OSk auditorne Vol 2

Lcl

(15) – mjere A/D pretvarača obzirom na šum i distorziju

1.) SINAD (signal to noise and distorsion)

{ukupan/total SNR}

$$SINAD = 10 \log \frac{P_S}{P_V + P_D}$$

2) SNR (signal to noise radio)

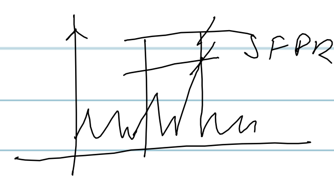
$$SNR = 10 \log \frac{P_S}{P_N}$$

3) THD (total harmonic distorsion)

$$THD = 10 \log \frac{P_S}{P_D}$$ (obično se izražava u dBc)
(i mjeri se na prvih 10 harmonika)

4) SFRD (~~signal~~ spurious free dynamic range)

$$SFDR = 10 \log \frac{P_S}{\max(P_N + P_D)}$$



– efektivni broj bitova (effective number of bits ENOB)

Određuje se iz

$$SINAD = 1{,}76 + 6{,}02 \cdot ENOB$$ ⇒ model šuma kvantizacije s ENOB bitova

$$ENOB = \frac{SINAD - 1{,}76}{6{,}02}$$

- Ulazna dinamika obično (uvijek) se izražava u dBFs (decibel relative to full scale)

$$U = 10^{\frac{U_{dBFS}}{20}} \cdot U_{FS}\ [V_{pp}]$$

Normirana vrijednost šuma izlaznog se izračunava:

$$U_{n,LSB} = \frac{U_n}{U_{LSB,rms}} = \frac{U_n}{\frac{U_{LSB}}{2}} = \frac{2U_n}{\frac{U_{FS}}{2^N}} =$$

$$= \frac{U_n}{U_{FS}} \cdot 2^{N+1}\ [LSB]$$

U našem slučaju je:

$N = 14$

$U_{FS} = 3\ V_{pp}$

$U_{n,LSB} = 0,6\ LSB$

$THD = 82\ dB_C$

$U_{dBFs} = -1\ dBFs \implies U = 10^{\frac{-1}{20}} \cdot 3 = 2,67\ V_{pp}$

$ENOB = ?$

Amplituda sin. sig:

$$U_m = \frac{2,67}{2} = 1,34V$$

Snaga:

$$P_S = \left(\frac{U_m}{\sqrt{2}}\right)^2 = 0,89\ W$$

$$THD = 10 \log \frac{P_S}{P_D} \Rightarrow P_D = 10^{\frac{-THD}{10}} \cdot P_S = 5{,}64 \cdot 10^{-9}\ W$$

$$U_n = \frac{U_{M,LSB} \cdot U_{FS}}{2^{N+1}} = \frac{0{,}6 \cdot 3}{2^{15}} = 5{,}49 \cdot 10^{-5}\ V$$

$$P_n = U_n^2 = 3{,}02 \cdot 10^{-9}\ W$$

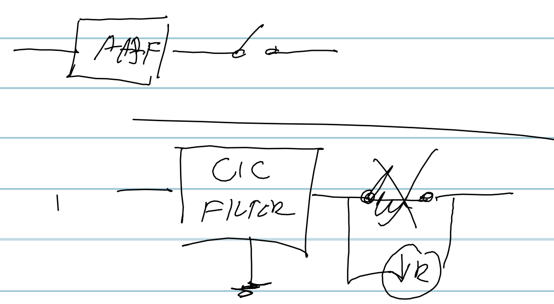
{ Puno ladica od CIC-a }

$$SINAD = 10 \log \frac{P_S}{P_n + P_D} = 80{,}14\ dB$$

$$\Rightarrow ENOB = \frac{80{,}14 - 1{,}76}{6{,}02} = 13{,}02$$

Uočiti: A/D pretvorač ima 14 bitova, a njegov šum i distorzija pojeli su 1 bit.

(16) CIC decimator



$f_{SH} = 1{,}2\ MHz$

$\omega_c = 0{,}005\pi$

$f_{SL} = 25\ kHz$

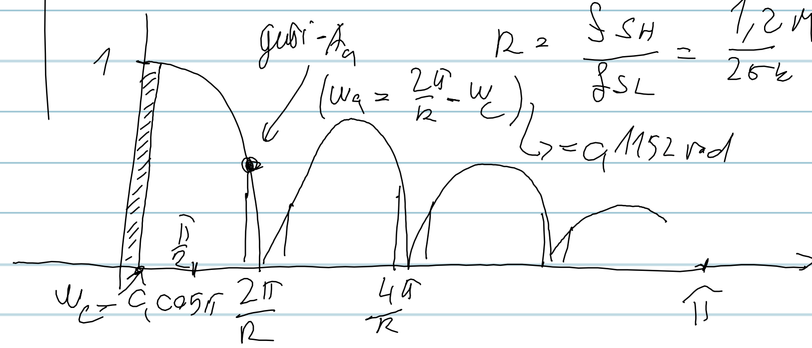
$A_a = 80\ dB$

$B_{in} = 18$

$N = ?,\ B_{max} = ?$

$$|H(\omega)| = \left| \frac{1}{R} \cdot \frac{\sin\left(\frac{\omega R}{2}\right)}{\sin\left(\frac{\omega}{2}\right)} \right|^N$$

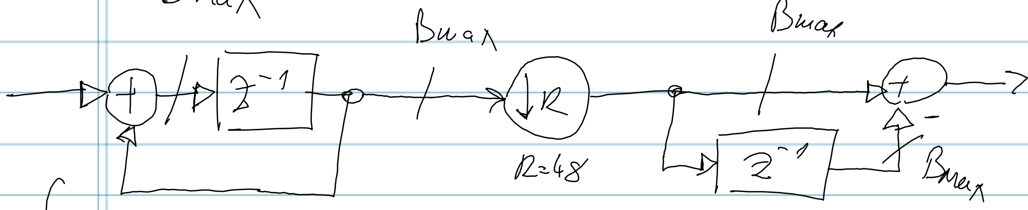
$$R = \frac{f_{SH}}{f_{SL}} = \frac{1{,}2M}{25k} = 48$$



$$20 \log |H(\omega_a)| = -A_a \implies N \geq \frac{-A_a}{20 \log \left| \frac{1}{R} \frac{\sin\left(\frac{\omega_a R}{2}\right)}{\sin\left(\frac{\omega_a}{2}\right)} \right|} = 4,57 \Rightarrow 5$$

ovaj $H(\omega_a)$ sa prošle str.

B_{max}



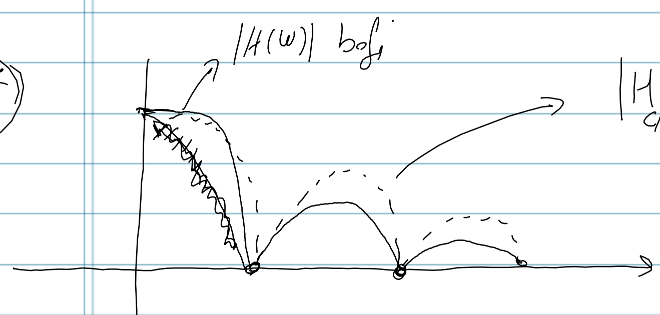
5 integratora

5 ~~co~~ combova

$$B_{max} = \lceil N \log_2(R) + B_{in} \rceil = 46 \text{ bitova}$$

$N \to 5$, $R \to 48$, $B_{in} \to 18$

(17)



$$|H_{cic}(\omega)| = \left| \frac{1}{R} \cdot \frac{\sin\left(\frac{\omega R}{2}\right)}{\sin\left(\frac{\omega}{2}\right)} \right|^N$$

→ značajan propad u pass bandu

→ nedovoljna atenuacija stop banda

Kako odrediti $H(z)$ koristeći $H_{cic}(z) = \left(\frac{1}{R} \cdot \frac{1-z^{-R}}{1-z^{-1}} \right)^N$?

Moramo uvesti faznu karakteristiku u izraz za $|H(\omega)|$.

$$|H(\omega)| = 3|H_{cic}(\omega)|^2 - 2|H_{cic}(\omega)|^3 \;\Big/ \cdot e^{j3\varphi_{cic}(\omega)}$$

$$\varphi_{cic}(\omega) = -D\omega$$

$$e^{j\varphi_{cic}(\omega)\cdot 3}\cdot|H(\omega)| = 3\cdot|H_{cic}(\omega)|^2\cdot e^{j2\varphi_{cic}(\omega)}\cdot e^{j\varphi_{cic}(\omega)} - 2|H_{cic}(\omega)|^3\cdot e^{j3\varphi_{cic}(\omega)}$$

$$H(z) = 3\cdot H_{cic}^2(z)\cdot z^{-D} - 2H_{cic}^3(z)$$

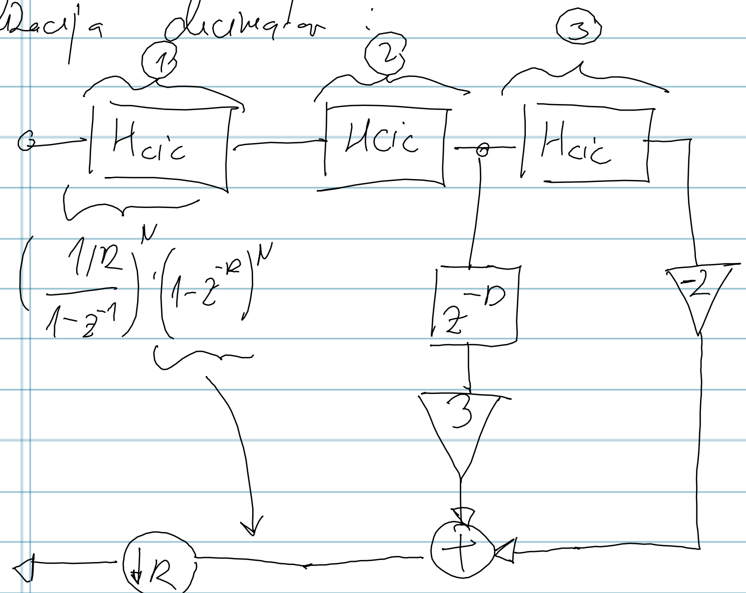
Duljina impulsnog odziva od $H_{cic}(z)$ je

$$L = N(R-1)+1$$

Budući je $H_{cic}(z)$ FIR filter s linearnom fazom njegovo kašnjenje je

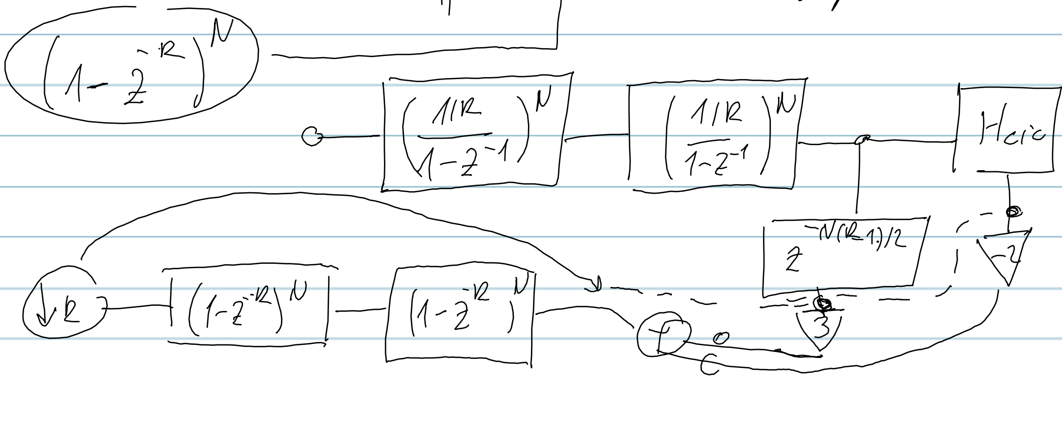
$$D = \frac{L-1}{2} \qquad \left(D = \frac{N(R-1)}{2}\right)$$

Realizacija decimatora:

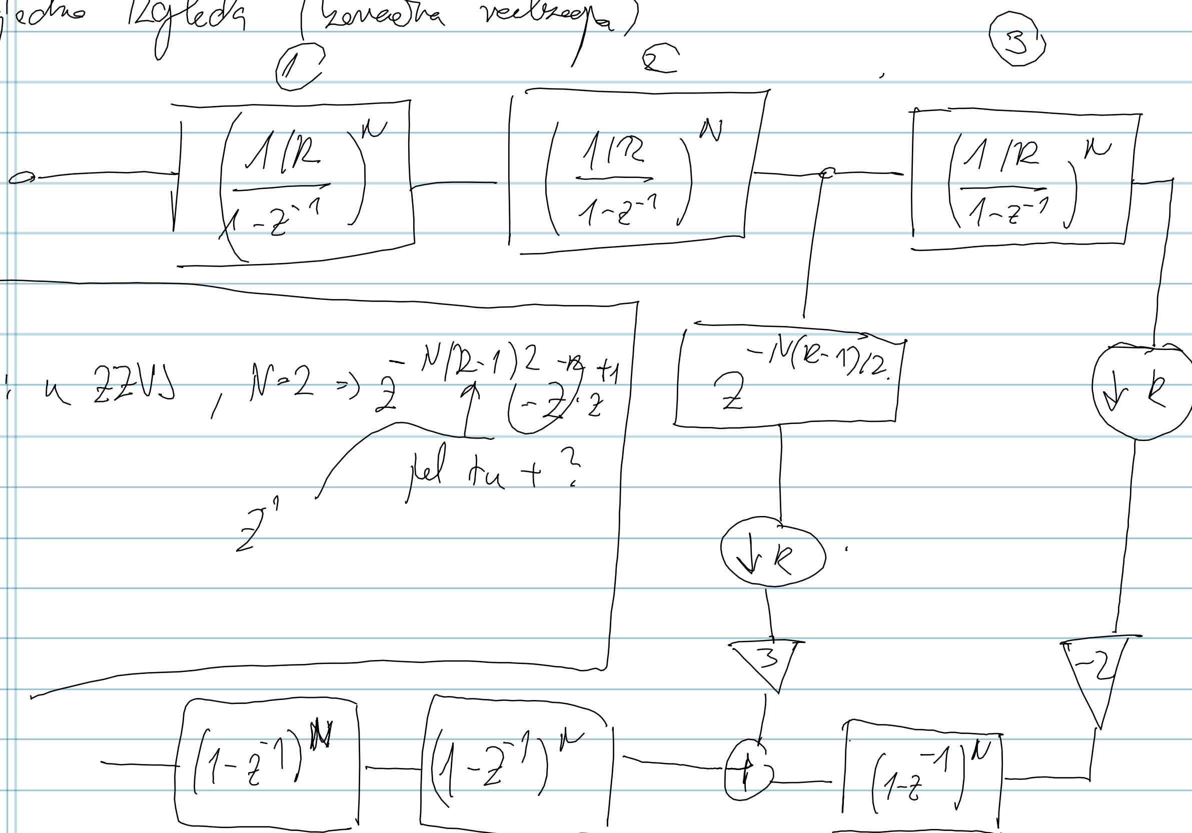


Filter je kaskada 1, 2 i 3 pa se može staviti poslije downsamplera

$\left(1-z^{-R}\right)^N$



Sve zajedno izgleda (konačna realizacija)



Napomena: u ZZVJ, N=2 ⇒ $z^{-N(R-1)2-R+1}$ $(-z^{?}\cdot z)$

jel tu + ?

z^{1}

Divno je bilo rekone nešto

Divno je bilo dobi sve...

wtf

podatak od prošlog puta

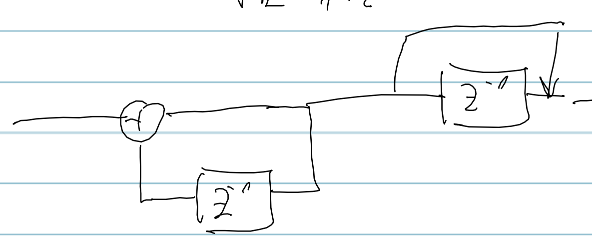
Sad kompenzacija... jeee...

$$H_{cic}(z) = \left(\frac{1}{R}\,\frac{1-z^{-R}}{1-z^{-1}}\right)^N \longrightarrow H(z) = \left(\frac{1}{R}\,\frac{1-z^{-R}}{1-z^{-1}}\cdot z^{-1}\right)^N$$

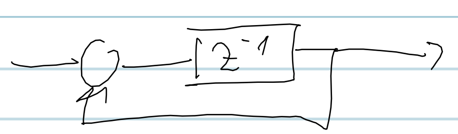
$$\hookrightarrow D = \frac{N(R-1)}{2} + N = \frac{N(R+1)}{2}$$

$N = 2$

$D = R+1$



$$I(z) = \frac{1/R}{1-z^{-1}}$$

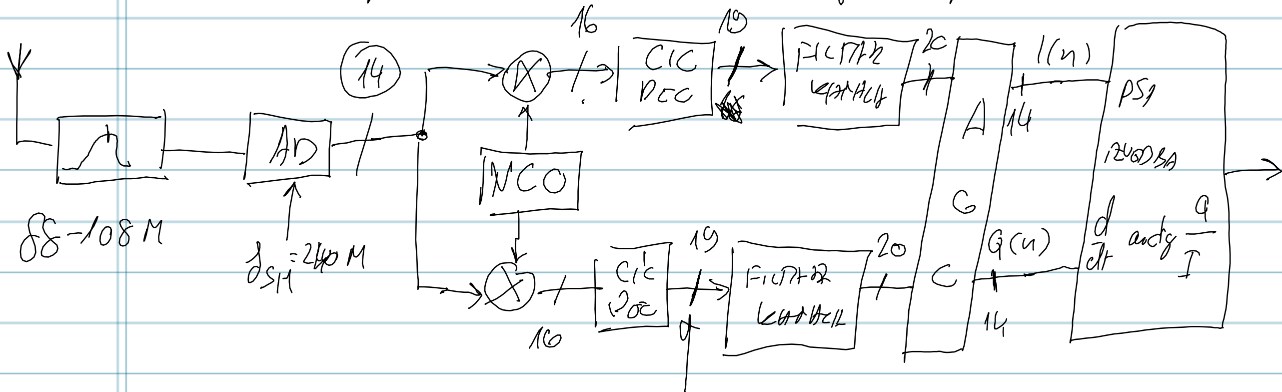


$$I(z) = \frac{1/R\cdot z^{-1}}{1+z^{-1}}$$

18. 2 bila teksta:

a) blok šema:

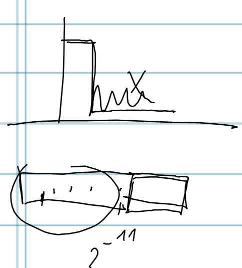
Prijemnik s uzorkovanjem u osnovnom freq. području



$f_{SL} = 300$ kHz (poslije CIC-a)

pomoće na sve strane ...

b)



Processing gain

$N \times N \to 2N$ uvodi -3 dB SNR

$N \times N \to N$ -6 dB

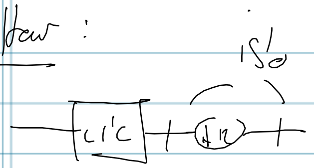
$N \times N \to N+1$ -4 dB

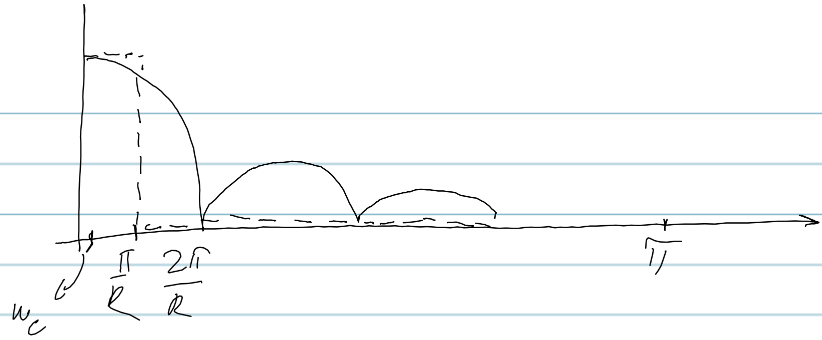
$N \times N \to N+2$ $-3,1$ dB ← do $k+3$

Na izlazu množila uzimamo 2 bita više kako bi osigurali min. gubitak od SNR-a od -3 dB!

Na izlazu CIC dec. i filtra kanala koji bitove odbacuje se u obzir (dobitak) processing (PG) gaina

CIC filtar :





Pretpostavimo da je ovo (---) LP karakteristika koju aproksimira CIC filtar
U tom slučaju je PG estimiran izrazom:

$$PG_{cic} = 10\log\frac{\text{cijeli band}}{\text{propusni band}} = 10\log\frac{\pi}{\pi/R} = \underline{\underline{10\log R}}$$

{Sve puno CICa}

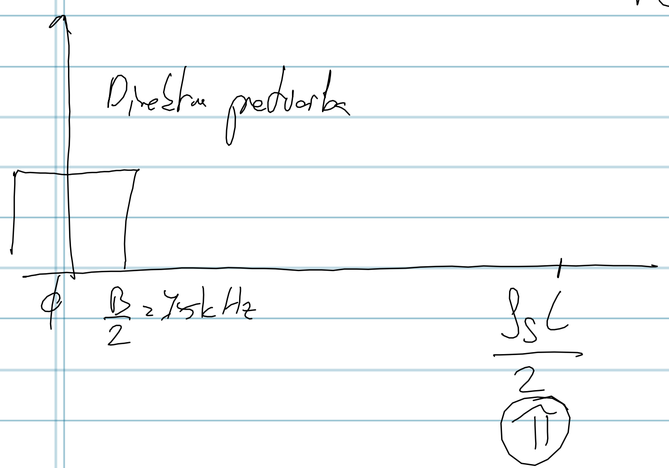
$$R = \frac{f_{SH}}{f_{SL}} = 800 \Rightarrow PG_{cic} = 29\,dB$$

Broj bitova koji treba dodati na ulazni broj bitova kako bi se osigurao
<u>dani PG</u> iznosi:

$$\frac{PG_{cic}}{6\,dB} = 4{,}8 \Rightarrow 5 \text{ bitova}$$

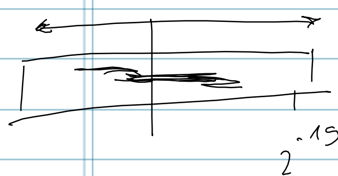
Na izlazu CIC decimatora imamo 14+5=19. Uočiti da kao referentni broj bitova uzimamo broj bitova AD pretvorača.
Razlog – mješalo smanjuje SNR za razliku od filtara koji ga povećavaju PG-om.

Filtar kanala



$$PG_{FK} = 10 \log \left(\frac{f_{SL}/2}{B/2} \right) = 10 \log \frac{150k}{75k} = 3\,dB$$

$$\frac{PG_{FK}}{6\,dB} = 0{,}5 \Rightarrow 1\,bit$$



c) AAAAAAAAA ... AAAAA ... !

$$SNR_{OUT} = SNR_{AD} + SNR_{Mix} + PG_{CIC} + PG_{FK}$$

$$= 70 + (-3) + 29 + 3 = 99\,dB$$ (točno našeg kanala kojeg slušamo)

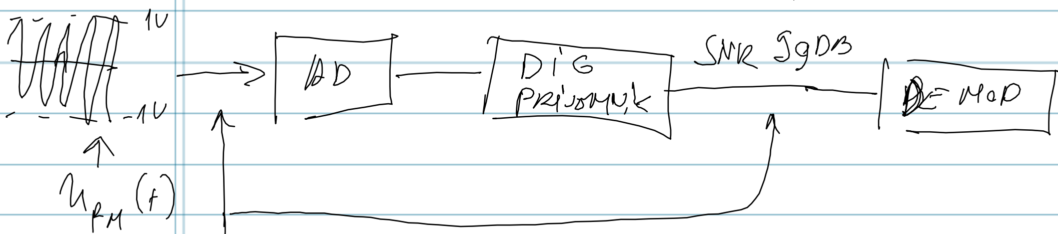
d) 17:22 h/sati

Ako na izlazu filtra kanala ne bi uzeli 1 bit kanala više tada bi izgubili njegov PG od 3 dB. Budući da i miješalo unosi gubitak od 3 dB ukupno bi bilo 6 dB (u vidu kanala 1 bit) ⇒ na izlazu prijemnika manje za 1 bit. U tom slučaju, prijemnik bi se ponašao kao da ima 15 bita na ulazu, a ne 14.

e) Ludilo brale...

Kada na izlazu imamo SNR 98dB?

Kada je na AD pretvarač doveden fm signal maksimalne dinamike, a sam toga na ulazu u pretvarač nema šuma (nema popodala...)



Snaga u tim točkama je ista $\quad P_S = \left(\frac{1}{\sqrt{2}}\right)^2 = \frac{1}{2}\ V$, a $SNR = 10 \lg \frac{P_S}{P_N}$

$$\Downarrow$$

$$P_N = P_S \cdot 10^{-\frac{SNR}{10}} = 6{,}3 \cdot 10^{-11}\ W$$

Ako je SNR=10dB tada je na ulazu snaga signala

$$P_S = P_N \cdot 10^{\frac{SNR}{10}} = 6{,}3 \cdot 10^{-11} \cdot 10^{\frac{10}{10}} = 6{,}3 \cdot 10^{-10}\ W$$

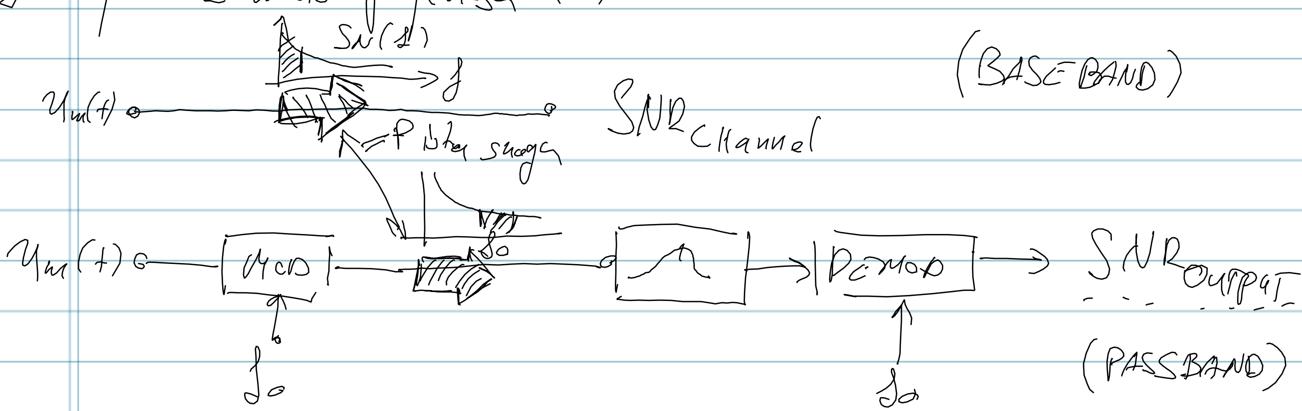
Efektivna vrijednost FM signala koji se još može čuti je u rms

$$U_{RMS} = \sqrt{P_S} = 25\ \mu V$$

KRAJ!

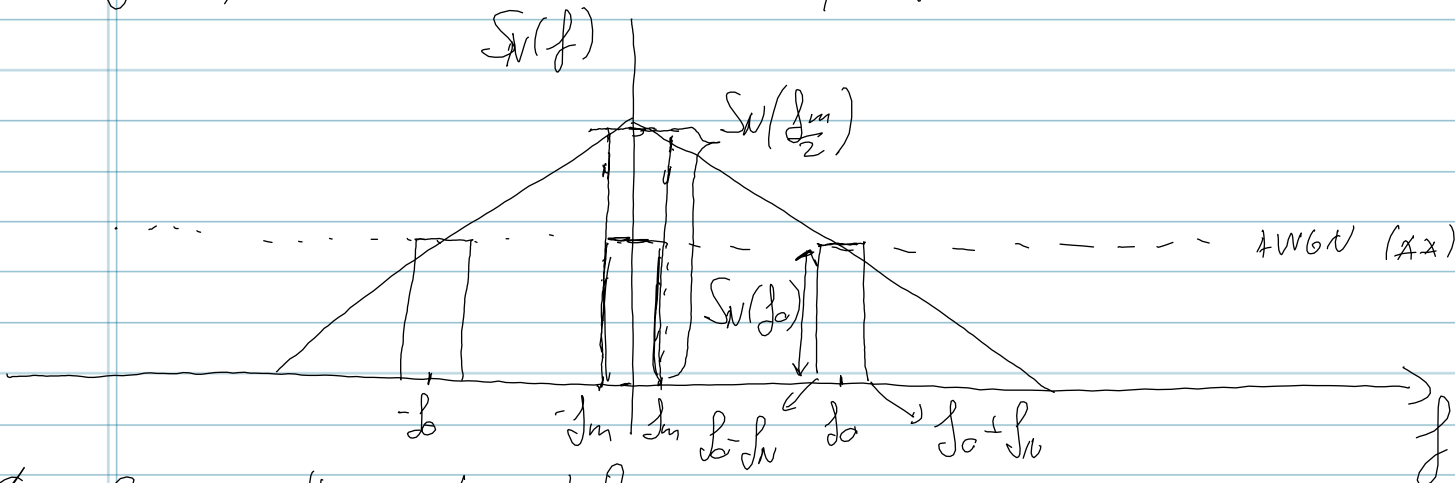
OSK aud. Vol. 2-2

(9) Mjera kvalitete prijenosa (*)



$$\boxed{M = \frac{SNR_O}{SNR_C}} \quad (*)$$

Ideja: svesti M za dani šum na M_{AWGN} na način $M = k \cdot M_{AWGN}$ jer je M_{AWGN} poznat za modulacijske postupke.

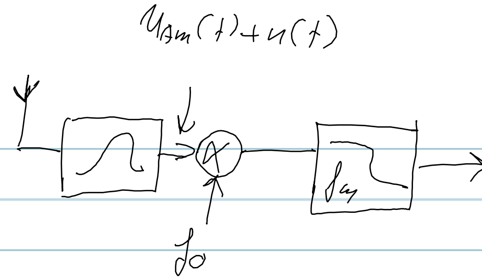


~~SNR_O~~ SNR_O je isti za ovako postavljen AWGN.

Ovo (**) odabiremo za AWGN, jer je tada SNR_O isti za dani šum i AWGN.

$$M = \frac{SNR_O}{SNR_C} = \frac{\overset{= SNR_{O,AWGN}}{SNR_O}}{\frac{P_{SC}}{P_{NC}}} = \frac{SNR_O}{\underbrace{\frac{P_{SC}}{2 f_m \cdot S_N(\frac{f_m}{2})} \cdot \frac{S_N(f_0)}{S_N(f_0)}}_{SNR_{C,AWGN}}} = \boxed{\frac{S_N(\frac{f_m}{2})}{S_N(f_0)}} \cdot M_{AWGN}$$

M_{AWGN} = ? Za koherentni prijemnik oblika



odredimo M_{AWGN}.

$$u_{AM} = \underbrace{U_0 \cos(\omega_0 t)}_{TC} + \underbrace{k_a u_m(t)\cos(\omega_0 t)}_{DSB}$$

$$P_0 = \frac{U_0^2}{2}, \quad P_{DSB} = E\left[k_a^2 u_m^2(t) \cos^2 \omega_0 t\right]$$

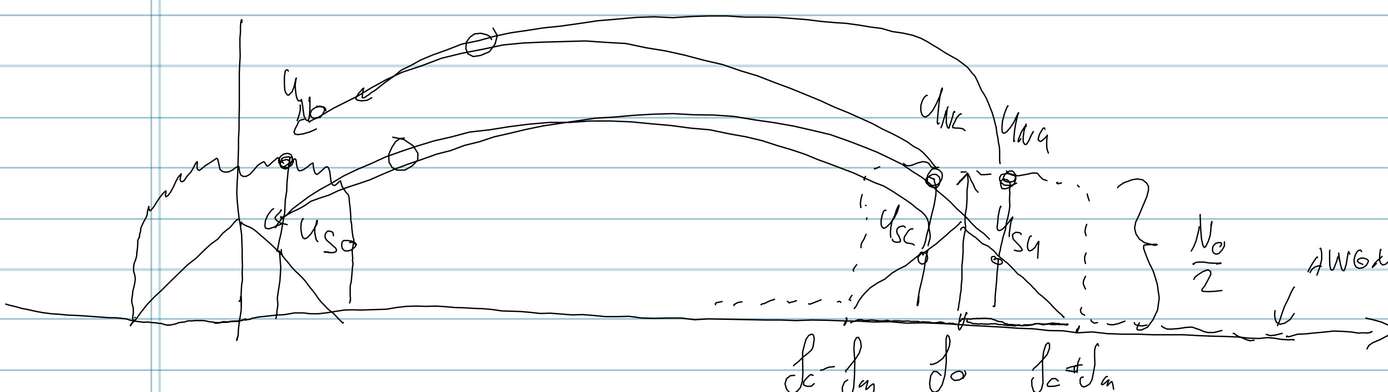
$$= E\left[k_a^2 u_m^2(t)\right] \cdot E\left[\cos^2 \omega_0 t\right]$$

$$= k_a^2 \cdot P \cdot \left(\frac{1}{\sqrt{2}}\right)^2 = \frac{k_a^2 P}{2}$$

Snaga od $u_m(t)$

• Passband, $SNR_{0,AWGN}$ = ?

U - rms, efektivne vrijednosti u bandu širine f_m
L - lower, U - upper



u_{SL} i u_{SU} su ~~korelirane~~ sekvence. Imaju takve faze da nakon KOHERENTNE DEMODULACIJE daju iste sekvence koje se zbrajaju i daju jednu dupo veću.

u_{NL} i u_{NU} su NEkorelirane sekvence, Imaju stohastičke faze pa „ne znamo" što dobivamo nakon demodulacije.

SNAGA ŠUMA na IZLAZU prijemnika (u_{No})

$$P_{NL} = P_{NU} = 2 f_m \cdot \frac{N_0}{2} = N_0 f_m \Rightarrow u_{NL} = u_{NU} = k\sqrt{P_{NL}} = k\sqrt{N_0 f_m}$$

konstanta demodulacije

$$\boxed{u_{No} = \sqrt{u_{NL}^2 + u_{NU}^2}} = \sqrt{2}\cdot k\sqrt{N_0 f_m} \Rightarrow P_{No} = u_{No}^2 = 2k^2 N_0 f_m$$

SNAGA SIGNALA na IZLAZU prijemnika

$$P_{SL} = P_{SU} = P_{SSB} \Rightarrow u_{SL} = u_{SU} = k\cdot\sqrt{P_{SSB}}$$

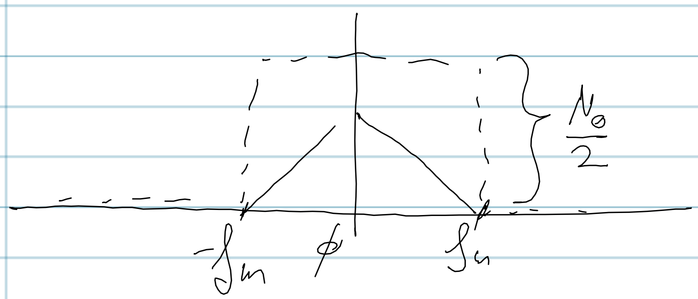
snaga 1 banda

$$\boxed{u_{So} = u_{SL} + u_{SU}} = 2k\sqrt{P_{SSB}} \Rightarrow P_{So} = u_{So}^2 = 4k^2 \cdot P_{SSB} = 2k^2 P_{DSB}$$

snaga 2 banda

$$\Rightarrow SNR_o = \frac{P_{So}}{P_{No}} = \frac{\cancel{2k^2} P_{DSB}}{\cancel{2k^2} N_0 f_m} = \frac{P_{DSB}}{N_0 f_m} = \frac{k_a^2 P}{2 N_0 f_m}$$

• BASEBAND prijenos, SNR_c - ?



Snaga šuma u kanalu poruke:

$$P_{NC} = 2 f_m \cdot \frac{N_0}{2} = N_0 f_m$$

Snaga signala u kanalu poruke:

$$P_{SC} = P_{AM} = \frac{U_0^2}{2} + \frac{k_a^2 P}{2} \quad (\text{uvjet za mjeru})$$

$$\Rightarrow SNR_c = \frac{P_{SC}}{P_{NC}} = \frac{U_0^2 + k_a^2 P}{2 N_0 f_m}$$

Napokon naša mjera:

$$M_{PSBTC-AM, AWGN} = \frac{SNR_0}{SNR_c} = \frac{k_a^2 P}{U_0^2 + k_a^2 P} = \left| m = \frac{k_a |u_m(t)|_{max}}{U_0} \right| =$$

$$= \frac{m^2 P}{|u_m(t)|_{max}^2 + m^2 P} < 1$$

ne isplati se za AWGN

U zadatku $f_0 = 360\,kHz$, $P_0 = 50\,W$, $f_m = 3\,kHz$ $P_{SSB} = 5\,W$

$$S_N(f) = -\frac{10^{-6}}{400} \cdot |f| + 10^{-6}, \quad |f| < 400 \quad \text{kHz}$$

$$S_N(f_c) = 10^{-7}\ W/Hz, \quad S_N\left(\frac{f_m}{2}\right) = 9{,}96 \cdot 10^{-7}\ W/Hz$$

$$\left.\begin{array}{l} P_{DSB} = 2P_{SSB} = \frac{k_a^2 P}{2} \Rightarrow k_a^2 P = 20 \\ P_0 = \frac{u_0^2}{2} \Rightarrow u_0^2 = 100 \end{array}\right\} \Rightarrow M_{AWGN} = \frac{20}{100+20} = \frac{1}{6}$$

$$M = 9{,}96 \cdot \frac{1}{6} = 1{,}66$$ (bolji AM od Baseband)

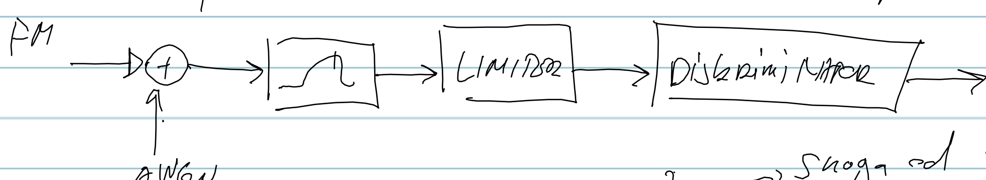
$$SNR_0 = \frac{P_{DSB}}{N_0 f_m} = \frac{P_{DSB}}{2S_N(f_0) \cdot f_m} = 1{,}67 \cdot 10^4 = 42\ dB$$

▷

20 Usporedba 2 tipa modulacije obzirom na SNR podrazumijeva usporedbu ~~odziva~~ odgovarajućih mjera

$M_{FM} > M_{DSB-TC-AM}$

Za općeniti modulacijski signal, AWGN kanal i direktan prijamnik oblika:



mjera prijenosa FM signala je $M_{FM} = \frac{3k_f^2 \cdot P}{f_m^2}$ → snaga od $u_m(t)$

$$M_{DSB\text{-}TK\text{-}AM} = \frac{\frac{m_{AM}^2}{2} P}{|u_m|_{max} + u_{AM}^2 P} = \frac{0{,}9^2 \cdot 0{,}08}{0{,}5^2 + 0{,}9^2 \cdot 0{,}08} = 0{,}2$$

$$\frac{3k_f^2 P}{f_m^2} > 0{,}2 \Rightarrow k_f > \sqrt{\frac{0{,}2 (5 \cdot 10^3)^2}{3 \cdot 0{,}08}} = 2{,}78 \text{ kHz/V}$$

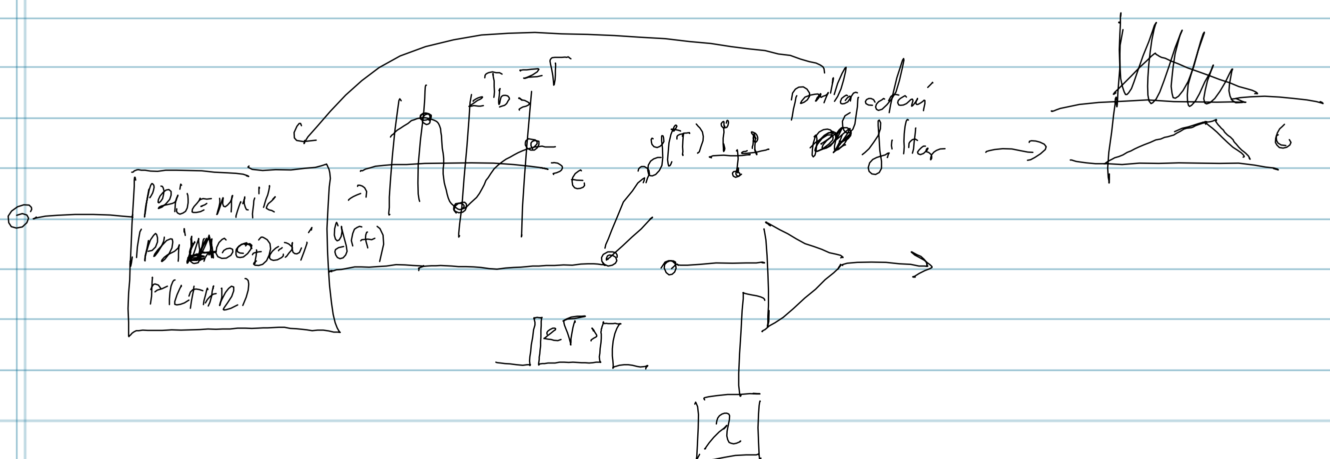
$$m_{fm} = \frac{\Delta f}{f_m} = \frac{k_f \cdot |u_m(t)|_{max}}{f_m}$$

$$> 2{,}78 \cdot 0{,}5$$

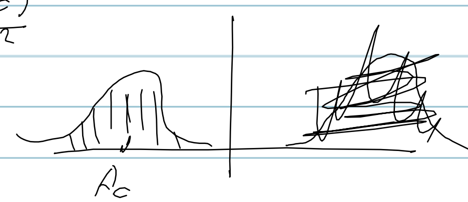
$$m_{FM} > 0{,}46$$

sad digitalni dio...

(21)



Neka je Y - slučajni proces koji opisuje signal $y \equiv y(t)$. U našem slučaju imamo binarni prijenos $(M=2)$ s amplitudama $A_0 = -1V$ i $A_1 = 1V$. F/c gustoća (pdf) vjerojatnosti amplituda su: $f_Y(y|A) = \frac{1}{\sqrt{2\pi}\,\sigma} \cdot e^{-\frac{(y-A)^2}{2\sigma^2}}$



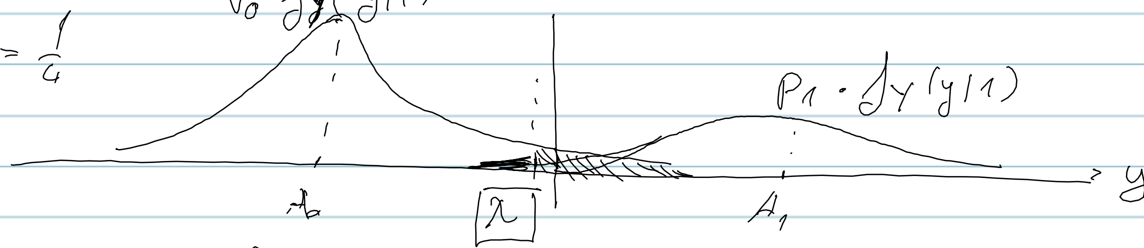
$P_0 = 1$

$$\cancel{f_y}\; f_y(y|1) = \frac{1}{\sqrt{2\pi}\,\sigma} \cdot e^{-\frac{(y-A_1)^2}{2\sigma^2}}$$

$P_1 = 1$ cijela vjer. sažeto 1.

Vjerojatnost pogrešne detekcije bitova (Probability of error detection)

$P_0 = \frac{3}{4}, P_1 = \frac{1}{4}$



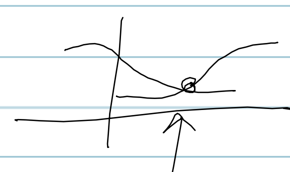
$$P_e = \int_{\lambda}^{\infty} P_0 \cdot f_y(y|0)\,dy \underset{\text{ili}}{+} \int_{-\infty}^{\lambda} P_1 \cdot f_y(y|1)\,dy$$

$$P_e = P_e(\lambda)$$

Optimalni λ je onaj koji minimizira P_e.

$$\frac{dP_e}{d\lambda} = 0$$

$$P_0 \underbrace{\frac{d}{d\lambda}\int_{\lambda}^{\infty} f_y(y|0)\,dy}_{= -f_y(\lambda|0)} + P_1 \underbrace{\frac{d}{d\lambda}\int_{-\infty}^{\lambda} f_y(y|1)\,dy}_{= f_y(\lambda|1)}$$



$\cancel{P_0 = P_1}$ $\quad P_0\, f_y(\lambda|0) = P_1\, f_y(\lambda|1)$ ⇐ sjecište fje

$$\frac{\cancel{\frac{1}{\sqrt{2\pi}\sigma}} \cdot e^{-\frac{(\lambda-A_0)^2}{2\sigma^2}}}{\cancel{\frac{1}{\sqrt{2\pi}\sigma}} \cdot e^{-\frac{(\lambda-A_1)^2}{2\sigma^2}}} = \frac{P_1}{P_0} \quad /\ln \;/ 2\sigma^2$$

$$2\lambda(A_0 - A_1) + A_1^2 - A_0^2 = 2\sigma^2 \ln\frac{P_1}{P_0} \quad \Big| \text{div } (A_1 - A_0)$$

$$\hookrightarrow = (A_1 - A_0)(A_1 + A_0)$$

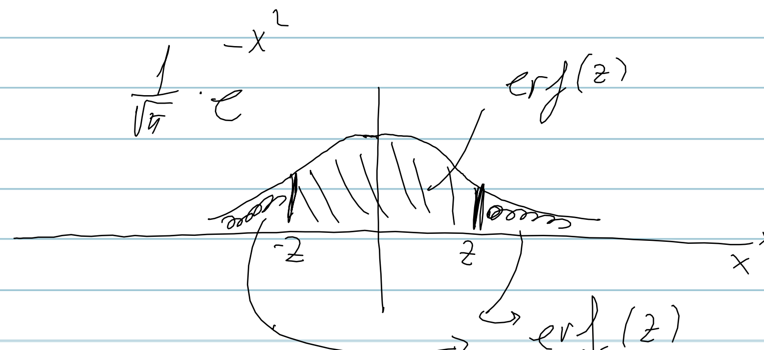
$$\lambda = \frac{A_0 + A_1}{2} - \frac{\sigma^2}{A_1 - A_0}\ln\left(\frac{P_1}{P_0}\right) = \frac{-1+1}{2} - \frac{0{,}2}{1-(-1)}\ln\frac{1/4}{3/4} = \underline{\underline{0{,}11\,V}}$$

Vraćamo se u Pe

$$P_e = P_0 \int_{\lambda}^{\infty} \frac{1}{\sqrt{2\pi}\,\sigma} \cdot e^{-\frac{(y-A_0)^2}{2\sigma^2}}\,dy + P_1 \int_{-\infty}^{\lambda} \frac{1}{\sqrt{2\pi}\,\sigma} \cdot e^{-\frac{(y-A_1)^2}{2\sigma^2}}\,dy$$

$$= P_0 \cdot \int_{\frac{\lambda - A_0}{\sqrt{2}\,\sigma}}^{\infty} \frac{1}{\sqrt{\pi}}\, e^{-\left(\frac{y-A_0}{\sqrt{2}\,\sigma}\right)^2} d\left(\frac{y-A_0}{\sqrt{2}\,\sigma}\right) + P_1 \int_{-\infty}^{\frac{\lambda - A_1}{\sqrt{2}\,\sigma}} \frac{1}{\sqrt{\pi}}\, e^{-\left(\frac{y-A_1}{\sqrt{2}\,\sigma}\right)^2} d\left(\frac{y-A_1}{\sqrt{2}\,\sigma}\right)$$

(integrali za ERFC fju)



$$\mathrm{erf}(z) + \mathrm{erfc}(z) = 1$$

$$P_e = \underbrace{P_0}_{3/4} \cdot \frac{1}{2} \cdot \mathrm{erfc}\Big(\underbrace{\frac{\lambda - A_0}{\sqrt{2}\,\sigma}}_{1{,}76}\Big) + \underbrace{P_1}_{1/4} \cdot \frac{1}{2} \cdot \mathrm{erfc}\Big(\underbrace{\frac{\lambda - A_1}{\sqrt{2}\,\sigma}}_{1{,}41}\Big) = \underline{\underline{10^{-2}}}$$

(izvedi sicher na ispitu ...)

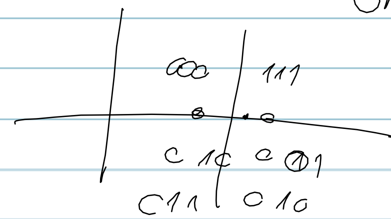
Lulilo!

(22) ASK – binarni prijenos, MASK – M-arni prijenos

$M = 8$ 3 bita po simbolu

$\sigma^2 = 0{,}07\ V^2$

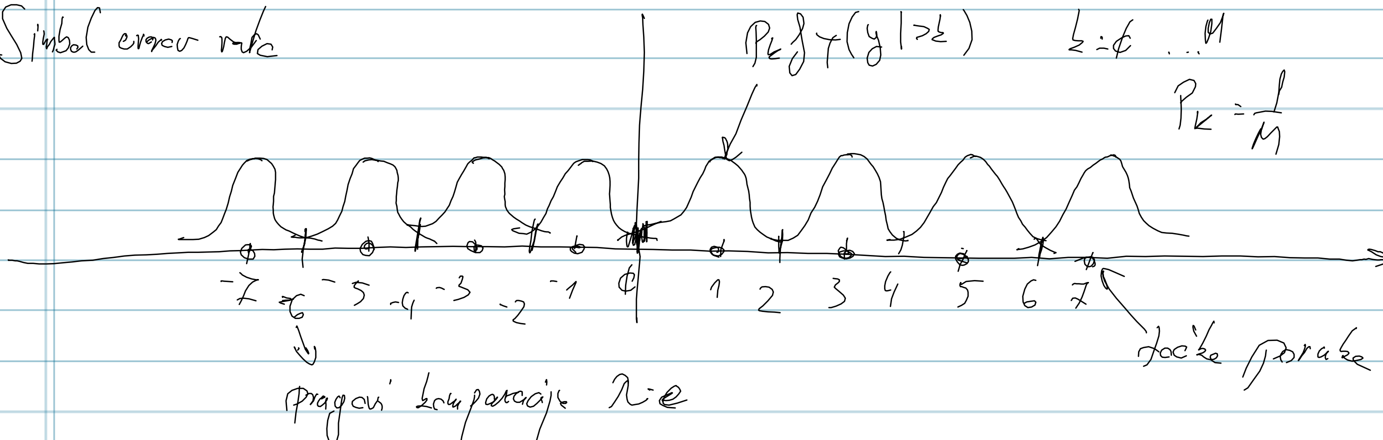
Grayev kod



a) Grayev kod

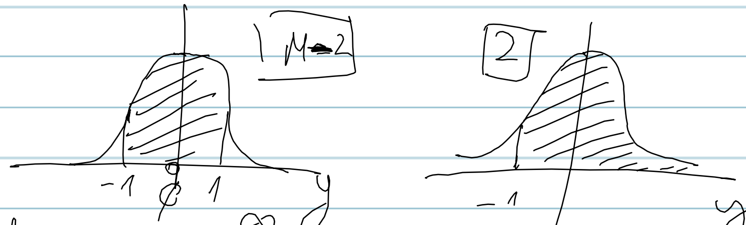
SYB	AMP
000	−7
001	−5
011	−3
010	−1
110	1
111	3
101	5
100	7

b) Simbol error rate



Vjerojatnost ispravne detekcije simbola (probability of correct detection – P_c, SER)

Translatacija pdf-a ne mijenja SER.



$$P_c = (M-2)\cdot\frac{1}{M}\cdot\int_{-1}^{1}\frac{1}{\sqrt{2\pi}\,\sigma}\cdot e^{\frac{-y^2}{2\sigma^2}}\,dy + 2\cdot\frac{1}{M}\int_{-1}^{\infty}\frac{1}{\sqrt{2\pi}\,\sigma}\,e^{\frac{-y^2}{2\sigma^2}}\,dy$$

$$P_c = \underbrace{(M-2)}_{\left(1-\frac{2}{M}\right)}\frac{1}{M}\underbrace{\int_{\sigma\sqrt{2}}^{\frac{-1}{\sigma\sqrt{2}}} \frac{1}{\sqrt{\pi}} \cdot e^{-\left(\frac{y}{\sqrt{2}\sigma^2}\right)^2} d\left(\frac{y}{\sqrt{2}\sigma}\right)}_{1-\operatorname{erfc}\left(\frac{1}{\sigma\sqrt{2}}\right)} + \frac{2}{M}\underbrace{\int_{\frac{-1}{\sigma\sqrt{2}}}^{+\infty} \frac{1}{\sqrt{\pi}} \cdot e^{-\left(\frac{y}{\sqrt{2}\sigma^2}\right)^2} d\left(\frac{y}{\sqrt{2}\sigma}\right)}_{1-\frac{1}{2}\operatorname{erfc}\left(\frac{1}{\sigma\sqrt{2}}\right)} =$$

$$P_c = 1 - \frac{M-1}{M}\operatorname{erfc}\left(\frac{1}{\sigma\sqrt{2}}\right)$$

$$P_e \equiv SER = 1 - P_c = \frac{M-1}{M}\operatorname{erfc}\left(\frac{1}{\sigma\sqrt{2}}\right) = \frac{7}{8}\operatorname{erfc}\left(2{,}67\right)$$

$$= 1{,}4 \cdot 10^{-4}$$