Chapter 8

Baseband Transmission of Digital Signals

(Part 2 of 2)

8.2 Intersymbol Interference (ISI)

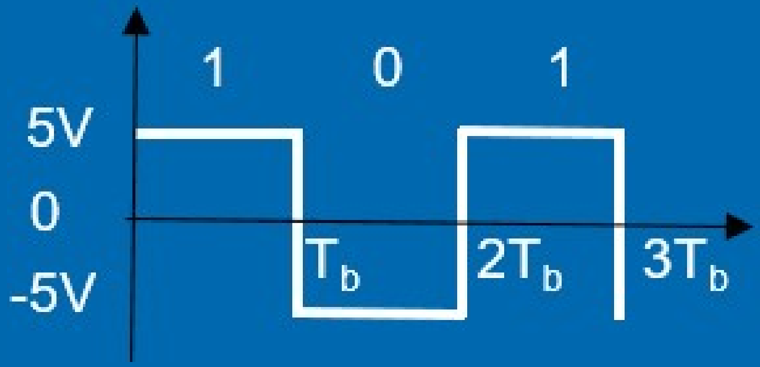
Channel noise

Limited channel bandwidth

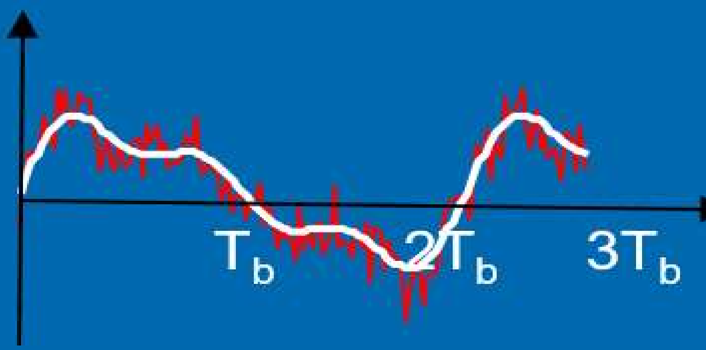
main sources of transmission errors

Signal waveform gets distorted when going through the channel.

Transmitted signal



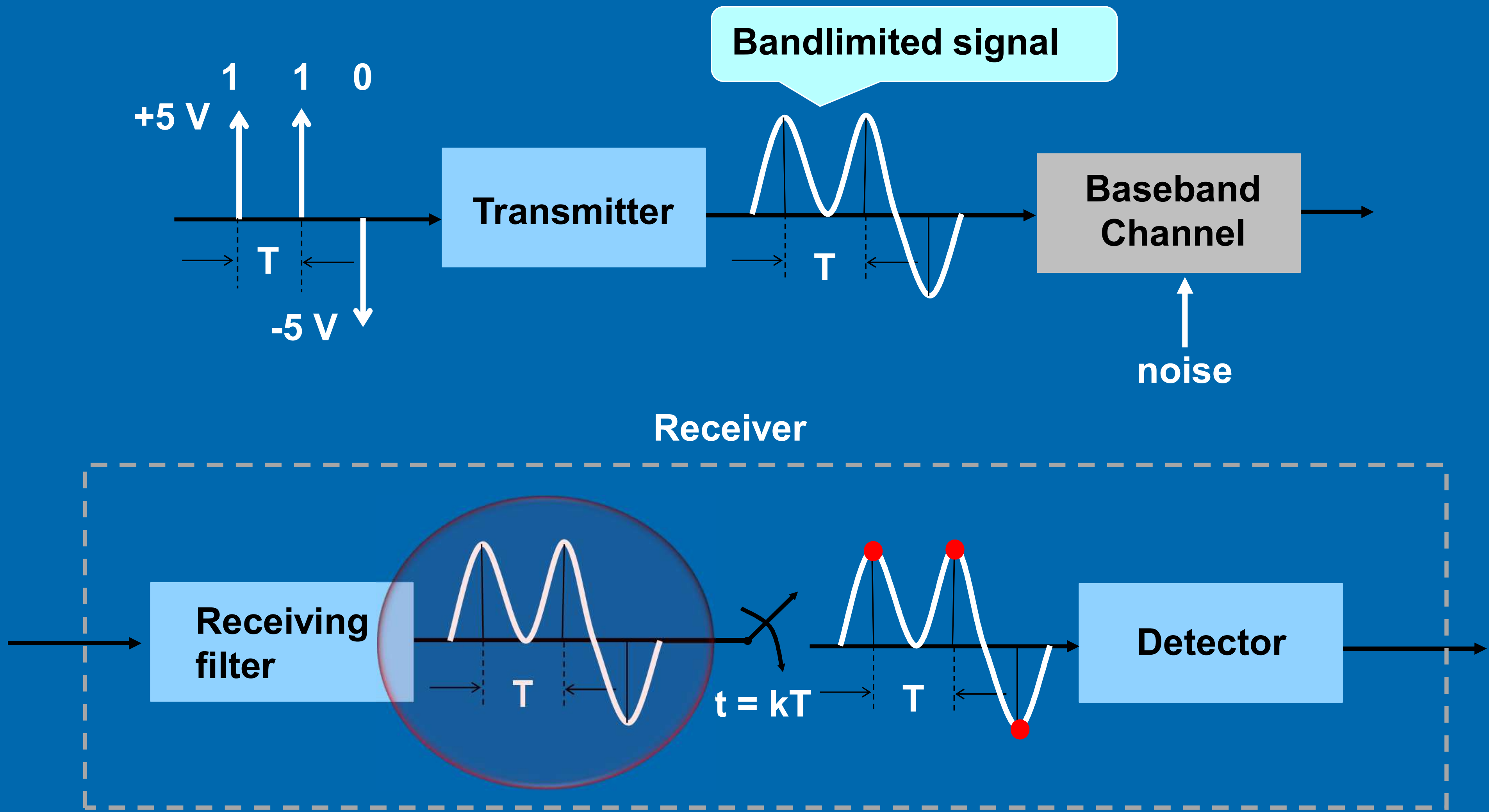
Received signal



Transmitter → Baseband Channel → Receiver

8.2 Intersymbol Interference (ISI)

Baseband digital communication system



8.2 Intersymbol Interference (ISI)

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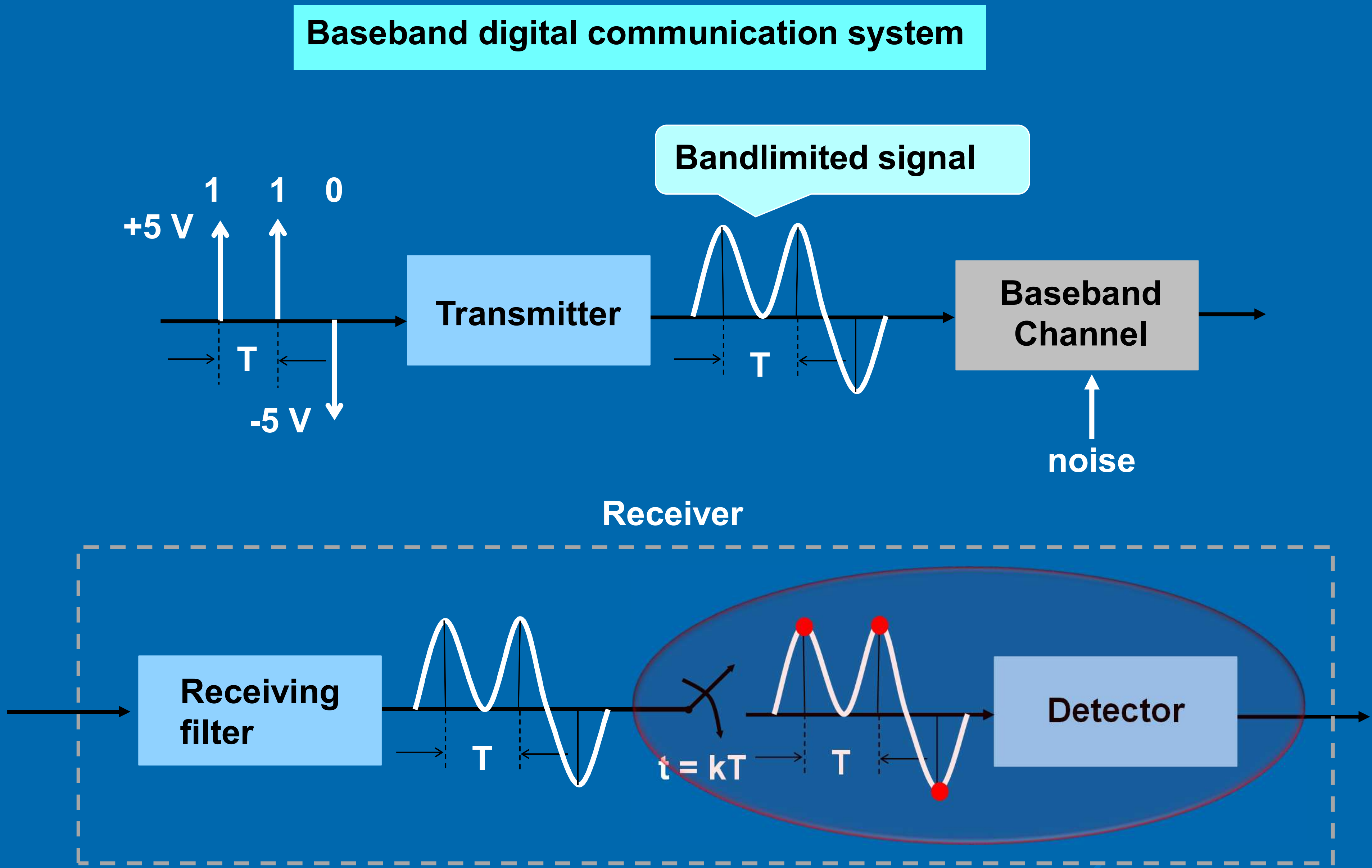

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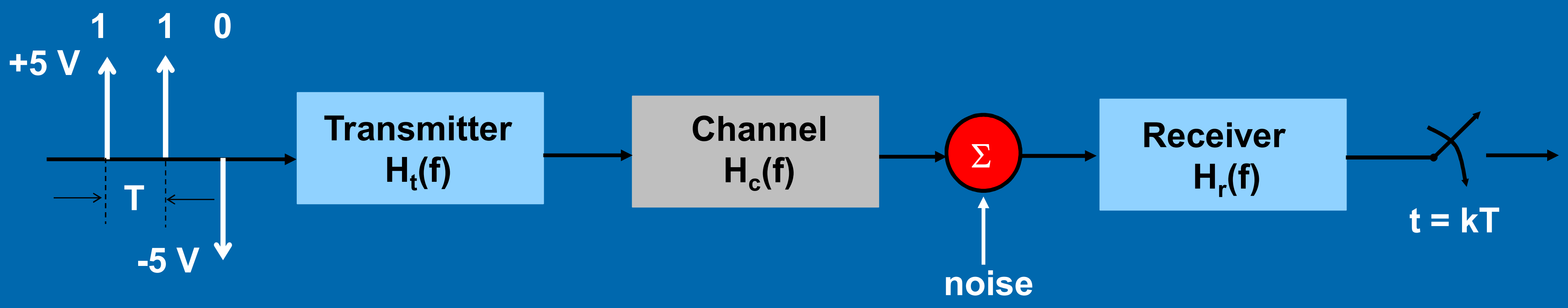
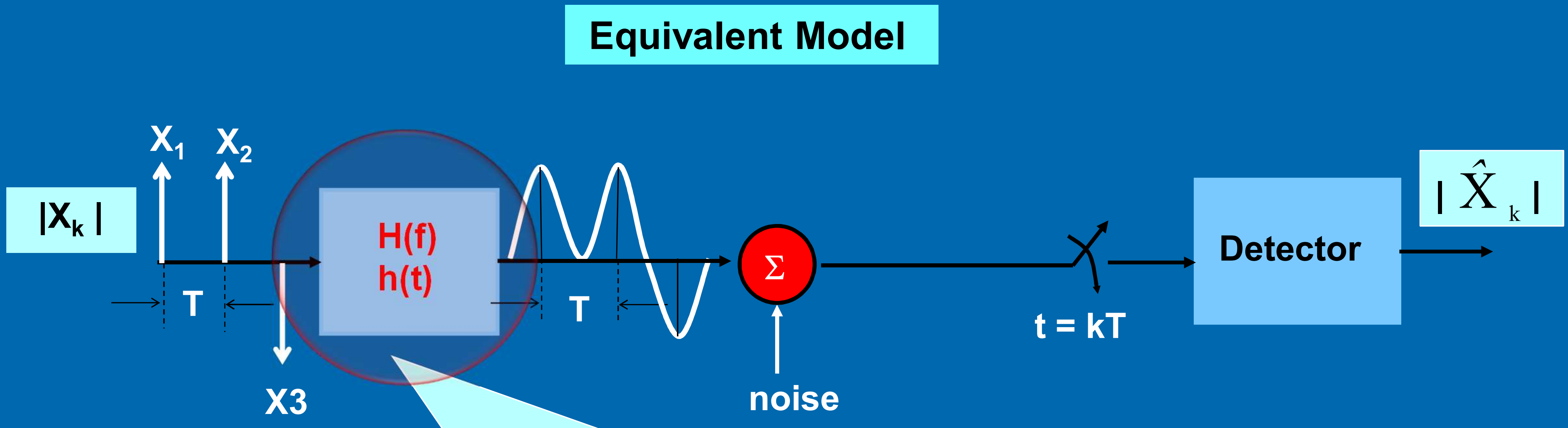
Baseband digital communication system model



$H_t(f)$ = transfer function of transmitting filter
$H_c(f)$ = transfer function of transmission channel
$H_r(f)$ = transfer function of receiving filter

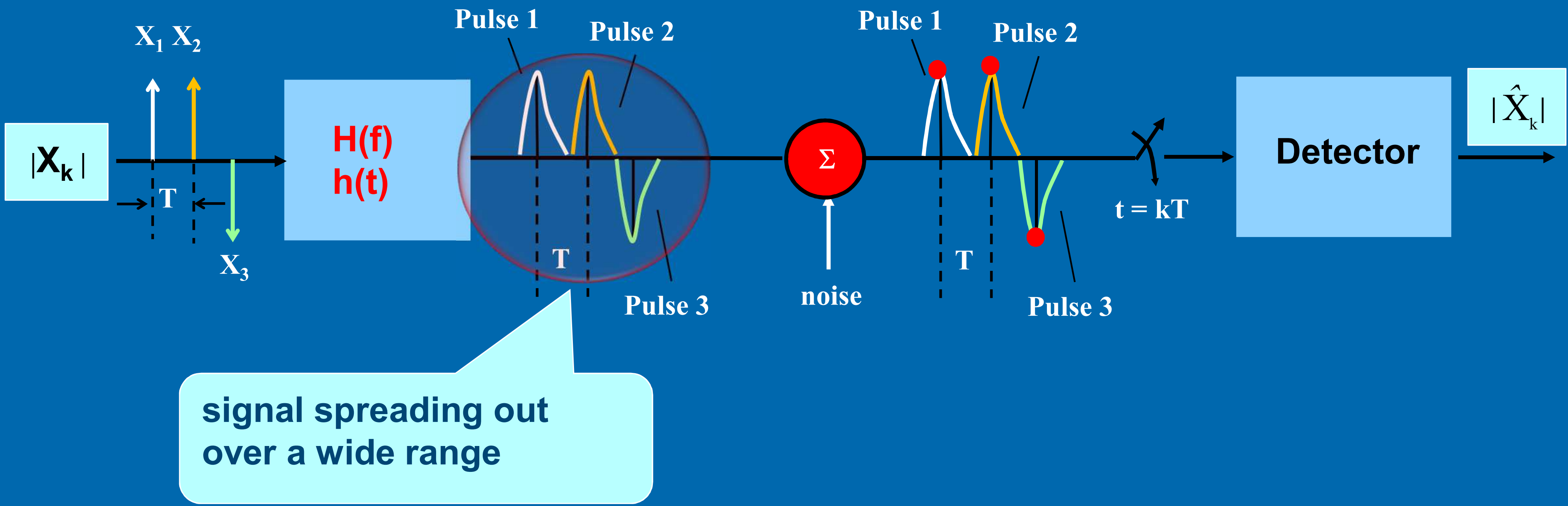
8.2 Intersymbol Interference (ISI)



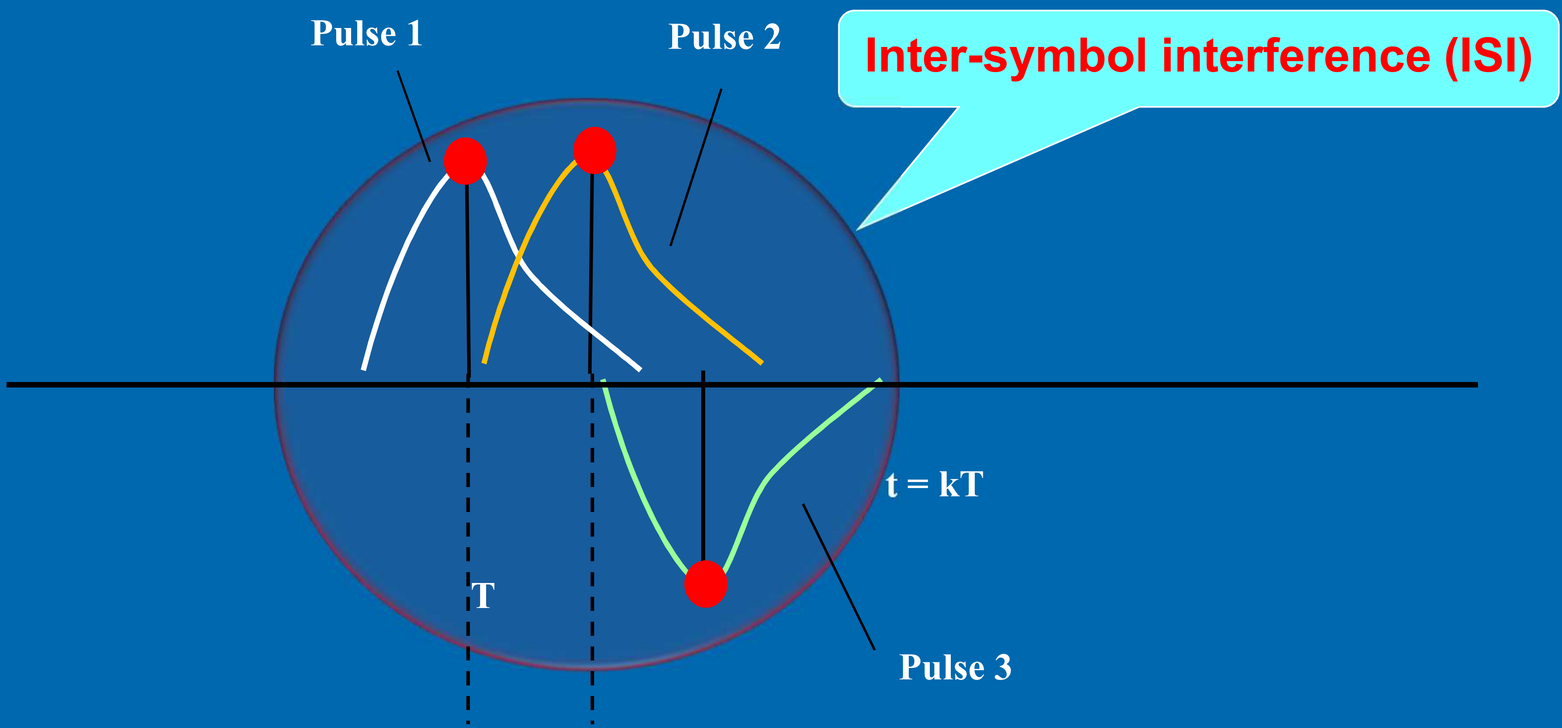
Overall equivalent system transfer function:

$$H(f) = H_t(f)\, H_c(f)\, H_r(f)$$

The effect of **system** band-limitation



The effect of more limited system bandwidth



- ISI occurs even in the absence of channel noise.
- Effect of ISI on detection can be minimised by selecting appropriate transmitting filter, channel and receiving filter.

8.2 Intersymbol Interference (ISI)

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Nyquist Transmission Theorem

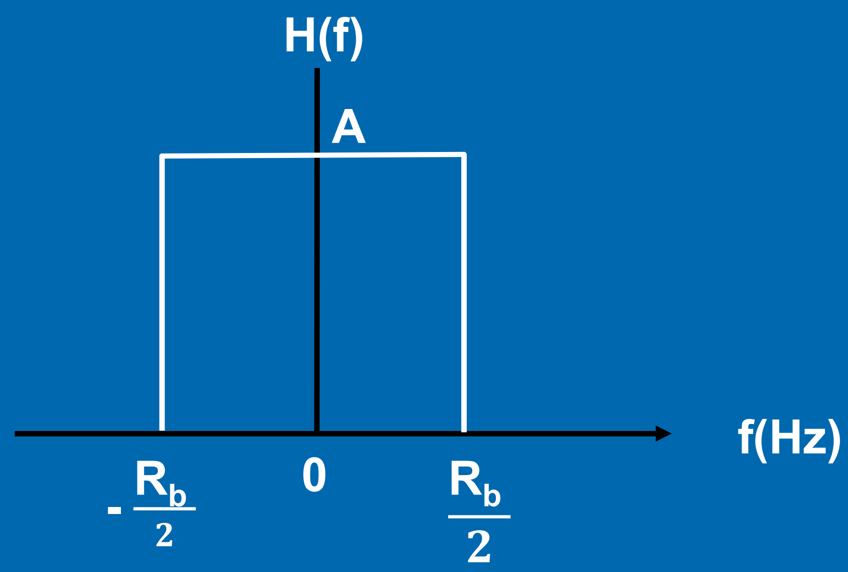
A special case investigated by Nyquist where H(f) is an ideal LPF.

Theorem : If the transmission rate is R_b bits/s, for no ISI the minimum system filter bandwidth is

$R_b/2$ Hz

$$R_b = \frac{1}{T_b}$$

$$\frac{R_b}{2} = \frac{1}{2T_b}$$



8.2 Intersymbol Interference (ISI)

Example 8.1

A binary source is transmitting information at a rate of 1 kb/s. A binary 1 is transmitted as a unit impulse, and a binary 0 as no pulse. The channel is an ideal LPF with zero phase shift.

What is the minimum cut-off frequency of the channel to allow ISI-free transmission?

8.2 Intersymbol Interference (ISI)

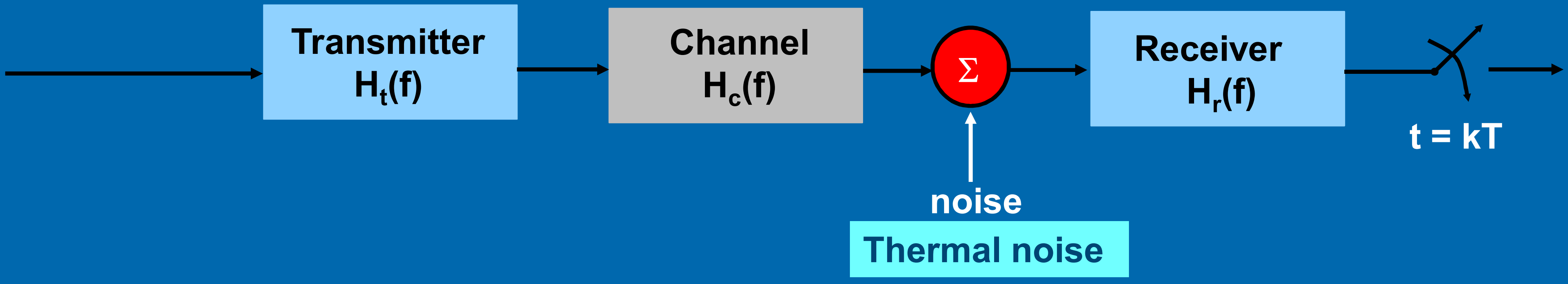
Solution

Given R_b = 1 kb/s.

From Nyquist's Theorem, the theoretical system bandwidth to detect R_b bits without ISI is $R_b/2$ Hz, if the system (or channel) has an ideal low pass filter characteristic.

Hence, the channel cut-off frequency is $f_c = R_b/2 = 500$ Hz.

8.3 Channel Noise



4 characteristics of channel noise

AWGN:
Additive white Gaussian noise

- Zero-mean voltage
- Gaussian probability density function (pdf)
- Corrupts the desired signal in an additive fashion
- White power spectral density (psd)
  i.e. constant psd over all frequencies.

8.3 Channel Noise

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Probability Density Function (pdf) and Probability of Gaussian Noise

- Zero-mean Gaussian pdf is given by

$$p(n) = \frac{1}{\sigma\sqrt{2\pi}} \exp\left[-\frac{1}{2}\left[\frac{n}{\sigma}\right]^2 \right]$$

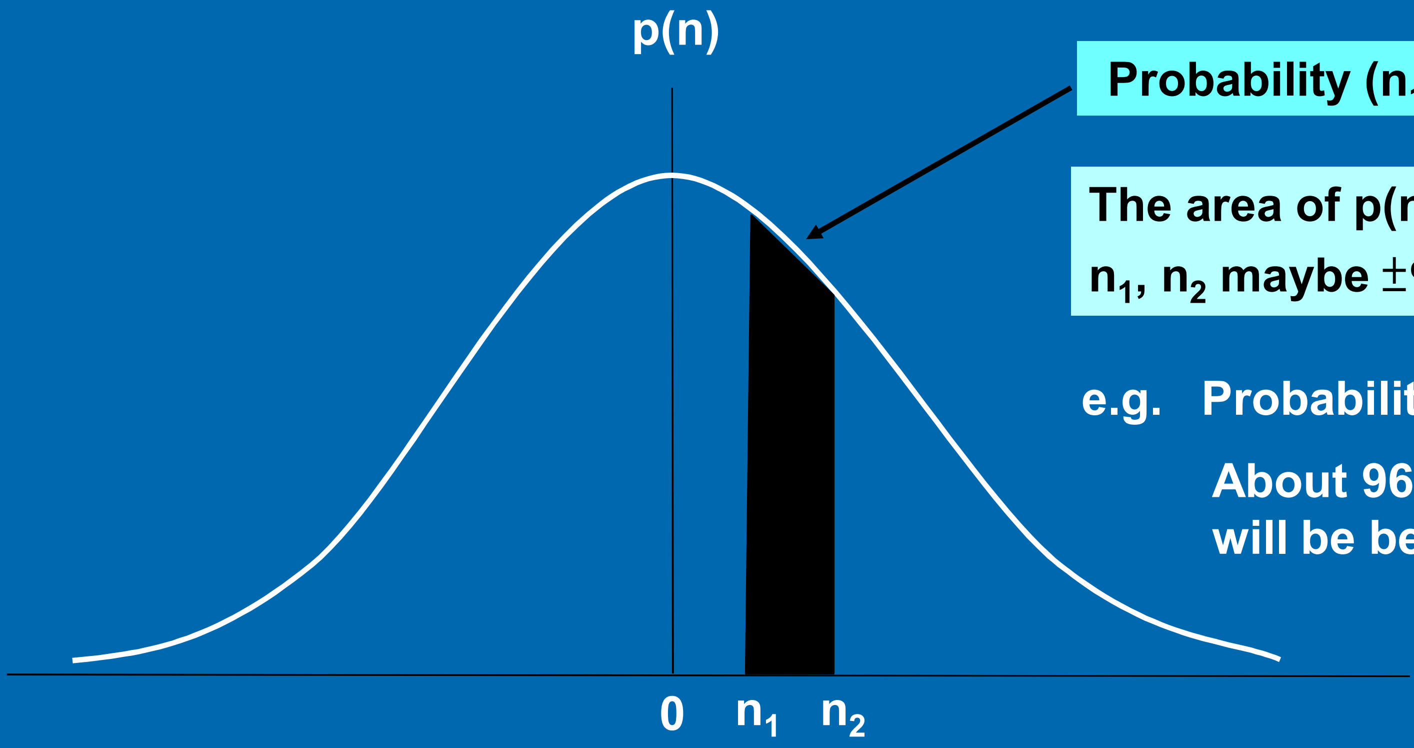
Formula not tested

where n is the magnitude of the noise signal.
σ = standard deviation = rms noise voltage

8.3 Channel Noise

Probability density function of Gaussian Noise

- **The probability of noise being within a certain magnitude range is**



Probability ($n_1 < n < n_2$) $= \int_{n_1}^{n_2} p(n)dn$

The area of p(n) under (n_1, n_2).
n_1, n_2 maybe $\pm\infty$ or any real number.

e.g. Probability (0.1v < n < 0.2v) = 0.96

About 96% of the time, noise amplitude will be between 0.1 and 0.2 volts.

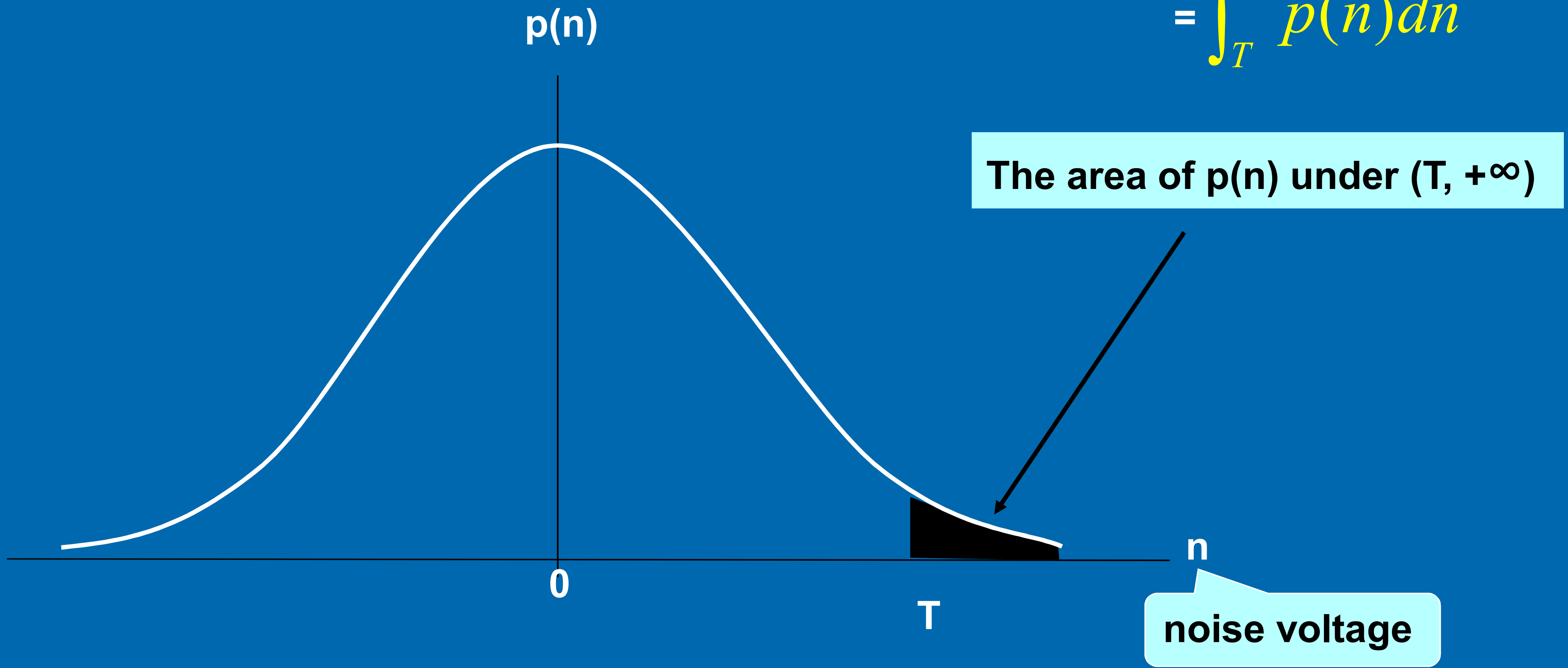
noise voltage

8.3 Channel Noise

Probability density function of Gaussian Noise

- The probability of n > T is given by **Probability (n>T)** = Prob (T<n< ∞)

$$= \int_T^{\infty} p(n)dn$$



8.3 Channel Noise

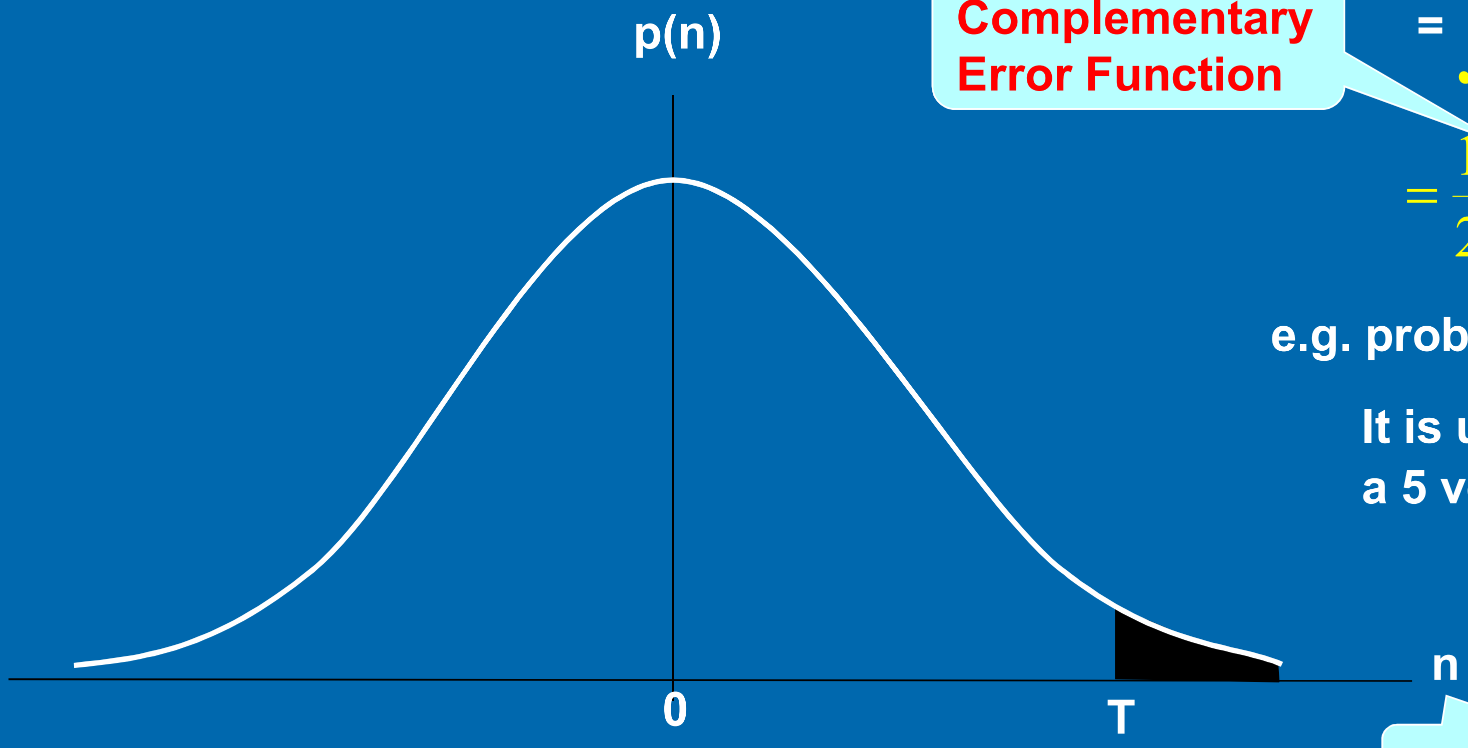
Probability density function of Gaussian Noise

- The probability of n > T is given by **Probability (n>T)** = Prob (T<n< ∞)

$$= \int_{T}^{\infty} p(n)dn$$

$$= \frac{1}{2}\, erfc\left(\frac{T}{\sqrt{2}\sigma}\right)$$

Complementary Error Function



noise voltage

e.g. probability (n > 0.5 v) = 0.001

It is unlikely that noise will affect a 5 volt pulse representing “ 1 ”.

8.3 Channel Noise

Example 8.2

What is the probability of a zero-mean white Gaussian noise:

(i) exceeding 8 mV, if it has an rms value of 2 mV ?

(ii) exceeding a magnitude of 5 mV, if it has an rms value of 3 mV ?

(iii) equal or less than a magnitude of 5 mV, if it has an rms value of 3 mV ?

What is the probability of a zero-mean white Gaussian noise:
(i) exceeding 8 mV, if it has an rms value of 2 mV ?

Solution

(i) The probability that the noise exceeds T volt is given by

$$P(n > T) = \frac{1}{2} erfc\left[\frac{T}{\sqrt{2}\sigma}\right]$$ where σ = rms value of noise signal.

Therefore $$P(n > 8mV) = \frac{1}{2} erfc\left[\frac{8mV}{\sqrt{2} \times 2mV}\right]$$

$$= \frac{1}{2} erfc[2.828] \longleftrightarrow \frac{1}{2} erfc[z]$$

Referring to the Erfc table to find the result for erfc[Z].

PROBABILITY AND STATISTICS

(cont.)

TABLE Complementary Error Function

Z	erfc(Z)	Z	erfc(Z)	Z	erfc(Z)
1.29	0.681014D-01	1.72	0.149972D-01	2.15	0.236139D-02
1.30	0.659920D-01	1.73	0.144215D-01	2.16	0.225285D-02
		1.74	0.138654D-01	2.17	0.214889D-02
1.31	0.639369D-01	1.75	0.133283D-01	2.18	0.204935D-02
1.32	0.619348D-01	1.76	0.128097D-01	2.19	0.195406D-02
1.33	0.599850D-01	1.77	0.123091D-01	2.20	0.186285D-02
1.34	0.580863D-01	1.78	0.118258D-01		
1.35	0.562378D-01	1.79	0.113594D-01	2.21	0.177556D-02
1.36	0.544386D-01	1.80	0.109095D-01	2.22	0.169205D-02
1.37	0.526876D-01			2.23	0.161217D-02
1.38	0.509840D-01	1.81	0.104755D-01	2.24	0.153577D-02
1.39	0.493267D-01	1.82	0.100568D-01	2.25	0.146272D-02
1.40	0.477149D-01	1.83	0.965319D-02	2.26	0.139288D-02
		1.84	0.926405D-02	2.27	0.132613D-02
1.41	0.461476D-01	1.85	0.888897D-02	2.28	0.126234D-02
1.42	0.446238D-01	1.86	0.852751D-02	2.29	0.120139D-02
1.43	0.431427D-01	1.87	0.817925D-02	2.30	0.114318D-02
1.44	0.417034D-01	1.88	0.784378D-02		
1.45	0.403050D-01	1.89	0.752068D-02	2.31	0.108758D-02
1.46	0.389465D-01	1.90	0.720957D-02	2.32	0.102449D-02
1.47	0.376271D-01			2.33	0.983805D-03
1.48	0.363459D-01	1.91	0.691006D-02	2.34	0.935430D-03
1.49	0.351021D-01	1.92	0.662177D-02	2.35	0.889267D-03
1.50	0.338949D-01	1.93	0.634435D-02	2.36	0.845223D-03
		1.94	0.607743D-02	2.37	0.803210D-03
1.51	0.327233D-01	1.95	0.582066D-02	2.38	0.763142D-03
1.52	0.315865D-01	1.96	0.557372D-02	2.39	0.724936D-03
1.53	0.304838D-01	1.97	0.533627D-02	2.40	0.688514D-03
1.54	0.294143D-01	1.98	0.510800D-02		
1.55	0.283773D-01	1.99	0.488859D-02	2.41	0.653798D-03
1.56	0.273719D-01	2.00	0.467773D-02	2.42	0.620716D-03
1.57	0.263974D-01			2.43	0.589197D-03
1.58	0.254530D-01				

TABLE Complementary Error Function

Z	erfc(Z)	Z	erfc(Z)	Z	erfc(Z)
2.58	0.263600D-03	3.01	0.207390D-04	3.44	0.114518D-05
2.59	0.249461D-03	3.02	0.194664D-04	3.45	0.106605D-05
2.60	0.236034D-03	3.03	0.182684D-04	3.46	0.992201D-06
		3.04	0.171409D-04	3.47	0.923288D-06
2.61	0.223289D-03	3.05	0.160798D-04	3.48	0.858995D-06
2.62	0.211191D-03	3.06	0.150816D-04	3.49	0.799025D-06
2.63	0.199711D-03	3.07	0.141426D-04	3.50	0.743098D-06
2.64	0.188819D-03	3.08	0.132595D-04		
2.65	0.178488D-03	3.09	0.124292D-04		
2.66	0.168689D-03	3.10	0.116487D-04	3.51	0.690952D-06
2.67	0.159399D-03			3.52	0.642341D-06
2.68	0.150591D-03	3.11	0.109150D-04	3.53	0.597035D-06
2.69	0.142243D-03	3.12	0.102256D-04	3.54	0.554816D-06
2.70	0.134333D-03	3.13	0.957795D-05	3.55	0.515484D-06
		3.14	0.896956D-05	3.56	0.478847D-06
2.71	0.126838D-03	3.15	0.839821D-05	3.57	0.444728D-06
2.72	0.119738D-03	3.16	0.786174D-05	3.58	0.412960D-06
2.73	0.113015D-03	3.17	0.735813D-05	3.59	0.383387D-06
2.74	0.106649D-03	3.18	0.688545D-05	3.60	0.355863D-06
2.75	0.100622D-03	3.19	0.644190D-05		
2.76	0.949176D-04	3.20	0.602576D-05	3.61	0.330251D-06
2.77	0.895197D-04			3.62	0.306423[illegible]
2.78	0.844127D-04	3.21	0.563542D-05	3.63	[illegible]
2.79	0.795818D-04	3.22	0.526935D-05	3.6[illegible]	[illegible]-06
2.80	0.750132D-04	3.23	0.492612[illegible]	[illegible]	[illegible]244483D-06
		3.24	0.46[illegible]-05	3.66	0.226667D-06
2.81	0.706933D-04	3.25	0.430278D-05	3.67	0.210109D-06
2.82	0.666096D-04	3.26	0.402018D-05	3.68	0.194723D-06
2.83	0.627497D-04	3.27	0.375542D-05	3.69	0.180429D-06
2.84	0.591023D-04	3.28	0.350742D-05	3.70	0.167151D-06
2.85	0.556563D-04	3.29	0.327517D-05	3.71	0.154821D-06
2.86	0.524012D-04	3.30	0.305771D-05	3.72	0.143372D-06

z is round down to 2.82 for worse case condition

$$erfc[2.828]$$

$$\downarrow$$

$$erfc[2.82]$$

z	erfc (z)
2.81	0.706933D-04
2.82	0.666096D-04
2.83	0.627497D-04
2.84	0.591023D-04

Solution

(i) The probability that the noise exceeds T volt is given by

$$P(n > T) = \frac{1}{2} erfc\left[\frac{T}{\sqrt{2}\sigma}\right]$$ where σ = rms value of noise signal.

Therefore $$P(n > 8mV) = \frac{1}{2} erfc\left[\frac{8mV}{\sqrt{2} \times 2mV}\right] = erfc[z]$$

$$= \frac{1}{2} erfc[2.828]$$

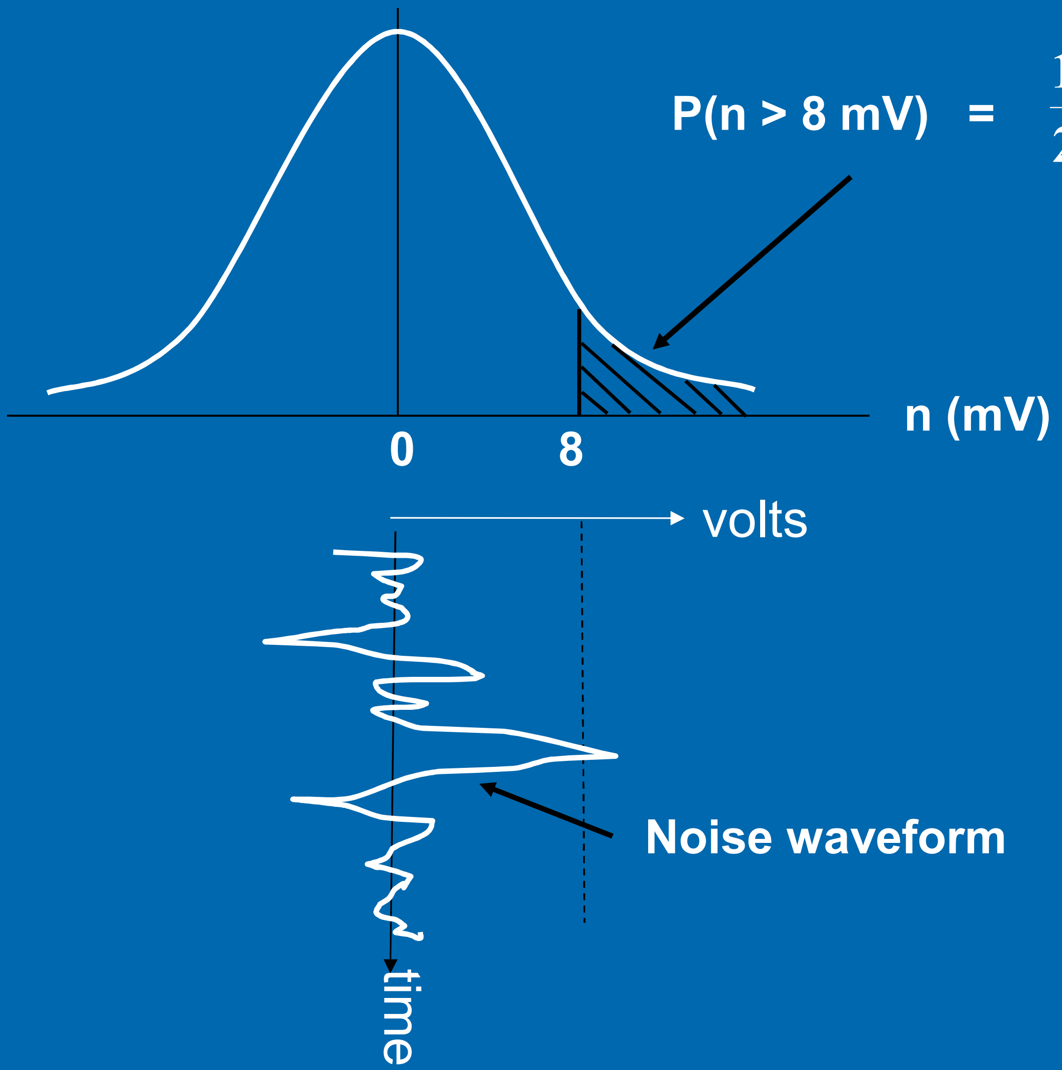
z is round down to 2.82 for worse case condition

z	erfc (z)
2.81	0.706933D-04
2.82	0.666096D-04
2.83	0.627497D-04
2.84	0.591023D-04

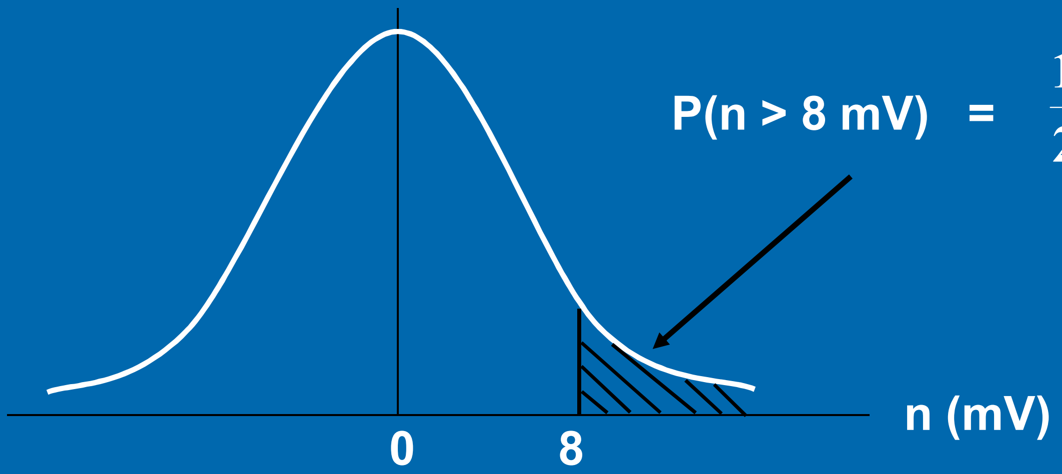
For z = 2.82; erfc(z) = 0.666×10^{-4}

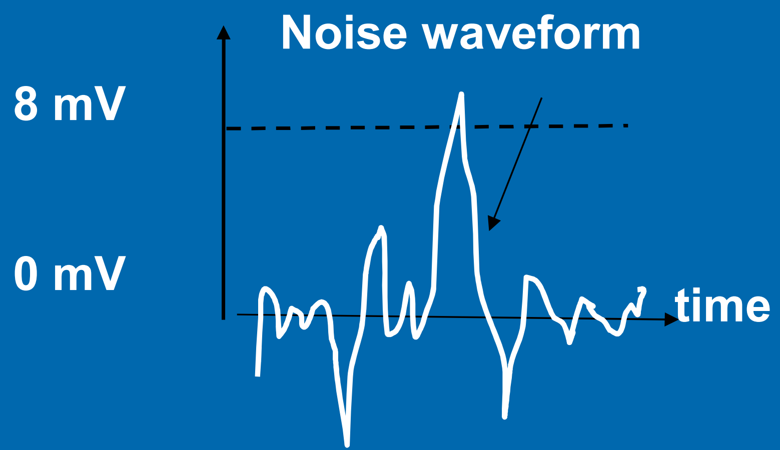
Therefore P(n > 8 mV) = 1/2 x 0.666 x 10^{-4} = 3.33 x 10^{-5}

$$P(n > 8\text{ mV}) \;=\; \frac{1}{2}\,erfc\left(\frac{8mV}{\sqrt{2}x2mv}\right)$$



$$P(n > 8\text{ mV}) = \frac{1}{2}\,erfc\left(\frac{8mV}{\sqrt{2}x2mv}\right)$$





The noise voltage is below 8 mV most of the time.

What is the probability of a zero-mean white Gaussian noise:
(ii) exceeding a magnitude of 5 mV, if it has an rms value of 3 mV ?

Solution

(ii) The probability that the noise exceeds a magnitude of T volt is given by

$P(|n| > T) = \text{erfc}\,[T/(\sqrt{2}\sigma)]$

as $|n| > T = (n > T)$ or $(n < -T)$

thus $P(|n| > T) = P(n > T) + P(n < -T)$

P(n) is symmetrical about y axis:
$P(n > T) = P(n < -T)$

$= 2\text{x}1/2\ \text{erfc}[\,T/(\sqrt{2}\sigma)\,] = \text{erfc}[\,T/(\sqrt{2}\sigma)\,]$

What is the probability of a zero-mean white Gaussian noise:
(ii) exceeding a magnitude of 5 mV, if it has an rms value of 3 mV ?

Solution

(ii) The probability that the noise exceeds a magnitude of T volt is given by

$$P(|n| > T) = \text{erfc}\,[T/(\sqrt{2}\sigma)]$$

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P(n) is symmetrical about y axis:
$P(n > T) = P(n < -T)$

$$= 2\text{x}1/2\ \text{erfc}[\,T/(\sqrt{2}\sigma)\,] = \text{erfc}[\,T/(\sqrt{2}\sigma)\,]$$

Therefore $P(|n| > 5\text{ mV}) = \text{erfc}\,[\,5\text{ mV}/(\sqrt{2} \times 3\text{ mV})\,]$

$$= \text{erfc}\,(1.179)$$

Referring to the Erfc table:

Z	erfc(Z)	Z	erfc(Z)	Z	erfc(Z)
0.00	1.00000	0.43	0.543113	0.86	0.223900
0.01	0.988717	0.44	0.533775	0.87	0.218560
0.02	0.977435	0.45	0.524518	0.88	0.213313
0.03	0.966159	0.46	0.515345	0.89	0.208157
0.04	0.954889	0.47	0.506255	0.90	0.203092
0.05	0.943628	0.48	0.497250		
0.06	0.932378	0.49	0.488332	0.91	0.198117
0.07	0.921142	0.50	0.479500	0.92	0.193232
0.08	0.909922			0.93	0.188436
0.09	0.898719	0.51	0.470756	0.94	0.183729
0.10	0.887537	0.52	0.462101	0.95	0.179109
		0.53	0.453536	0.96	0.174576
0.11	0.876377	0.54	0.445061	0.97	0.170130
0.12	0.865242	0.55	0.436677	0.98	0.165768
0.13	0.854133	0.56	0.428384	0.99	0.161492
0.14	0.843053	0.57	0.420184	1.00	0.157299
0.15	0.832004	0.58	0.412077		
0.16	0.820988	0.59	0.404063	1.01	0.153190
0.17	0.810008	0.60	0.396144	1.02	0.149162
0.18	0.799064			1.03	0.145216
0.19	0.788160	0.61	0.388319	1.04	0.141350
0.20	0.777297	0.62	0.380589	1.05	0.137564
		0.63	0.372954	1.06	0.133856
0.21	0.766478	0.64	0.365414	1.07	0.130227
0.22	0.755704	0.65	0.357971	1.08	0.126674
0.23	0.744977	0.66	0.350623	1.09	0.123197
0.24	0.734300	0.67	0.343372	1.10	0.119795
0.25	0.723674	0.68	0.336218		
0.26	0.713100	0.69	0.329160	1.11	0.116467
0.27	0.702582	0.70	0.322199	1.12	0.113212
0.28	0.692120			1.13	0.110029
0.29	0.681716	0.71	0.315334	1.14	0.106918
0.30	0.671373	0.72	0.308567	1.15	0.103876
		0.73	0.301896	1.16	0.100904
0.31	0.661092	0.74	0.295322	1.17	0.979996D-01
0.32	0.650874	0.75	0.288844	1.18	0.951626D-01
0.33	0.640721	0.76	0.282463	1.19	0.923917D-01
0.34	0.630635	0.77	0.276178	1.20	0.896860D-01

z	erfc (z)
1.15	0.103876
1.16	0.100904
1.17	0.979996D-01
1.18	0.951626D-01

erfc(1.17) = 0.98 x 10^{-1}

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What is the probability of a zero-mean white Gaussian noise:
(ii) exceeding a magnitude of 5 mV, if it has an rms value of 3 mV ?

Solution

(ii) The probability that the noise exceeds a magnitude of T volt is given by

$P(|n| > T) = \text{erfc}\,[T/(\sqrt{2}\sigma)]$

as $|n| > T = (n > T)$ or $(n < -T)$

thus $P(|n| > T) = P(n > T) + P(n < -T)$

P(n) is symmetrical about y axis:
$P(n > T) = P(n < -T)$

$= 2\text{x}1/2\ \text{erfc}[\ T/(\sqrt{2}\sigma)\ ] = \text{erfc}[\ T/(\sqrt{2}\sigma)\ ]$

Therefore $P(|n| > 5\text{ mV}) = \text{erfc}\,[\ 5\text{ mV}/(\sqrt{2} \times 3\text{ mV})\ ]$

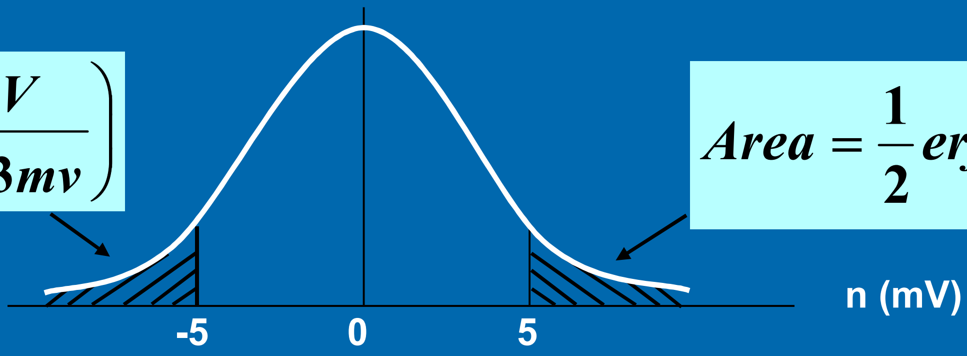
$= \text{erfc}\,(1.179) = \text{erfc}\,(1.17)$ $= 0.98 \times 10^{-1}$

Therefore $P(|n| > 5\text{ mV}) = 0.98 \times 10^{-1}$

What is the probability of a zero-mean white Gaussian noise:
(iii) equal or less than a magnitude of 5 mV, if it has an rms value of 3 mV ?

P(|n| > 5 mV) = Total shaded area $= 0.98 \times 10^{-1}$

$$Area = \frac{1}{2} erfc\left(\frac{5mV}{\sqrt{2}x3mv}\right)$$



$$Area = \frac{1}{2} erfc\left(\frac{5mV}{\sqrt{2}x3mv}\right)$$

Unshaded area = 1 - 0.98×10^{-1} = 0.902

Hence, P(|n| < 5 mV) = 0.902

8.3 Channel Noise

Probability of Bit Error

Probability of Bit Error for a basic digital receiver

- The performance of a digital communication system, is measured by probability of bit error, P_e, i.e. the probability of receiving a wrong bit.
- The higher the noise, the higher the P_e.
- The practical measurement of P_e is bit error rate, BER.

$$\boxed{BER = N_e/N_t}$$

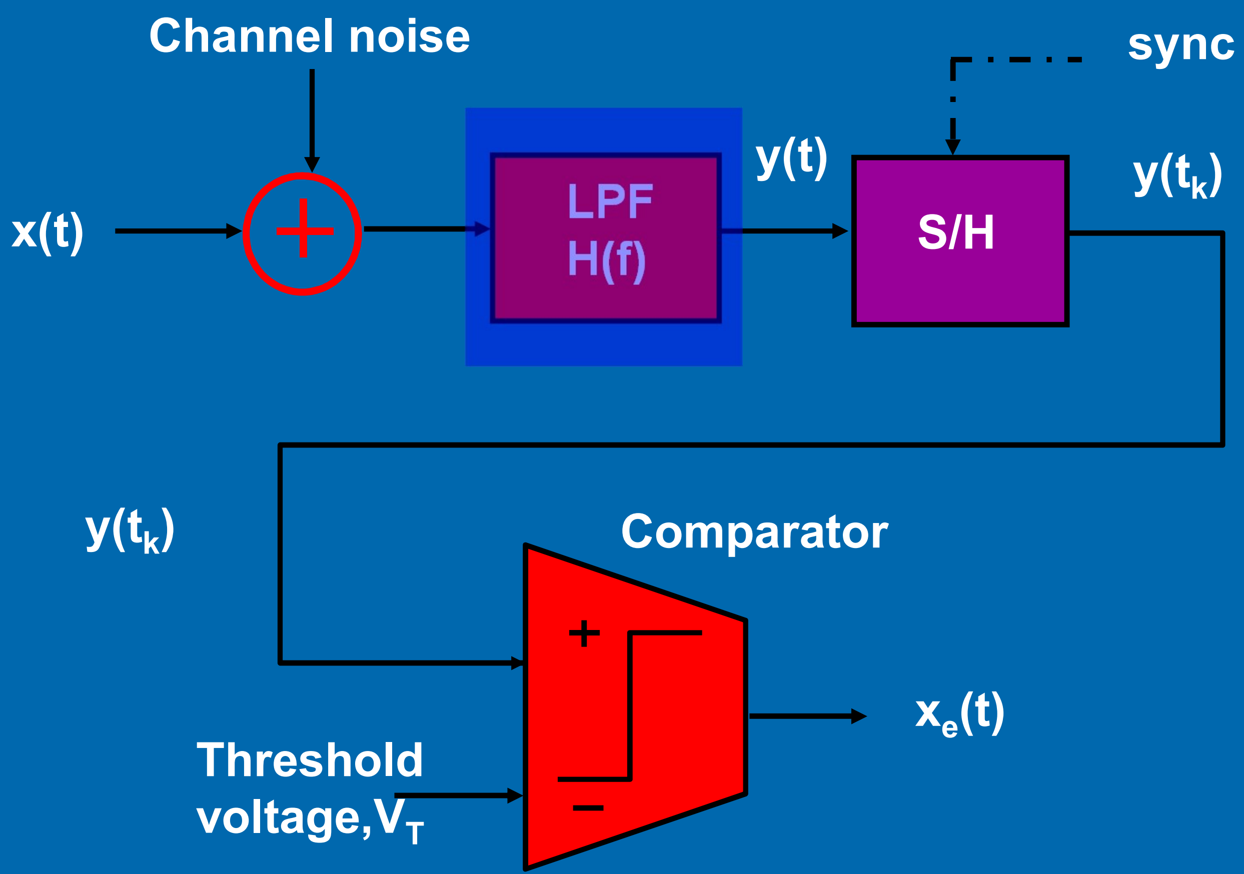
N_e = total number of error bits over time interval T

N_t = total number of bits transmitted over time interval T

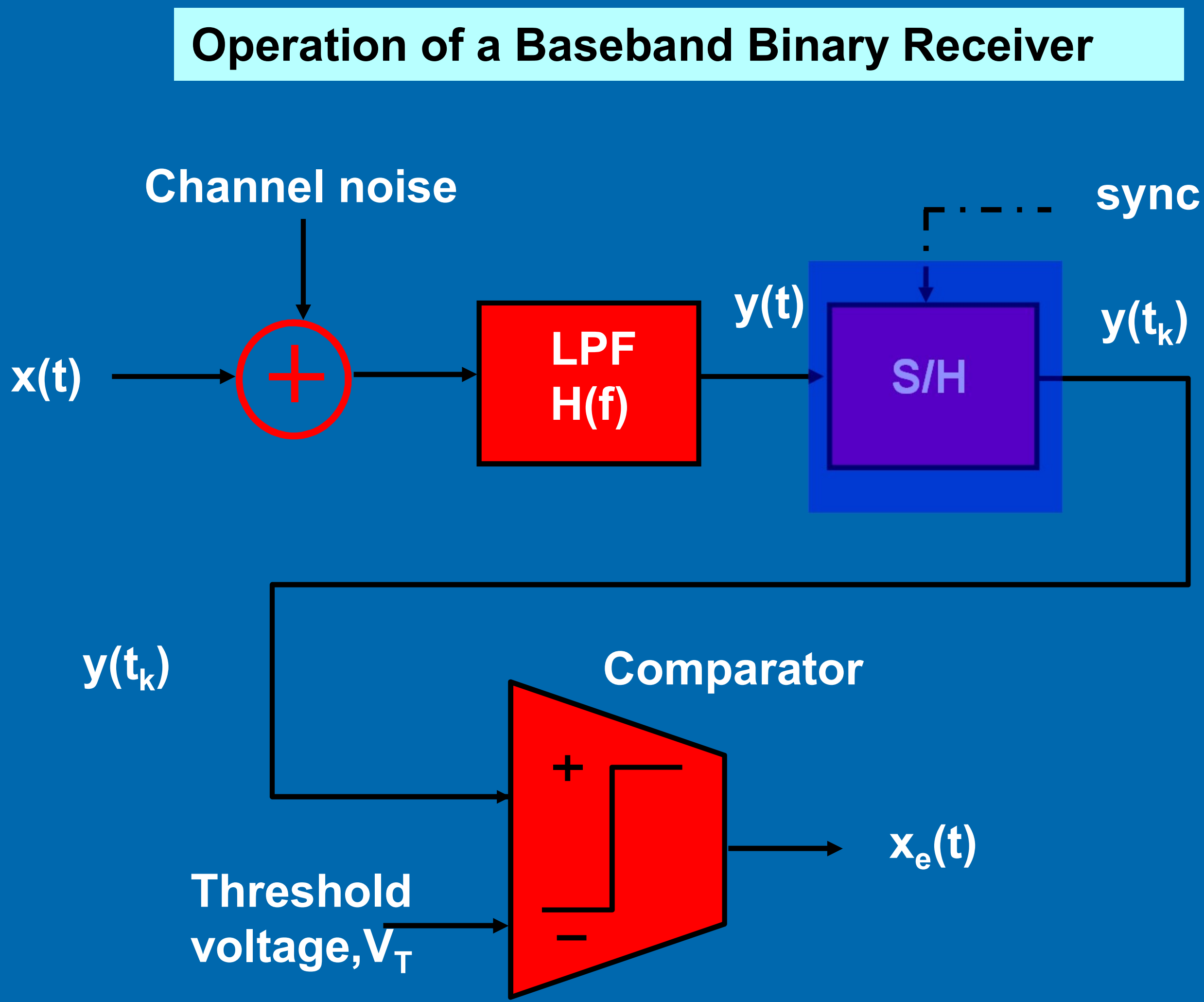
- BER in practical systems : 10^{-4} to 10^{-7}.

8.3.3 Operation of a Baseband Binary Receiver

Operation of a Baseband Binary Receiver

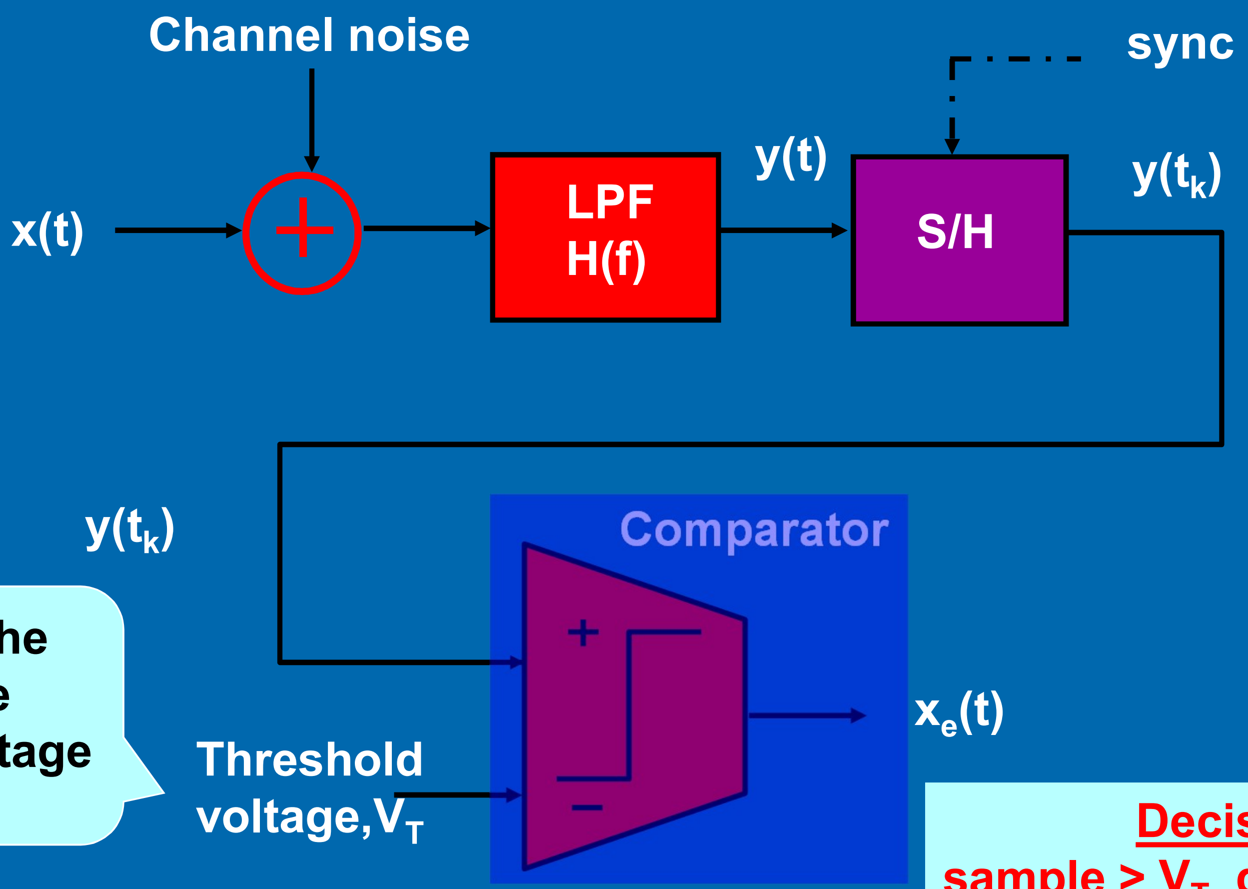


8.3.3 Operation of a Baseband Binary Receiver



8.3.3 Operation of a Baseband Binary Receiver

Operation of a Baseband Binary Receiver



V_T is set at the middle value between voltage of '1' and '0'

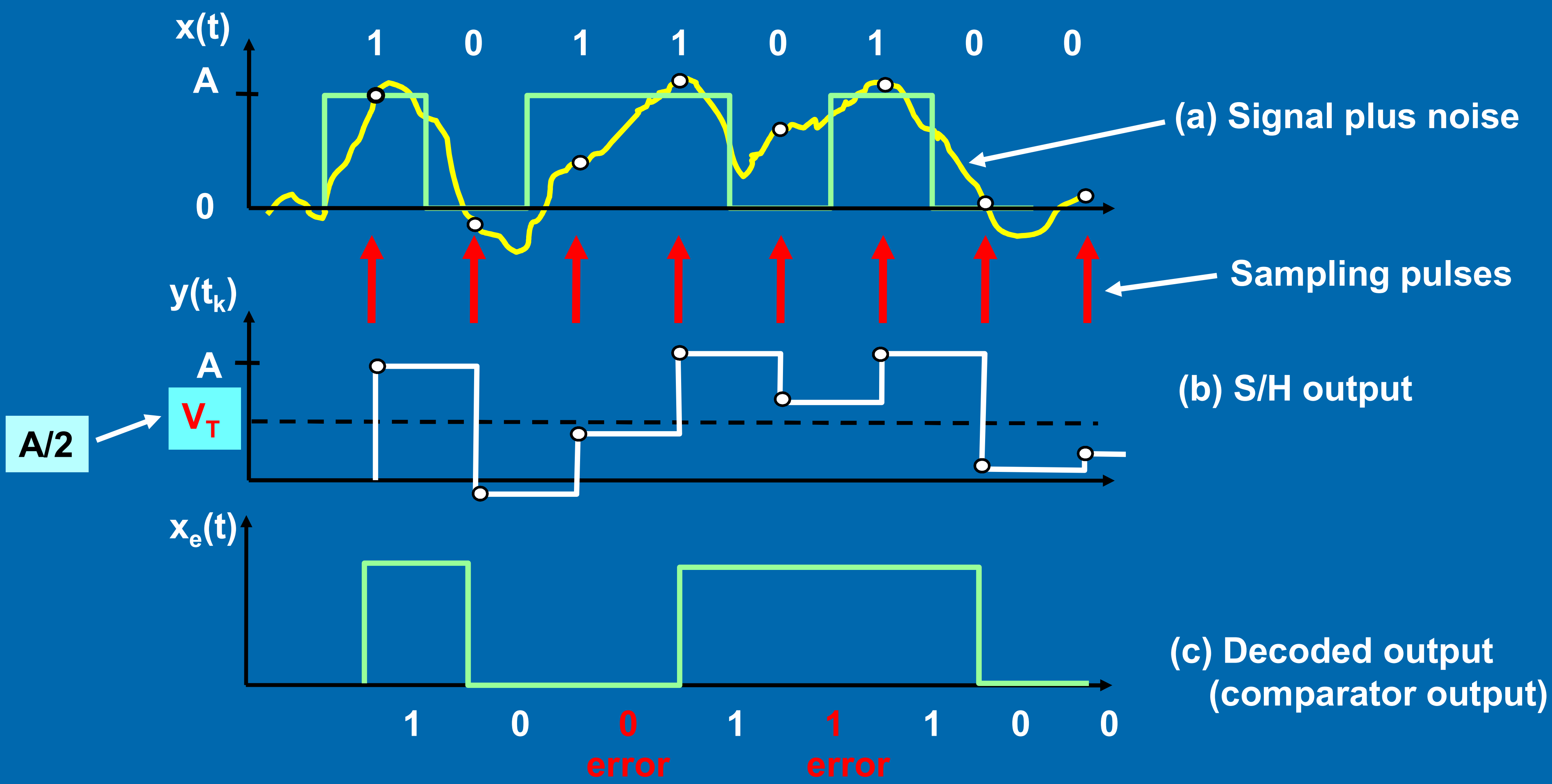
Decision rule:

sample > V_T decode binary 1

sample < V_T decode binary 0

8.3.3 Operation of a Baseband Binary Receiver

Regeneration of a unipolar NRZ signal



8.3.3 Operation of a Baseband Binary Receiver

Singapore Polytechnic

Probability of error in a baseband binary receiver

Probability of error P_e = $P(1) \times P([V_1 + n] < V_T)$ + $P(0) \times P([V_0 + n] > V_T)$

Probability that binary one voltage plus noise is below the threshold voltage.

Probability that binary zero voltage plus noise is above the threshold voltage.

where

$P(1)$ = probability of transmitting binary '1'

$P(0)$ = probability of transmitting binary '0'

$V_1 + n$ = voltage level for binary '1' + noise voltage

$V_0 + n$ = voltage level for binary '0' + noise voltage

8.3.3 Operation of a Baseband Binary Receiver

Singapore Polytechnic

Probability of error in a baseband binary receiver

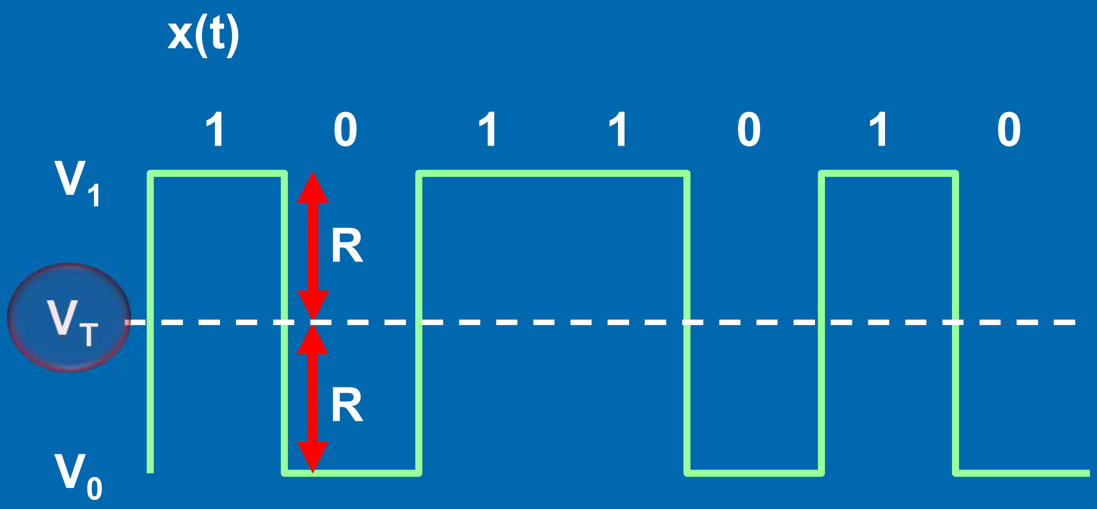
$$P_e = 0.5P([V_1 + n] < V_T) + 0.5P([V_0 + n] > V_T)$$

P(1) = P(0) = 0.5

$$= 0.5P(n < [V_T - V_1]) + 0.5P(n > [V_T - V_0])$$

Singapore Polytechnic

Probability of error in a baseband binary receiver



$V_T = 0.5(V_1 + V_0)$, mid-point of V_1 and V_0

$R = 0.5(V_1 - V_0)$, half signal excursion

8.3.3 Operation of a Baseband Binary Receiver

Probability of error in a baseband binary receiver

$P_e = 0.5P([V_1 + n] < V_T) + 0.5P([V_0 + n] > V_T)$ — **P(1) = P(0) = 0.5**

$= 0.5P(n < [V_T - V_1]) + 0.5P(n > [V_T - V_0])$ — $V_T = 0.5(V_1 + V_0)$, mid-point of V_1 and V_0

$= 0.5P(n < [0.5(V_1 + V_0) - V_1]) + 0.5P(n > [0.5(V_1 + V_0) - V_0])$

$= 0.5P(n < [-0.5(V_1 - V_0)]) + 0.5P(n > [0.5(V_1 - V_0)])$

$= 0.5P(n < -R) + 0.5P(n > R)$ — $R = 0.5(V_1 - V_0)$, half signal excursion

$= P(n > R)$ — $P(n < -R) = P(n > R)$, symmetrical about n=0

$$P_e = P(n > R) = \frac{1}{2} erfc\left[\frac{R}{\sqrt{2}\sigma}\right]$$

8.3.3 Operation of a Baseband Binary Receiver

Probability of error in a baseband binary receiver

Example 8.3

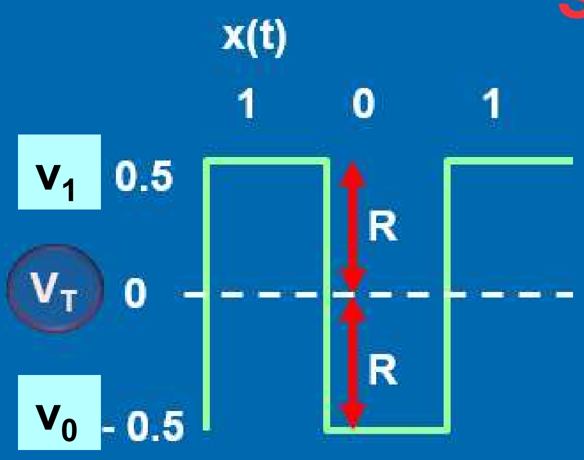
A discrete data source is transmitting a random binary signal such that the probability of transmitting 1 or 0 is equiprobable. The signal input to the comparator at the receiver is 0.5 volt for binary 1 and -0.5 volt for binary 0. The channel noise is AWGN with an rms value of 0.2 volt.

(i) What is the bit error rate (or P_e)?

(ii) If a million bit is transmitted for each block of message, on the average, how many bits are received incorrectly per block?

Solution

(i) $$P_e = P(n > R) = \frac{1}{2} erfc\left[\frac{R}{\sqrt{2}\sigma}\right]$$



$R = 0.5(V_1 - V_0) = 0.5(\ 0.5 - (-0.5)) = 0.5$ V

$P_e = 1/2 \text{ erfc } (\ 0.5/(\sqrt{2} \times 0.2\ )$

$= 1/2 \text{ erfc } (1.76)$

$= 1/2 \times \boxed{0.128 \times 10^{-1}}$

$= 6.4 \times 10^{-3}$

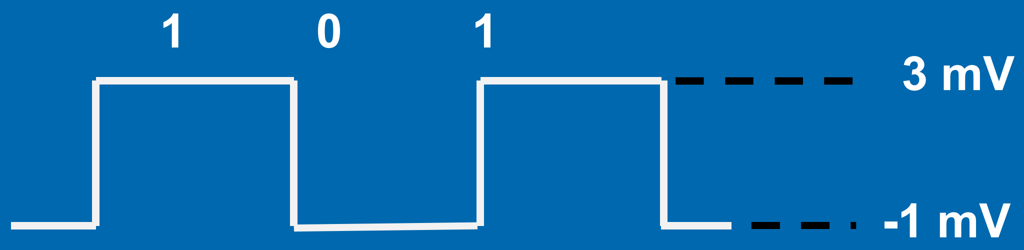
From the Prob & Stat Table :
If z = 1.76, erfc(z) = 0.128×10^{-1}.

Z	erfc(Z)
1.72	0.149972D-01
1.73	0.144215D-01
1.74	0.138654D-01
1.75	0.133283D-01
1.76	0.128097D-01

(ii) On the average, $10^6 \times 6.4 \times 10^{-3}$ = 6400 bits are received incorrectly, for every million bits transmitted.

Example 8.4

The signal component to the receiver of a baseband transmission system is of the form:



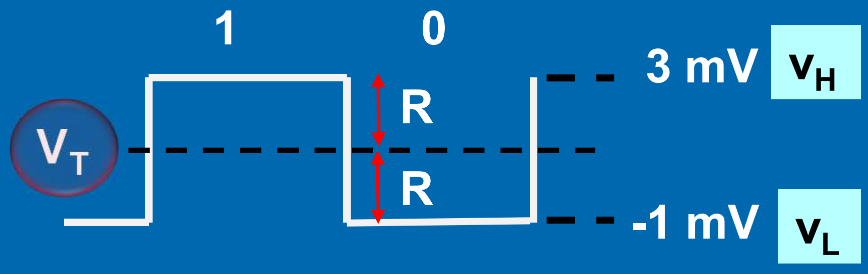
The signal is corrupted by additive white Gaussian noise (AWGN) which has a rms value of 0.8 mV. Assume equal probability of transmitting binary 1 or 0 and independent bit transmission.

(i) Calculate the threshold voltage V_T of the receiver comparator for minimum bit error.

(ii) Calculate the probability of bit error P_e at the receiver.

(iii) If the transmission bit rate is 1 Mb/s, what is the average duration between bit errors?

Solution



(i) $V_H = 3$ mV; $V_L = -1$ mV;

$$V_T = \frac{V_H + V_L}{2} = 1\ \text{mV}$$

$$R = \frac{V_H - V_L}{2} = \mathbf{2\ mV}$$

(ii)

$$\mathbf{P_e} = \frac{1}{2}\,\text{erfc}\left(\frac{R}{\sqrt{2}\,\sigma}\right) = \frac{1}{2}\,\text{erfc}\left(\frac{2\ \text{mV}}{\sqrt{2}\ 0.8\ \text{mV}}\right) = \frac{1}{2}\,\text{erfc}(1.768\ ) = \frac{1}{2}\,\text{erfc}(1.76)$$

$$= \frac{1}{2}\ \text{x}\ 0.128\ \ \text{x}\ 10^{-1} = 6.4\ \text{x}\ 10^{-3}$$

Z	erfc(Z)
1.72	0.149972D-01
1.73	0.144215D-01
1.74	0.138654D-01
1.75	0.133283D-01
1.76	0.128097D-01

(iii) In one sec, there are 10^6 x 6.4 x 10^{-3} = 6400 error bits.

Therefore, average duration between error bits = 1/6400 =1.563 x 10^{-4} = 0.156 ms .

8.4 Jitters

- Synchronisation clock at the receiving end is usually derived from the zero crossings of the received signal.
- ISI and channel noises cause variations in the clock rate and phase.

↓

jitters

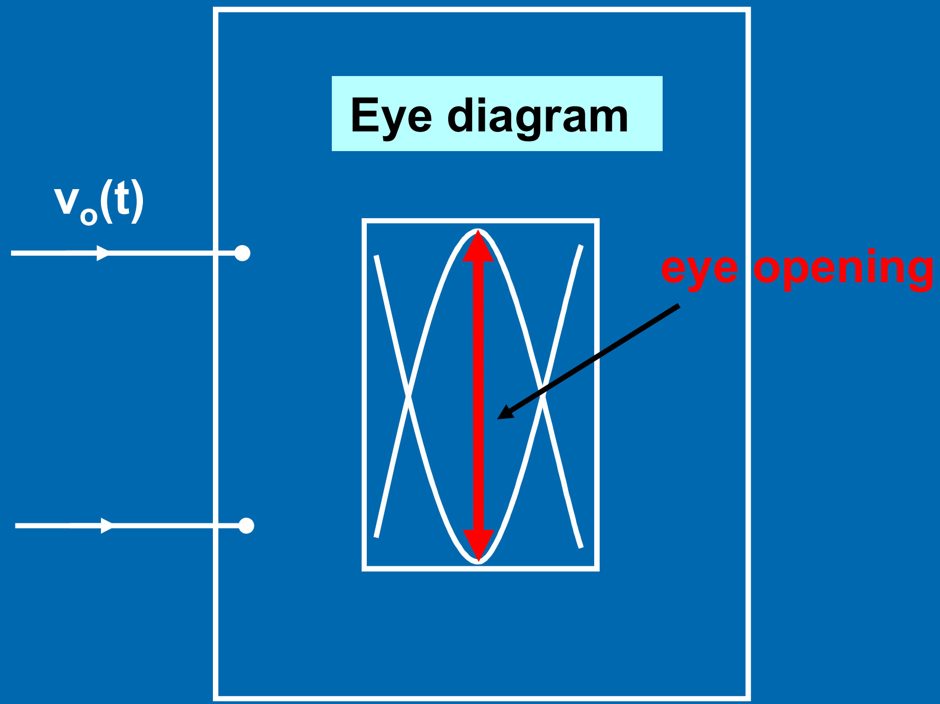
8.5 Eye Diagram

- **Useful experimental method for assessing the quality of a digital transmission system:**

Noise margin

ISI degradation

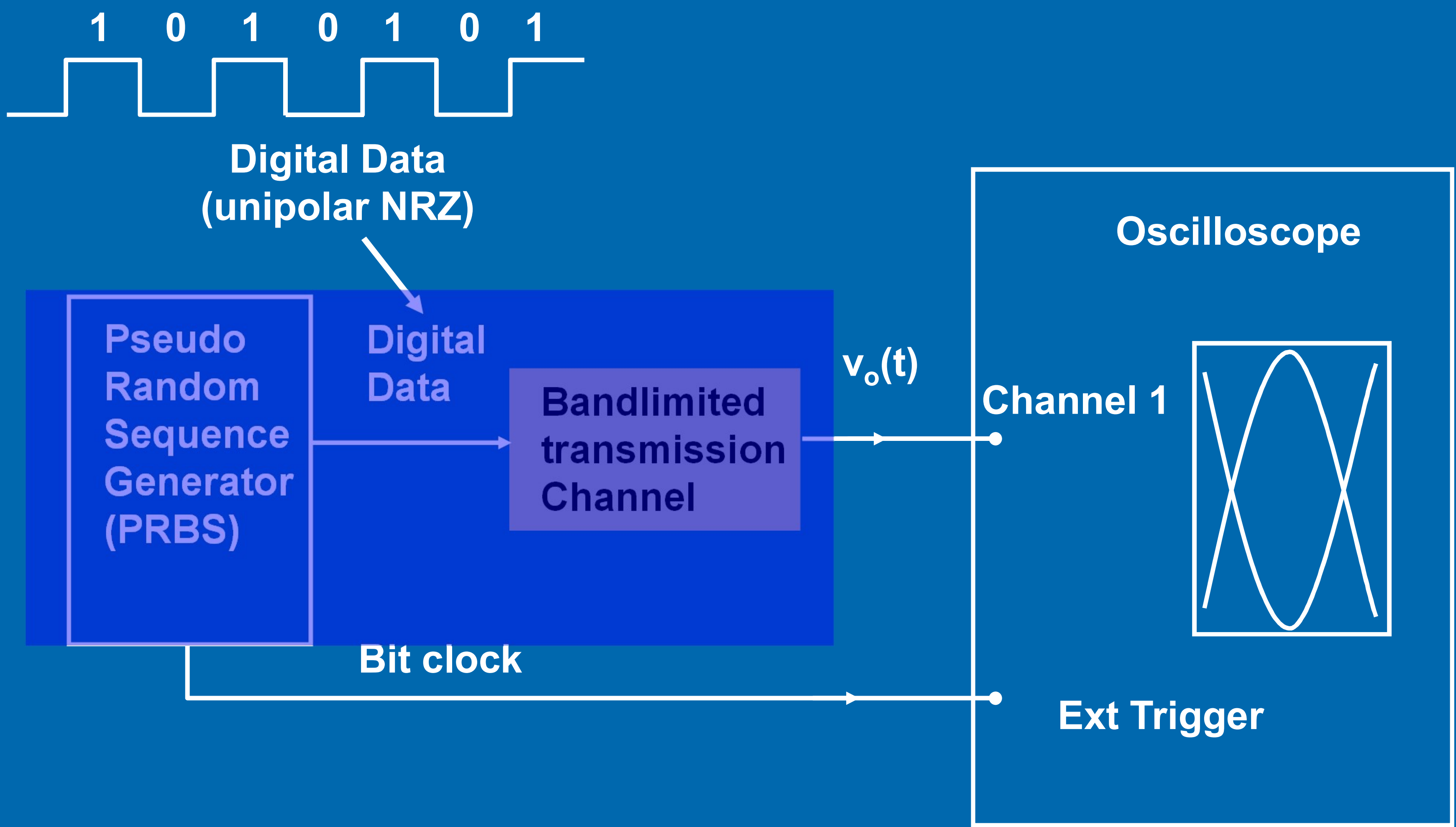
Jitter



- **Larger the eye opening, better is the transmission system.**

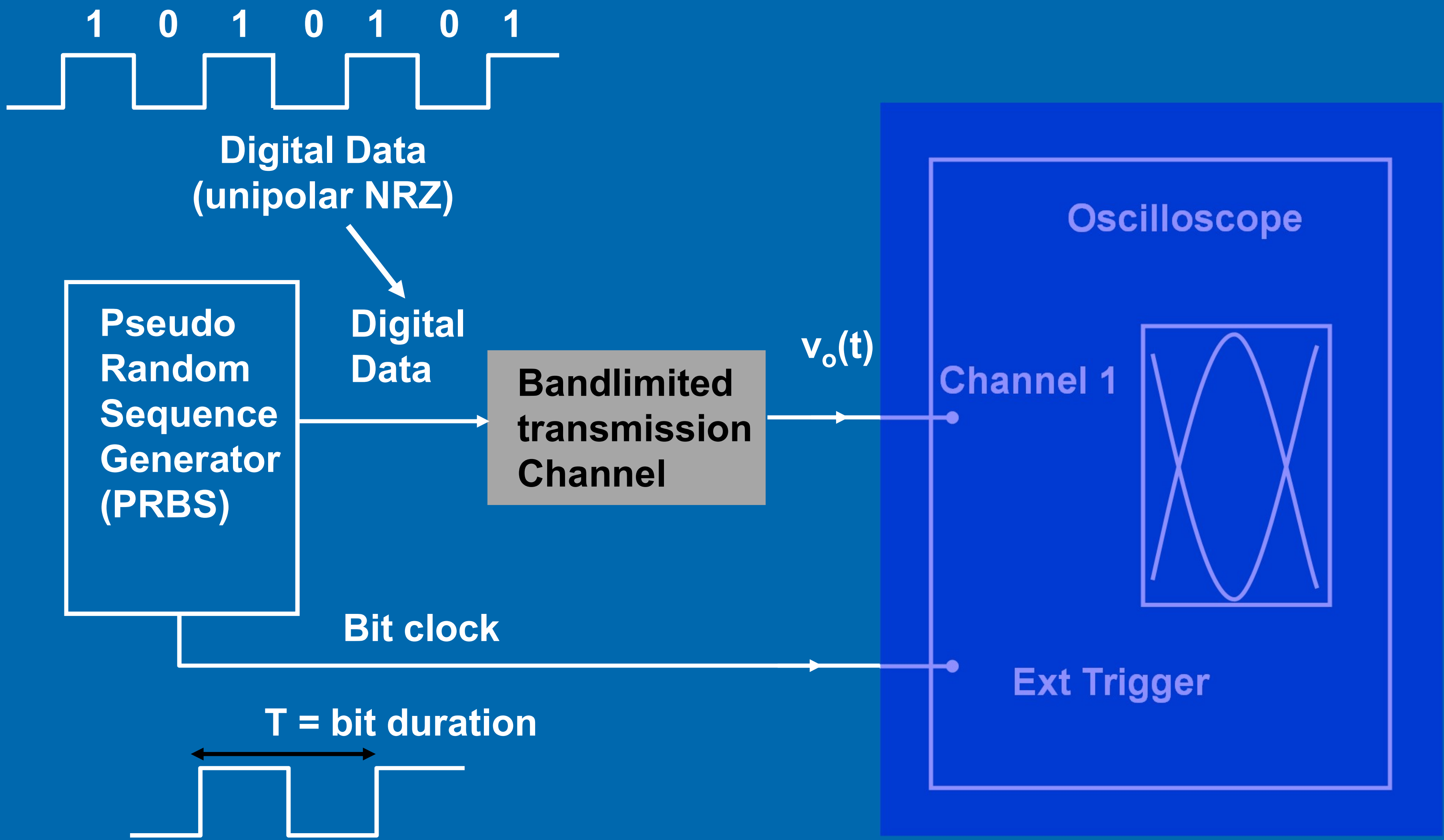
8.5 Eye Diagram

Eye diagram measurement set-up



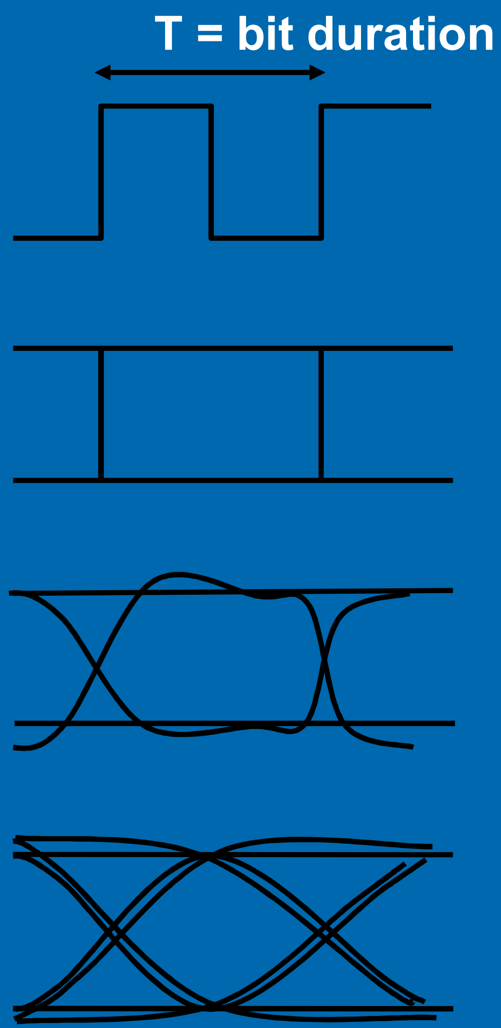
8.5 Eye Diagram

Eye diagram measurement set-up



8.5 Eye Diagram

Eye diagrams under different channel conditions



channel conditions

(a) 1 0 1 0 1 0

Infinite BW
-No ISI and Noise free

(b) Eye pattern of PRBS connected directly to CRO (bypassing system under test).

Slightly bandlimited
-No ISI and Noise free

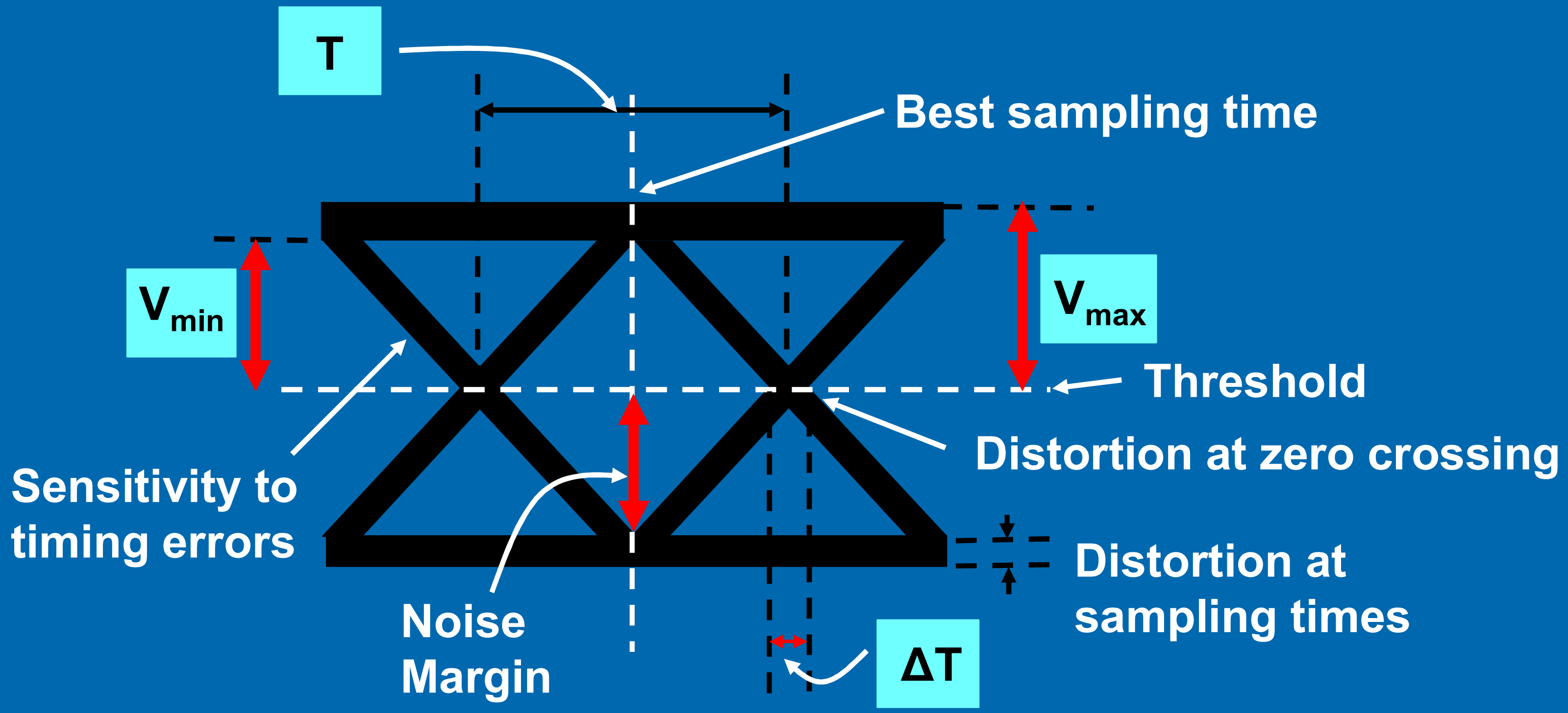
(c) Eye pattern of a channel that is free from ISI and noise.

Bandlimited
- with ISI, but Noise free

(d) Eye pattern of a channel with ISI (but free from noise) due to insufficient bandwidth.

8.5 Eye Diagram

Eye Diagram measurements



Noise Margin (%) = V_{min}/V_{max} x 100 %

ISI Degradation = 20 $\log_{10}(V_{max}/V_{min})$ dB

Jitter (%) = $\Delta T/T$ x 100 %
where T = one bit interval

8.5 Eye Diagram

Eye Diagram measurements

Ideal Channel

- Noise Margin = 100%
- ISI degradation = 0 dB
- Jitter = 0 %

Worst Channel

- Noise Margin = 0%
- ISI degradation = ∞ dB
- Jitter = 100 %

End

CHAPTER 8

(Part 2 of 2)