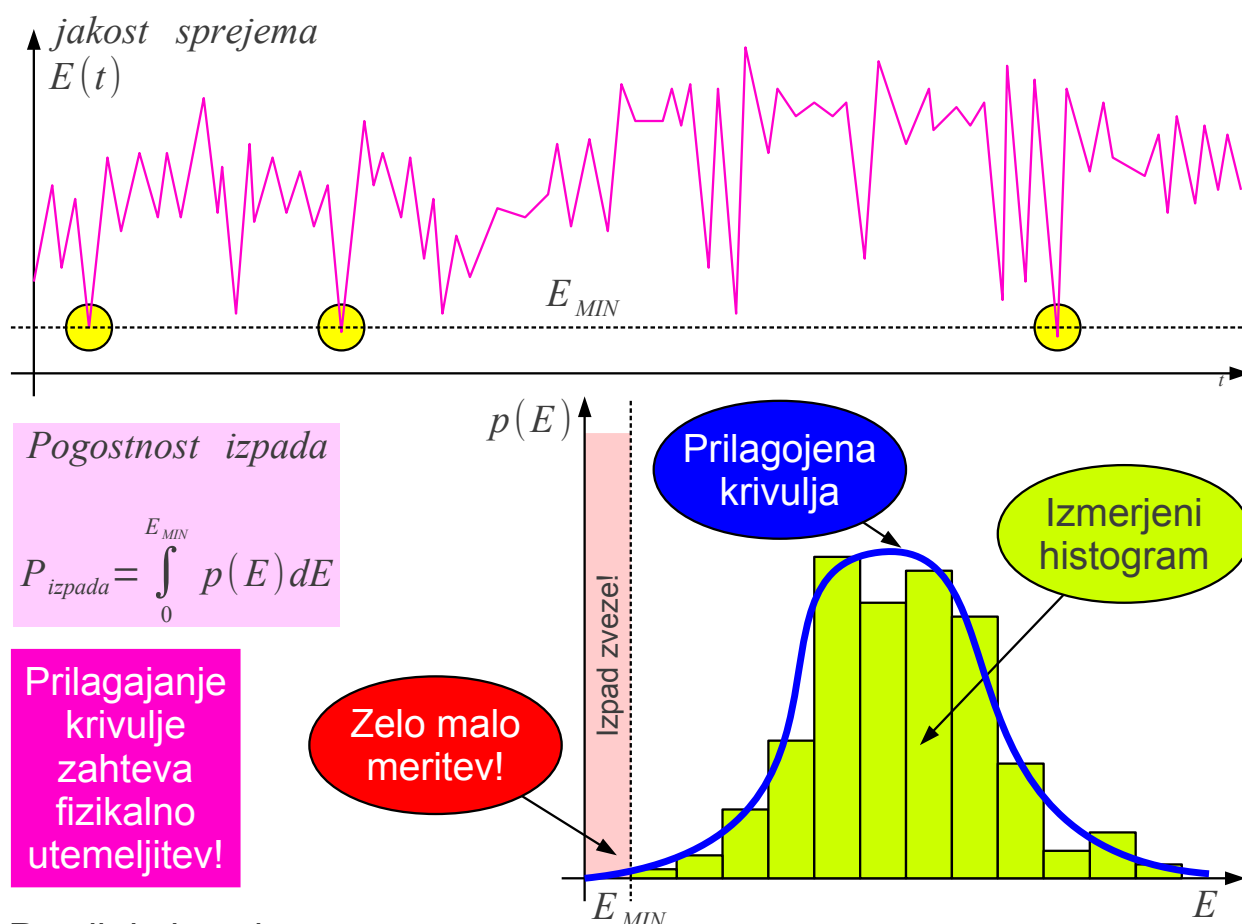
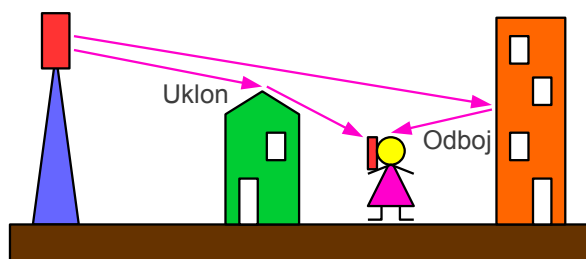


17. Večpotje v radijski zvezi

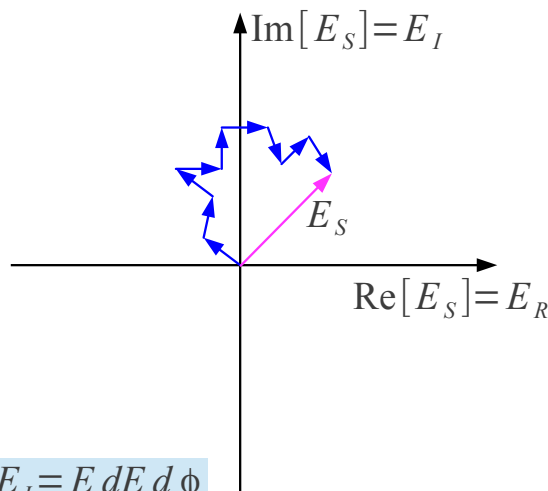
Večina nalog iz anten in razširjanje valov zahteva obravnavo v treh dimenzijah prostora. Tako skalarne kot tudi vektorske veličine so funkcije časa in vseh treh dimenzij prostora. Ozkopasovne signale $B \ll f$ radia največkrat smemo v izračunih ponazoriti s harmonskim signalom ene same krožne frekvence $\omega = 2\pi f$, kar poenostavi časovne odvode v $\partial/\partial t = j\omega$.



Presih in izpad zveze



Večpotje brez vidljivosti: Rayleigh ($\langle E^2 \rangle$)
vsota mnogo naključnih malih kazalcev



Gaussova porazdelitev komponent

$$p(E_R) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{E_R^2}{2\sigma^2}}$$

$$p(E_I) = \frac{1}{\sigma \sqrt{2\pi}} e^{-\frac{E_I^2}{2\sigma^2}}$$

$$E_S = E_R + jE_I = E e^{j\phi}$$

$$E = |E_S|$$

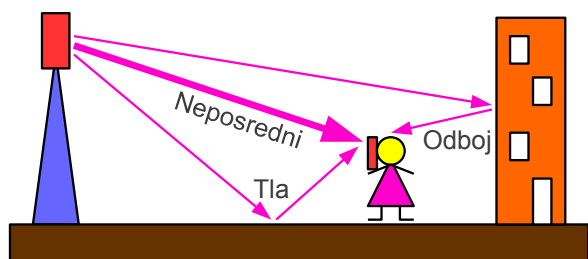
$$dE_R dE_I = E dE d\phi$$

$$p(E_R, E_I) = p(E_R) p(E_I) = \frac{1}{\sigma^2 2\pi} e^{-\frac{E_R^2 + E_I^2}{2\sigma^2}} = p(E) p(\phi)$$

$$\langle E^2 \rangle = 2\sigma^2$$

$$p(E) = \int_0^{2\pi} p(E_R, E_I) E d\phi = \int_0^{2\pi} \frac{1}{\sigma^2 2\pi} e^{-\frac{E^2}{2\sigma^2}} E d\phi = \frac{E}{\sigma^2} e^{-\frac{E^2}{2\sigma^2}} = \frac{2E}{\langle E^2 \rangle} e^{-\frac{E^2}{\langle E^2 \rangle}}$$

Rayleighjeva porazdelitev

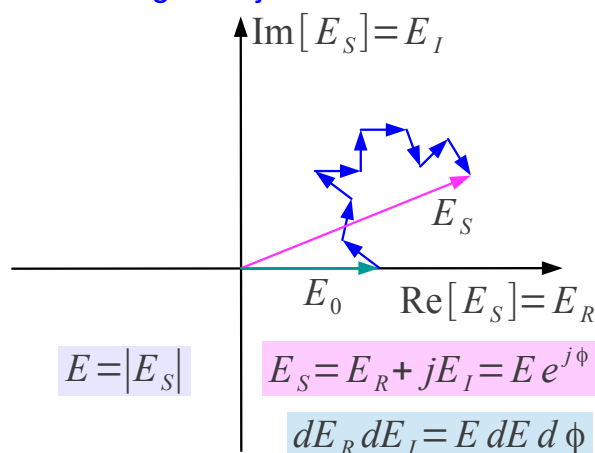


Večpotje z neposrednim žarkom: Rice (E_0, σ)
en velik in mnogo naključnih malih kazalcev

Gaussova porazdelitev komponent

$$p(E_R) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(E_R - E_0)^2}{2\sigma^2}}$$

$$p(E_I) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{E_I^2}{2\sigma^2}}$$

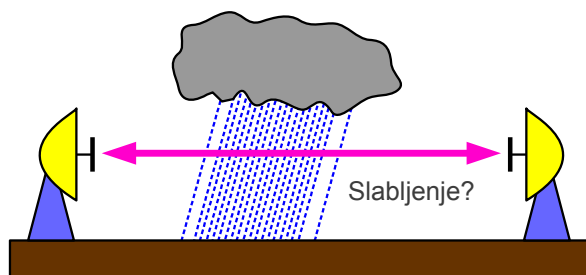


$$p(E_R, E_I) = \frac{1}{\sigma^2 2\pi} e^{-\frac{(E_R - E_0)^2 + E_I^2}{2\sigma^2}} = \frac{1}{\sigma^2 2\pi} e^{-\frac{E^2 + E_0^2}{2\sigma^2}} e^{\left(\frac{E_R E_0}{\sigma^2}\right)} = \frac{1}{\sigma^2 2\pi} e^{-\frac{E^2 + E_0^2}{2\sigma^2}} e^{\left(\frac{E_0 E}{\sigma^2}\right) \cos \phi}$$

$$p(E) = \int_0^{2\pi} p(E_R, E_I) E d\phi = \frac{E}{\sigma^2} e^{-\frac{E^2 + E_0^2}{2\sigma^2}} I_0\left(\frac{E_0 E}{\sigma^2}\right)$$

Riceova porazdelitev

$$\int_0^{2\pi} e^{\left(\frac{E_0 E}{\sigma^2}\right) \cos \phi} d\phi = 2\pi I_0\left(\frac{E_0 E}{\sigma^2}\right)$$



Neznane razmere: log-normalna ($\langle E_{\text{dB}} \rangle, \sigma_{\text{dB}}$)

Fizikalno neutemeljeno!

$$p(E_{\text{dB}}) = \frac{1}{\sigma_{\text{dB}} \sqrt{2\pi}} e^{-\frac{(E_{\text{dB}} - \langle E_{\text{dB}} \rangle)^2}{2\sigma_{\text{dB}}^2}}$$

$$E_{\text{dB}} = 20 \log_{10} \left(\frac{|E_s|}{E_{\text{REF}}} \right) = 20 \log_{10} \left(\frac{E}{E_{\text{REF}}} \right) = \frac{20}{\ln 10} \ln \left(\frac{E}{E_{\text{REF}}} \right)$$

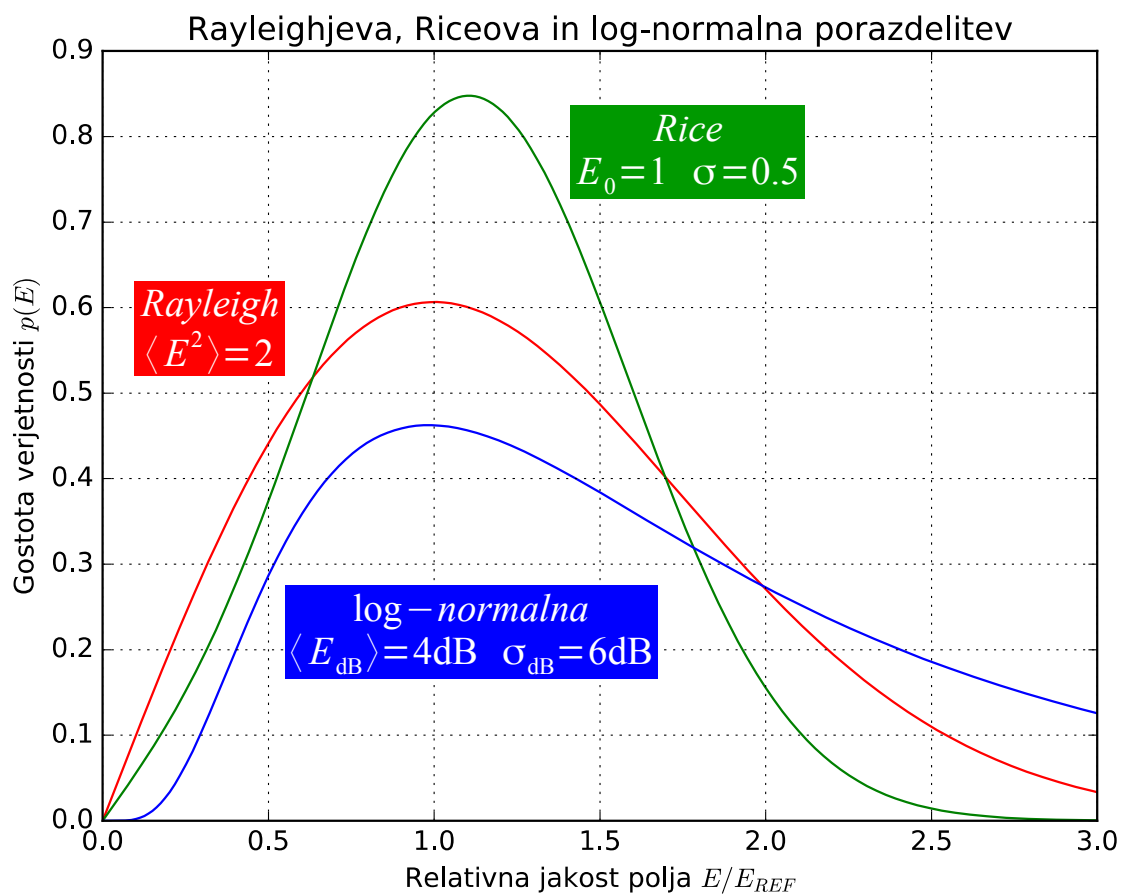
$$\sigma_{\text{dB}} = \sqrt{\langle (E_{\text{dB}} - \langle E_{\text{dB}} \rangle)^2 \rangle}$$

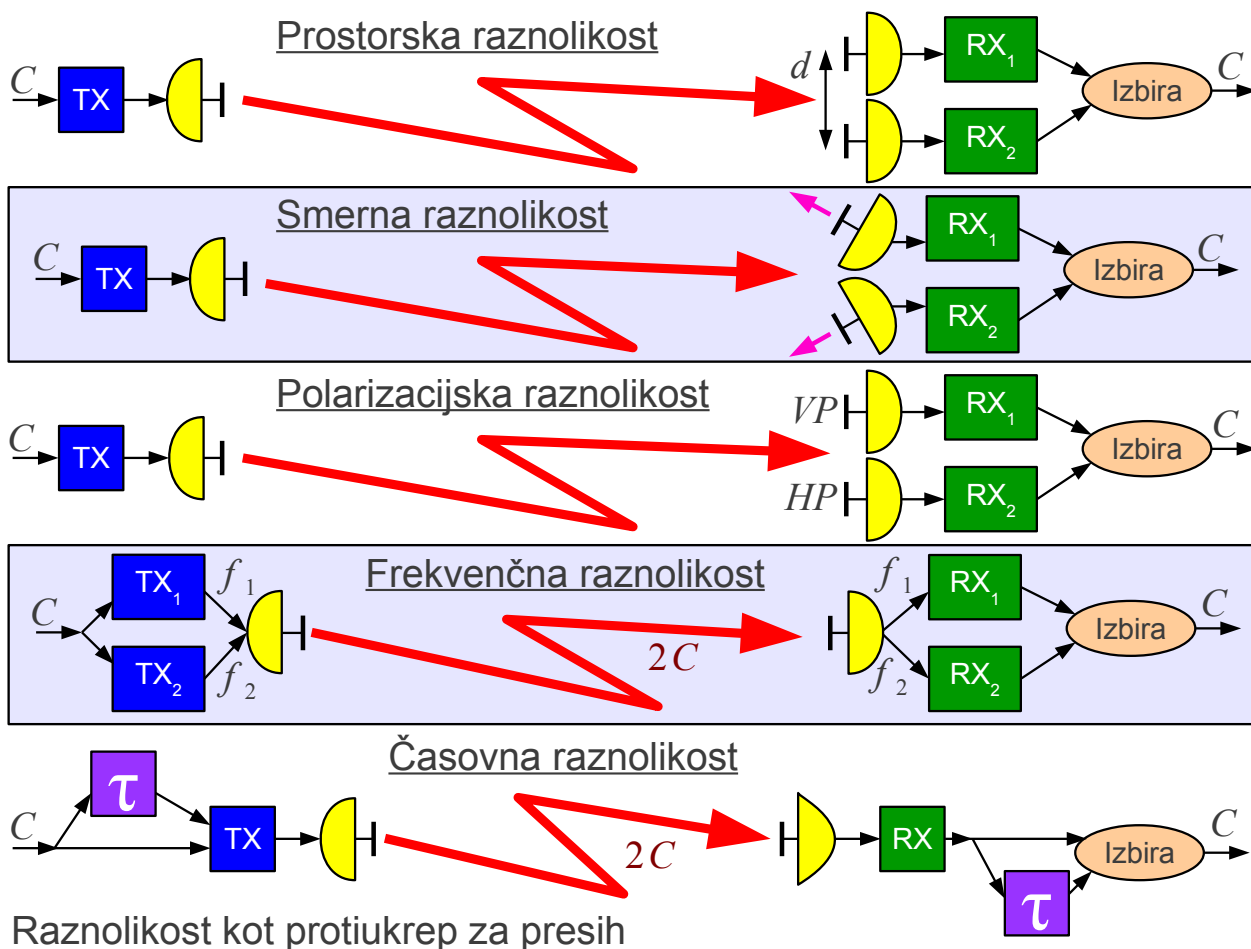
$$p(E_{\text{dB}}) dE_{\text{dB}} = p(E) dE$$

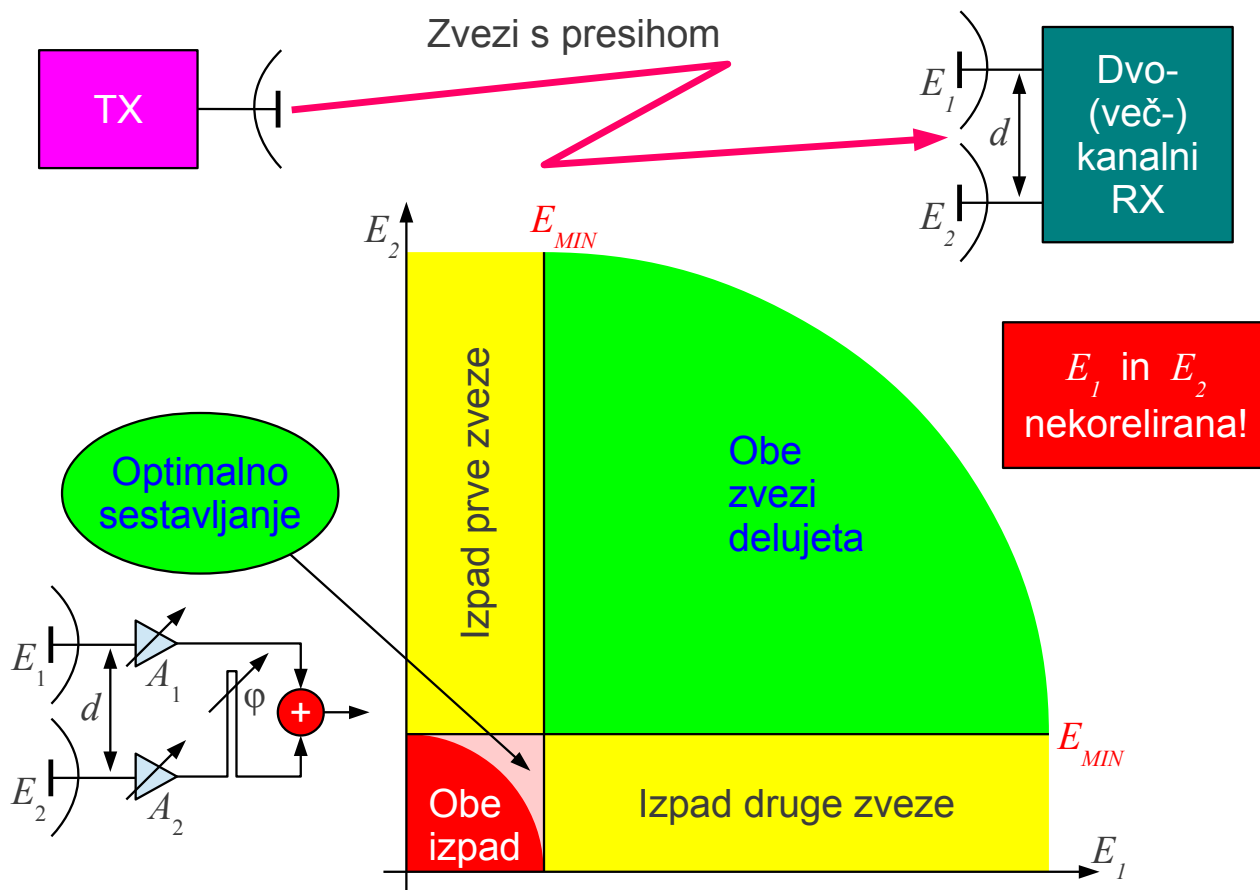
$$\frac{dE_{\text{dB}}}{dE} = \frac{20}{\ln 10} \left(\frac{E_{\text{REF}}}{E} \right) \frac{1}{E_{\text{REF}}} = \frac{20}{E \ln 10}$$

$$p(E) = p(E_{\text{dB}}) \frac{dE_{\text{dB}}}{dE} = p(E_{\text{dB}}) \frac{20}{E \ln 10} = \frac{20}{E (\ln 10) \sigma_{\text{dB}} \sqrt{2\pi}} e^{-\frac{\left[20 \log_{10} \left(\frac{E}{E_{\text{REF}}} \right) - \langle E_{\text{dB}} \rangle \right]^2}{2\sigma_{\text{dB}}^2}}$$

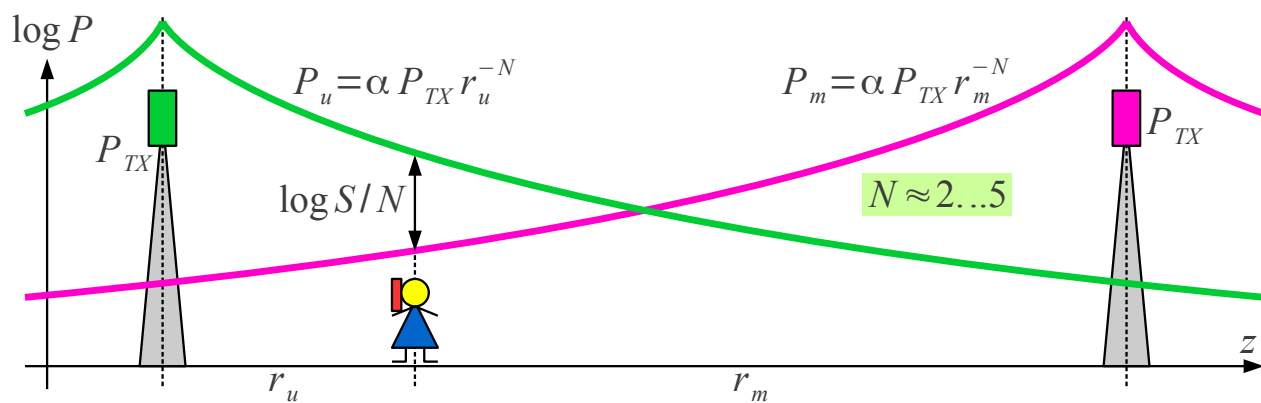
Log-normalna porazdelitev







Pogostnost izpada pri nekoreliranem sprejemu

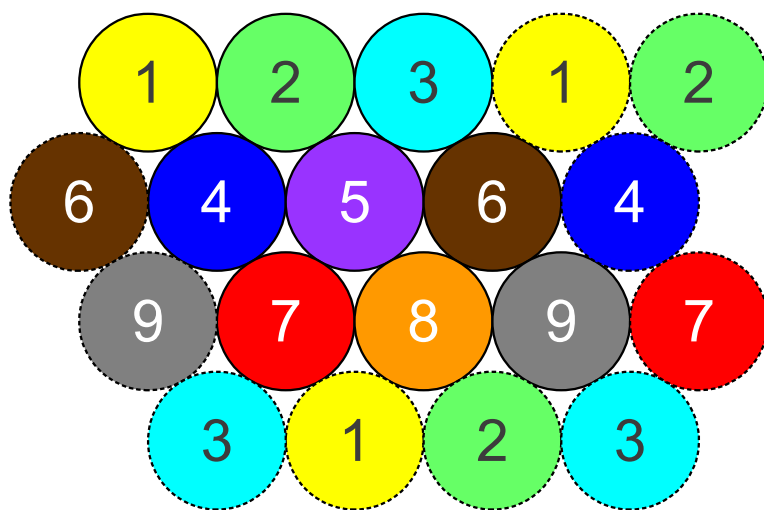


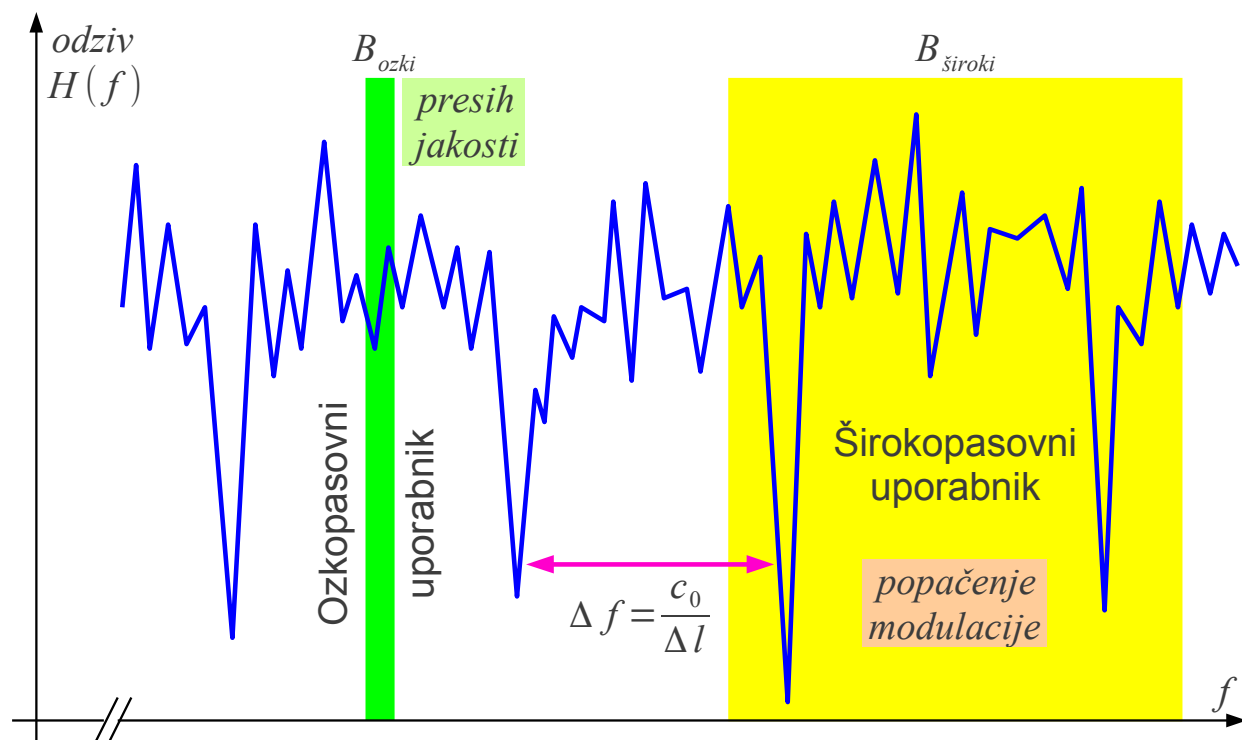
$$S/N = \frac{P_u}{P_m} = \left(\frac{r_m}{r_u} \right)^N$$

Primer: $N=4$
 $S/N = 28\text{dB} = 625$
 z rezervo presiha!

$$r_m = r_u \sqrt[N]{S/N} \approx 5 r_u$$

Ponovna uporaba spektra





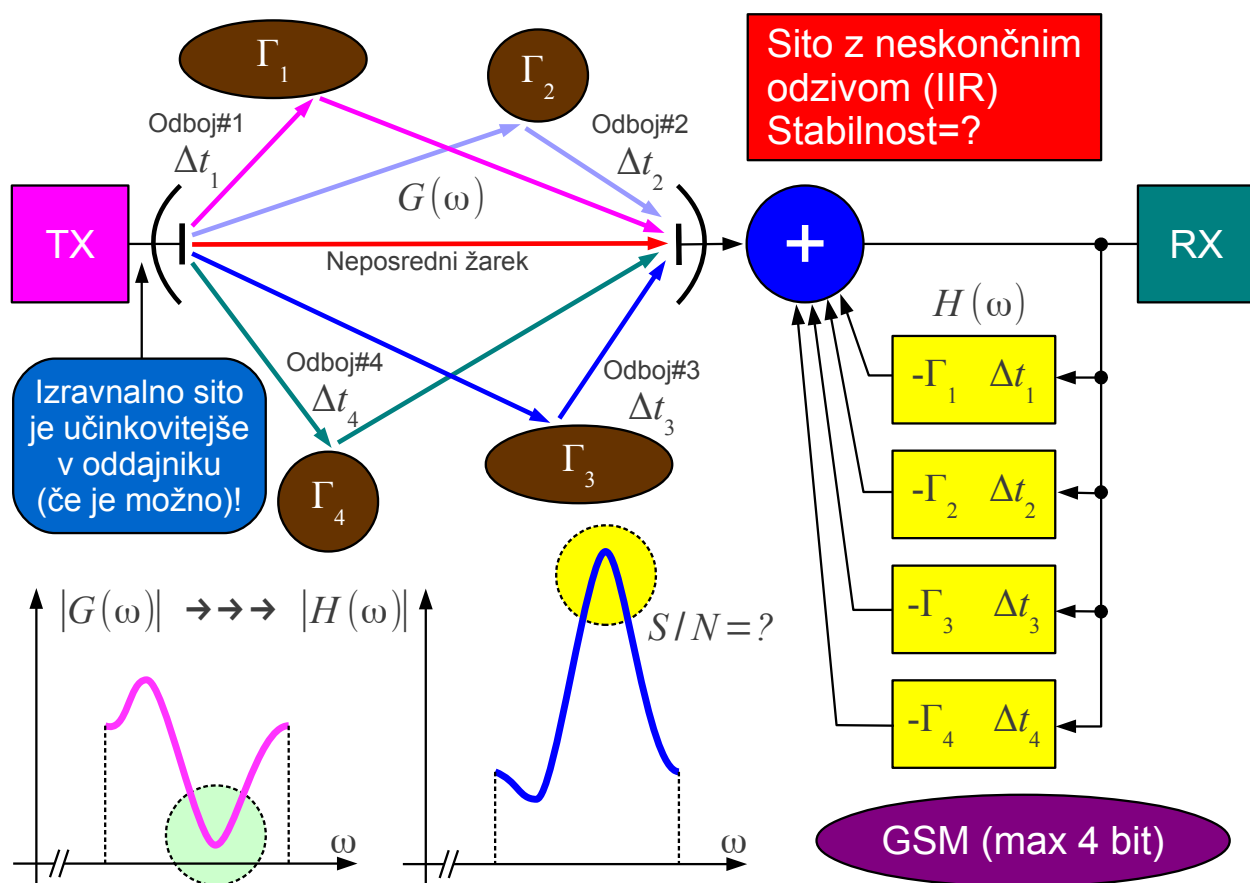
$$B_{ozki} \ll \Delta f \ll B_{široki}$$

Mestno okolje $f_0 \approx 450\text{MHz}$

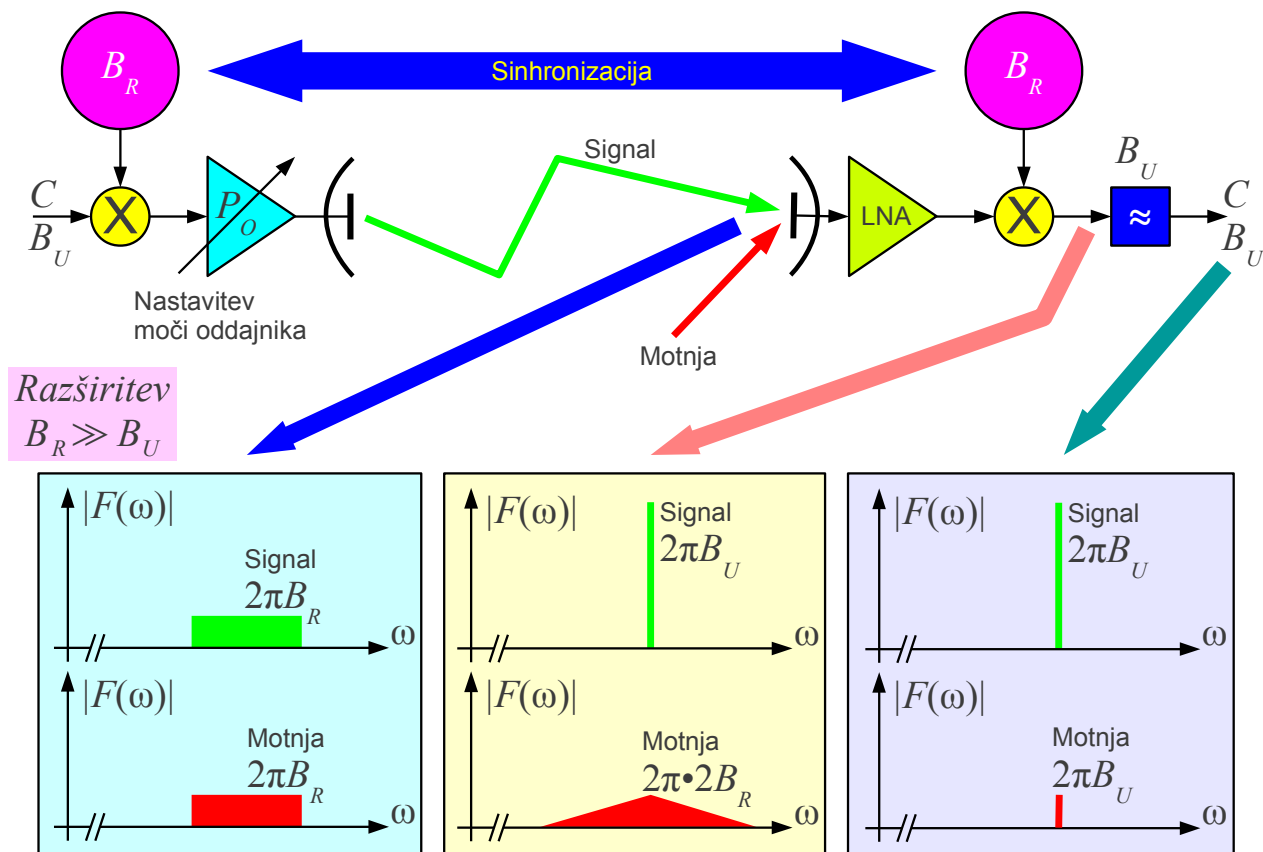
$\Delta l = 200\text{m} \dots 1.5\text{km}$

$\Delta f = 1.5\text{MHz} \dots 200\text{kHz}$

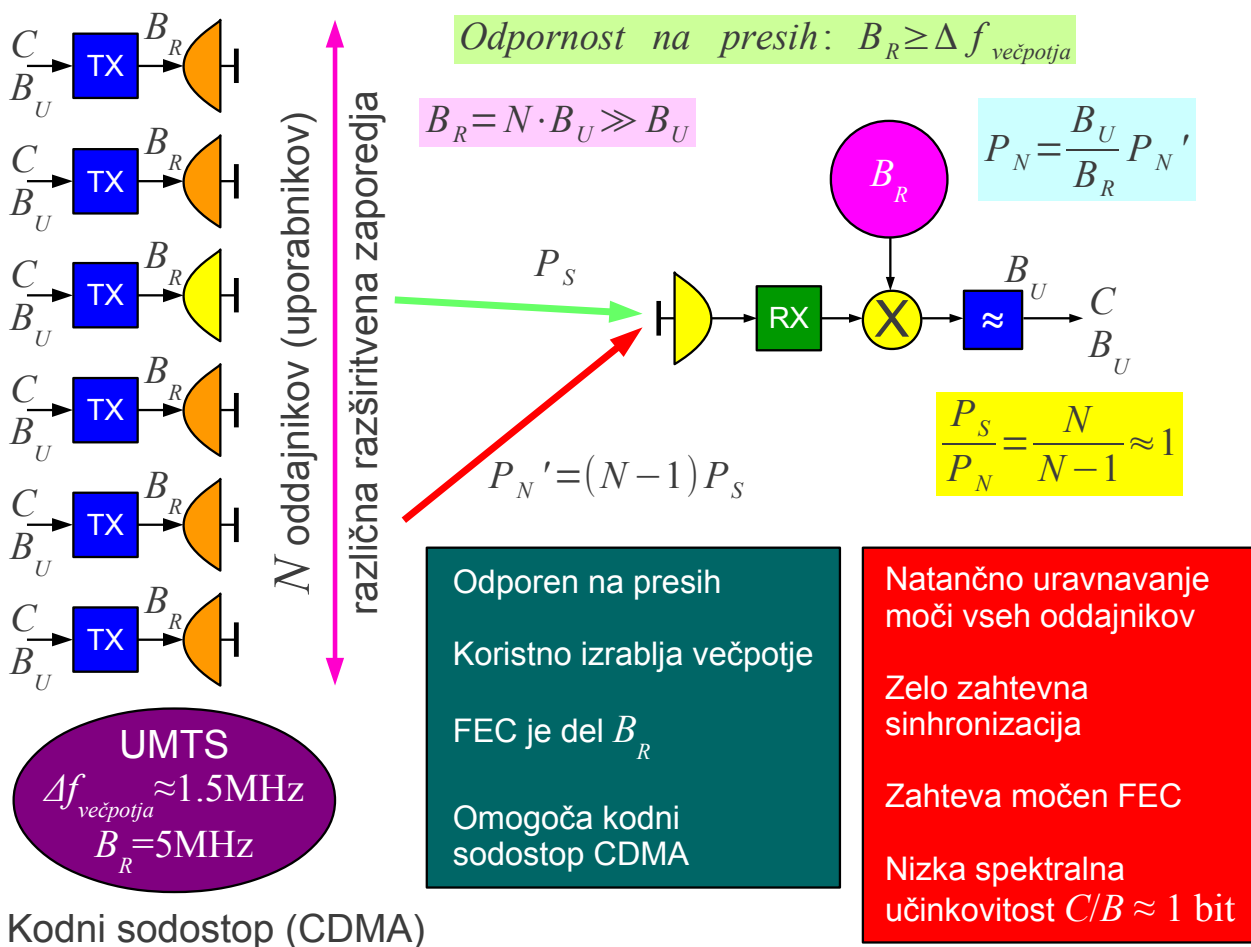
Večpotje v frekvenčnem prostoru

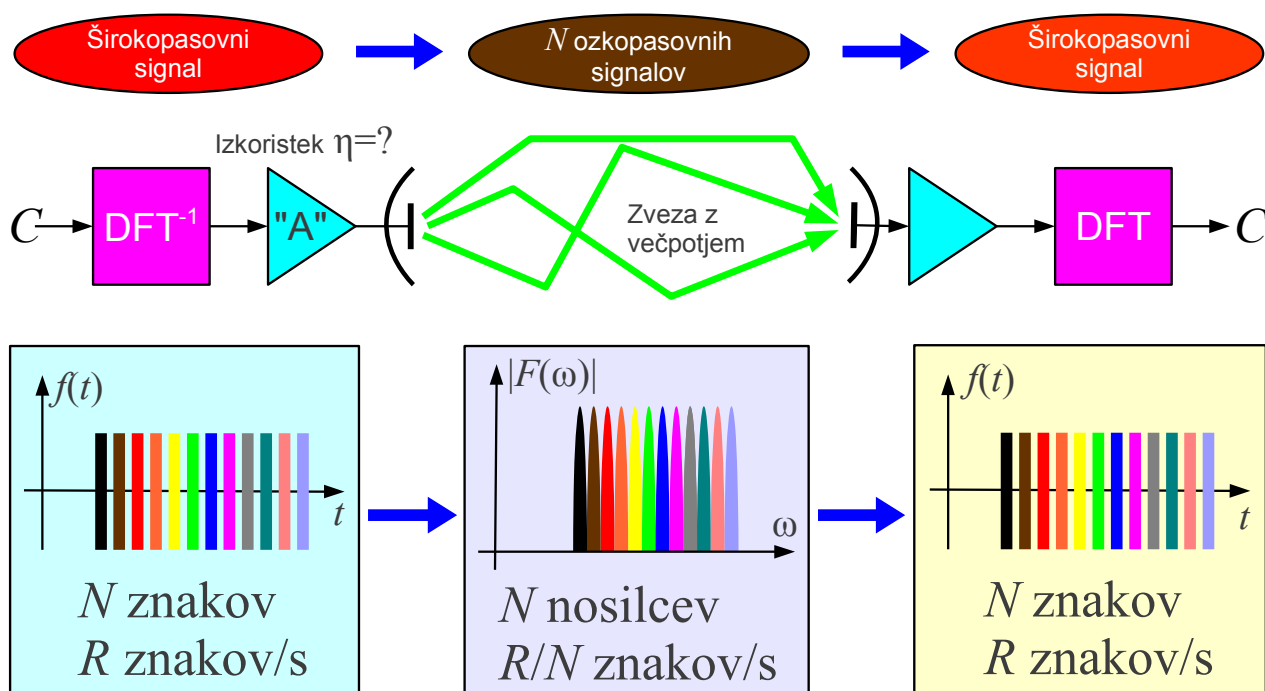


Odpravljanje popačenja večpotja z izravnalnim sitom



Razširjeni spekter (Spread spectrum)

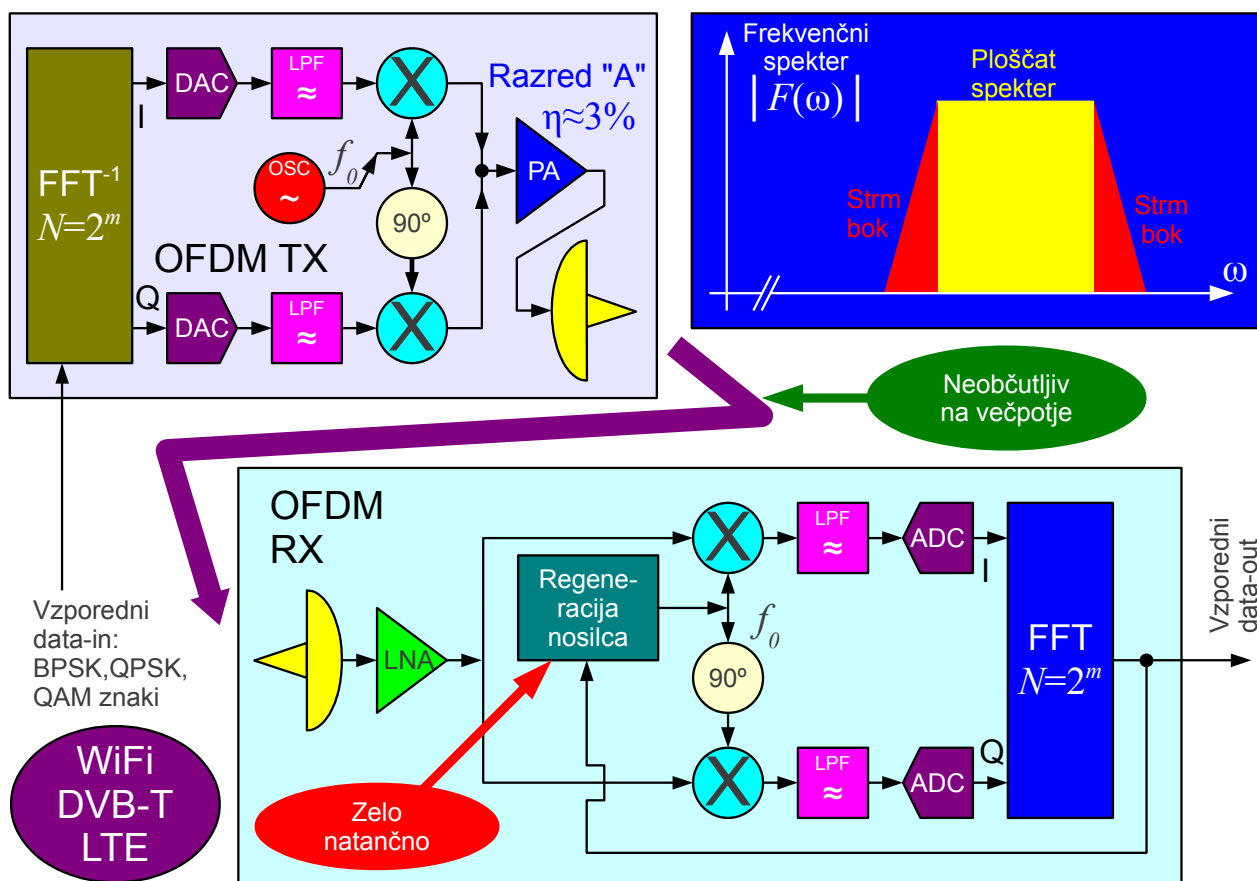




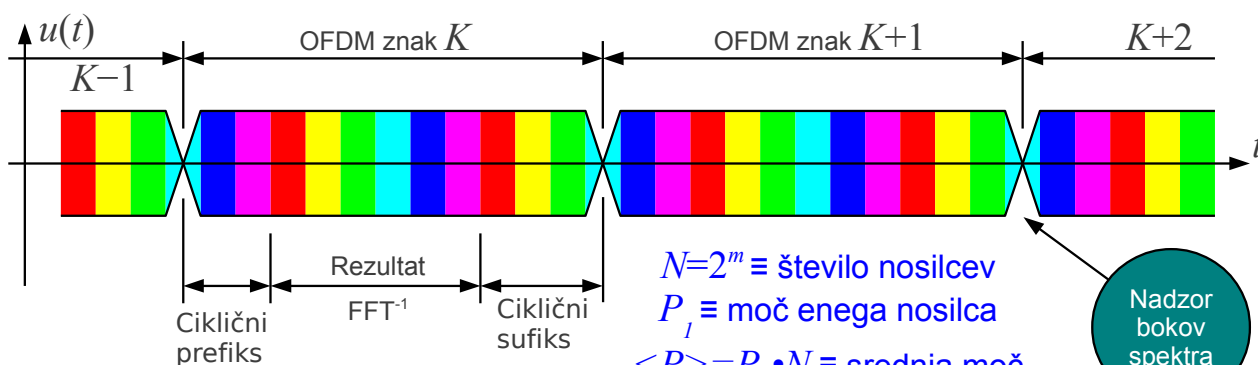
~1950 analogni večtonski modem za ionosferske zveze

~2000 številski DFT → OFDM WLAN (WiFi) 802.11a (FFT)

Večtonski modem kot protiukrep za popačenje večpotja



Orthogonal Frequency-Division Multiplex (OFDM)



$$t_{\text{prefiks}} + t_{\text{sufiks}} \geq \Delta t_{\text{večpotja}}$$

$N=2^m \equiv$ število nosilcev
 $P_I \equiv$ moč enega nosilca
 $\langle P \rangle = P_I \cdot N \equiv$ srednja moč
 $P_{MAX} = P_I \cdot N^2 \equiv$ vršna moč

Nastavljiva odpornost na $\Delta t_{\text{večpotja}}$
 Skoraj pravokoten frekvenčni spekter
 Zadošča šibek FEC
 Spektralni izkoristek C/B dosega teoretske vrednosti BPSK, QPSK, QAM
 Omogoča enofrekvenčna omrežja SFN (Single-Frequency Network)

Lastnosti OFDM

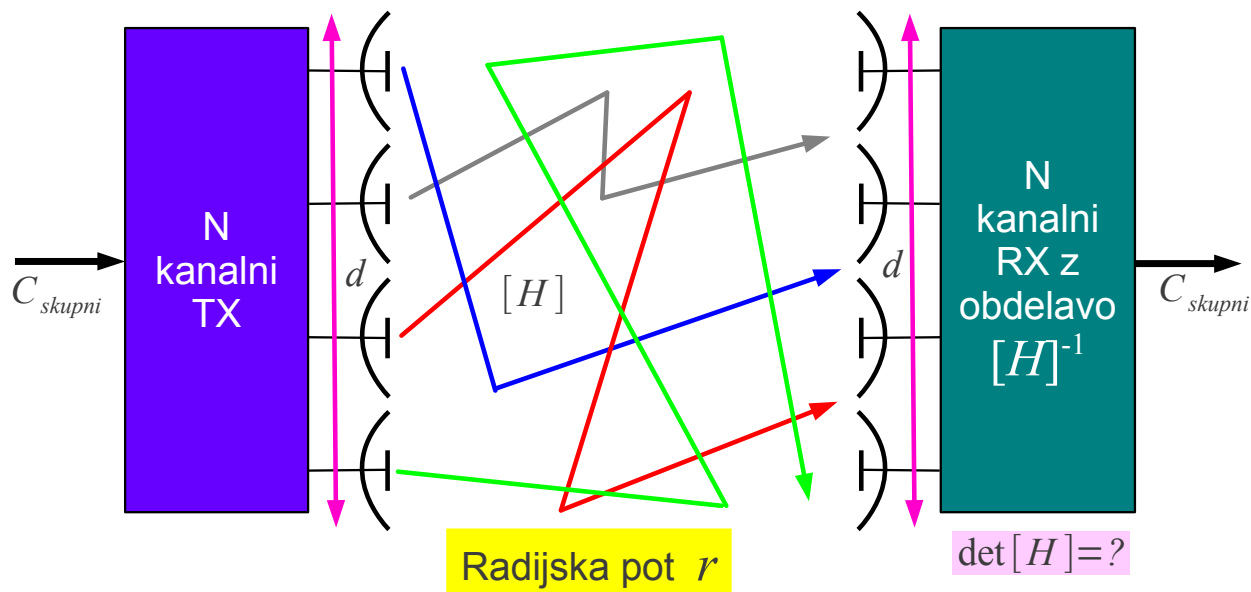
Visoko razmerje $P_{MAX}/\langle P \rangle = N$ pogojuje slab izkoristek oddajnika $\eta \approx 3\%$

FFT zahteva $N \cdot \log_2 N$ računskih operacij

Ozkopasovni nosilci zahtevajo visoko frekvenčno stabilnost $\Delta f \leq 10\% R/N$

Preveliki znaki ~ 12000 bit ($N \approx 2000$, $C/B \approx 6$ bit) za nekatere protokole

Ozkopasovne motnje rušijo sinhronizacijo



Koristna uporaba večpotja!

$$C_{skupni} = N \cdot C_{kanala} = N \cdot B \cdot \log_2 \left(1 + \frac{P_s}{P_n} \right)$$

(+) visoka spektralna učinkovitost: $C/B \approx 10 \text{ bit}$

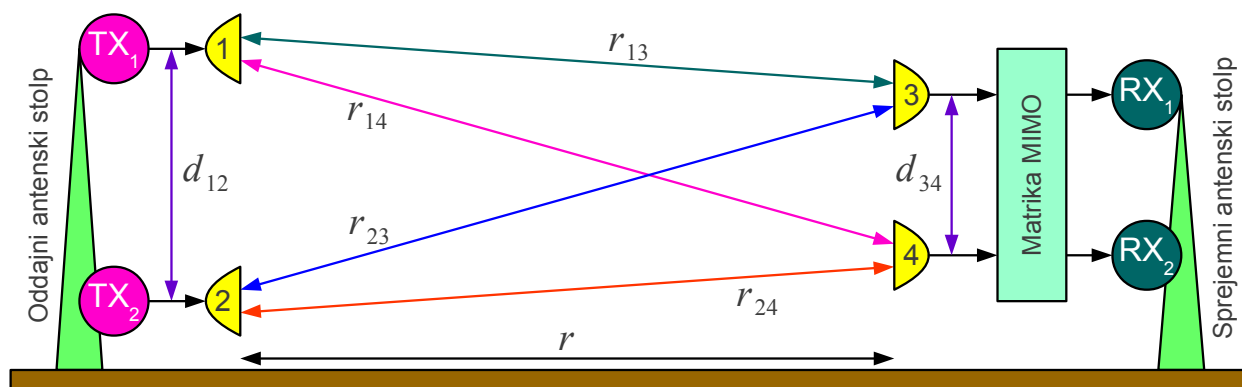
(-) zahteva N oddajnih anten in N sprejemnih anten

(+) preprosta rešitev MIMO 2x2: uporaba obeh polarizacij

(-) več kot dve polarizaciji $\det[H] \neq 0$ le na kratkih poteh $r \approx 2d^2/\lambda$

MIMO (Multiple-In Multiple-Out)

Podvojevanje C/B mikrovalovne zveze \equiv Line-Of-Sight MIMO



Pogoj za $\max \det[MIMO]$: $r_{14} - r_{13} - r_{24} + r_{23} = \lambda/2$

$C/B > 40\text{bit}$

$$r_{13} = r_{24} = \sqrt{r^2 + ((d_{12} - d_{34})/2)^2} \approx r + \frac{d_{12}^2 - 2d_{12}d_{34} + d_{34}^2}{8r}$$

$$r_{14} = r_{23} = \sqrt{r^2 + ((d_{12} + d_{34})/2)^2} \approx r + \frac{d_{12}^2 + 2d_{12}d_{34} + d_{34}^2}{8r}$$

$$r_{14} - r_{13} - r_{24} + r_{23} \approx \frac{d_{12}d_{34}}{r} \rightarrow d_{12}d_{34} = r \cdot \lambda/2$$

MIMO brez večpotja

Zgled:

$$r = 10\text{km} \quad f = 15\text{GHz}$$

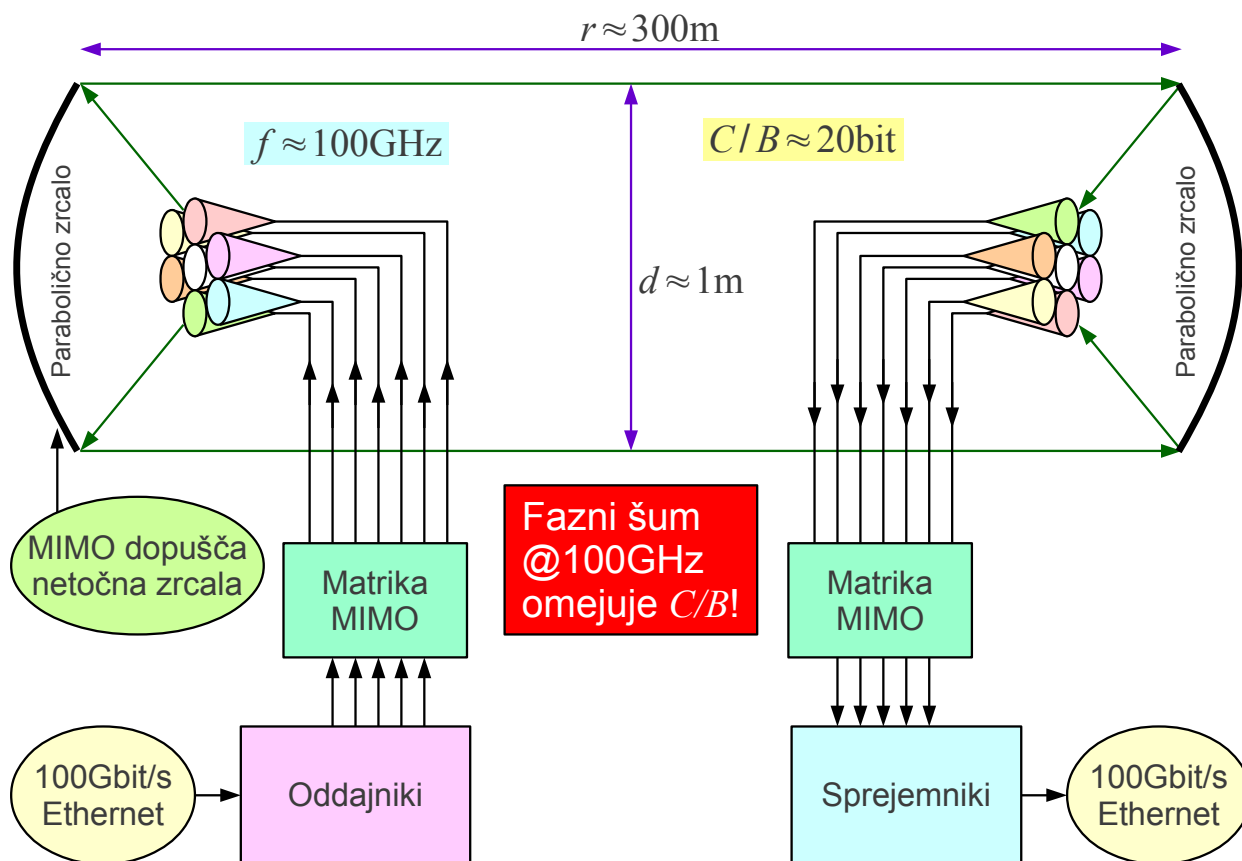
$$\lambda = c_0/f = 2\text{cm}$$

$$\langle d \rangle = \sqrt{d_{12}d_{34}}$$

$$\langle d \rangle = \sqrt{r \cdot \lambda/2} = 10\text{m}$$

Preizkus:

$$r = \frac{2\langle d \rangle^2}{\lambda} = 10\text{km}$$



Visokozmogljiva zveza na kratko razdaljo

* * * * *