

M1-IRELE

**ELEC-H401 Modulation and coding**

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# DVB-C project

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## Introduction

This report aims to complete the code that simulates a DVB-C transmission chain in matlab. It provides additional information from the theoretical part of the project and it shows the main results.

To simulate a transmission, each disturbance block is added and then the correction blocks are designed to compensate for the disturbances. The appropriate signals and plot are shown for each intermediate step to ensure that the blocks are working correctly.

The first step is to simulate the channel shown in figure 1. It is then followed by the addition of synchronization errors and the corresponding correction blocks.

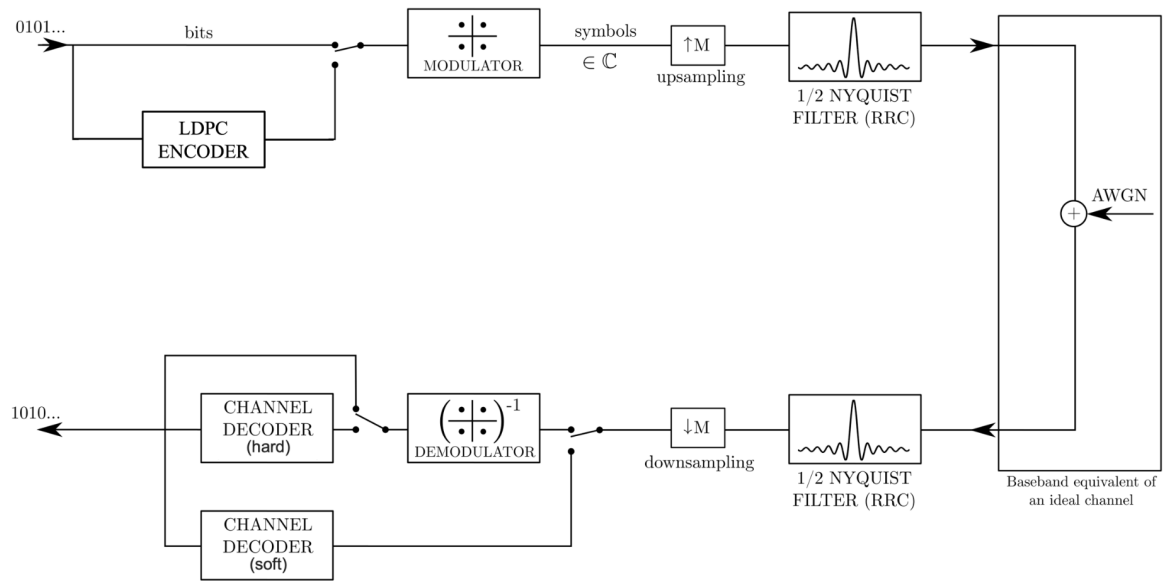


Figure 1: DVB-C transmission chain

### Baseband representation

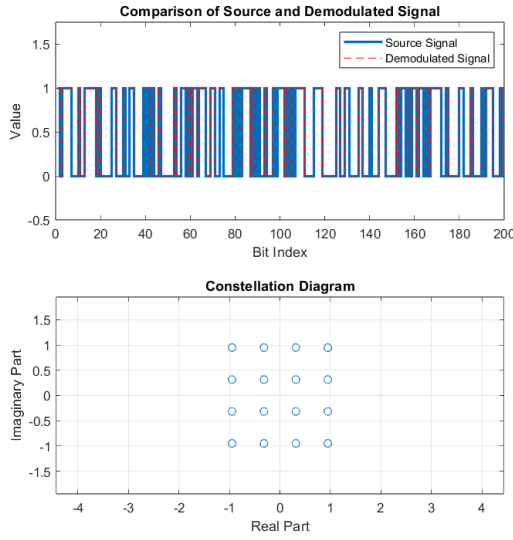
By looking at the block diagram of the transmission chain 1, one can see we never move the baseband signal to the carrier frequency. As the simulation runs on a computer, using the bandpass representation of the signal would require much more samples as the sampling frequency would need to be at least twice the carrier frequency. By simulating the chain in baseband, the minimal sampling frequency is reduced to the symbol rate in order to have at least one sample per symbol.

Because the signal is oversampled, the sampling frequency is then equal to the symbol rate multiplied by the oversampling factor.

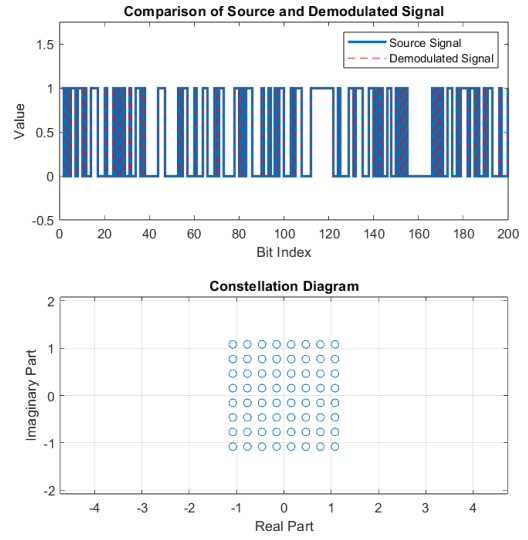
### Modulation and Demodulation

After generating  $N$  random bits, they are modulated. This allows to send fewer symbols than the number of bits. We chose QAM modulation as it combines ASK and PSK. Depending on the number of bits per symbol ( $N_{\text{bps}}$ ), the number of bits sent ( $N$ ) had to be chosen such that  $N/N_{\text{bps}} \in \mathbb{N}$ .

Figure 2 compares the constellation diagrams obtained for QAM-16 and QAM-64. As the constellations points are more spaced on the left, QAM-16 is less prone to a wrong demodulation (when noise will be added). This comes at the cost of a lower bitrate: for the same symbol rate, QAM-64 will send 6 bits while QAM-16 only send 4. It clearly shows a compromise between reliability and capacity.



(a) QAM-16 modulation



(b) QAM-64 modulation

Figure 2: Comparison of QAM modulations, where the mean square error is computed between the transmitted and received bitstream

## Optimal demodulator and detector

First, it is important to remind that the transmitted signal is represented by a set of coefficients which results from the projection of the signal on an orthonormal basis related to the chosen modulation. Once transmitted, the signal is affected by noise (AWG noise here). In the general case, this noise moves the signal, resulting in a change in its coefficient in the basis, as can be seen on Figure 3

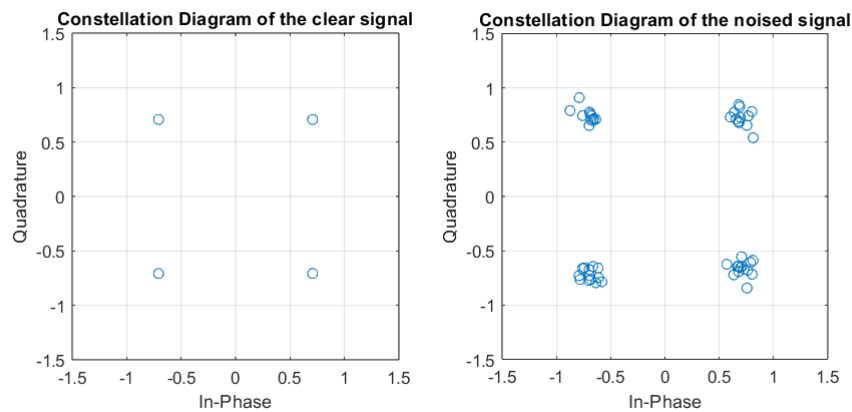


Figure 3: Effect of noise on the constellation diagram

To construct an optimal demodulator, 2 criteria should be taken into account. The first one is the sufficient statistic criteria. It is proven that once the received signal is projected on the sub-space defined by the previous basis functions, the noise component outside of the sub-space is independent from the pro-

jected signal. It means that there is no information loss when projecting the received signal on the original sub-space and the optimal decision can therefore be made using the projection of the incoming signal.

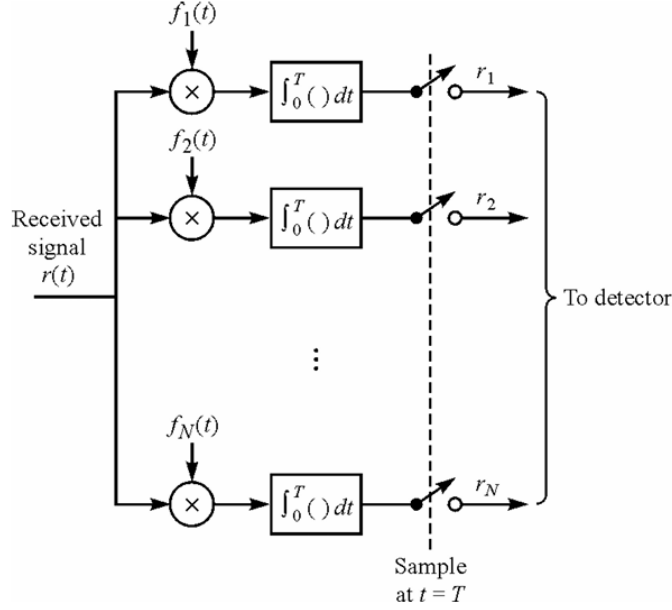


Figure 4: Projection on basis sub-space

$$\begin{aligned}
 E[n'(t)r_k] &= E[n'(t)]s_{mk} + E[n'(t)n_k] \\
 &= E[n'(t)n_k] \\
 &= E\left[\left(n(t) - \sum_{l=1}^K n_l f_l(t)\right) n_k\right] \\
 &= \int_{t'=-\infty}^{\infty} E[n(t)n(t')] f_k(t') dt' - \sum_{l=1}^K E[n_l n_k] f_l(t) \\
 &= \frac{N_0}{2} f_k(t) - \frac{N_0}{2} f_k(t) = 0
 \end{aligned}$$

Figure 5: Criteria of sufficient statistics

The second criteria is the usage of matched filters. The demodulator used to achieve the sufficient statistic property is composed of a bank of correlators (projection on a basis function). Instead of using a bank of correlators, we can use a bank of filters matched to the basis functions of the chosen modulation. It is proven that such filters at the demodulator gives a maximized SNR (minimize the power of the noise at the exit of the demodulator).

In conclusion, by using a bank of filters matched on the orthonormal basis function set by the choice of the modulation, we can construct a optimal demodulator which will ensure an optimal decision based on the received signal and ensure a maximum SNR at the output of this demodulator.

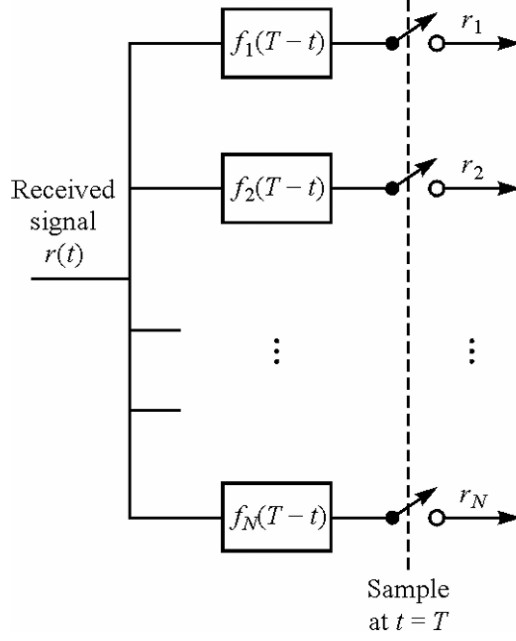


Figure 6: Bank of filters matching basis functions

$$\text{SNR} := \frac{\left[ \int_{\tau=-\infty}^{\infty} s(\tau) h(-\tau) d\tau \right]^2}{\frac{N_0}{2} \int_{\tau=-\infty}^{\infty} h^2(-\tau) d\tau}$$

Cauchy-Schwartz inequality:

$$\left[ \int_{t=-\infty}^{\infty} g_1(t) g_2(t) dt \right]^2 \leq \int_{t=-\infty}^{\infty} g_1^2(t) dt \int_{t=-\infty}^{\infty} g_2^2(t) dt$$

Equality if  $g_1(t) = k g_2(t)$  for any arbitrary constant  $k$

Figure 7: Maximum SNR demonstration

At the output of the demodulator, we still need to make sure the optimal choice of the  $M$  possible  $s_m(t)$  is made based on the received signal. To achieve this, the maximum likelihood criteria is used. It is equivalent to the maximum a posteriori criteria (general criteria) in the case of equiprobable symbols  $s_m(t)$ . The criteria leads to the following result : the optimizal  $s_m(t)$  choice is found by taking the minimum euclidian distance between the observable received signal  $r(t)$  and all the possible modulated signal  $s_m(t)$ .



## Pulse shaping

With modulation only, the bandwidth of the transmitted signal is infinite. This is problematic as it could interfere with neighboring channels. A filtering is applied to resolve this but the chosen filter must respect two other constraints: it must cancel inter-symbol interference (ISI) and must maximize the SNR.

The raised cosine filter is chosen as it limits the bandwidth and cancels ISI. To maximize the SNR, it is applied as a matched filter by using the square root of it at the transmitter and at the receiver.

The time domain and frequency domain representation of the raised cosine filter is shown in Figure 8. Figure 9 shows how the signal is shaped in the time domain and how there is indeed no ISI. Finally, the power spectral density <sup>1</sup> of the transmitted signal is plotted in figure 10 where the frequency band is limited to  $[-3, 3]$  MHz.

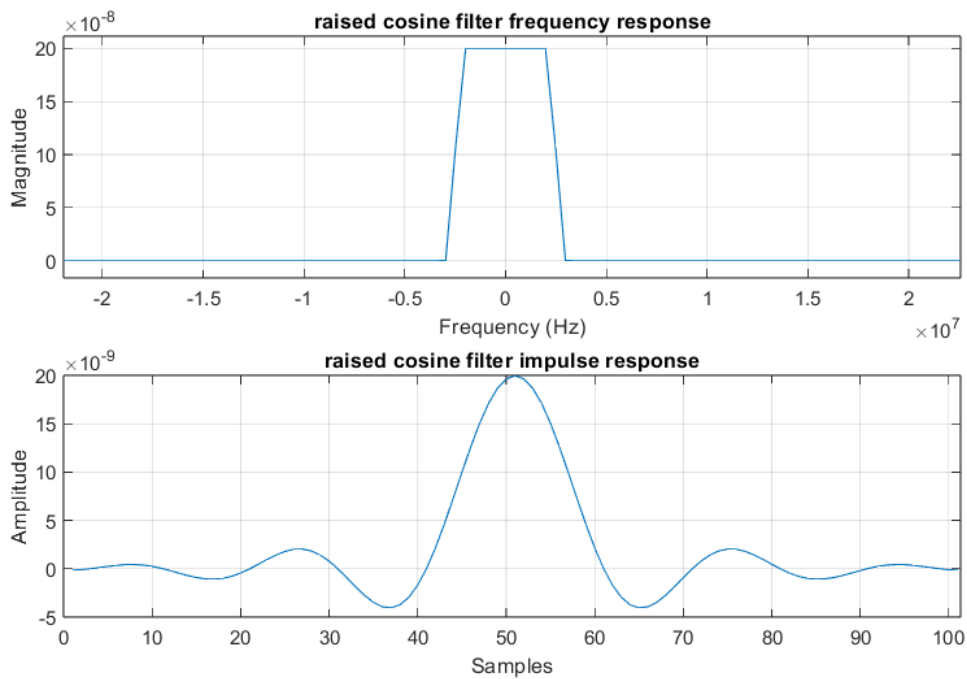


Figure 8: Time and frequency domain representation of the raised cosine filter

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<sup>1</sup>PSD as the signal is a random variable

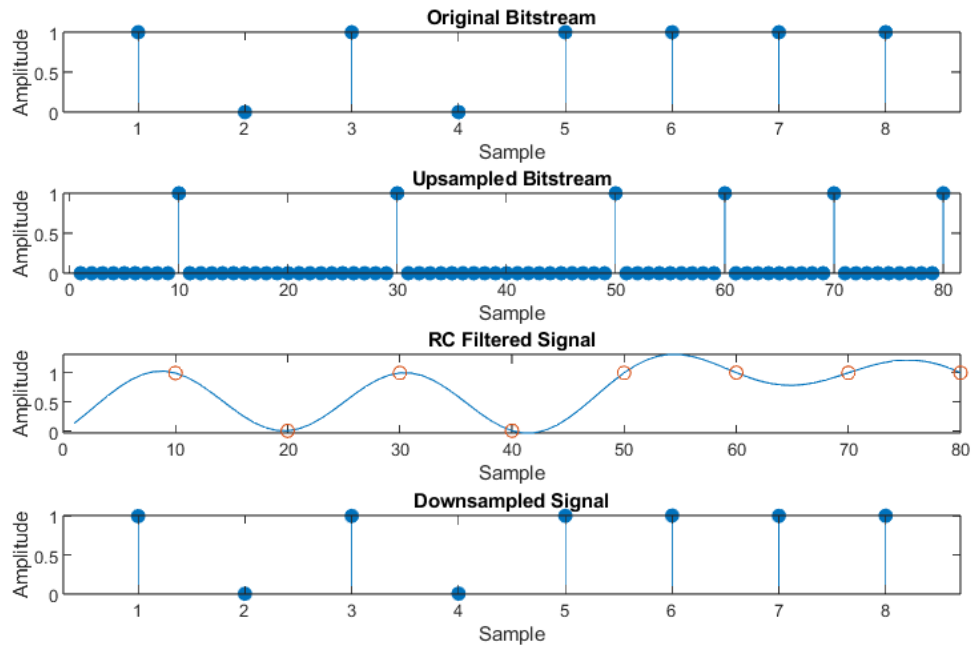


Figure 9: Pulse shaping with a raised cosine filter

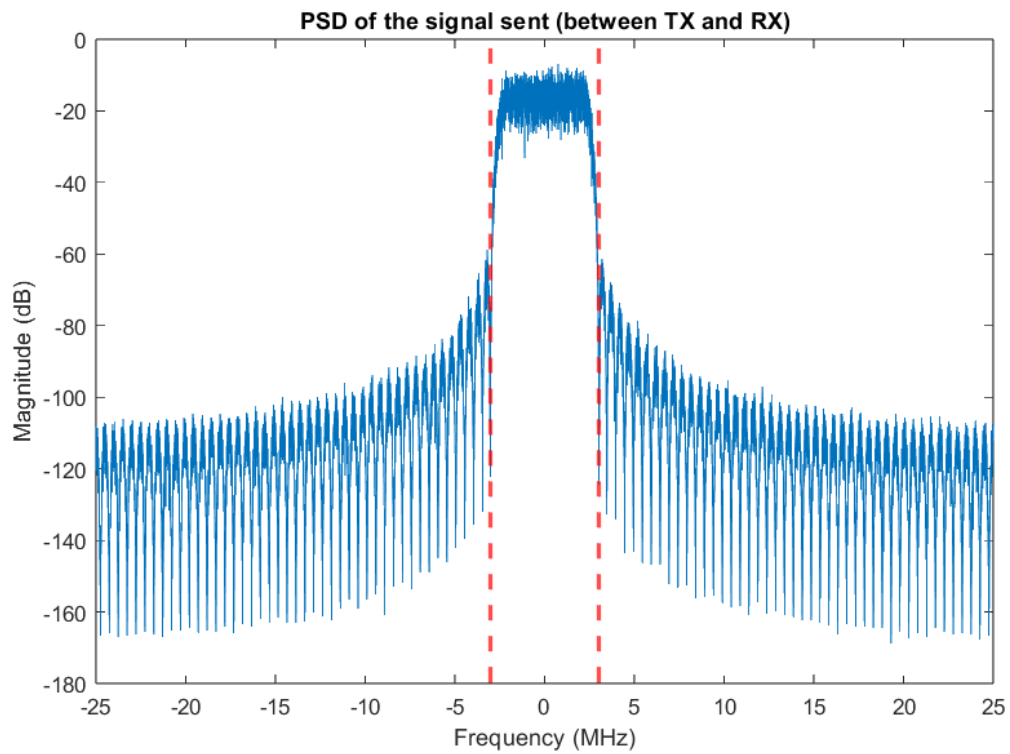


Figure 10: PSD of the transmitted signal after pulse shaping

## Noise addition

The last building block is a noise source. It generates additive white Gaussian noise in baseband. When the signal is too much corrupted, the demodulation can fail. The BER curves are plotted in figure 11 and they show the impact of the noise power  $N_0$  on the bit error rate. The compromise between reliability and capacity is again visible: in the same conditions (same  $E_b/N_0$ ), a modulation with lower capacity will have a smaller BER.

The theoretical BER curves are plotted on figure 11 and are compared with the simulation results. They stay close to each other until the BER reaches  $10^{-4}$ . This limit could go even lower by increasing the number of bits sent but we limited it to  $10^6$  in order for the code to run quite fast.

To impose a value of  $E_b/N_0$ , we start by computing the energy of the transmitted signal before adding the noise. The power of the noise is then chosen as  $N_0 = E_b / (E_b/N_0)_{\text{desired}}$ .

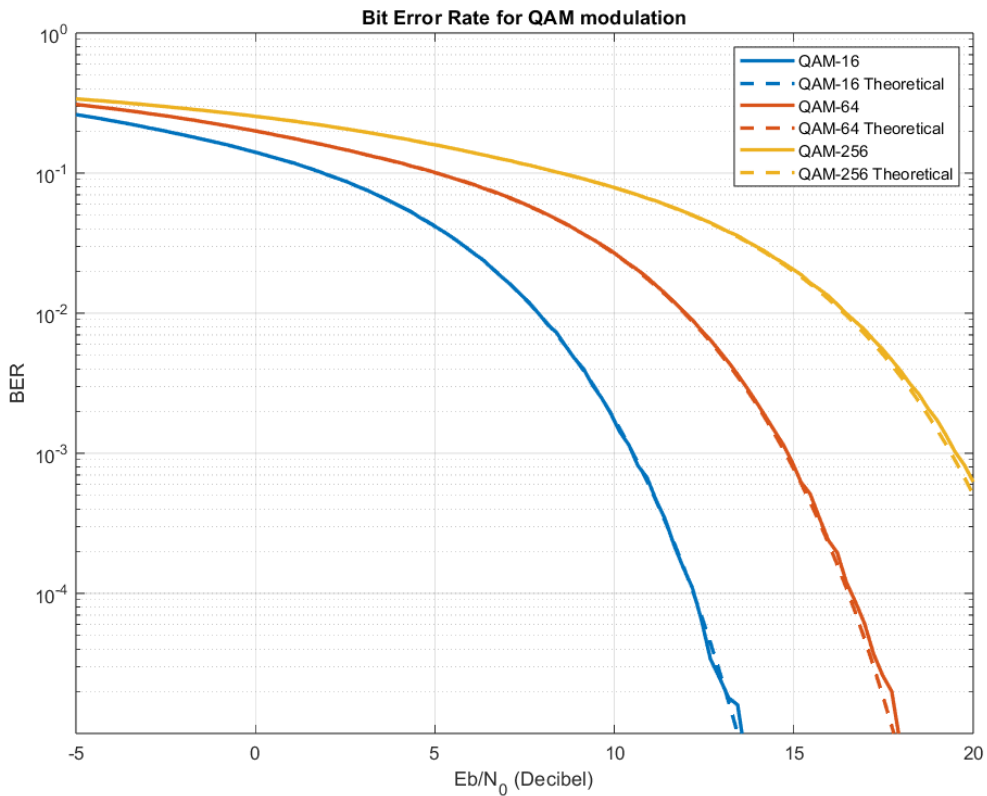


Figure 11: BER curves for different QAM modulations

## Bit rate

Considering the following characteristics :

- (a) Physical bandwidth of  $B_{\text{physical}} = 6 \text{ MHz}$
- (b) Roll-off factor  $\beta = 0.2$
- (c) QAM 16 modulation  $\rightarrow \text{Nbps} = 4$

We can derive the symbol rate from the physical bandwidth

$$f_{\text{symbol}} = \frac{B_{\text{physical}}}{1 + \beta} = 5 \text{ MHz}$$

$$\text{Bit-rate} = f_{\text{symbol}} * \text{Nbps} = 5 \text{ MHz} * 4 = 20 \text{ MBps}$$

### Description

Because the receiver and transmitter are not at the same location, the carrier frequencies and the samplers at TX and RX will have a different phase and due to the inaccuracies of the oscillator, the frequencies will also be slightly different.

This is summarized in 4 effects:

- **Carrier frequency offset (CFO):** The difference in the carrier frequencies at TX and RX ( $= \Delta\omega$ ). It will add ISI as the RRC are not anymore matched and a linearly increasing phase shift will appear.
- **Phase offset:** The difference between the phase of the carrier signal at TX and RX.
- **Sampling frequency offset (SFO):** The difference in the sampling frequencies at TX and RX.
- **Time shift:** The timing offset of the sampling at TX and RX.

### Implementation

#### CFO

The CFO implementation is done by multiplying the signal with a complex exponential  $e^{j2\pi\phi_{\text{ppm}}f_c t}$ . The phase offset is added to the CFO. It is defined in ppm (part per million) where the ppm value is  $\frac{\Delta\omega}{f_c} 10^{-6}$ .

Figure 12 shows the BER curves with different CFO values. In order to have useful results, the linear phase shift is removed right after the second RRC filter. This allows to only keep the effect of ISI on the BER curve.

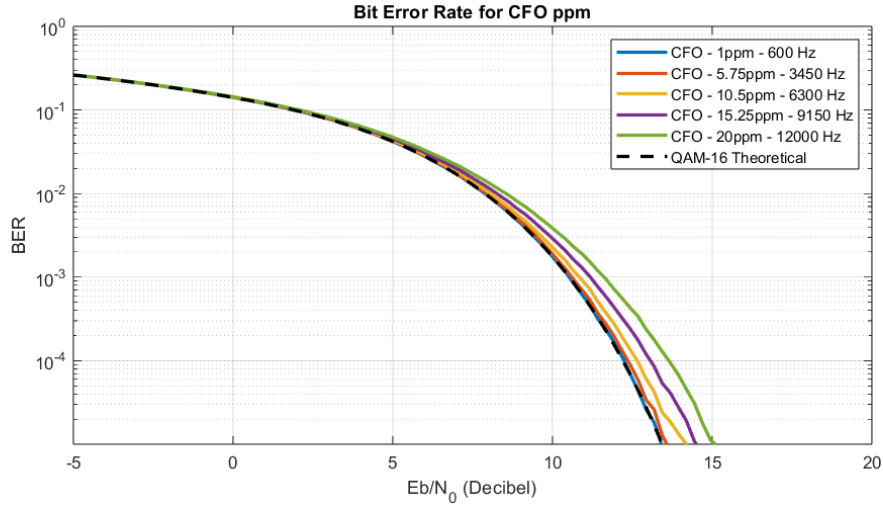


Figure 12: BER with different CFO values

Figure 13 shows the effect of CFO on the symbol constellation for QAM-16. The linear increase of the phase due to CFO makes the received symbols to form circles in the constellation diagram.

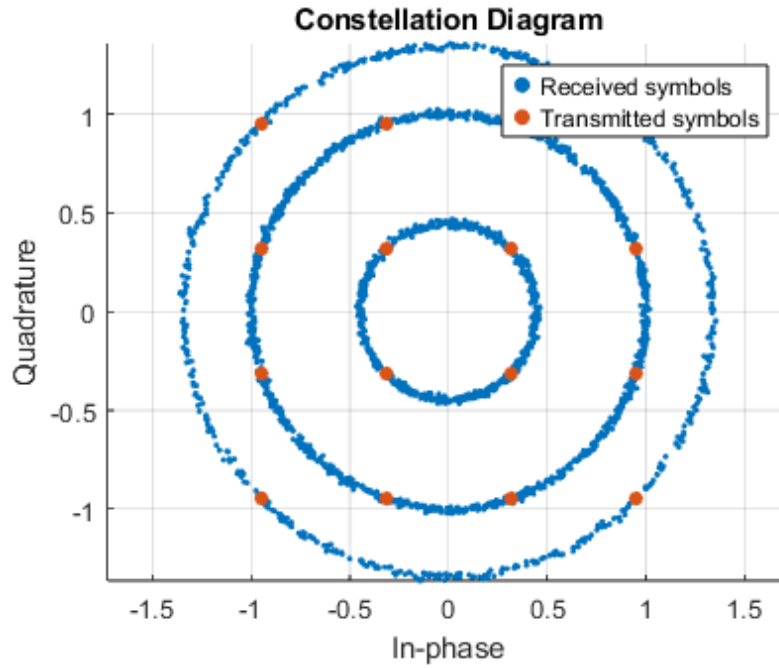


Figure 13: Constellation before and after CFO

### Phase offset

The same is done for the phase offset where the exponential is simply  $e^{j\phi}$  where  $\phi$  is chosen once at the beginning of the simulation.

The effect of the phase offset is only visible on the constellation plot (figure 14) where every point is rotated by a fixed angle (whereas CFO rotated the symbols linearly with time).

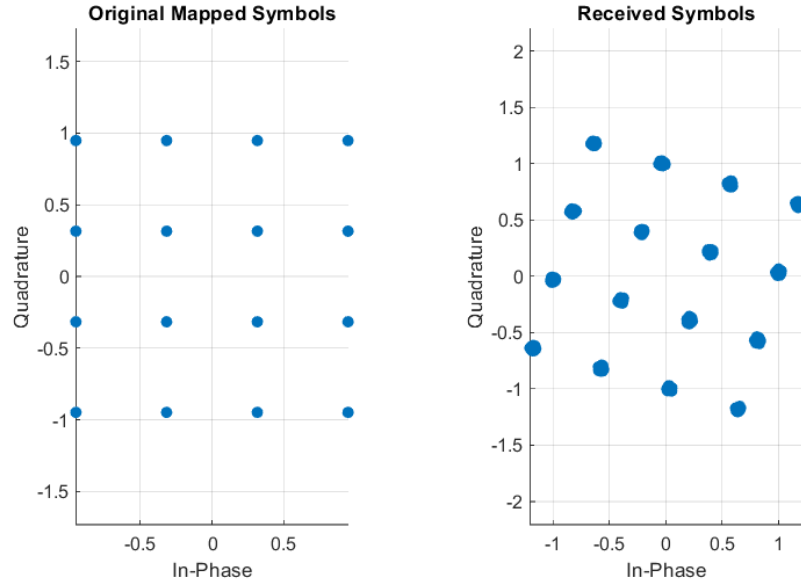


Figure 14: Constellation before and after phase offset

On a BER curve (figure 15), the phase is not visible as from the errors originating from the phase offset are either on every symbol or on none and this is why the error does not depend anymore on  $E_b/N_0$ .

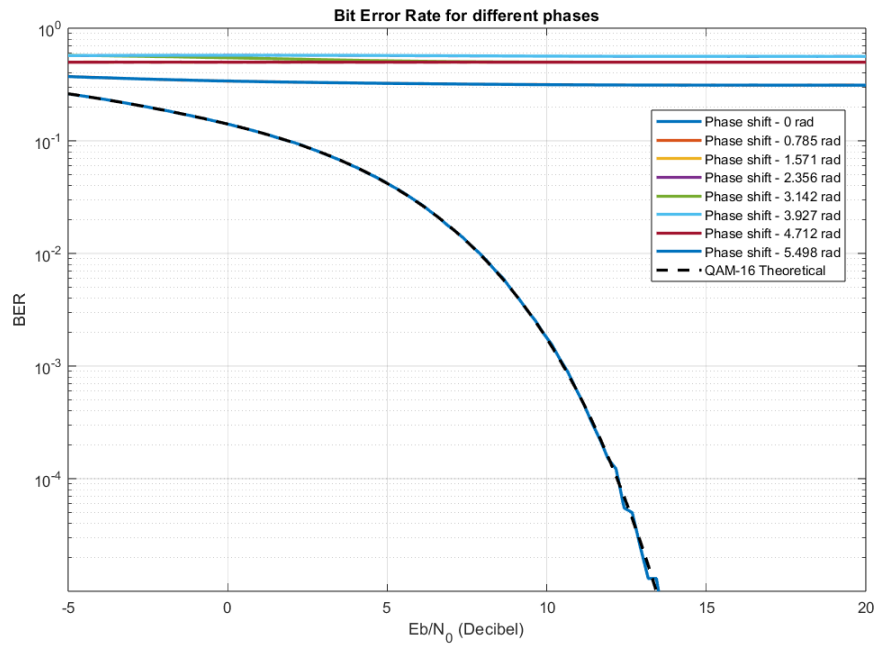


Figure 15: BER with phase offset

## SFO

The SFO is neglected in the simulation as it would need some interpolation and more complex computations.

## Time shift

The time shift is implemented by simply shifting the samples in the array with an oversampling factor that is large enough.

A larger time shift will increase the BER as the samples will be taken at the wrong time. For sufficiently low values, it will still behave as a "classical" BER curve but from some point, there is just no more correlation between the measured sample and the received one and the BER tends to a 0.5 line, as shown in figure 16.

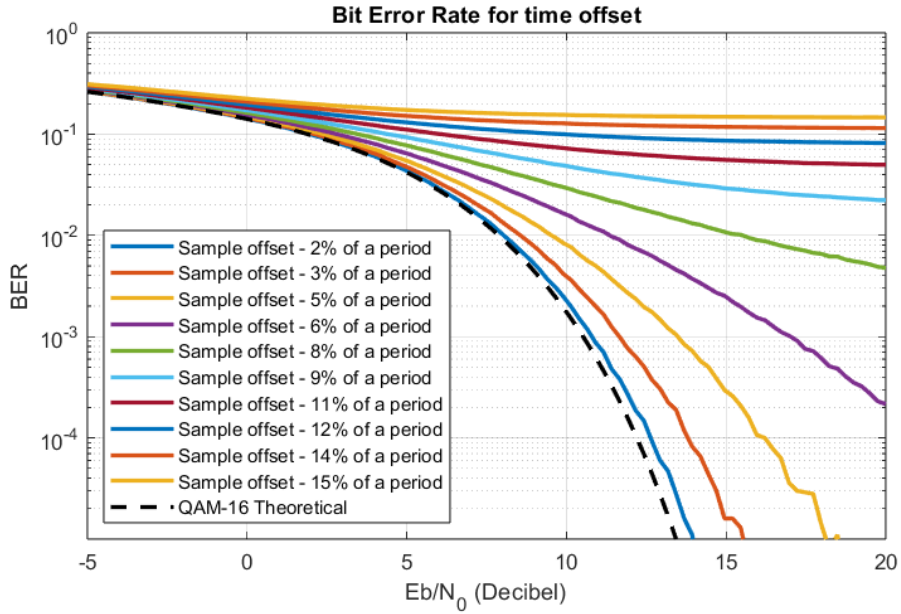


Figure 16: BER with time shift

As the phase offset makes the receiver sample the signal between true symbols, the constellation at its output has points that are spread around the initial symbols, as shown in figure 17. This effect is a form of ISI as the measured samples are between two symbols and therefore suffers from interference.

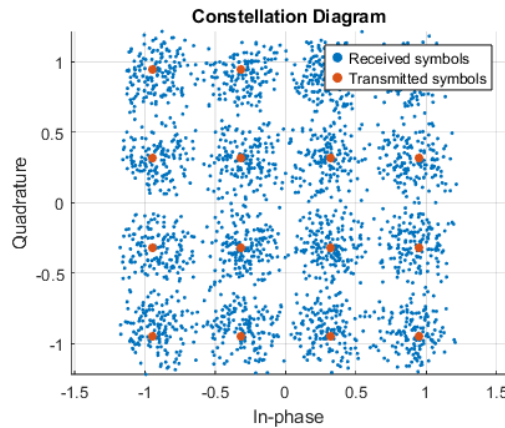


Figure 17: Constellation diagram with a phase offset of 15% of the symbol period



## Choice of $E_b/N_o$

Securing a SNR high enough to ensure a remaining acceptable time error after Gardner algorithm implementation « $\lll$ » (2 percents of the symbol rate) is a necessary condition to fulfill.

The impact on the BER can be seen on a previous graph - figure 16. In our case, for a symbol rate of 5MHz, the SNR should be above 4dB - 5dB and will be used in our simulation. Moreover, this SNR allows us to achieve, once the frame synchronization implemented, a remaining carrier frequency offset of 2 ppm which is very close from the BER performance we can get without CFO - figure 12.

===== (2 percents of the symbol rate) is a necessary condition to fulfill.

The impact on the BER can be seen on the graph below - figure ???. In our case, for a symbol rate of 5MHz, the SNR should be above 4dB - 5dB by referring to the simulation plots projected during the course of Professor Horlin.

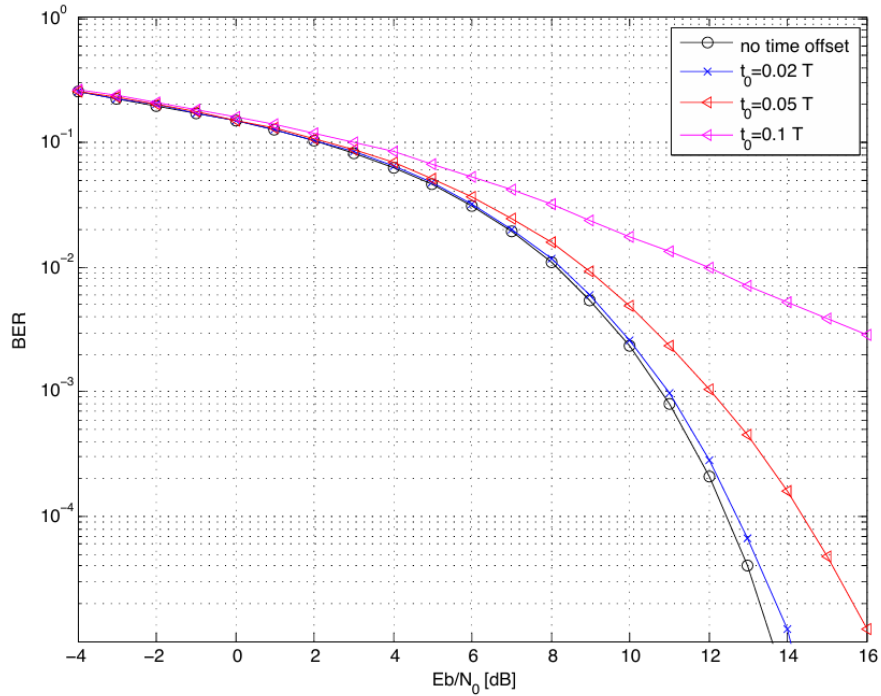


Figure 18: Impact of time shift on bit error rate

To confirm this assumption, we run Gardner algorithm for different SNR values in order to confirm the remaining time shift after Gardner. The result is plotted in the figure ??? for 2500 symbols and a bandwidth of 5MHz. Figure ??? shows the time shift estimation evolution for different SNR and 2500 symbols. One can notice that the remaining time shift drops below 1.5% of the symbol rate from a SNR of 4dB which is inline with what was expected from the result shown during the course of Modulation and Coding. For the remaining tasks, a SNR of 5dB will be used as safety margin. Moreover, this SNR allows us to achieve, once the frame synchronisation implemented, a remaining carrier frequency offset of 2 ppm which is very close from the BER performance we can get without CFO - figure ??.

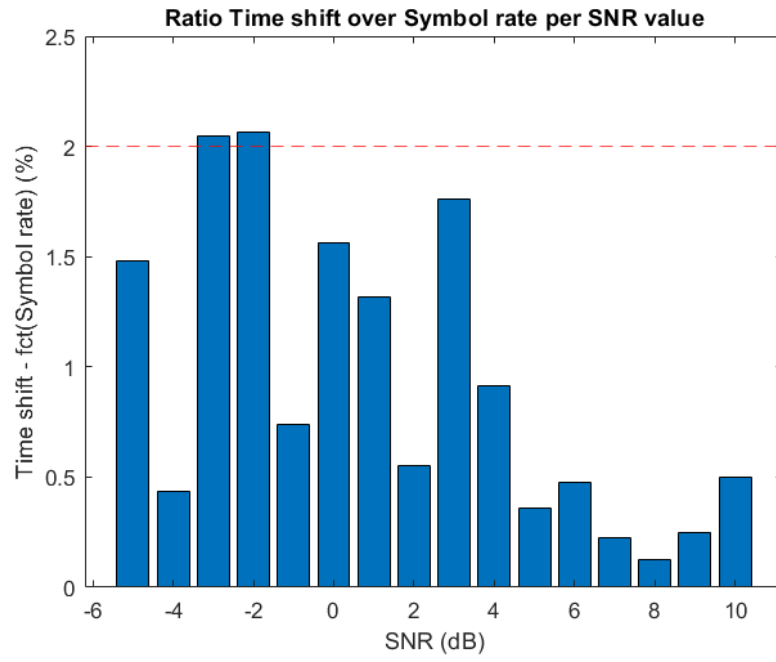


Figure 19: Remaining time shift after Gardner expressed in symbol rate percentage

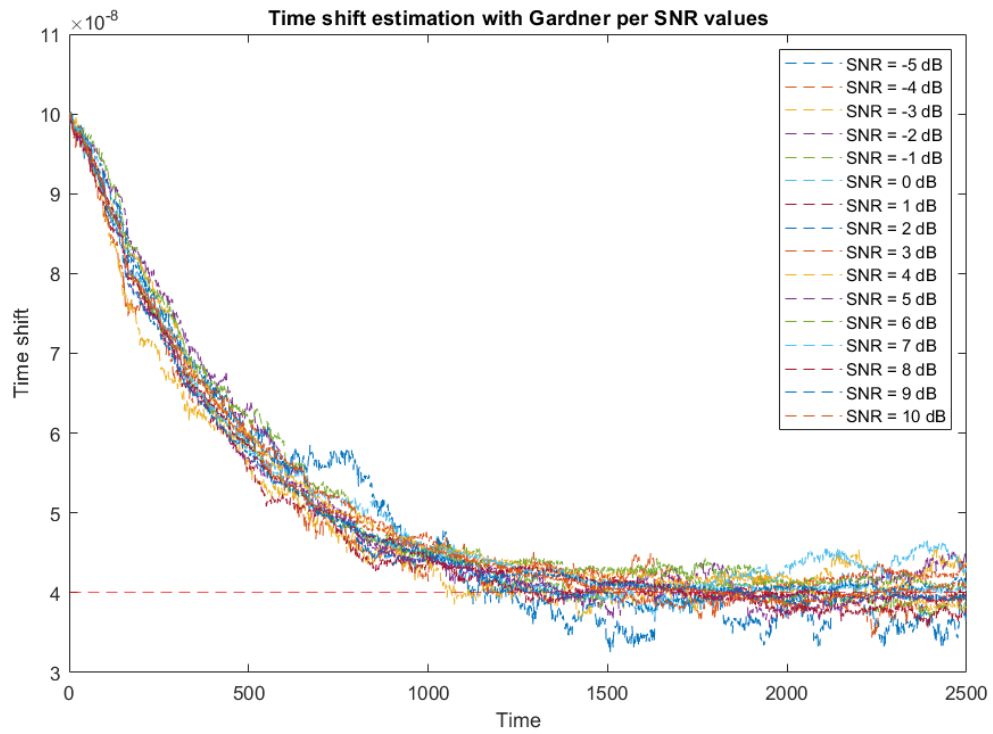


Figure 20: Gardner Algorithm : Time shift evolution per different SNR values

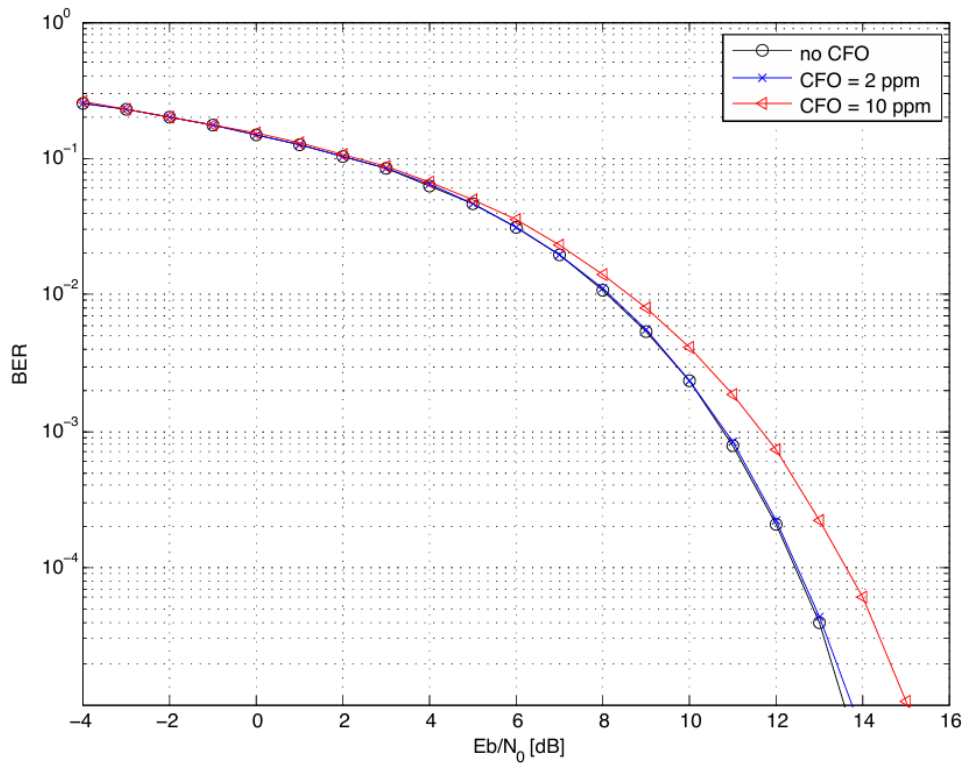


Figure 21: Impact of carrier frequency offset on bit error rate

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## Length of the pilot and the data sequence

Another condition to successfully implement the frame synchronization algorithm and secure a remaining CFO of 2 ppm, for a SNR of 4-5dB, is to ensure to get:

- A preamble with a large enough number of symbols ( $N > 20$ ).
- Cross-correlation sub-windows which are enough separated ( $K > 8$ ).

## Correction

### synchronization error correction order

««««< HEAD The main bottleneck of the synchronization error correction is the combination of the time shift error and the carrier frequency error. This error combination leads us to find a algorithm which correct one without being affected by the other. The Gardner algorithm is fulfilling this condition as it is able to correct the time shift error and it is robust to CFO.

Once the time shift error is corrected, the second algorithm can be implemented and detect/estimate the frequency shift introduced by the CFO. The results of the implementation of this Gardner algorithm for different time shifts and different weight coefficients  $\mathbf{k}$  are plotted below. ===== The main bottleneck

of the synchronisation error correction is the combination of the time shift error and the carrier frequency error. This error combination leads us to model an algorithm which correct one without being affected by the other. The Gardner algorithm is fulfilling this condition as it is able to correct the time shift error and is also robust to CFO. Once the time shift error is corrected, the second algorithm can be implemented and detect/estimate the frequency shift introduced by the CFO.

The results of the implementation of this Gardner algorithm for different time shifts and different weight coefficients  $k$  are plotted below showing the performance of the coded algorithm inline with what was expected. »»»» 736bb2671939881055f3fcb1390741923261e08e

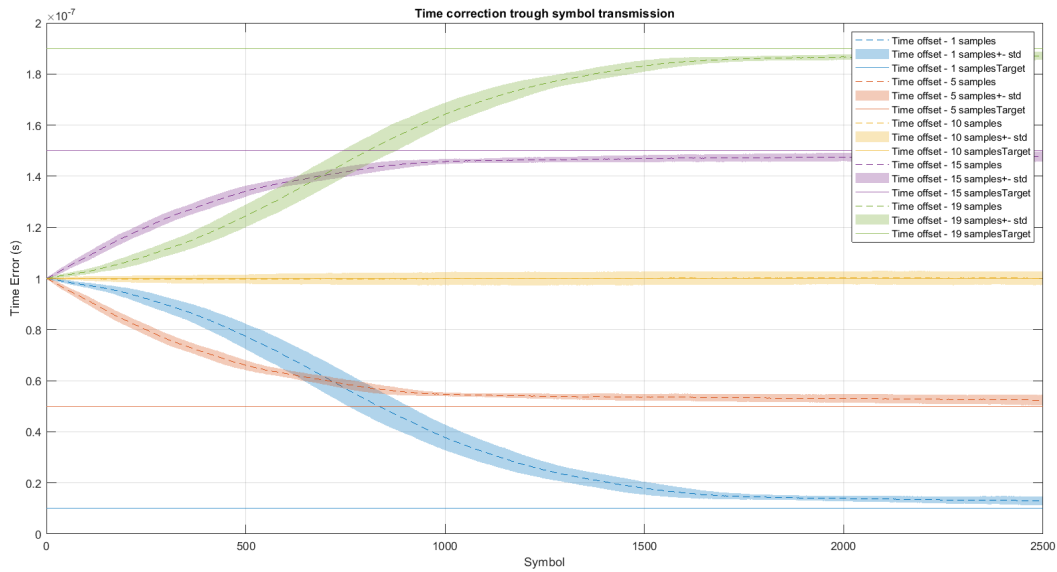


Figure 22: Time offset estimation over the samples with different time shifts

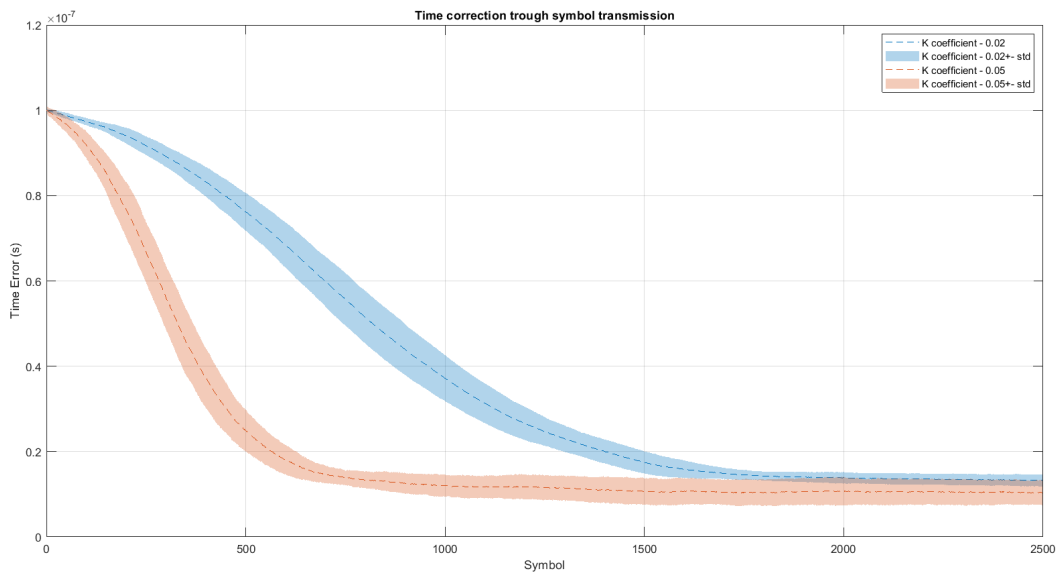


Figure 23: Time offset estimation over the samples with different weight coefficients

It is also interesting to mention that the Gardner algorithm is a **continuous** error correction - which means that the time shift error is corrected along the symbol stream sent.

In the other hand, The frame synchronization is a correction done by analyzing a **window** of symbols.

### CFO robustness of the Gardner algorithm and error interpolation

To understand why the Gardner algorithm is robust to CFO, we would need to analyze mathematically the algorithm:

$$\epsilon_{n+1} = \epsilon_n - \frac{2k}{T} R[y_{\epsilon_n}[n - \frac{1}{2}](y_{\epsilon_n}^*[n] - y_{\epsilon_{n-1}}^*[n - 1]))]$$

By taking a close look to the equation, one can observe that the error is corrected by taking the midpoint and multiplying the difference between 2 adjacent symbols (which is why the algorithm is continuous). This specificity limits the effect of a phase shift. Indeed, multiplying the midpoint with the complex conjugates of 2 adjacents points results to a difference of terms of opposite rotation with negligible phase impact for realistic CFO value. Thus, leading to Gardner algorithm being robust to CFO.

It should be mentioned that the Gardner algorithm is used with an interpolation function as the time error calculated per symbol may not fall accurately to a time sample bin. Therefore, it would be wise to oversample the symbol stream judiciously to compute an accurate time error after interpolation.

Figure ?? shows a visualisation of the Gardner algorithm for PAM-2 modulation with midpoints, actual sampling instants, correct sampling instants and sampling points slope.

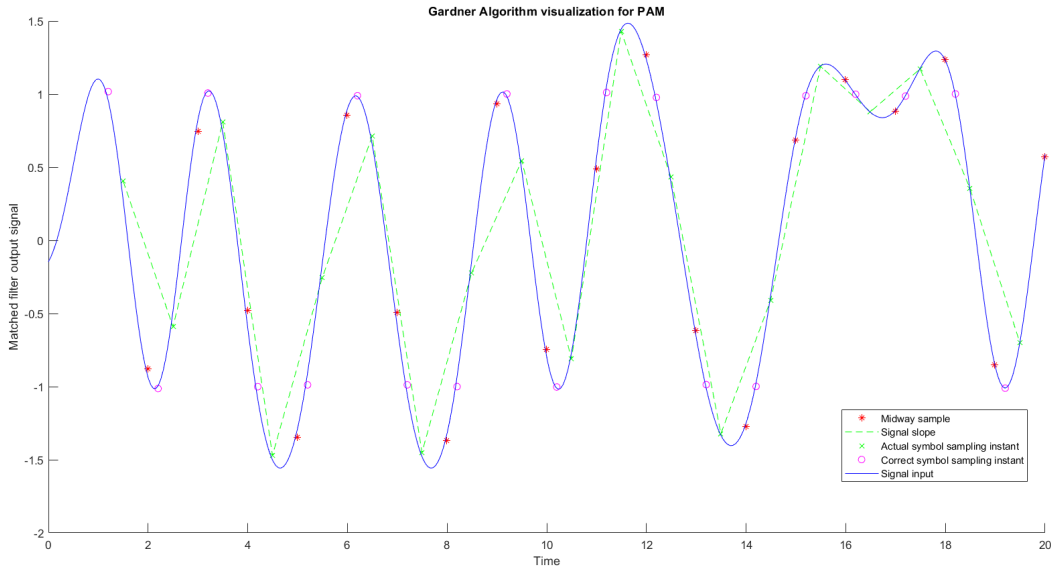


Figure 24: Gardner algorithm for PAM-2 modulation

## Differential cross-correlation

Let's have a closer look to the cross correlation equation to grasp the intuition behind the need to use the differential cross-correlation.

$$\sum_l y_{n+l}^* a_l = \sum_l I_{n+l}^* a_l e^{-j\phi_0} e^{-j\Delta w(n+l)T}$$

We can observe that the CFO term is increasing with  $\mathbf{l+n}$  resulting to a cross correlation equals to 0 even if the preamble is fitting the window.

Therefore, the idea behind the usage of the differential cross correlation is to remove the dependency of the phase shift with  $\mathbf{l+n}$ . This idea leads to modify the equation and multiply the correlation between  $y$  and  $a$  with its complex conjugate term. Indeed the exponential terms are cancelling and remains an exponential dependent on  $k$ , the window division term. Therefore, by computing the differential cross correlation, the calculation will result to a peak once the preamble will match with the synchronization window, function of  $e^{-j\Delta w k}$  and 0 in the other cases.

To reply to the sub-question quoting "Isn't interesting to start the summation at  $k = 0$  (no time shift)?", of course the reply is no as explained above.

The robustness of the gardner algorithm implemented in our Matlab code can be seen in 20

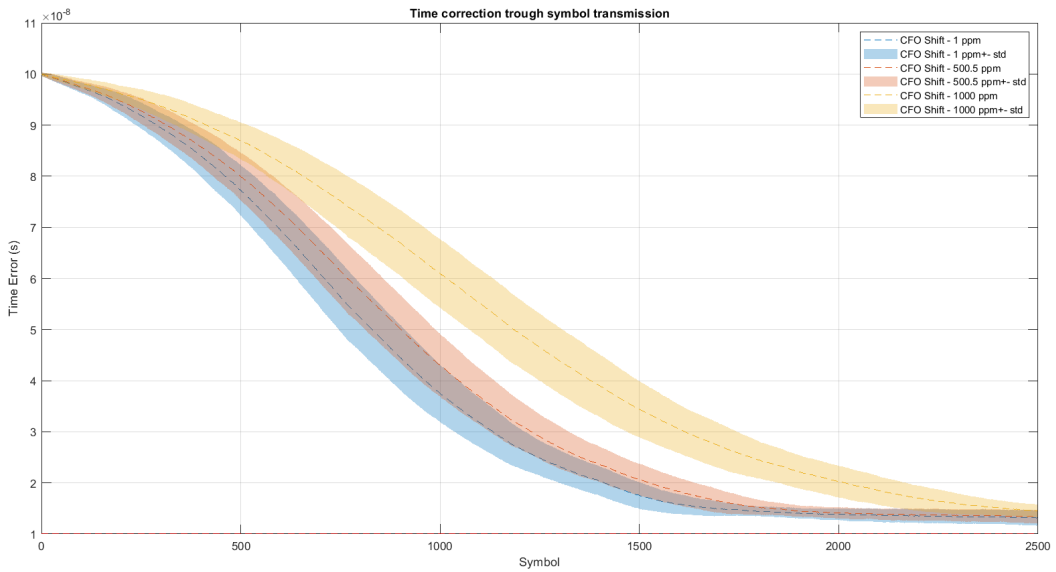


Figure 25: CFO robustness results from our Matlab code

## Optimal criteria

To summarize, to have a perfect frame synchronization which means to have a frame time arrival standard deviation equals to 0 for a realistic CFO error and a remaining time error of 2 percents at the end of Gardner module, a sine qua none condition is to get a large number of samples ( $N > 20$ ) and a large sub-division term

( $K > 8$ ).

With the previous correction, the receiver knows when to sample but there still is some uncertainty on the frequency. The way to remove the CFO is to send in the data a known pilot and the first step is to detect when this pilot is received. This is known as frame acquisition and it is performed with the differential cross-correlator:

$$D_k[n] = \frac{1}{N-k} \sum_{l=k}^{N-1} (y^*[n+l]a[l]) (y^*[n+l-k]a[l-k])^*$$

Where  $a$  is the known pilot,  $N$  its length and  $k$  the delay between the two correlations.

$D_k[n]$  is computed for every time index  $n$  and for every shift  $k$  until its maximum value,  $K$ . The estimation of the index of the start of the frame  $\hat{n}$  and the estimation of the CFO  $\hat{\Delta f}$  are given by:

$$\hat{n} = \arg \max_n \sum_{k=1}^K |D_k[n]|$$

$$\hat{\Delta f} = -\frac{1}{K} \sum_{k=1}^K \frac{\angle D_k[\hat{n}]}{2\pi kT}, \quad T \text{ being the symbol duration.}$$

The implementation of the time of arrival estimator has been done on figure 21 by placing the pilot at the 100th sample and by then plotting  $\sum_{k=1}^K |D_k[n]|$ . The peak at the 100th sample clearly indicates the time of arrival of the pilot and validates the implementation. A similar test was done for the CFO estimation but it is not shown here.

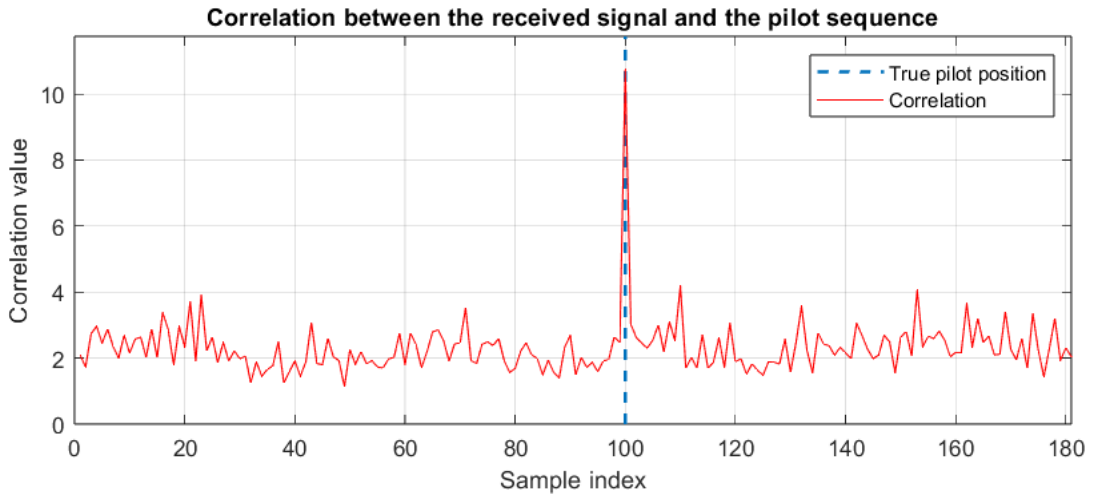


Figure 26: Time of arrival estimation ( $N=20$ ,  $K=8$ )

The standard deviation of both estimators has been measured on 250 runs for both a varying pilot length  $N$  and a varying maximal shift  $K$  for an increasing  $\frac{E_b}{N_0}$  in figures 22 and 23.

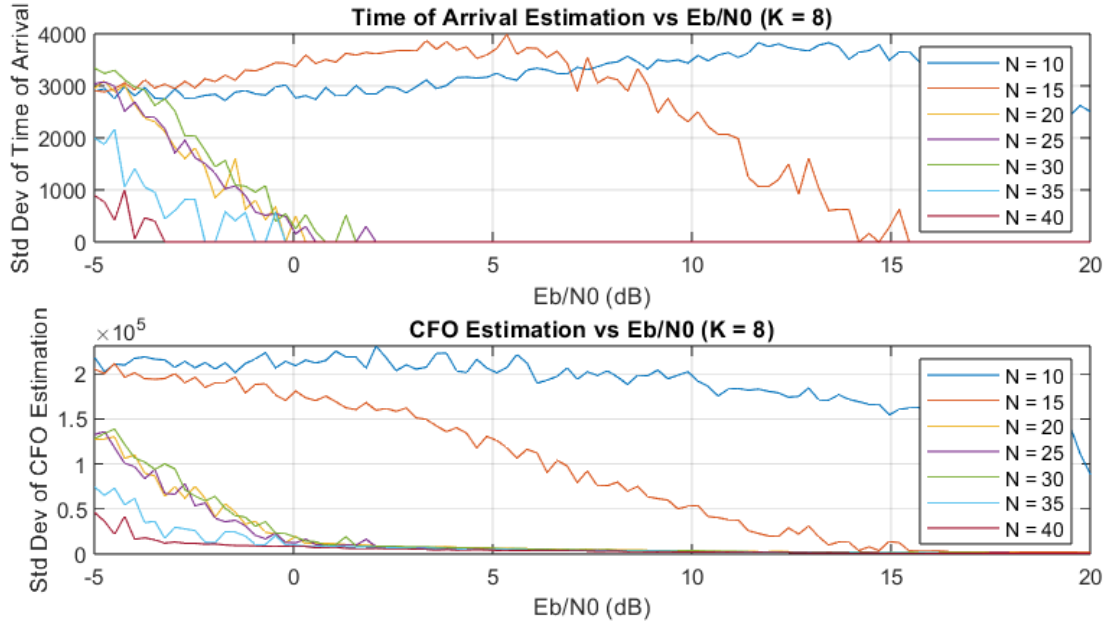


Figure 27: Standard deviation of the CFO estimator with varying pilot length

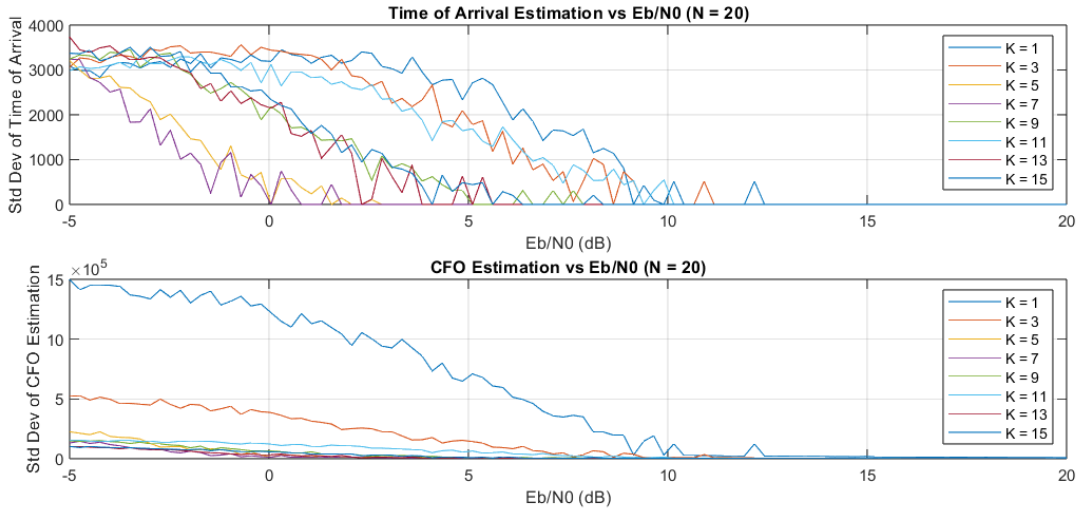


Figure 28: Standard deviation of the CFO estimator with varying maximal shift

As expected, a longer pilot and a larger shift will lower the uncertainty of the estimation and the same goes by for an increasing SNR. The fact that the line corresponding to  $N = 10$  on figure 22 does not seem to decrease with  $\frac{E_b}{N_0}$  is explained by the fact that  $N$  and  $K$  are too close to each other.

The robustness of the frame acquisition is also tested against a varying CFO by measuring the standard deviation of the time of arrival estimator for a varying CFO. The results are shown in figure 24 and it can be seen that the CFO has no impact on the time of arrival estimator. This is because the used algorithm is a differential cross-correlator and not a classical correlator.



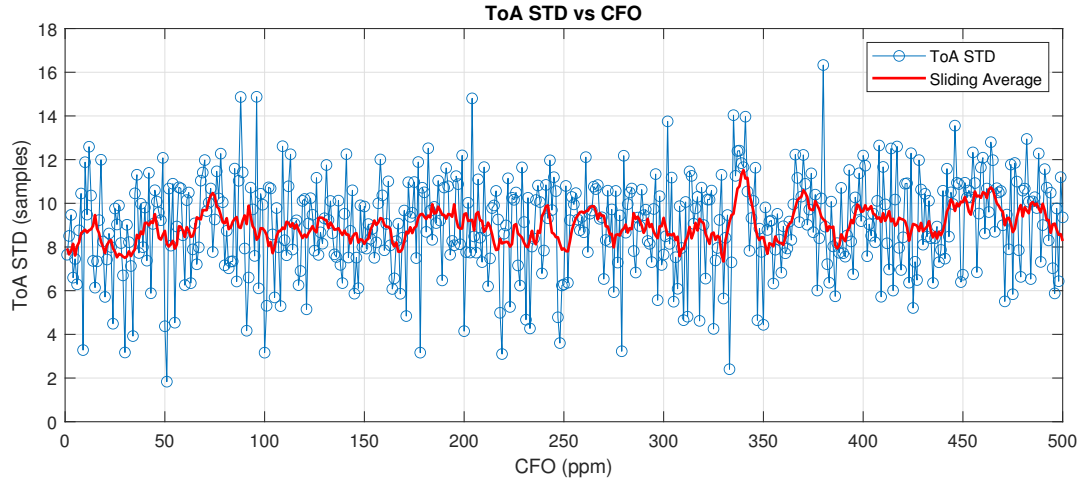


Figure 29: Standard deviation of the ToA estimator with varying CFO (N=20, K=8)

A similar test was done for the CFO estimator and the results are shown in figure 25. The CFO estimator is as robust as it is based on the time of arrival estimator, which was robust to CFO. Its estimation starts to get further away from the real CFO only for unrealistic values of the CFO. The standard deviation is pretty high, which means that a few pilots would be needed to average the estimation and have a value close to the real CFO.

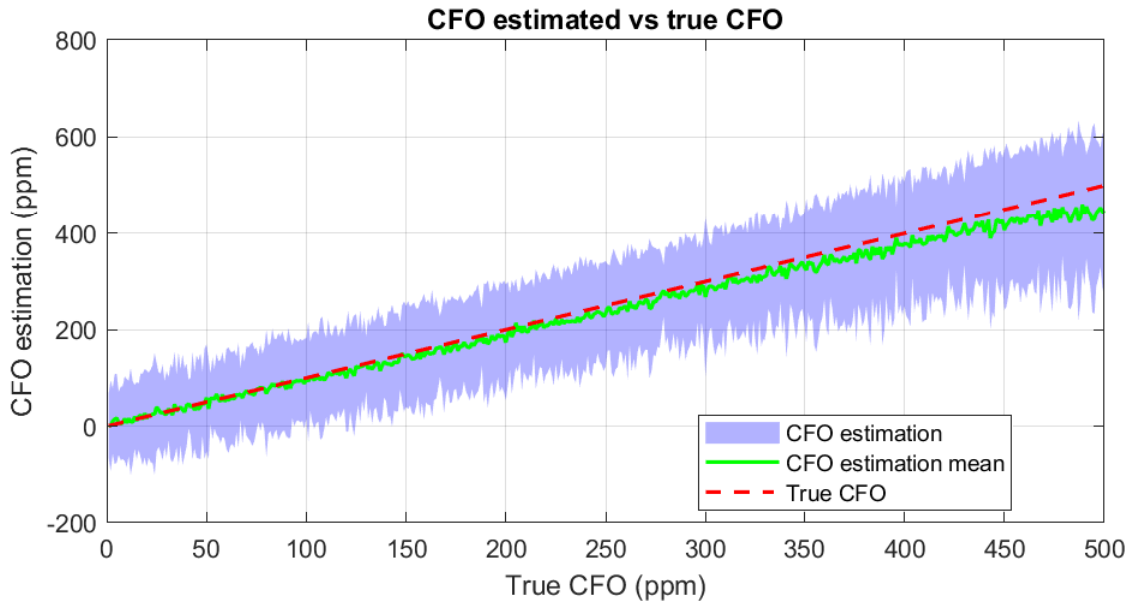


Figure 30: CFO estimation with varying CFO (N=20, K=8)

To avoid needing a lot of pilots, the same plot was done for a higher size of the pilot and a larger shift. The results are shown in figure 26. The standard deviation is now much lower and the estimation is still not affected by the CFO.

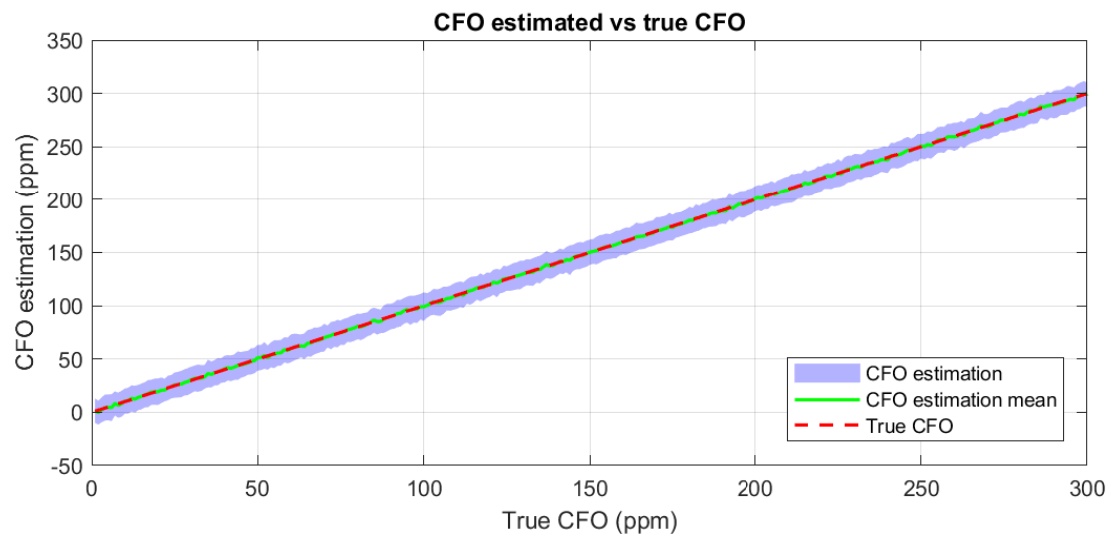


Figure 31: CFO estimation with varying CFO (N=50, K=12)

## Structure

Now that every block of the transmission channel has been built and tested separately, the full channel can be simulated. It's structure is the following:

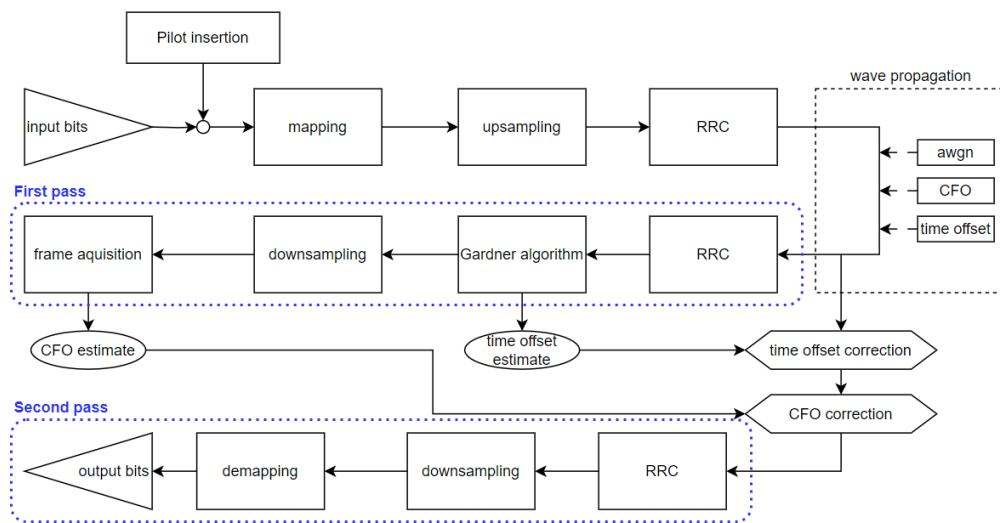


Figure 32: Full channel structure

As it is not highlighted on the diagram, it should be mentioned that the time error is corrected before the CFO estimate at the frame acquisition module.

## Single pilot

The following figure shows the error between the input and the output bits of the channel and the position of the pilot:

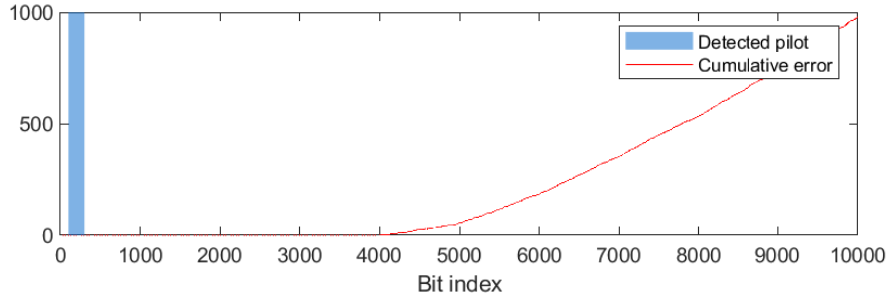


Figure 33: Error between input and output bits for a single pilot ( $N = 50$ ,  $K = 12$ )

As expected, the error is very low close at the beginning of the packet. This proves that the Gardner algorithm has successfully estimated the time offset and the CFO estimation was close to the real value. Errors start to appear after 4000 bits due to the linearly increasing phase added by the CFO. This simple example showed the importance of having multiple pilots in a packet.

## Multiple pilots

As shown on figure 26, the standard deviation of the CFO estimation is lowered for a longer pilot but it still remains different from zero. This means that multiple pilots should be sent in order to have a better estimation of the CFO.

This is what has been done in the following simulation. A total of 10 pilots of  $N = 50$  bits have been sent in a packet of 10.000 bits. The CFO is computed based on each pilot separately and the final estimation is the average of the individual estimations. The estimated CFO of the case in figure 29 is 3.098 ppm for an actual value of 3 ppm, which is quite close.

Because the channel is fully simulated, awgn is present and the  $E_b/N_0$  is set to 10 dB.

Once again, most of the errors are located closer to the end of the packet because the phase shift due to uncorrected CFO is linearly increasing with the bit index.

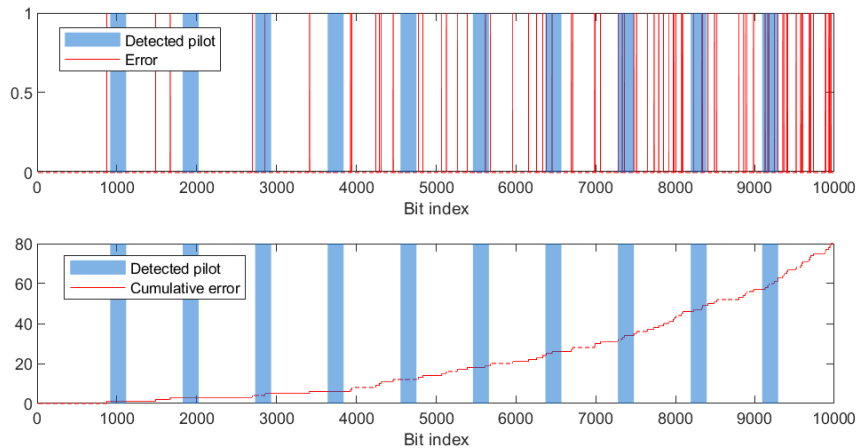


Figure 34: Error between input and output bits for multiple pilots ( $N = 50$ ,  $K = 30$ )

For this same case, the constellation diagrams of different signals are shown in figure 30:

- The one in the top left corner is the input signal.
- Below it, the output signal if no CFO compensation and no time shift corrector are applied. It is chaotic and no information can be retrieved from it.
- The top right corner shows the output signal after the Gardner algorithm has been applied. The time shift is corrected but the CFO is still present. The constellation is now made of 2 circles, which already shows that the modulation used is QAM-16. Those circles are the result of the CFO (as shown previously in figure 13)
- The bottom right corner shows the output signal after the Gardner algorithm and the CFO compensation have been applied. The points are now grouped around the initial constellation points. They are not perfectly aligned because the CFO estimation is not perfect and because of the noise added to the signal.

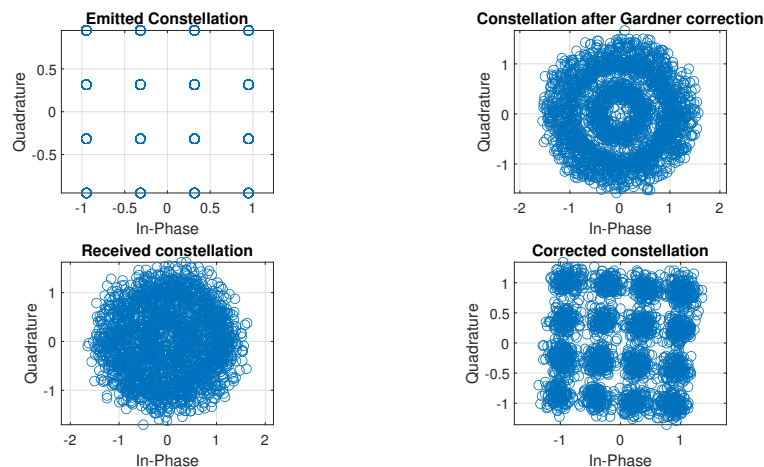


Figure 35: Constellation diagrams for multiple pilots ( $N = 50$ ,  $K = 30$ )

### **Describe the architecture of the HFC network and its main components. Where is the capacity bottleneck today?**

HFC stands for Hybrid Fiber Coaxial. It means that the network is made of both fiber optic and coaxial cables. The optic fiber is used between the headend and the *nodes* and the coaxial cables are used from those nodes to the individual houses.

The coaxial part is the bottleneck but upgrading to fiber is very expensive and would need a cooperation between the different operators.

### **What will be the evolution of the HFC network in the coming years? What are the key technologies to make this happen?**

The *nodes* discussed in the previous question will be shifted towards the houses and, after some time, the objective is to have a direct fiber connection from the headend to each house. This is done by splitting the light for downstream and a *time division multiplexing* for upstream traffic.

### **Which are the typical incidents happening on Orange's network? Explain the procedure foreseen to cope with them.**

A typical incident is a broken cable. It can happen due to civil works, weather conditions and so on.

If no signal can be sent through the line, the broken segment is identified and the exact distance at which it broke is computed using the *Optical Time Domain Reflectometer* (OTDR). It computes the time it takes for a light pulse to go through the fiber and come back (bounce due to improper termination).

A technician is then sent to the location to solder the two broken fiber ends together and all of it happens in typically less than 8 hours.

### **Describe the main Orange's data center in numbers (storage, in/out capacity, consumed power, area, maintenance...). How does it compare to others?**

Not much data was given about the data center. It consumes 1.5 MW of power (which will increase to 3 MW when the datacenter will be used at full capacity). The building is 3.000 m<sup>2</sup> large and the data center moves 23 TB of data every second. It also requires 2 technicians to be maintained.

It is complicated to compare it to other data centers because the data is not public.