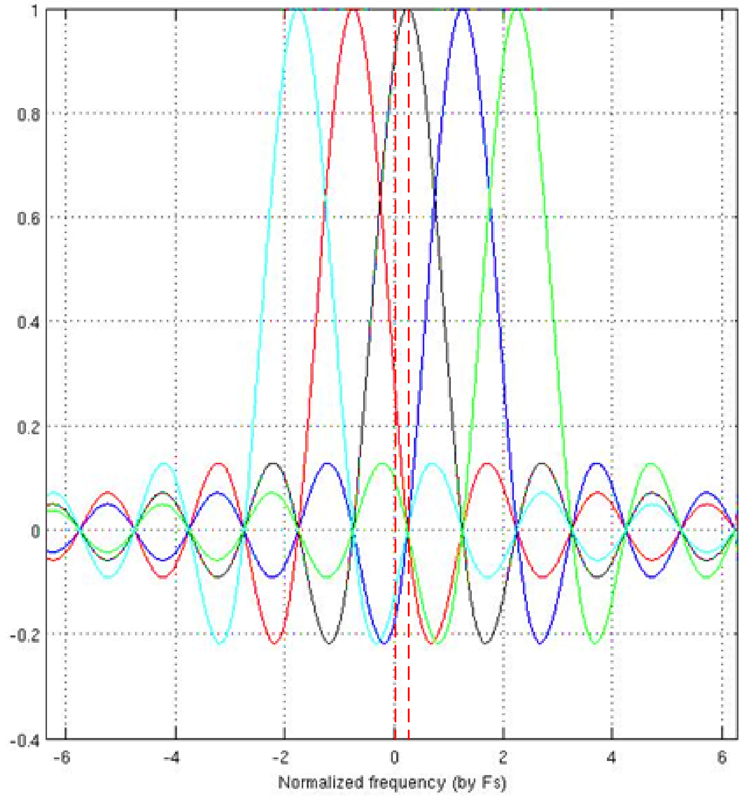


- **The frequency offset error introduces ICI**

Perfect synchronization ($f_{Tx}$-$f_{Rx}$=0)




Synchronization error ($f_{Tx}$-$f_{Rx}$=Δf != 0)



- The carrier separation is $\mathbf{1}/\boldsymbol{T_s}$

- In a general expression $\Delta \boldsymbol{f} = \boldsymbol{n}(\mathbf{1}/\boldsymbol{T_s}) + \boldsymbol{\delta f}$
  - $\boldsymbol{n}$ is an integer
  - $\boldsymbol{\delta f}$ is a real number in $[-\mathbf{1}/\mathbf{2}\boldsymbol{T_s}, \ \mathbf{1}/\mathbf{2}\boldsymbol{T_s}]$

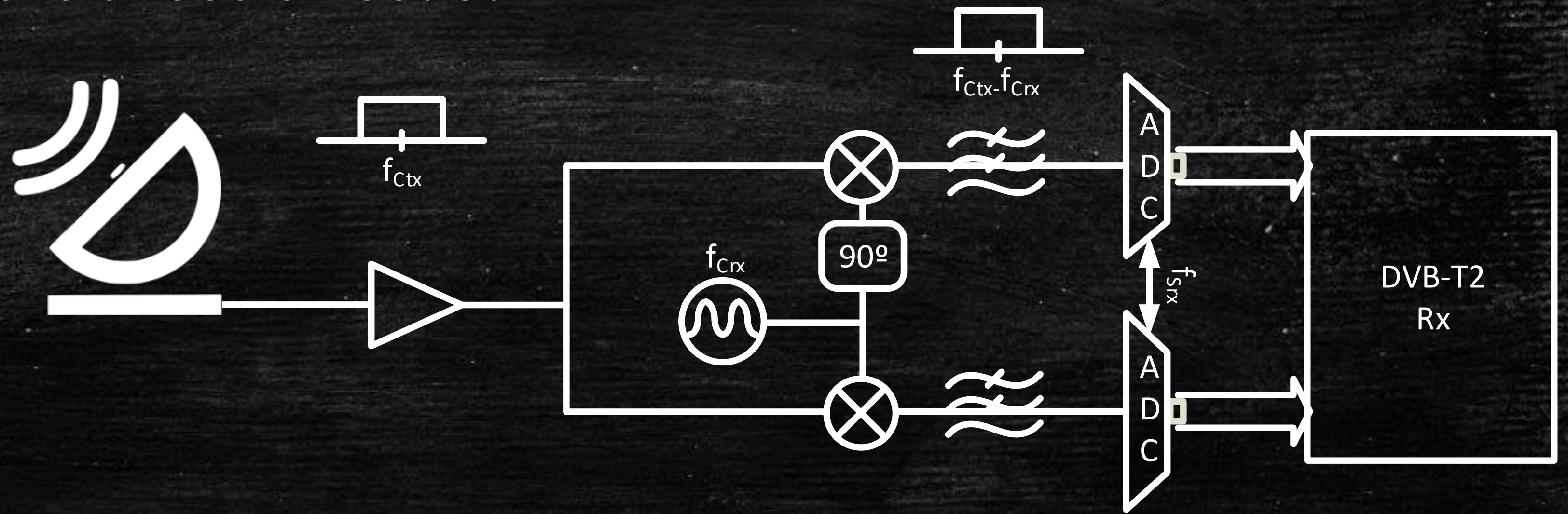
- $\boldsymbol{n}$ doesn't generate ICI, but the carrier reference is lost
  - The $\mathbf{0}$ carrier becomes the $\boldsymbol{nth}$

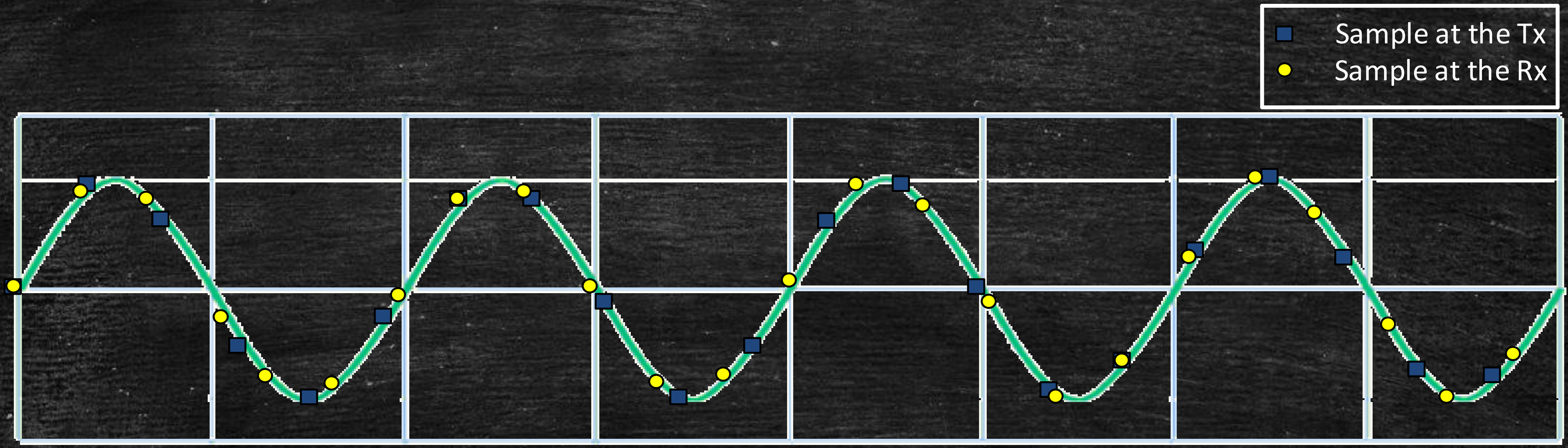
- $\boldsymbol{\delta f}$ causes the lost of orthogonality and the ICI
  - Needs to be corrected before working in the frequency domain

- Two approaches can be followed to correct it
  - Act over the analogue oscillator
  - Digital correction
- As a general truth it is better to work in the digital domain
- If we consider
  - Desired signal $s(t)$
  - Received signal $s_{rx}(t) = s(t)e^{j2\pi\Delta f t}$
- If we knew the value of $\Delta f$, we would only need to multiply $s_{rx}(t)$ by $e^{-j2\pi\Delta f t}$, obtaining the desired signal
- Digitally I need to multiply $s_{rx}(kT)$ by $e^{-j2\pi\Delta f kT}$, being $T$ the sampling time
  - By using a DSS (Digital Signal Synthesizer) we generate sine and cosine to generate the complex exponential

# Sampling frequency offset

- Again the difference between clocks
  - DAC at the Tx and ADC at the receiver have a frequency deviation
  - $f_{sampRx} = f_{sampTx}(1 + \delta)$
  - $\delta$ is measured in ppm (parts per million)
    - Depends on the precision of the crystal in the clock (typical value 50 ppm)
    - Varies in the time due to temperature fluctuations
      - A tracking of the offset is needed






- In the example the clock at the receiver is faster
  - The receiver will end up taking samples of a different OFDM symbol (ISI) due to the lost of the temporal synchronism
  - The first period has 6 samples at the transmitter and 7 at the receiver
  - For the receiver the signal is 6/7 slower
  - This produces a spectrum compression/expansion

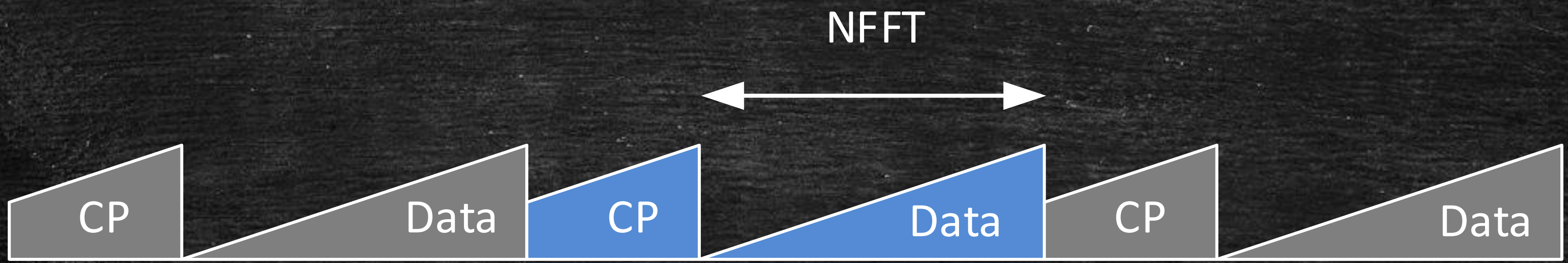
- The effects of this are:
  - ISI, because of the lost of temporal synchronism
  - ICI, because of the expansion/compression
- However:
  - The deviation will be as high as 100ppm
  - For a 10MHz clock this implies an error of ±1kHz
  - A sample of every 10000 is lost
  - The error will take a lot of time to be noticeable
  - A sample deviation in  more than 2000 samples symbol is not a lot
- To ease this problem interpolation can be used to know what point was transmitted (Lagrange coefficients)
- This implies that the deviation (δ) of the sampling frequency offset needs to be estimated

# Synchronization

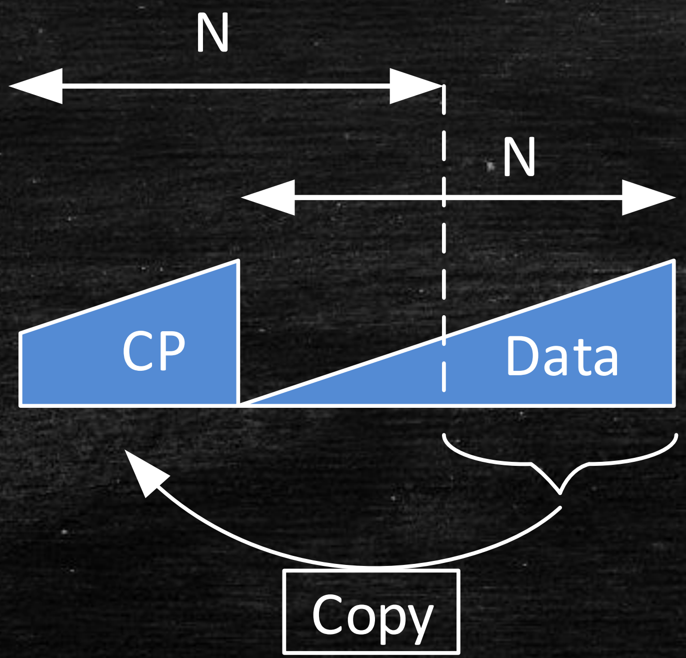
- **When the reception starts:**
  - **The transmission mode is unknown**
  - **The cyclic prefix is unknown**
  - **The temporal beginning of the symbol is unknown**
  - **Frequency offset error**
  - **Sampling frequency offset error**
- **This is all a mess!**

- The synchronization is carried out by performing the following process
  - Time domain
    - Mode detection
    - Cyclic prefix detection
    - Coarse time synchronization
    - Fine frequency synchronization
  - Frequency domain (AFTER THE FFT!)
    - Coarse frequency synchronization
    - Frequency and sampling frequency offset error tracking
    - Fine time synchronization

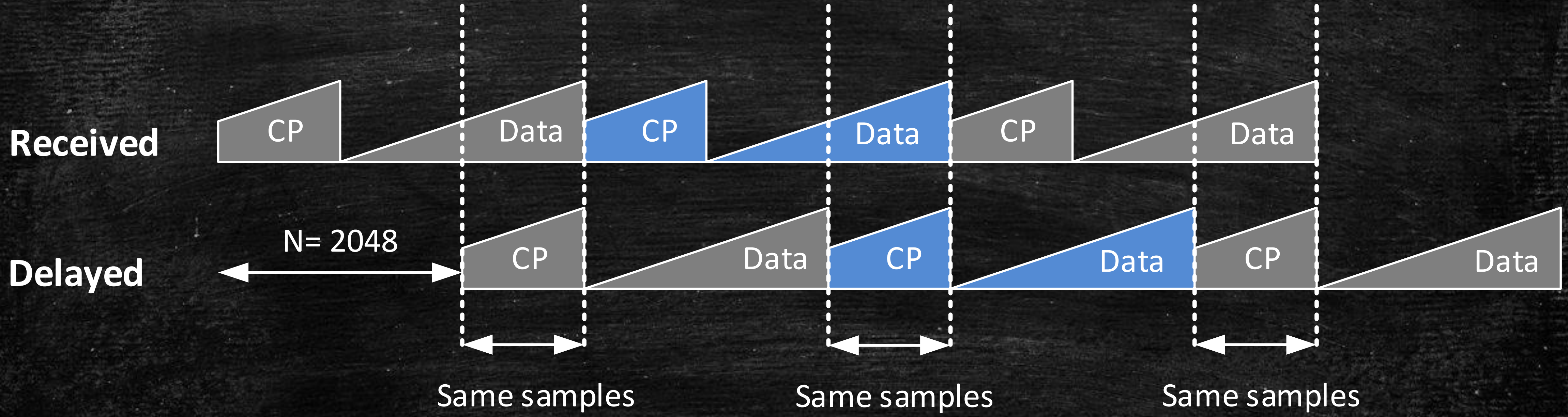
- **Mode detection**
  - **Transmitted symbols may have different amount of samples**



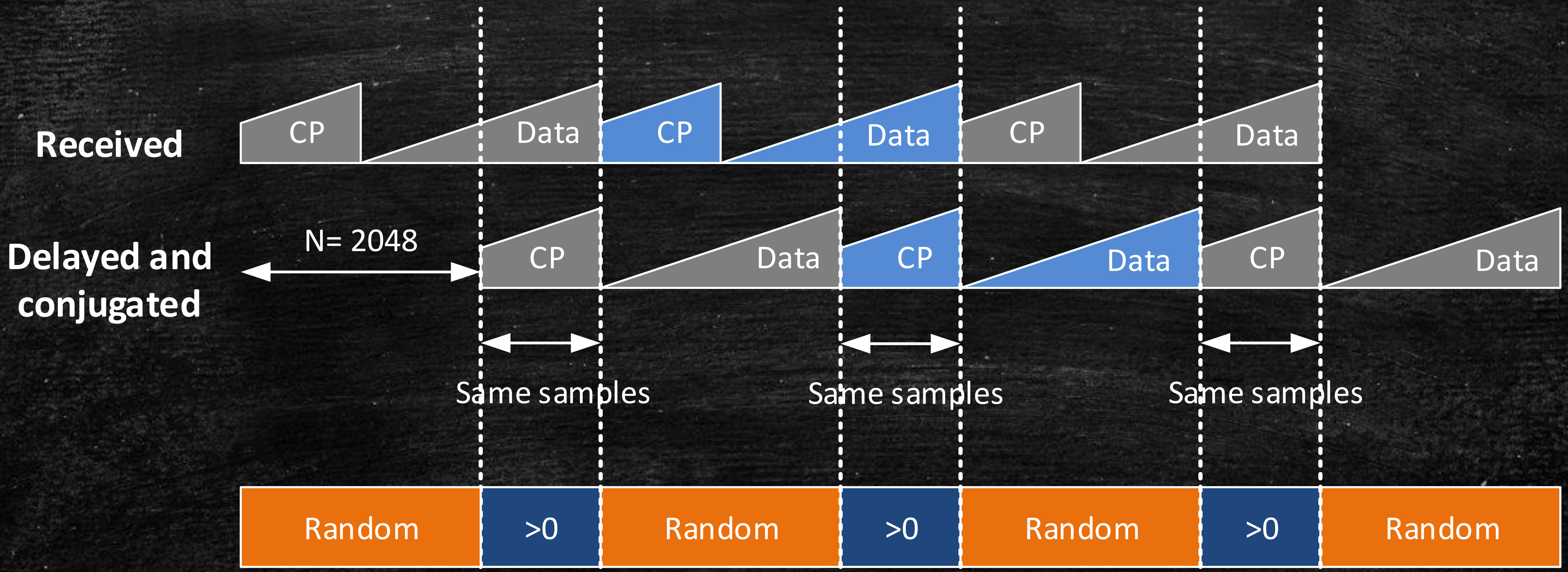

  - **The CP is a copy of the last samples in the data part of the symbol**



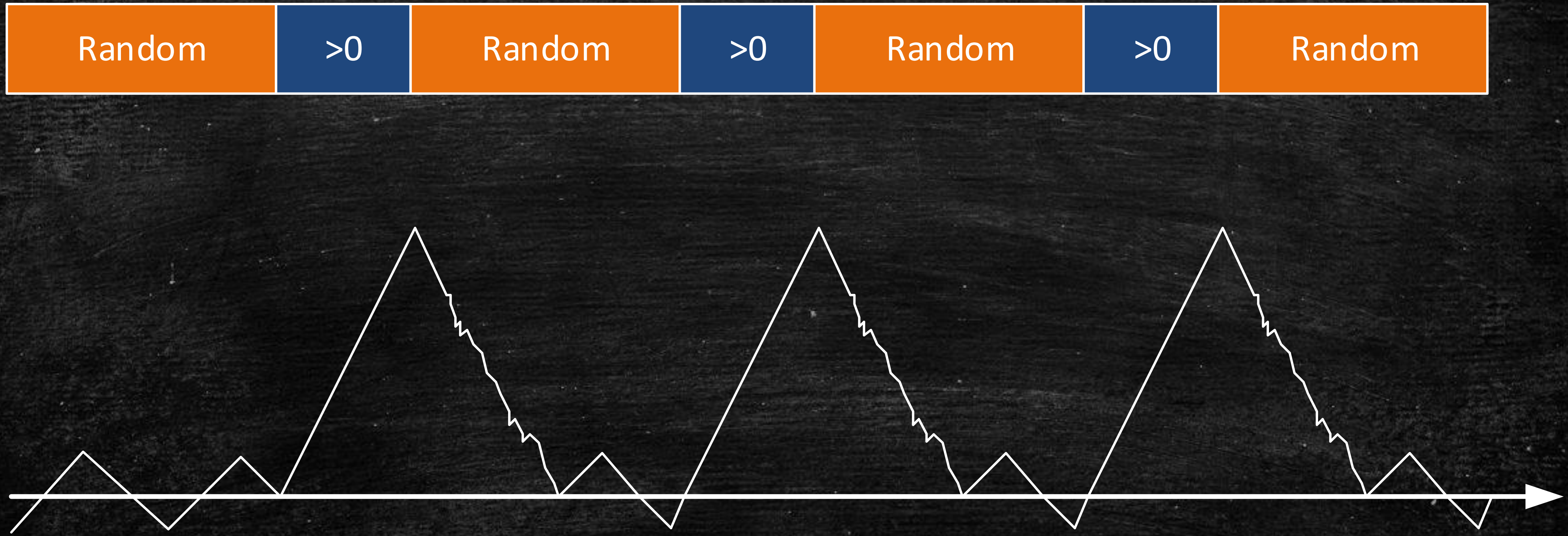
- Lets suppose that we have a 2k mode transmission (N=2048)
- By delaying the received signal 2048 samples (FIFO with length 2048)



- By multiplying the conjugated delayed version of the received signal by the original received signal
  - In the zone with same samples the result is the modulus (always greater than o)
  - In the other zones the product will be a random complex number



- **Integrating the result in a window of length the number of samples in the CP (NCP)**



- Mathematically this corresponds with the autocorrelation of a window of NCP samples

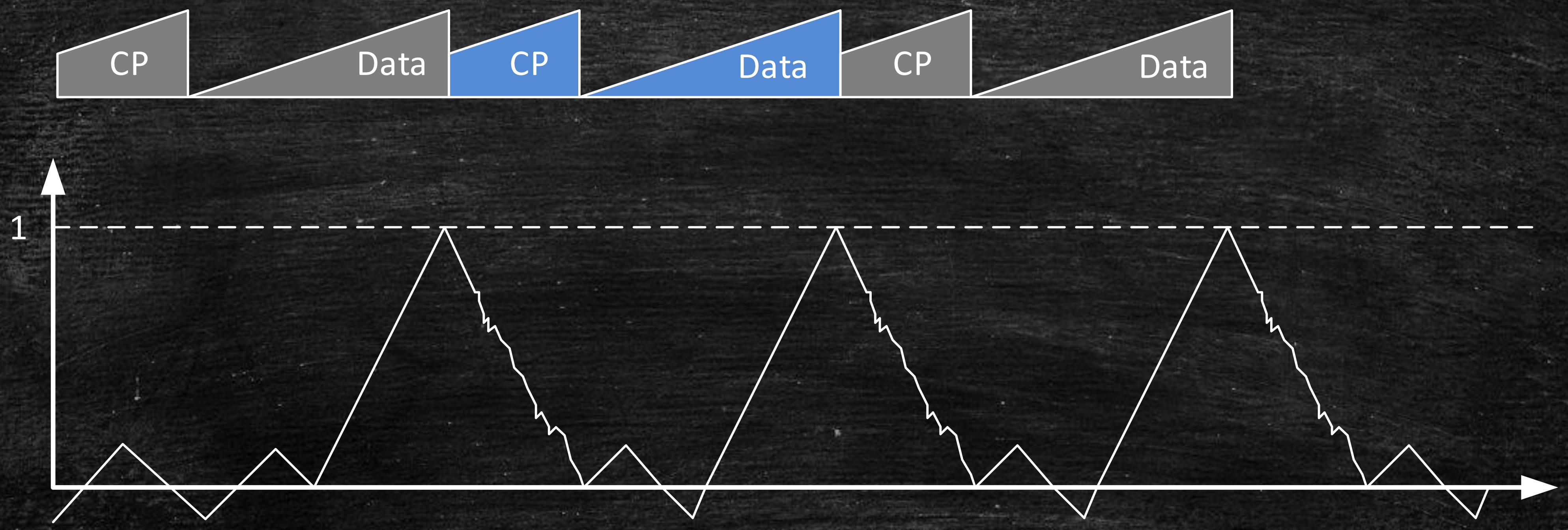
$$y(k) = \sum_{n=0}^{NCP-1} s(k-n)s^*(k-n-N)$$

- We can also define the energy of the signal as follows

$$e(k) = \sum_{n=0}^{NCP-1} s(k-n)s^*(k-n)$$

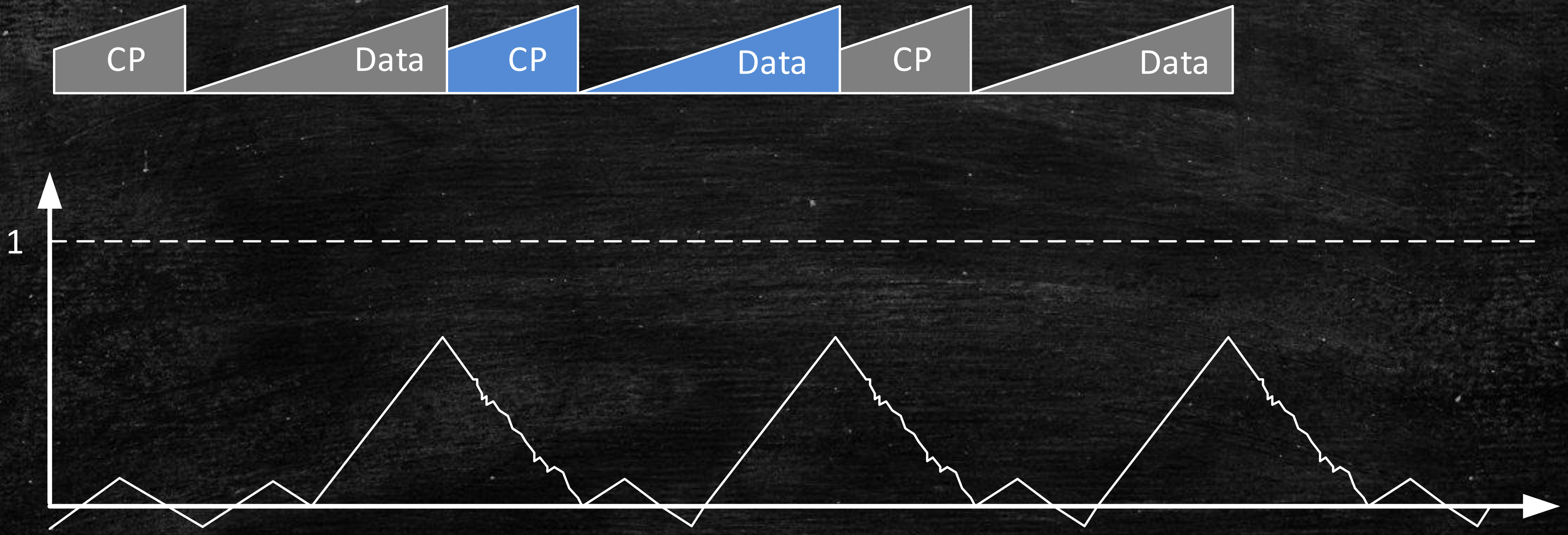
  - $e(k)$ is always positive and real
  - $e(k)$ and $y(k)$ only coincide in one sample, the last of the symbol

- We can normalize $y(k)$ by $e(k)$

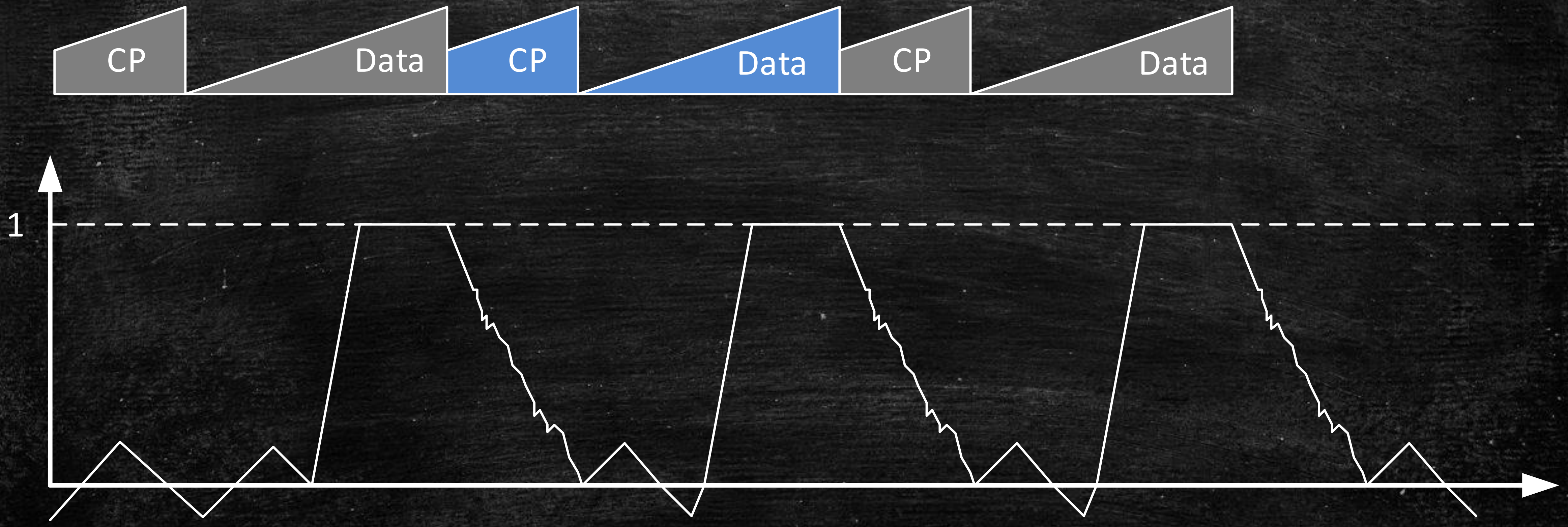



- Ideally the peaks will reach 1, but because of noise and interferences this won't happen, 0.5 is used as threshold

- In all this we have supposed that we know NCP, but in a real situation WE DON'T KNOW!
- If any NCP is fixed and the used one is smaller
  - The integration of the energy, e$(k)$, is bigger than the peak obtained in the autocorrelation, $y(k)$

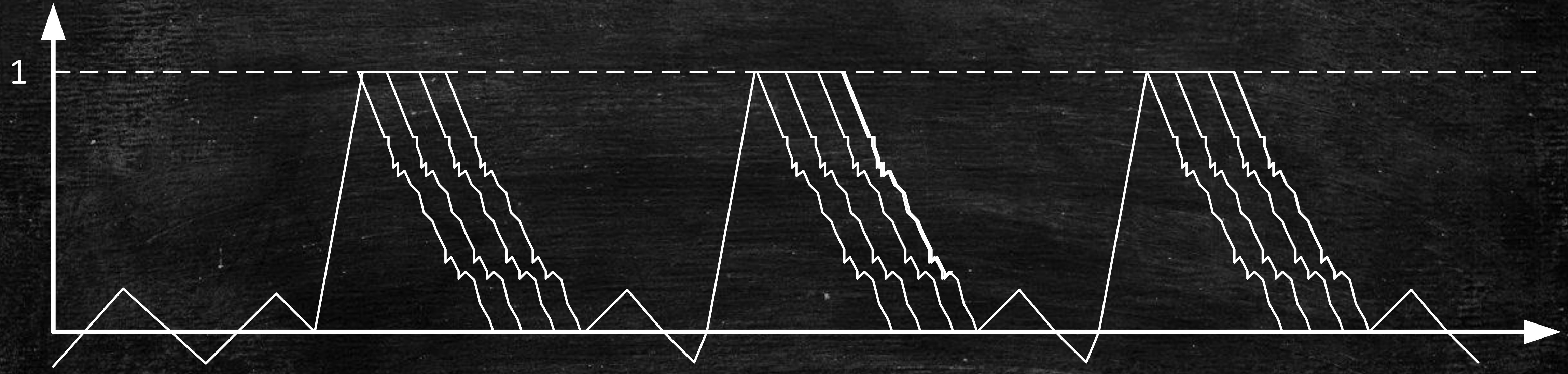


- If the opposite happens and the received CP is bigger than the one we set a mesa appears instead of a peak



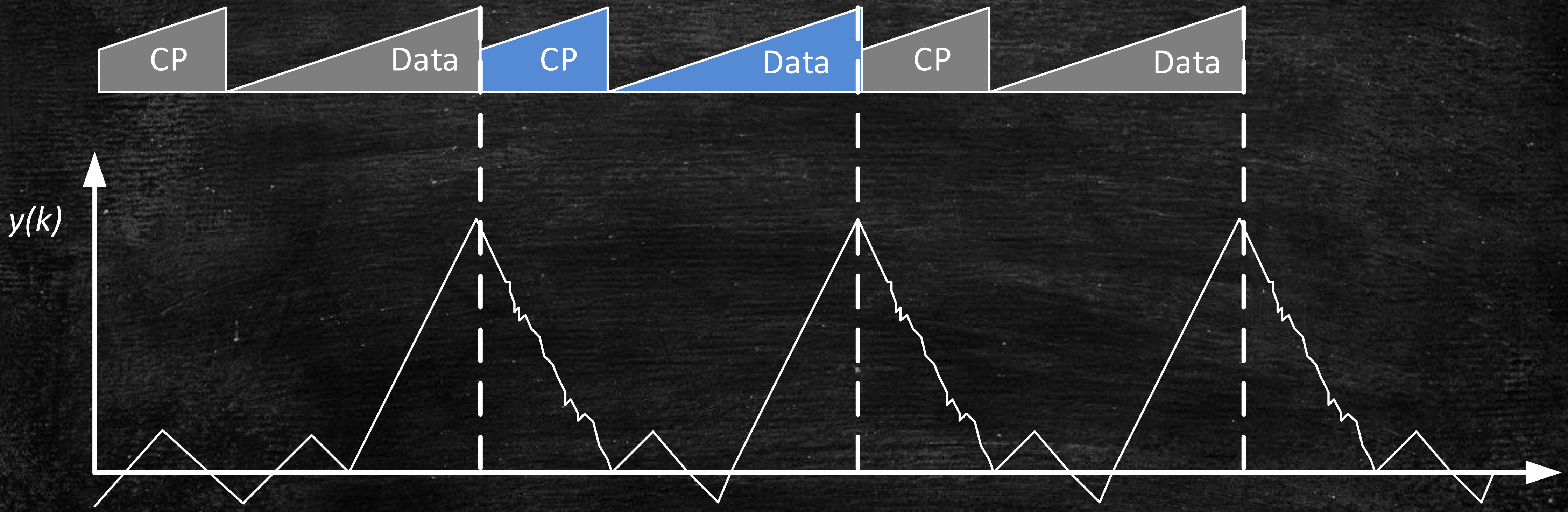
- As a method to detect the mode we can
  - Set as default the smaller mode with the smaller CP ( we don’t want to have the situation where the peak is attenuated by averaging, we are using a threshold to detect)
  - Calculate the autocorrelation and the energy
  - If $\mathbf{y}(\boldsymbol{k})/\boldsymbol{e}(\boldsymbol{k}) \geq \mathbf{0.5}$ the mode is the one currently being tested
  - After a timeout the  mode is not found change to the next smaller mode and repeat the process
  - If the time out is surpassed after trying all the modes … maybe there is no signal in the air!

- Cyclic prefix detection
  - The mode is already known
  - Again the autocorrelation is calculated as well as the energy supposing the smaller CP




  - Counting the samples in the mesa (until the normalized autocorrelation is lower than the threshold) we can guess what CP the transmitted signal is using

- Coarse time synchronization
  - Already knowing the mode and the CP
  - Again we calculate the autocorrelation




  - The peaks coincide with the last data sample of a symbol

- The presented method has some problems
- The maximum is found in one sample
  - Ideally this would lead to a perfect synchronization
  - The transmitted signal is immersed in a noisy environment, the sample will not usually be the one we expected
- However this will be enough to allocate the FFT window

- Fine frequency synchronization
  - The carrier separation is $\mathbf{1}/\boldsymbol{T_s}$
  - In a general expression $\Delta \boldsymbol{f} = \boldsymbol{n}(\mathbf{1}/\boldsymbol{T_s}) + \boldsymbol{\delta f}$
    - $\boldsymbol{n}$ is an integer
    - $\boldsymbol{\delta f}$ is a real number in $[-\mathbf{1}/\mathbf{2}\boldsymbol{T_s},\ \mathbf{1}/\mathbf{2}\boldsymbol{T_s}]$
  - $\boldsymbol{n}$ doesn't generate ICI, but the carrier reference is lost
  - $\boldsymbol{\delta f}$ causes the lost of orthogonality and ICI
    - Needs to be corrected before working in the frequency domain
  - The remaining par t of the frequency offset can be fixed afterwards

- Lets suppose that the received signal has a frequency offset of $\Delta f$ :

$$s_{rx}(t) = s(t)e^{j2\pi\Delta f t}$$

- In discrete form

$$s_{rx}(k) = s(k)e^{j2\pi\Delta f kT}$$

  – Being $T$ the sampling time

- We can rewrite the expression obtained for the autocorrelation

$$y(k) = \sum_{n=0}^{NCP-1} s_{rx}(k-n)s_{rx}^{*}(k-n-N) =$$

$$= \sum_{n=0}^{NCP-1} s(k-n)s^{*}(k-n-N)e^{j2\pi\Delta f(k-n)T}e^{-j2\pi\Delta f(k-n-N)T}$$

- Analysing the previous expression

$$e^{j2\pi\Delta f(k-n)T}e^{-j2\pi\Delta f(k-n-N)T} = e^{j2\pi\Delta fNT}$$

- Taking again that In a general expression $\Delta f = m(1/T_s) + \delta f$ and applying that $T_s = NT$

$$e^{j2\pi\Delta fNT} = e^{j2\pi\left(\frac{m}{NT}+\delta f\right)NT} = e^{j2\pi m}e^{j2\pi\delta fNT} = e^{j2\pi\delta fNT}$$

- And returning to the expression fore the autocorrelation

$$y(k) = \sum_{n=0}^{NCP-1} s(k-n)s^*(k-n-N)\, e^{j2\pi\delta fNT}$$

- If we consider the expression for the last sample

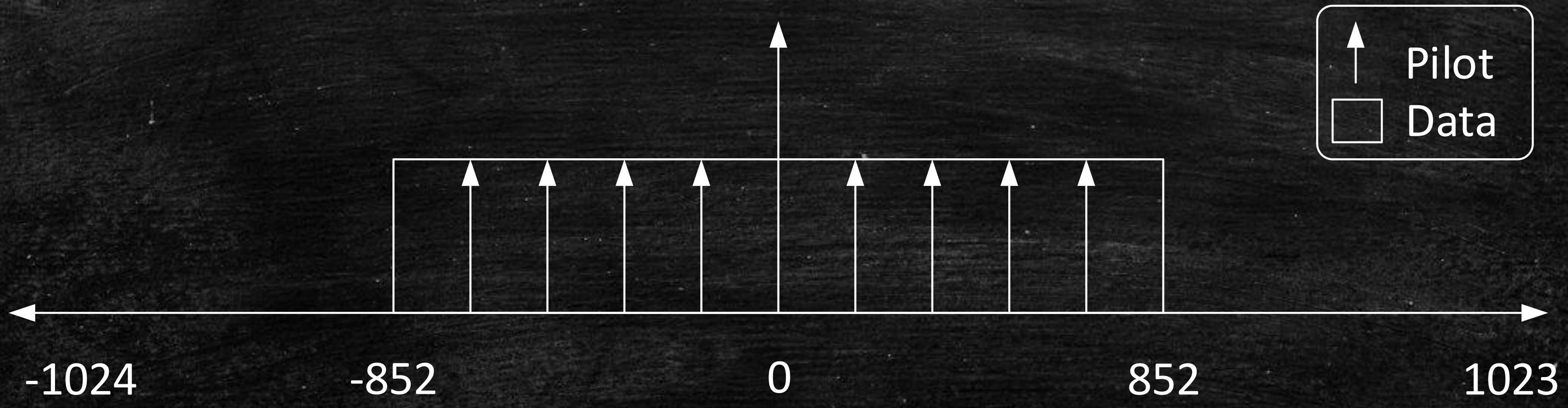
$$s(k-n) = s(k-n-N) \qquad 0 \le n \le NCP-1$$
$$s(k-n)s^*(k-n-N) = |s(k-n)|^2 \qquad 0 \le n \le NCP-1$$
$$y(k) = \sum_{n=0}^{NCP-1} |s(k-n)|^2 \, e^{j2\pi\delta f NT} = Ke^{j2\pi\delta f NT} \qquad K \in \Re$$

- This position is the maximum of the autocorrelation already evaluated in the coarse time synchronization
- The estimation for $\delta f$ is:

$$\delta f = \frac{\text{angle}(y_{max})}{2\pi NT}$$

- Coarse frequency synchronization
  - We already know the mode an CP
  - We have an estimation for the beginning of the symbols
    - We know the samples to apply the FFT (bounding the ISI)
  - The fine frequency offset has been estimated and can be corrected by means of a DSS
    - The ICI is eliminated
  - We can already apply the FFT and perform the rest of the synchronization in the frequency domain

- In a general expression $\Delta f = n(1/T_s) + \delta f$
- $\delta f$ has been already corrected
- The remaining to correct is a entire number of carriers shift
- Continual pilots are used for this purpose, if they are not in their place if this offset exists




OFDM symbol in the frequency domain (2k mode)

- As stated in the standard the location of the continual pilots is known and fixed always with the same information
- We denote as $S_n(k)$ the nth transmitted symbol (in the frequency domain)
- In reception $S_n^{rx}(k) = S_n(k)H(k)$, being $H(k)$ the frequency response of the channel, that can be expressed as $H(k) = h(k)e^{j\theta(k)}$
- Computing the following product

$$S_n^{rx}(k)S_{n-1}^{rx}(k)^* = S_n(k)S_{n-1}(k)^* h(k)^2$$

- In general this expression will be a random complex number, but in the continual pilot positions

- The transmitted pilots use a BPSK constellation [-A, A]
  - The amplitude is different for the different pilot patterns (4/3, 7/4 or 7/3)
- If *P* is the set of points corresponding to the continual pilots location

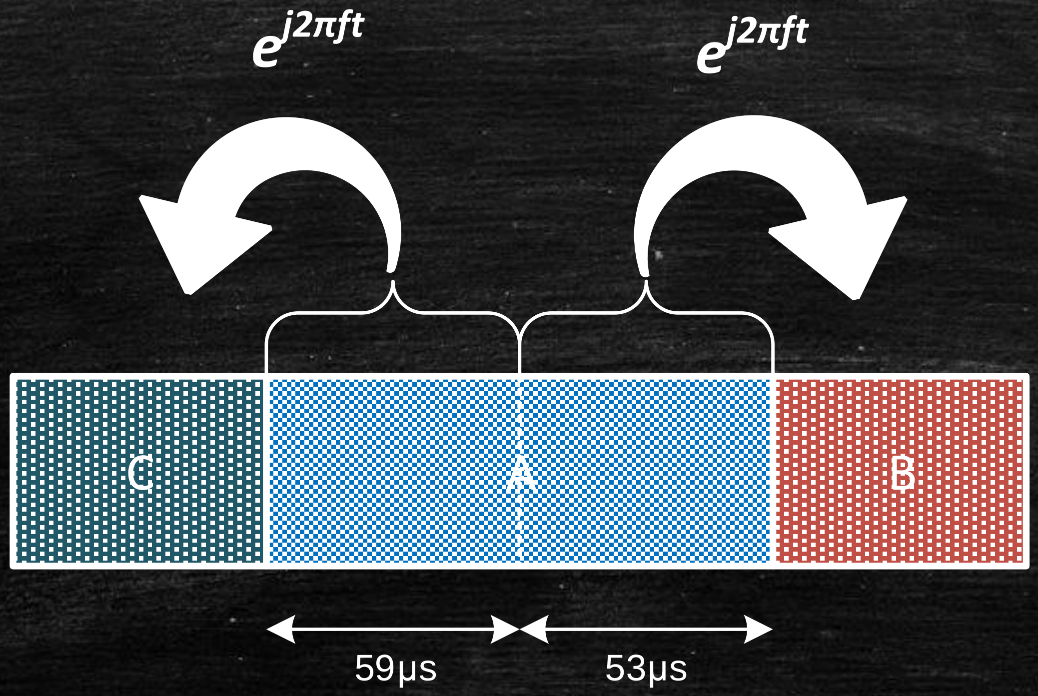
$$S_n(k)S_{n-1}(k)^* = A^2 \quad k \in P$$

$$S_n^{rx}(k)S_{n-1}^{rx}(k)^* = S_n(k)S_{n-1}(k)^* h(k)^2 = (A^2)h(k)^2 \quad k \in P$$

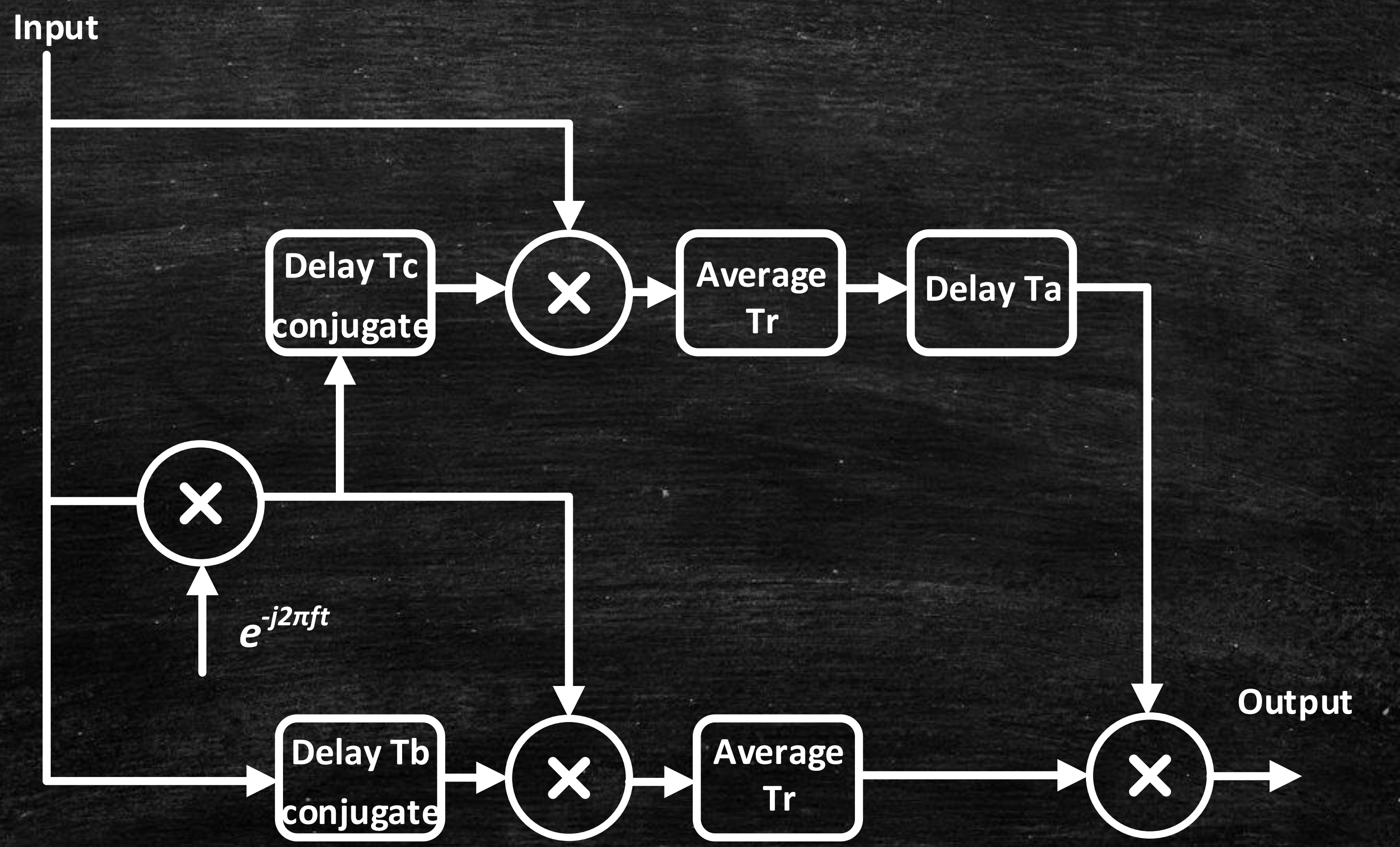
  - A real and positive number
- Otherwise the result will be a random complex number
- If there is a frequency offset the pilots will be in *P+m* instead of in *P*

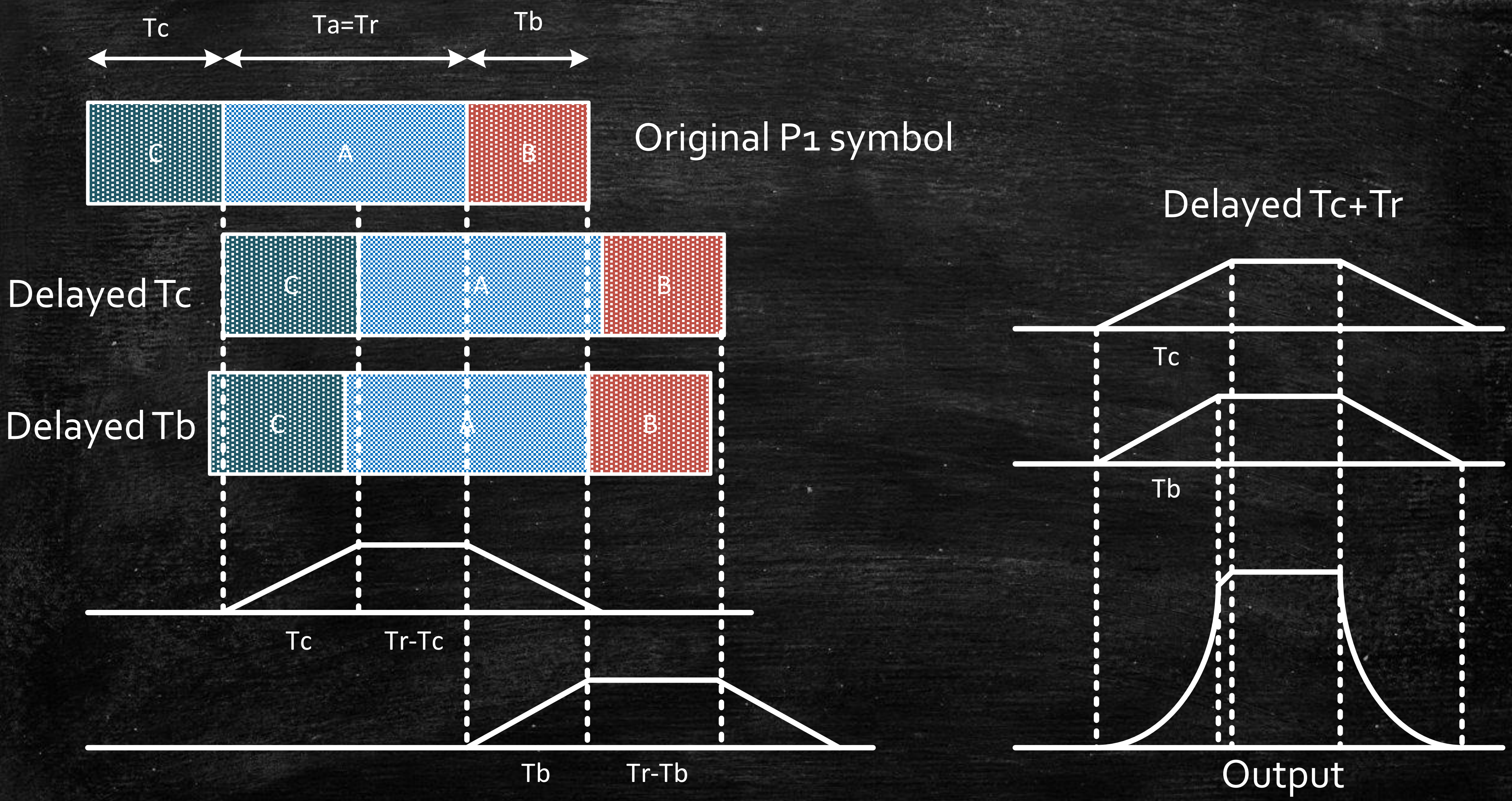
- A possible algorithm to correct the coarse frequency offset
  - We define the search interval $m \in [-M_{max}, M_{max}]$
  - The sum $S_n(k)S_{n-1}(k)^*$ for $k \in P + m$ is calculated
  - If the sum is higher than for the previous maximum the value and the index $m$ are stored
  - The final maximum's index will be the frequency offset
  - The frequency offset will be corrected with a DSS

- **P1 aided detection**
  - A 1K OFDM symbol with two "guard interval-like" portions added
  - The total symbol lasts 224 µs in 8 MHz system, being 112 µs, the duration of the useful part 'A' of the symbol plus two modified 'guard-interval' sections 'C' and 'B' of roughly 59 µs (542 samples) and 53 µs (482 samples)
  - The copies are frequency displaced to avoid common wave interference



- The special characteristics of the P1 symbol allow to perform the detection with the following scheme



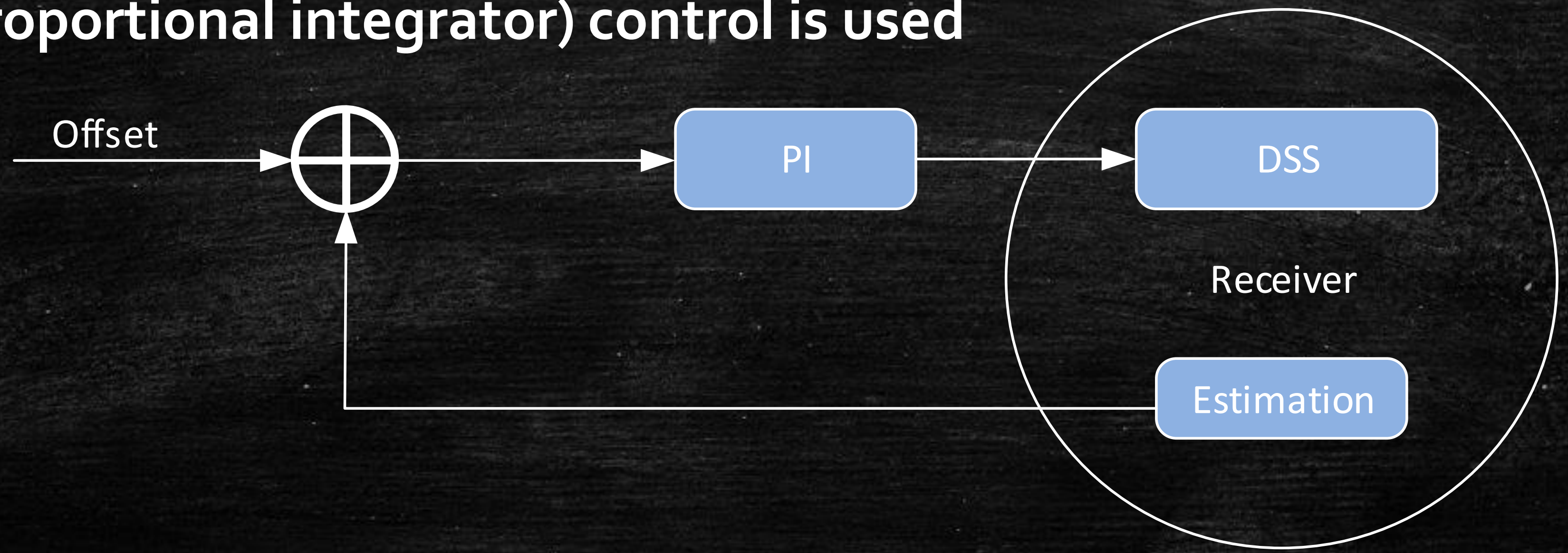


Tc
Ta=Tr
Tb
C
A
B
Original P1 symbol
Delayed Tc
C
A
B
Delayed Tb
C
A
B
Tc
Tr-Tc
Tb
Tr-Tb
Delayed Tc+Tr
Tc
Tb
Output

- $T_R$ is chosen to be the reciprocal of $f_{SH}$ and thus corresponds to 1024 sample periods, the same as $T_A$
  - This is chosen to eliminate unwanted complex-constant terms at the outputs of the two correlators which might otherwise be caused by CW interference or certain other unwanted correlation conditions
- The argument of the correlator outputs contains information about the fine frequency offset, but also the frequency shift
  - By multiplying the two correlator pulses the effect of the unknown arbitrary phase is cancelled
  - The argument of the final output pulse can be shown to be proportional to the fine component of the frequency offset.

# Frequency tracking

- The frequency offset varies in the time (drift)
- With the previous method we have stated an instantaneous offset value
- This needs to be tracked to correct its possible deviations
- A PI (proportional integrator) control is used



- **Frequency offset estimation**
  - **We use a similar process to the one for coarse frequency**
  - $\boldsymbol{S_n^{rx}(k)S_{n-1}^{rx}(k)^* = S_n(k)S_{n-1}(k)^* h(k)^2}$
  - **The result should be a positive real number for $\boldsymbol{k \in P}$**
  - **If a frequency offset exists the phase of the previous product is different from zero and proportional to the frequency offset**

- The algorithm for the frequency offset tracking
  - For every couple of received symbols
    - The sum $Y$ of the products $S_n(k)S_{n-1}(k)^*$ for $k \in P$ is calculated
    - The frequency offset is $\Delta f = \frac{angle(Y)}{2\pi\left(1+\frac{NCP}{N}\right)}$
    - This estimation actuates over the DSS through the PI control
  - The control loop constants must be calculated taking into account
    - Must be fast to follow the drift of the clock
    - Must be slow in comparison with the channel temporal fadings

- The sampling frequency offset also needs to be tracked and corrected
- The correction is very similar to the frequency offset one but instead of a DSS a Farrow filter is applied
- However it is much more complex

# Channel estimation

- After the channel propagation

$$S_{rx}(f) = S(f)H(f) + n(f)$$

  - Being $n(f)$ the noise in the channel

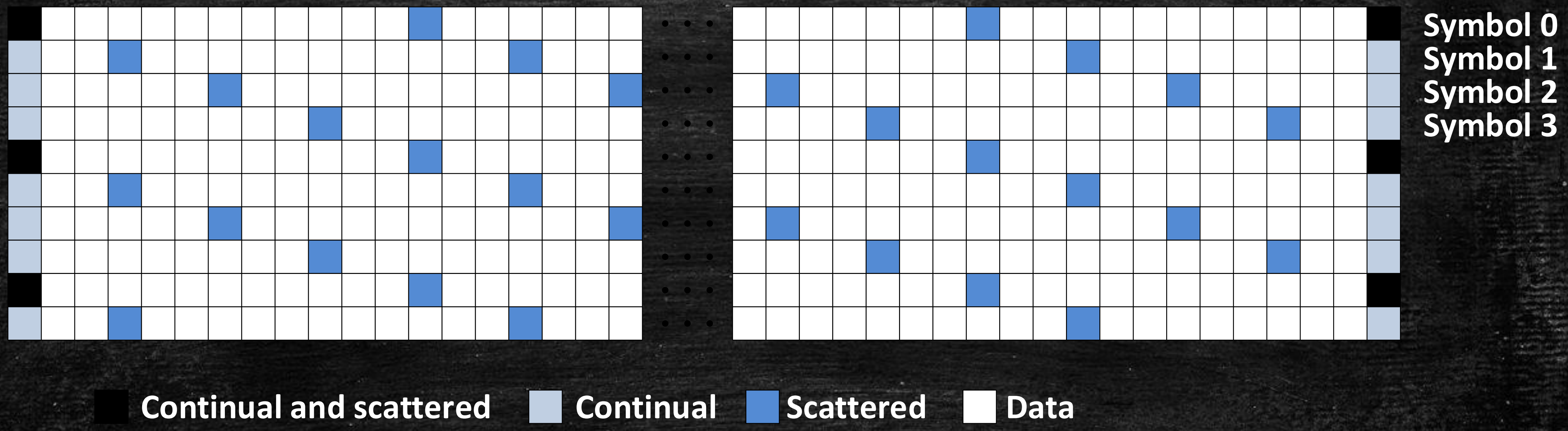
- In the discrete domain (after the FFT)

$$S_{rx}(k) = S(k)H(k) + n(k)$$

- In order to demodulate the received signal $H(k)$ must be calculated
  - $\widetilde{H}(k)$ represents the estimation of $H(k)$
  - The estimation of $S(k)$ is obtained by equalizing

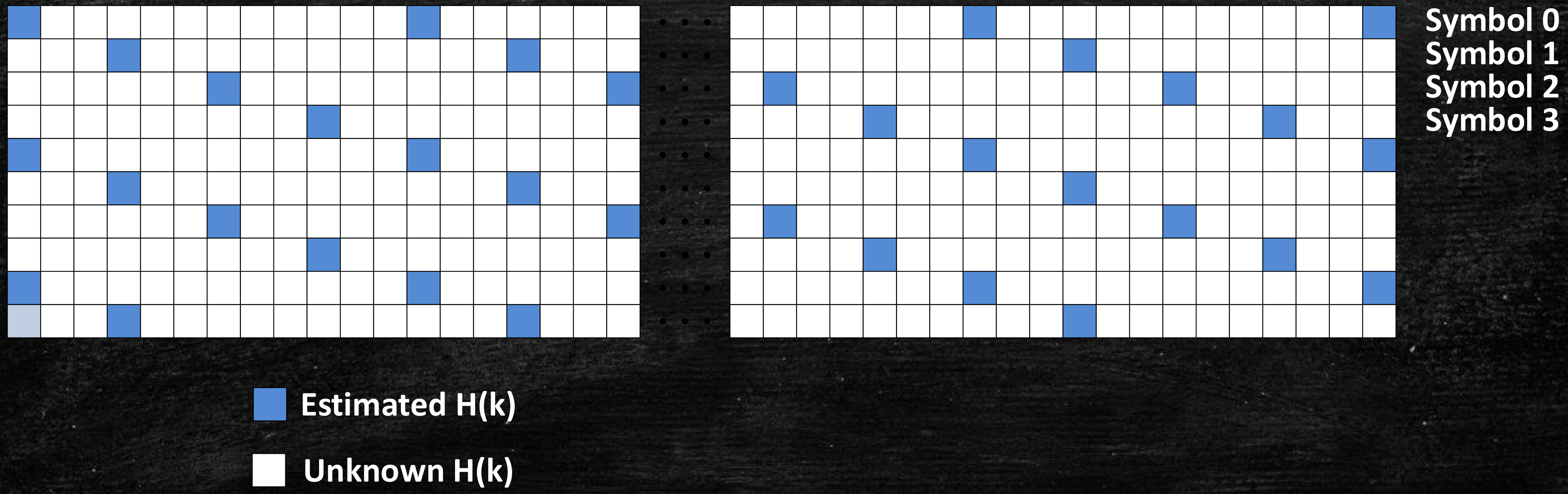
$$\tilde{S}(k) = S_{rx}(k)/\widetilde{H}(k) = S(k)H(k)/\widetilde{H}(k) + n(k)/\widetilde{H}(k)$$

- The channel is estimated by using the scattered pilots inserted in the OFDM symbol



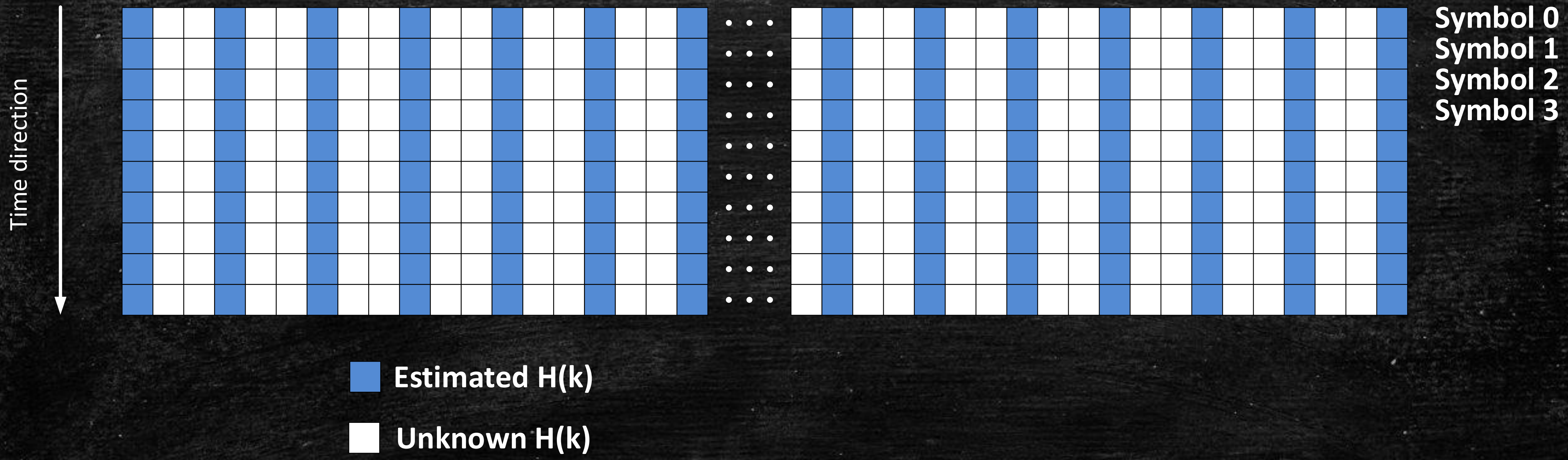
- At the receiver $S_{rx}(k) = \mathrm{S}(k)\mathrm{H}(k) + \mathbf{n}(\mathbf{k})$
  - If $k$ is a scattered pilot carrier, the value of $S(k)$ is known
  - So the estimation in those positions can be obtained by dividing by the value of $S(k)$

$$\widetilde{H}(k) = S_{rx}(k)/S(k)$$

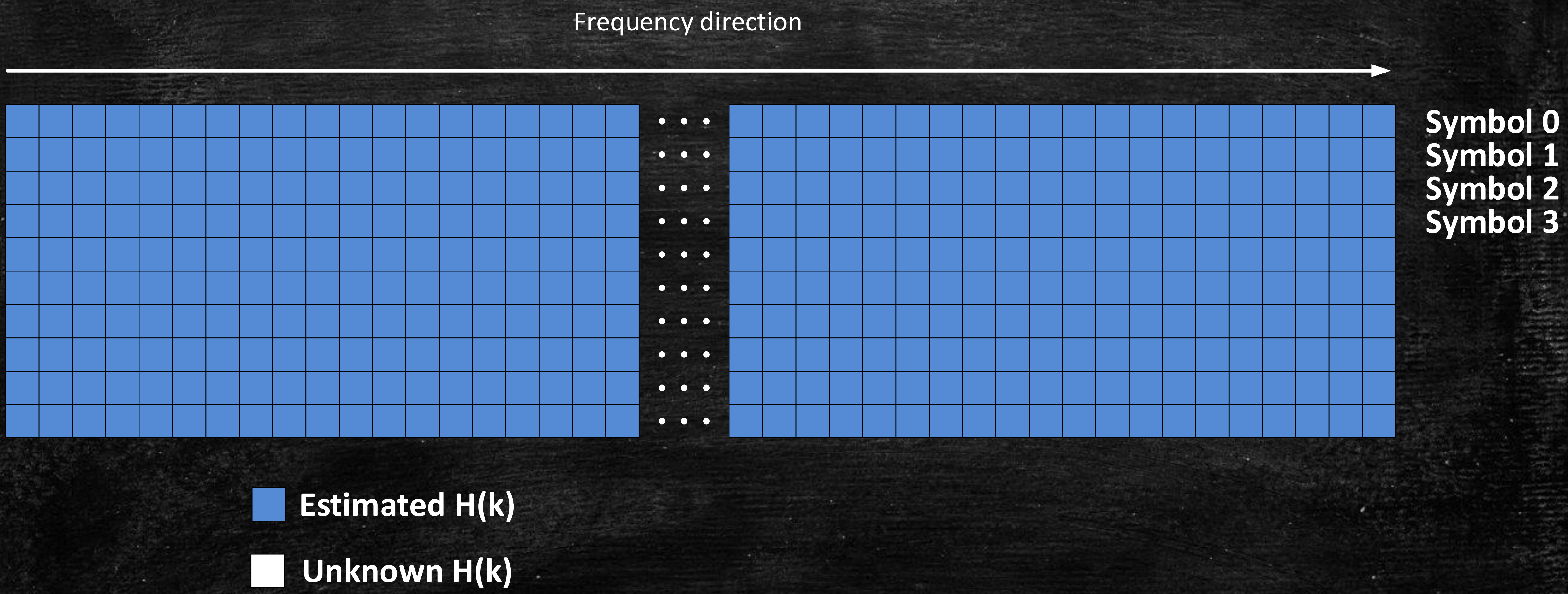


- The remaining positions are estimated in two steps
  - Channel estimation in time direction
  - Channel estimation in frequency direction

- For the temporal estimation a carrier $k$ is fixed and by means an interpolator filter the unknown positions are calculated



- After the temporal interpolation, a frequency interpolation is carried out
  - A symbol is selected and the unknown positions are interpolated



- The interpolator filters are designed taking into account the characteristics of the radio channel
  - A WSS-US (Wide Sense Stationary-Uncorrelated Scattering)

- As the signals propagates through a noisy channel wiener filters are used to minimize the square root mean error

# THANKS !

Any questions?

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