Digital Modulations

Tutorial 1

Course of RF Circuit Design

Electronics Engineering

Outline

- **QPSK modulator in Mathworks Matlab**
- **Demodulation in Keysight VSA 89600**
- **Effects of RF transmitter impairments**

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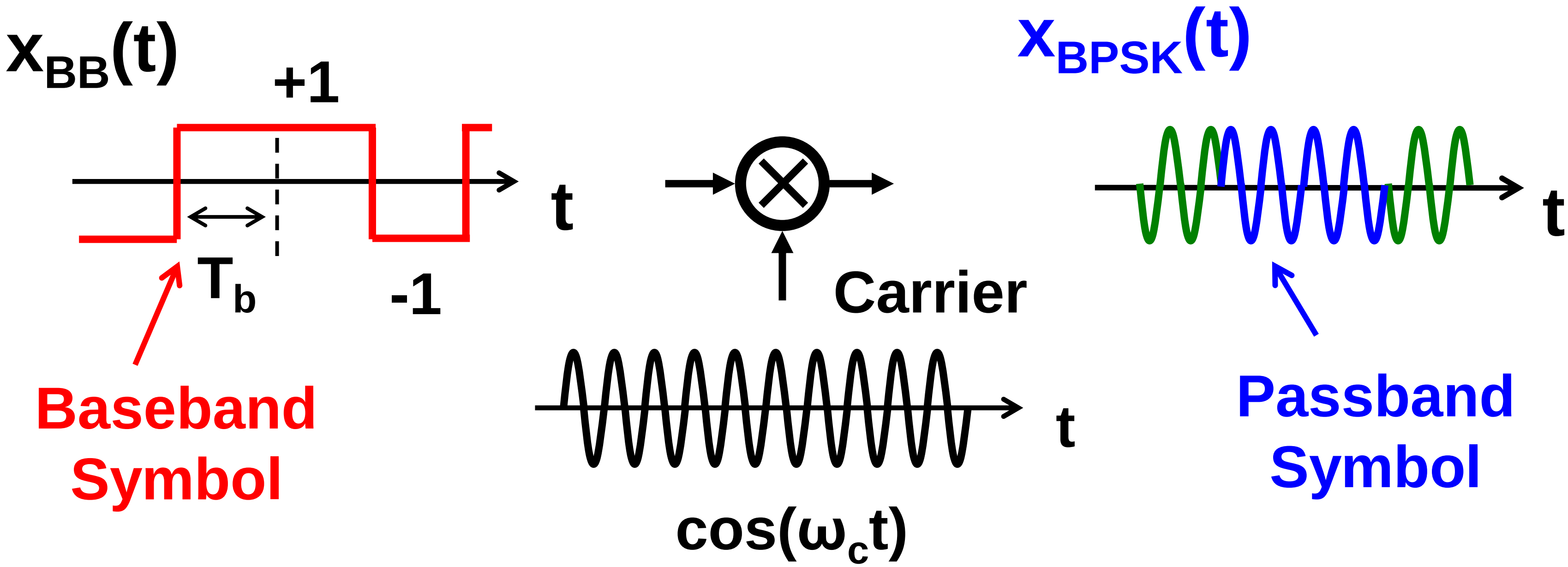
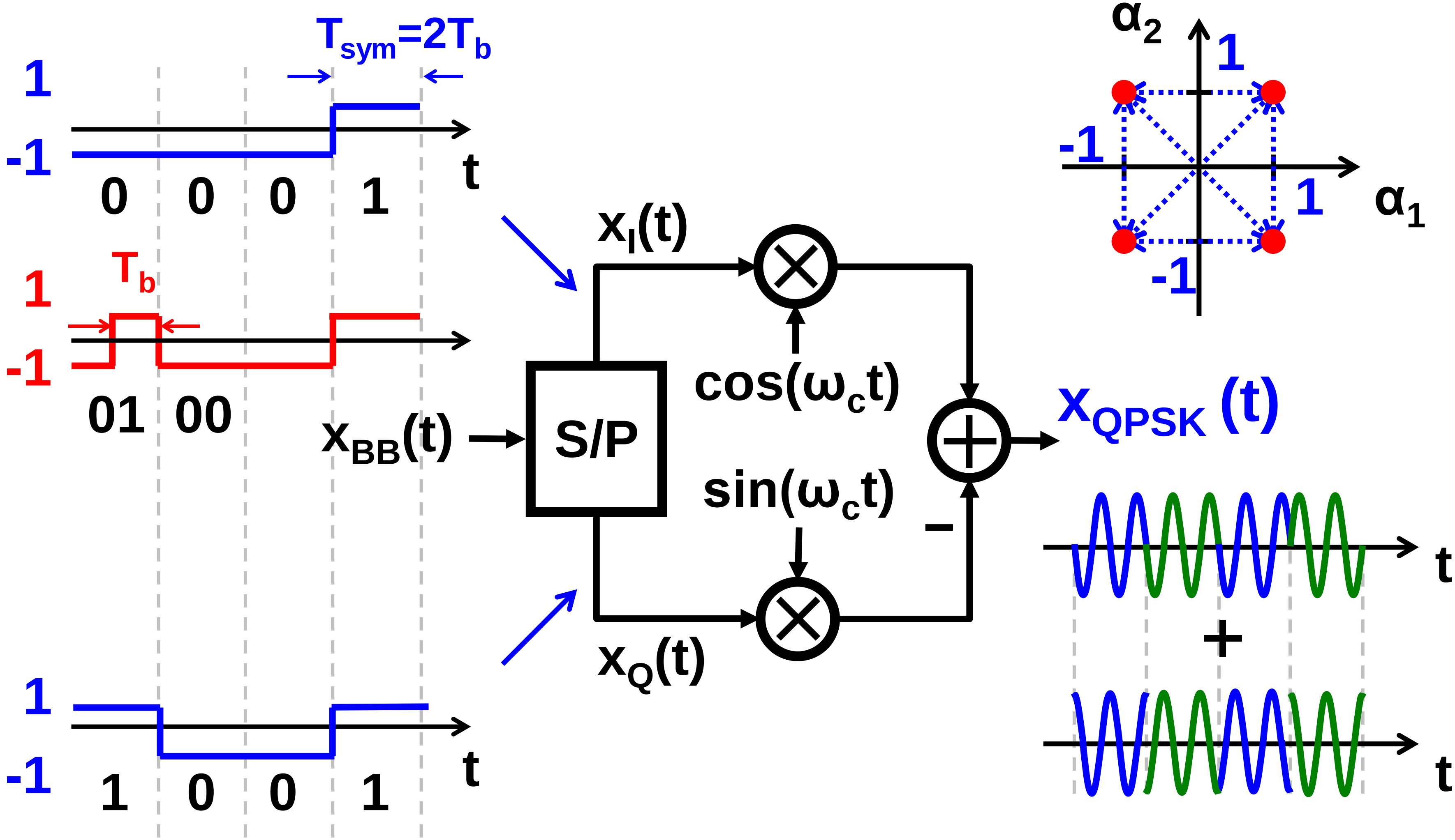
BPSK Modulator

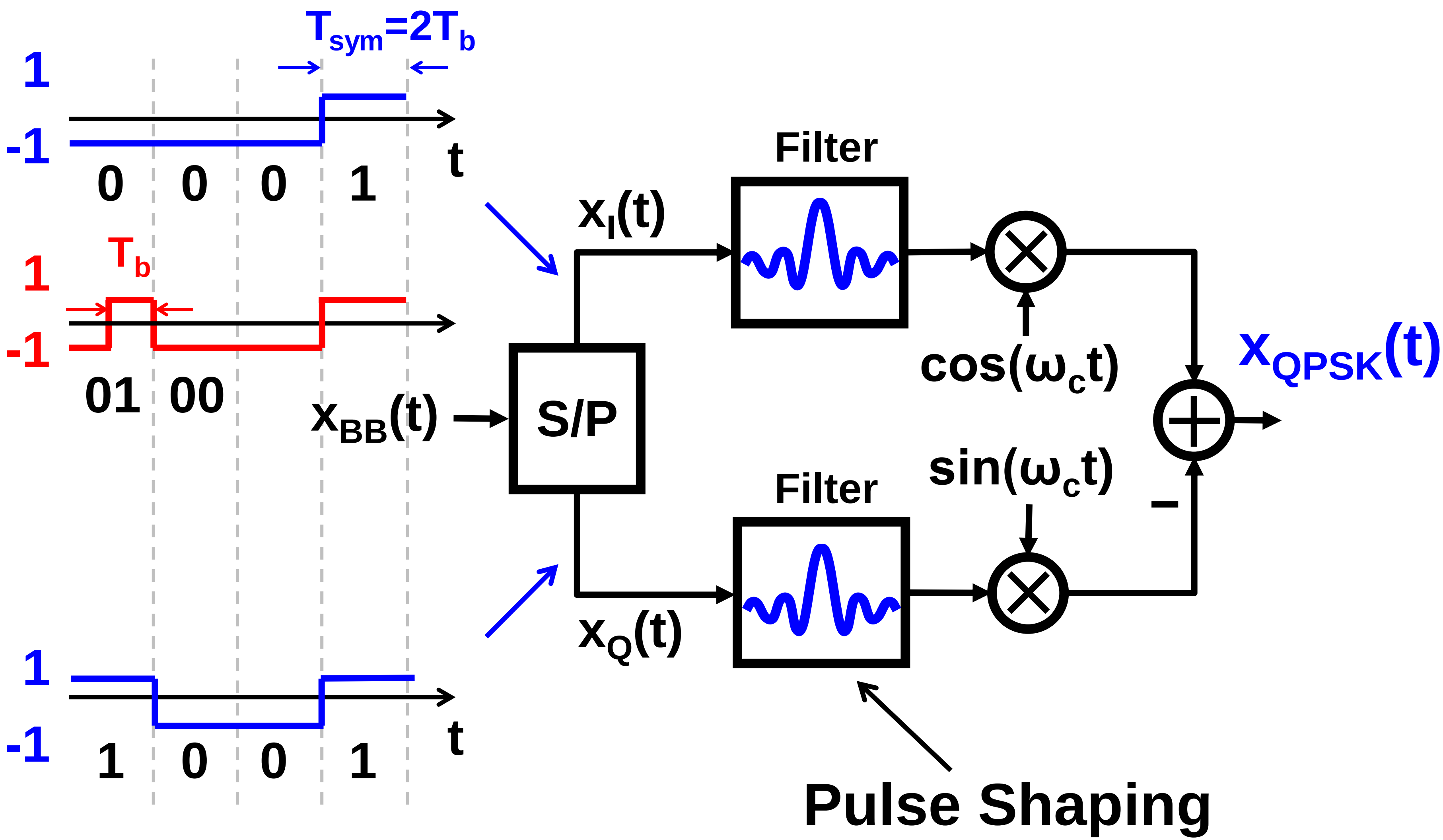


$$x_{BB}(t) = \sum_n b_n p(t - nT_b) \qquad b_n = +1,-1$$

QPSK Modulator



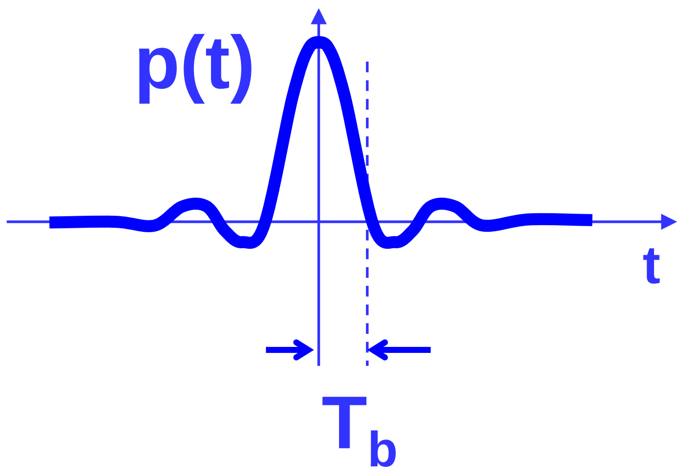
QPSK Modulator with Pulse Shaping

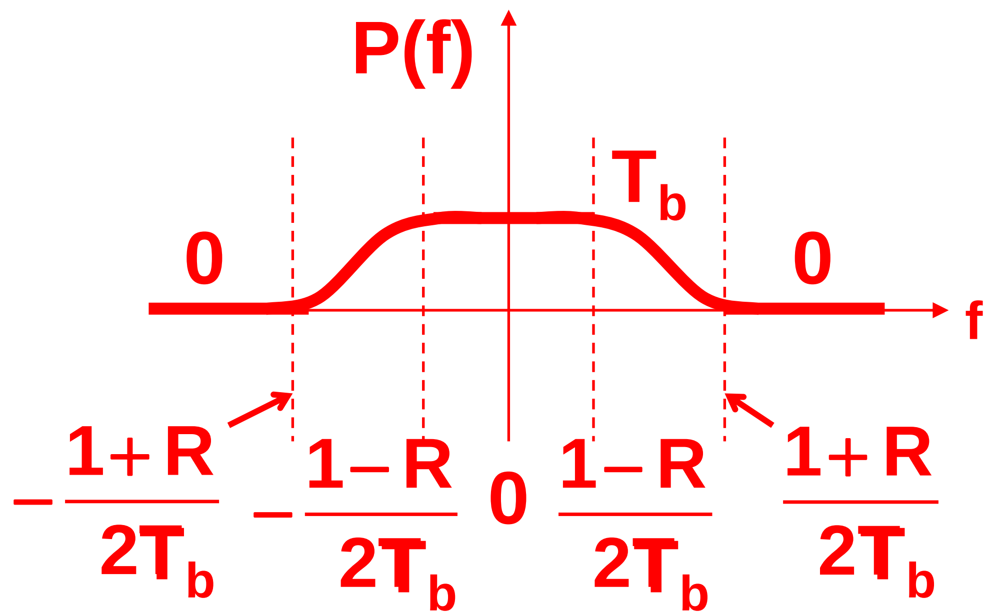


Raised-Cosine Pulse Shape

$$p(t) = \mathrm{sinc}\left(\frac{t}{T_b}\right)\frac{\cos\left(\frac{pRt}{T_b}\right)}{1 - \frac{4R^2t^2}{T_b^2}}$$

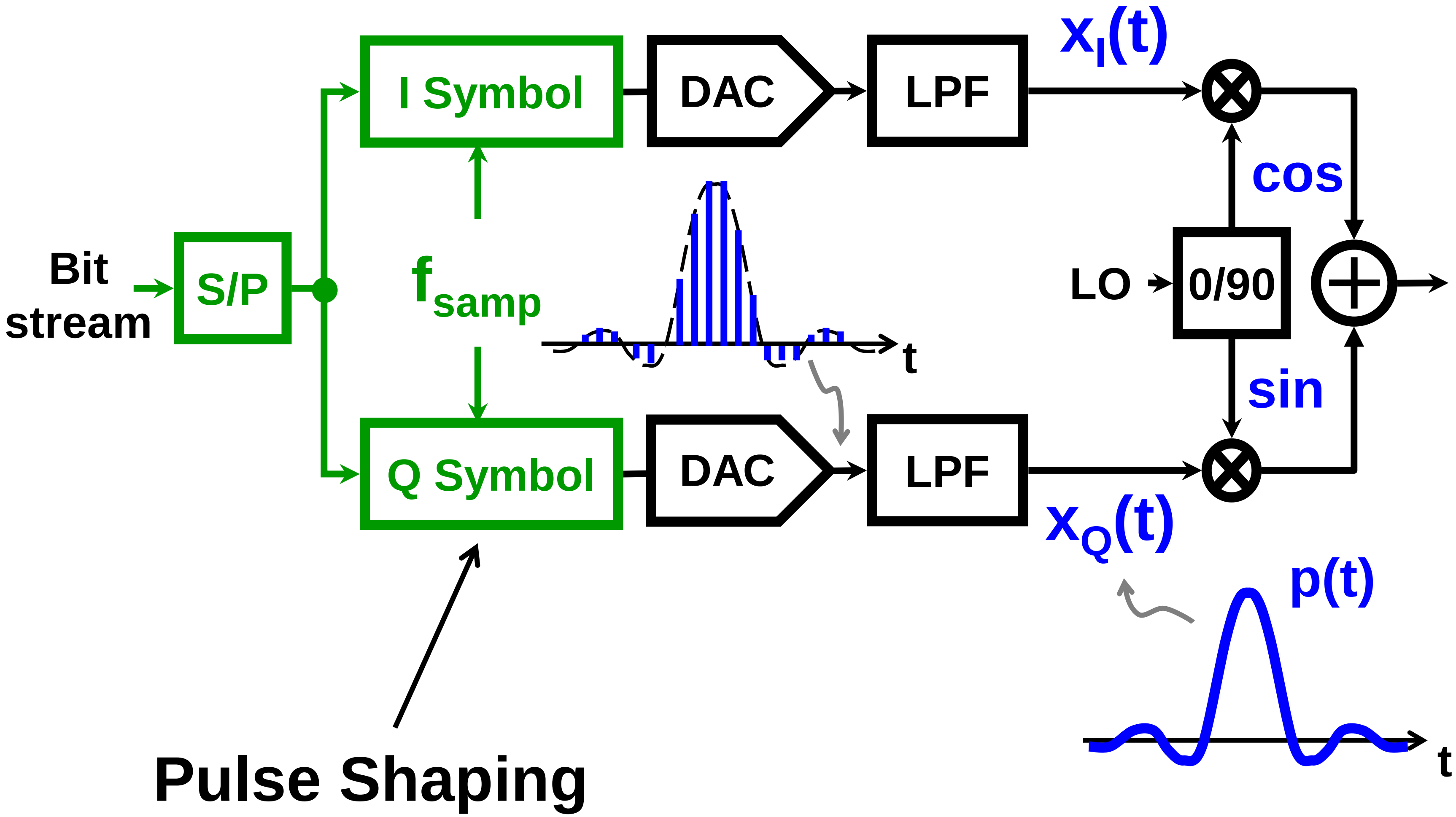
$$P(f) = 1 + \cos\left(\frac{pT_b}{R}\right)\left(|f| - \frac{1-R}{2T_b}\right)\frac{T_b}{2}$$



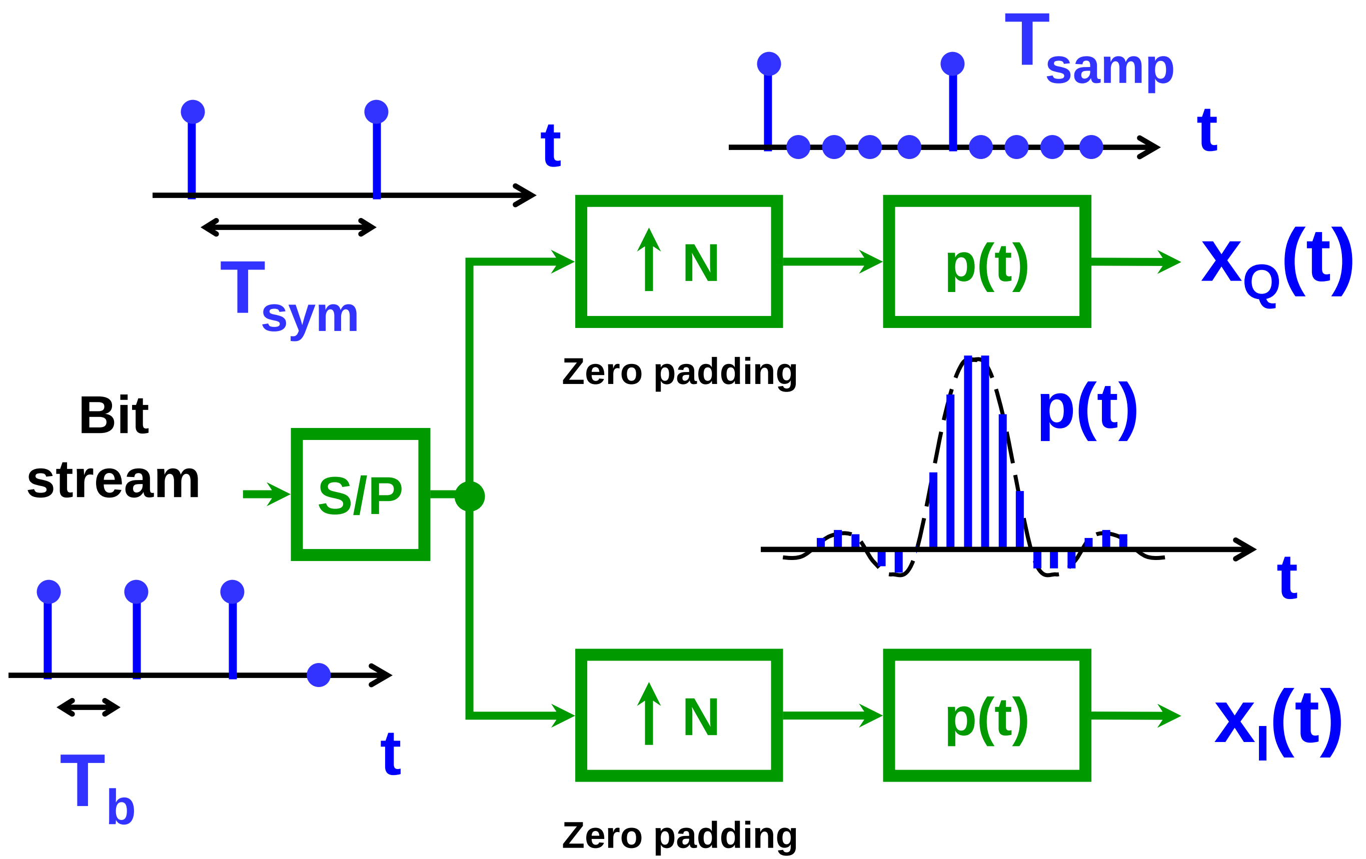


- R = 0: Minimum BW (Rectangular spectrum)
- R = 1: Maximum BW

Practical Quadrature Modulator



Simulation Model of Transmitter

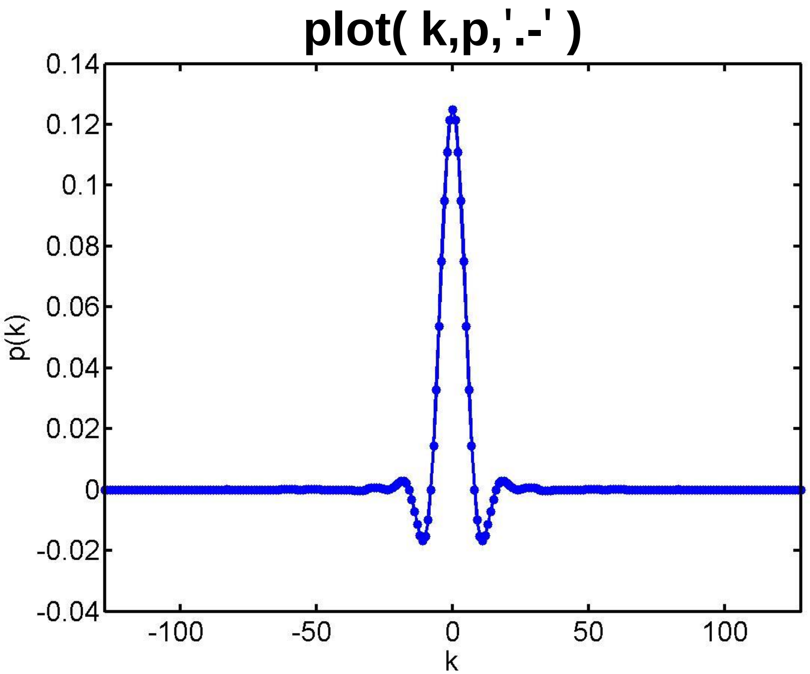


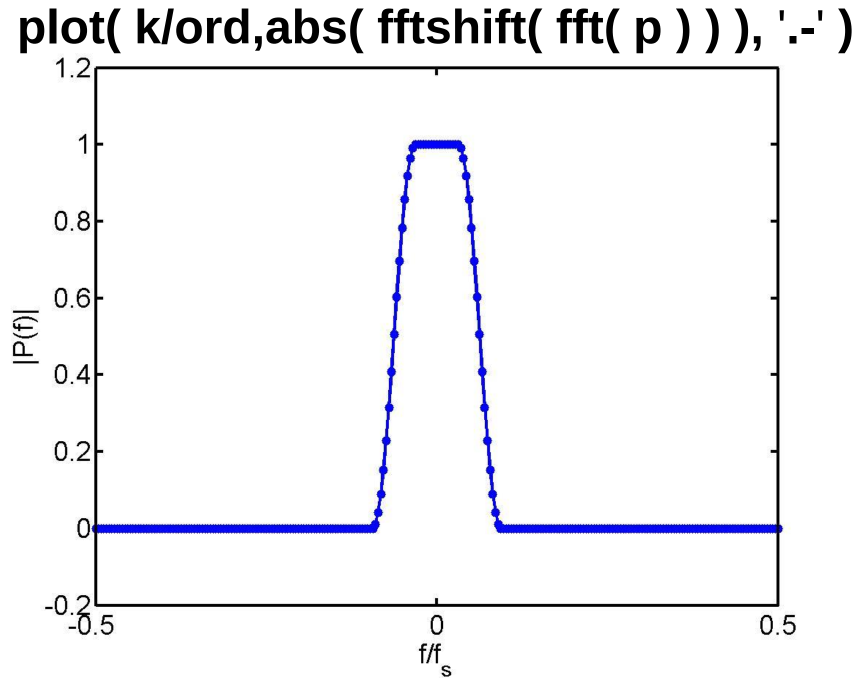
$T_{sym} = 2T_b$ $\qquad$ $T_{samp} = T_{sym}/N$

Raised-Cosine Filter

```
N = 8;          ← Number of samples per symbol
R = 0.5;
ord = 256;      ← Filter order (number of FIR taps)
p = rcosdesign( R, ord/N, N, 'normal' );
k = ( -ord/2:1:ord/2 );
```

Matlab code





PRBS Sequence and Pulse Shaping

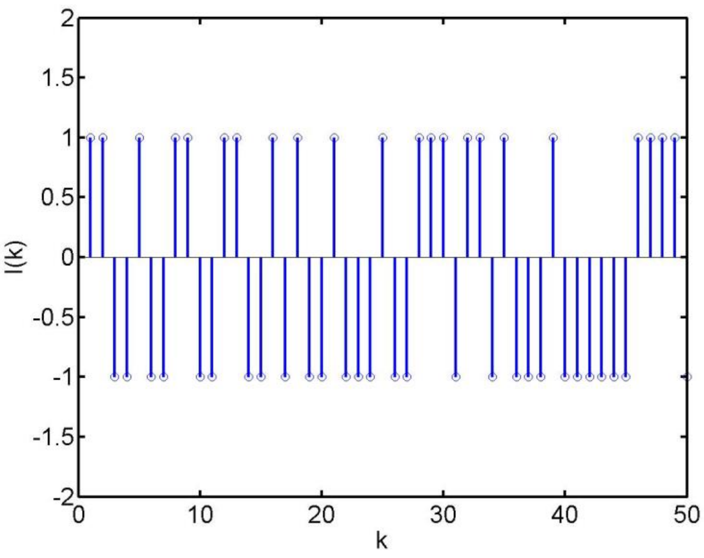
```
Nbit = 3000;
s = sign( rand( Nbit,1 )-0.5 );
I = s( 1:2:end );
Q = s( 2:2:end );
xI = conv( upsample( I, N ), p );
xQ = conv( upsample( Q, N ), p );
xI = xI( ord/2:end-ord/2-1 );
xQ = xQ( ord/2:end-ord/2-1 );
```

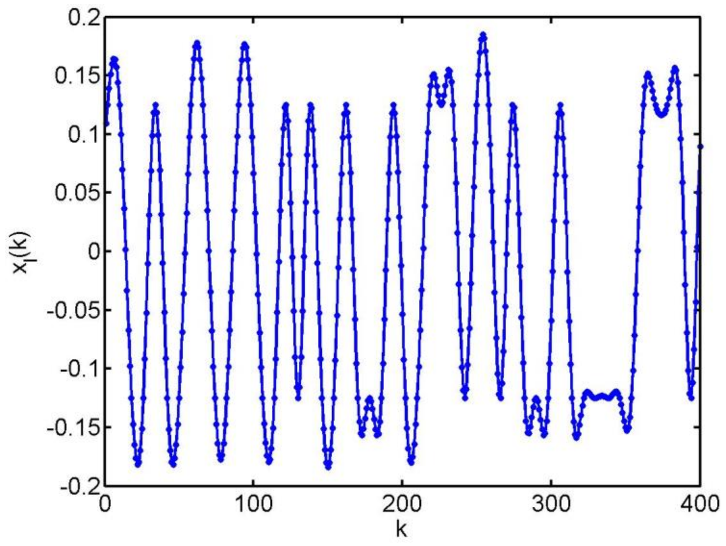
Pseudo-random bit stream

Symbol stream

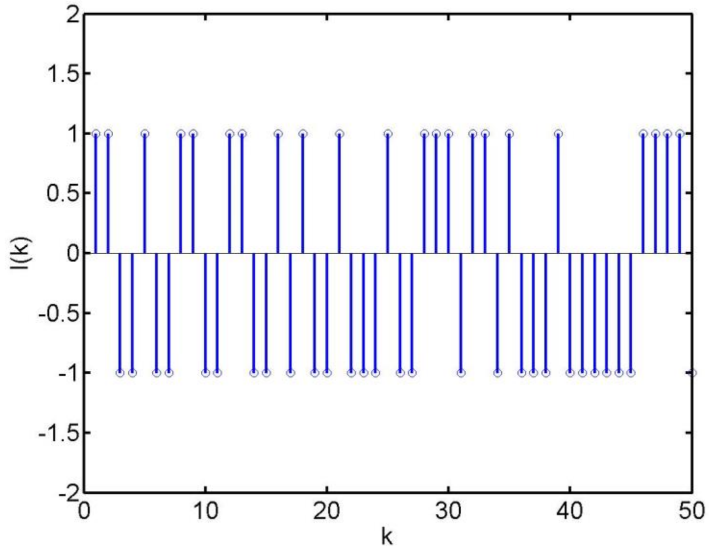
Pulse Shaping

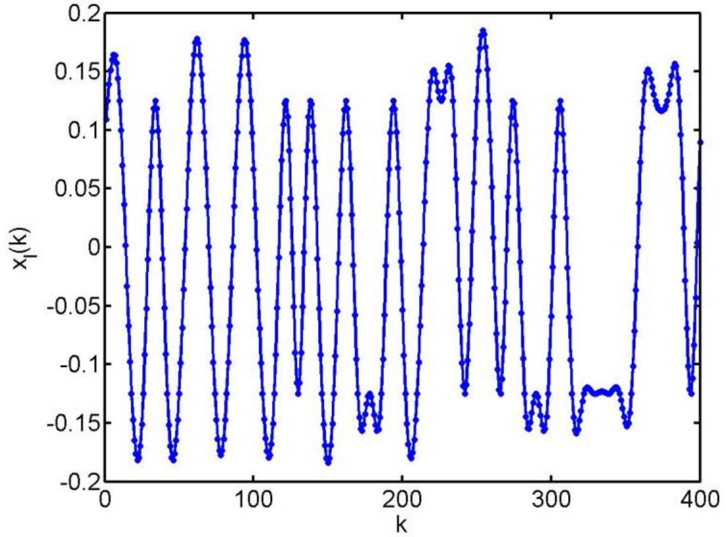
Eliminating initial and final samples





Save xI(t) and xQ(t) Signals





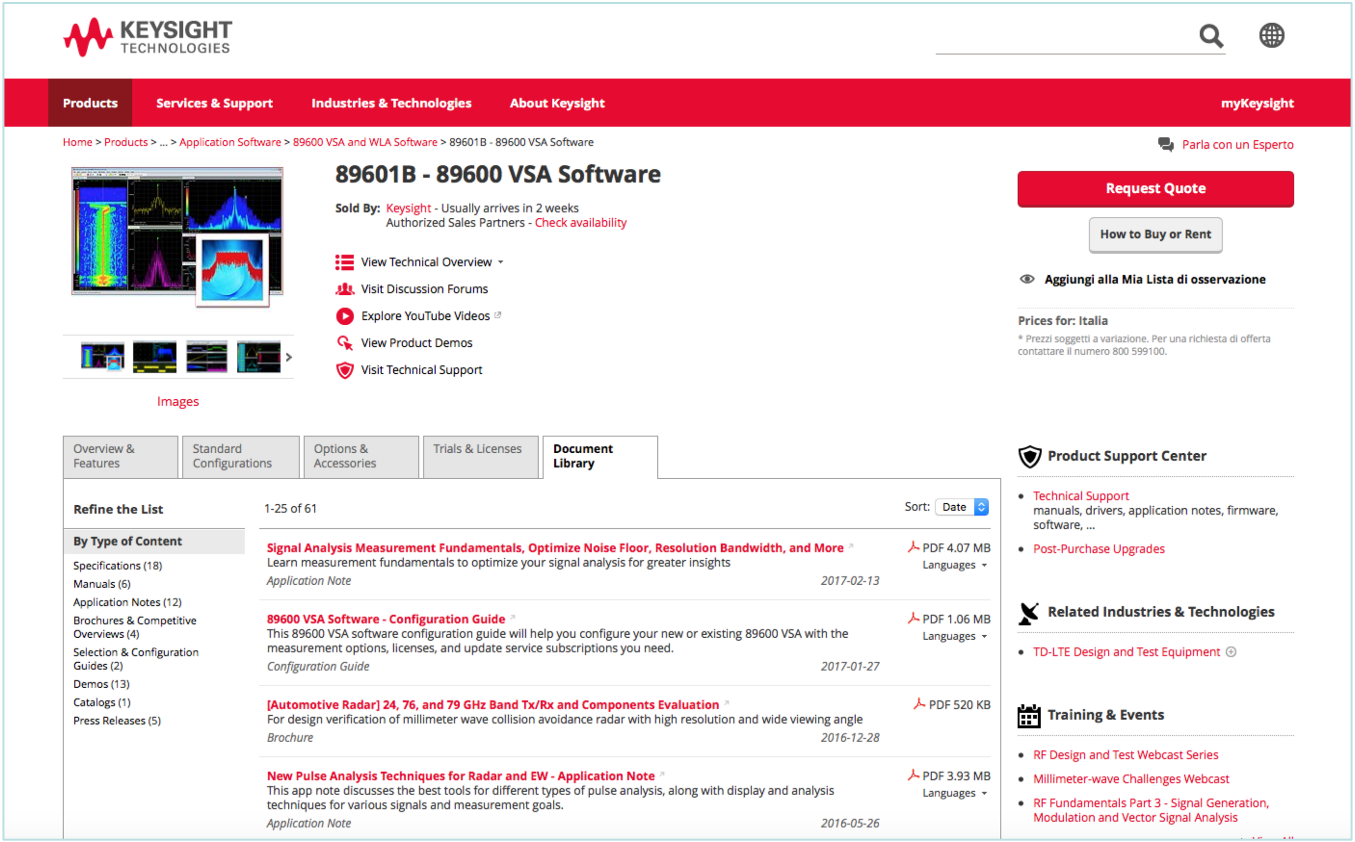

```
file_name='bb.txt';
save_data=[xI xQ];
save(file_name,'save_data','-ascii','-tabs')
```

save I/Q signal

Outline

- QPSK modulator in Mathworks Matlab
- **Demodulation in Keysight VSA 89600**
- Effects of RF transmitter impairments

Keysight (formerly Agilent) 89600 VSA Software



- **Download and install 89600 VSA on Windows OS**
- **Apply for trial license (<u>use polimi email address</u>)**

Preparing data file for VSA

<tab>

bb.txt

```
InputCenter	0.0
XDelta	62.5e-9
XUnit	Sec
YUnit	V
Y
 1.4462461e-001  6.5858005e-002
 1.0782906e-001  1.1953276e-001
 6.5689542e-002  1.4180947e-001
 3.5731248e-002  1.4629397e-001
 4.3731718e-002  1.4512024e-001
-4.4409018e-003  1.6316632e-001
-5.2750480e-002  1.7373438e-001
-8.3756295e-002  1.7905953e-001
-1.3691047e-001  1.4986813e-001
-1.3739223e-001  1.3365792e-001
-1.1316234e-001  1.1509579e-001
…
```

<CR>

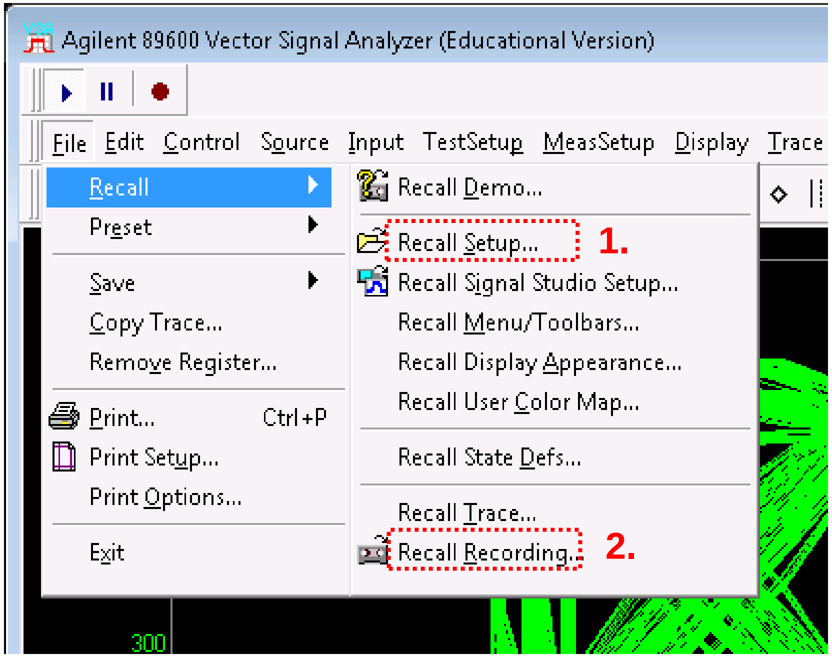
Add header to data file (header.txt to bb.txt)

T_{samp} = 62.5 ns
f_{samp} = 16 MHz
$f_{sym} = f_{samp}/N$ = 2 MHz

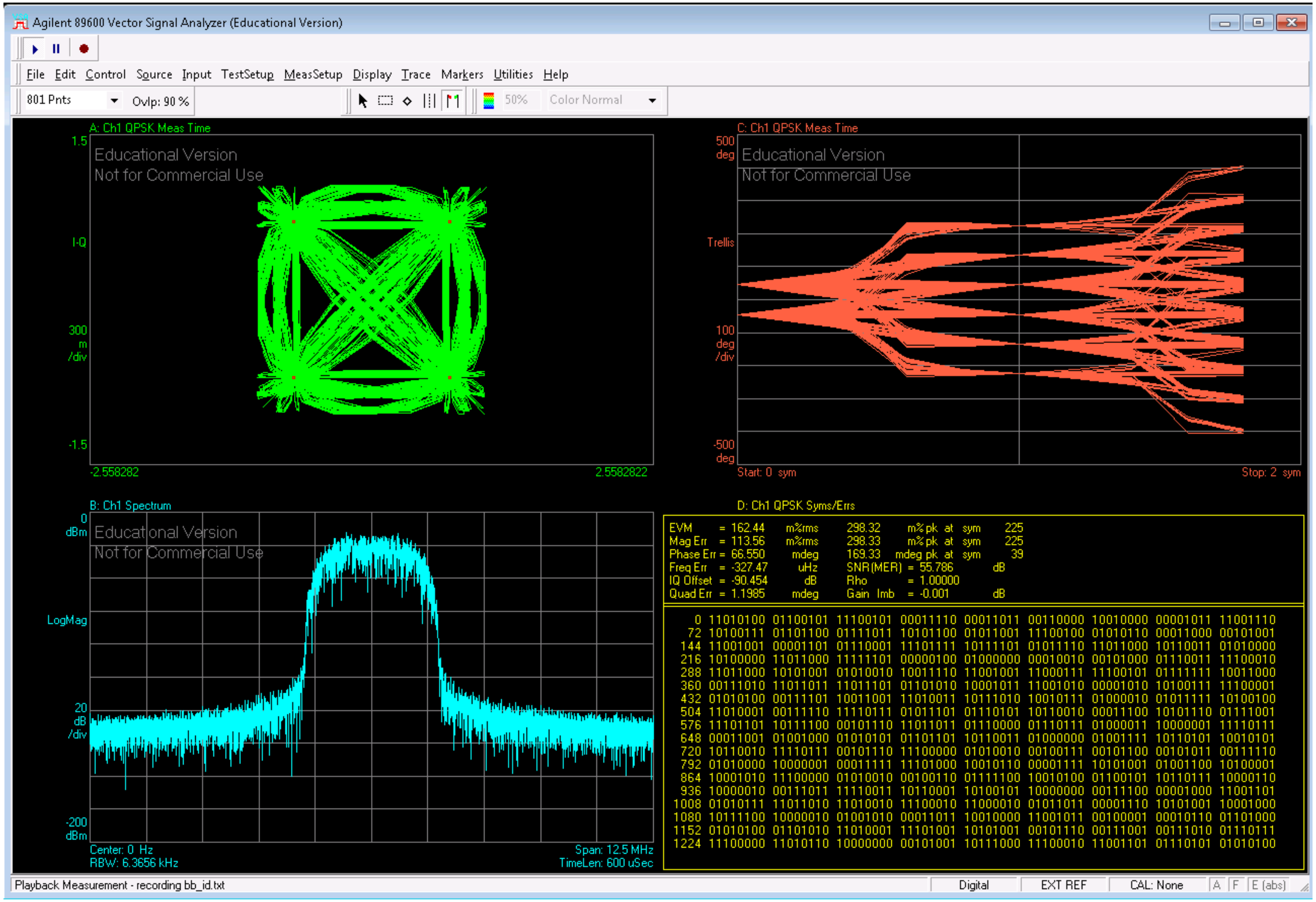
Demodulation with VSA Software

From File menu:

- **“Recall setting” (.set file available in Beep website)**
- **“Recall recording” (.txt file previously saved in Matlab)**
- **“Play”**



Demodulation with VSA Software



Exercise #1

- **What happens in case different values of R? Try for instance R = 0.1 and R = 1 and note down how the spectrum and the constellation (and SNR) change**

- **Can you explain the result?**

Exercise #1 – Results

SNR from VSA (at R = 0.1) = __________

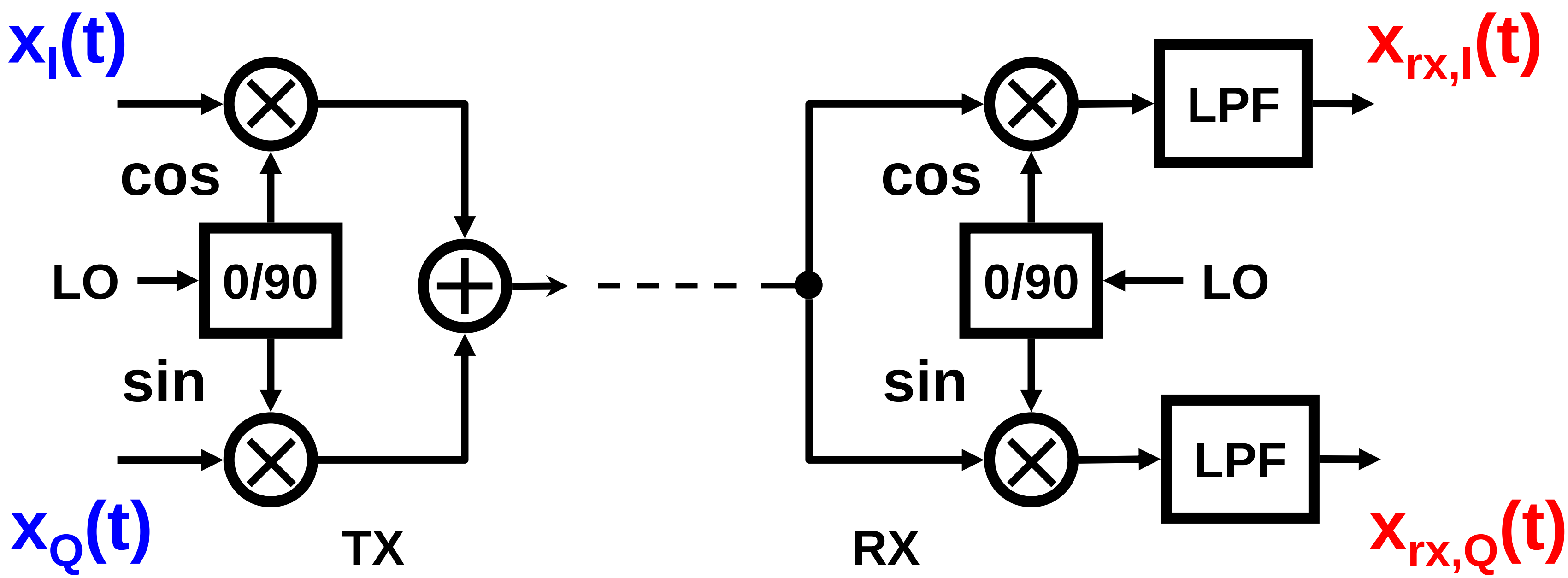
SNR from VSA (at R = 1) = __________

Explanation:

Outline

- QPSK modulator in Mathworks Matlab
- Demodulation in Keysight VSA 89600
- **Effects of RF transmitter impairments**
  - **Amplitude/Phase Imbalances**
  - **Phase Noise**

Effect of LO Amplitude and Phase Imbalances



$$x_{LOI}(t) = (1+\varepsilon/2)\cos(\omega_c t + \theta/2)$$
$$x_{LOQ}(t) = (1-\varepsilon/2)\sin(\omega_c t - \theta/2)$$

$$\Rightarrow \quad \boxed{SNR_{TX} \approx \frac{1}{\frac{\varepsilon^2}{4} + \frac{\theta^2}{4}}}$$

Equivalent Error on Base-Band Signals

$$
\begin{aligned}
&x_I(t)\cos(\omega_c t+\theta/2)+x_Q(t)\sin(\omega_c t-\theta/2)=\\
&=\underbrace{x_I(t)\cos(\theta/2)}\cos(\omega_c t)-\underbrace{x_Q(t)\sin(\theta/2)}\cos(\omega_c t)+\\
&\quad-\underbrace{x_I(t)\sin(\theta/2)}\sin(\omega_c t)+\underbrace{x_Q(t)\cos(\theta/2)}\sin(\omega_c t)
\end{aligned}
$$

```
theta = 10*pi/180;
xI = xI*cos( theta /2 ) - xQ*sin( theta /2 );
xQ = -xI*sin( theta /2 ) + xQ*cos( theta /2 );
```

← **10 deg phase error**

← **add LO phase error**

```
file_name='bb.txt';
save_data=[xI xQ];
save(file_name,'save_data','-ascii','-tabs');
```

← **save I/Q signal**

Exercise #2

- **Compute SNR from theory and from VSA with 10-degree LO quadrature error in TX.**

- **How does the constellation look like? Explain the result.**

Exercise #2 - Results

SNR from VSA = __________

SNR from theory = __________

Constellation:

____

____

Exercise #3

- **Compute SNR from theory and from VSA with 10% LO amplitude error in TX.**

- **How does the constellation look like? Explain the result.**

Exercise #3 - Results

SNR from VSA = ___________

SNR from theory = ___________

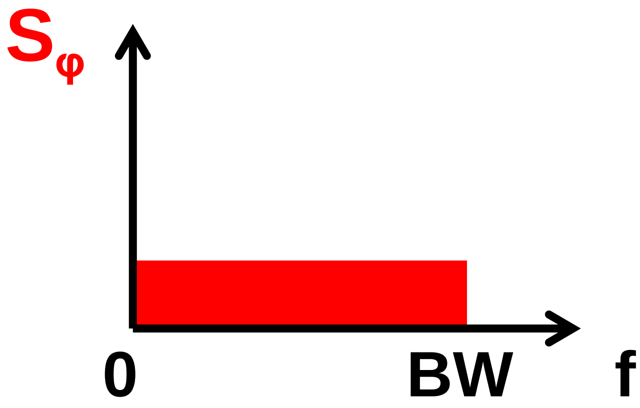
Constellation:

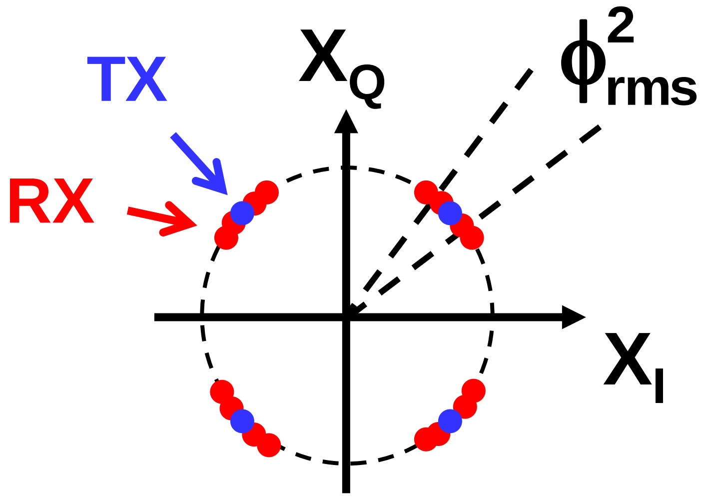
____

____

Effect of LO Phase Noise

$$V_{LO}(t) = A_0 \cos\left[\omega_c t + \phi(t)\right]$$





$$\phi^2_{rms} = \int_0^{BW} S_\phi(f)\,df$$

$$\boxed{SNR \approx \frac{1}{\phi^2_{rms}}}$$

Phase Noise on Base-Band Signals

$$
\begin{aligned}
& x_I(t)\cos(\omega_c t+\phi)+x_Q(t)\sin(\omega_c t+\phi)= \\
&= \underbrace{x_I(t)\cos(\phi)}\cos(\omega_c t)+\underbrace{x_Q(t)\sin(\phi)}\cos(\omega_c t)+ \\
&\quad \underbrace{-\,x_I(t)\sin(\phi)}\sin(\omega_c t)+\underbrace{x_Q(t)\cos(\phi)}\sin(\omega_c t)
\end{aligned}
$$

```
phi = 1 * pi/180 * randn( length(xI),1 );
xI = xI.*cos( phi ) + xQ.*sin( phi );
xQ = -xI.*sin( phi ) + xQ.*cos( phi );
```

← 1 deg-rms Gaussian noise

← add LO phase noise

```
file_name='bb.txt';
save_data=[xI xQ];
save(file_name,'save_data','-ascii','-tabs')
```

← save I/Q signal

Exercise #4

- **Compute SNR from theory and from VSA with 1-degree-rms phase noise of the local oscillator.**

- **How does the constellation look like?**

Exercise #4 - Results

SNR from VSA = __________

SNR from theory = __________

Constellation:

____

____

Exercise #5

- **Combine all the previous LO impairments (10% amplitude error, 10 deg phase error, 1 deg-rms phase noise) and evaluate the SNR at the demodulator**

Exercise #5 - Results

SNR from VSA = __________

SNR from theory = __________