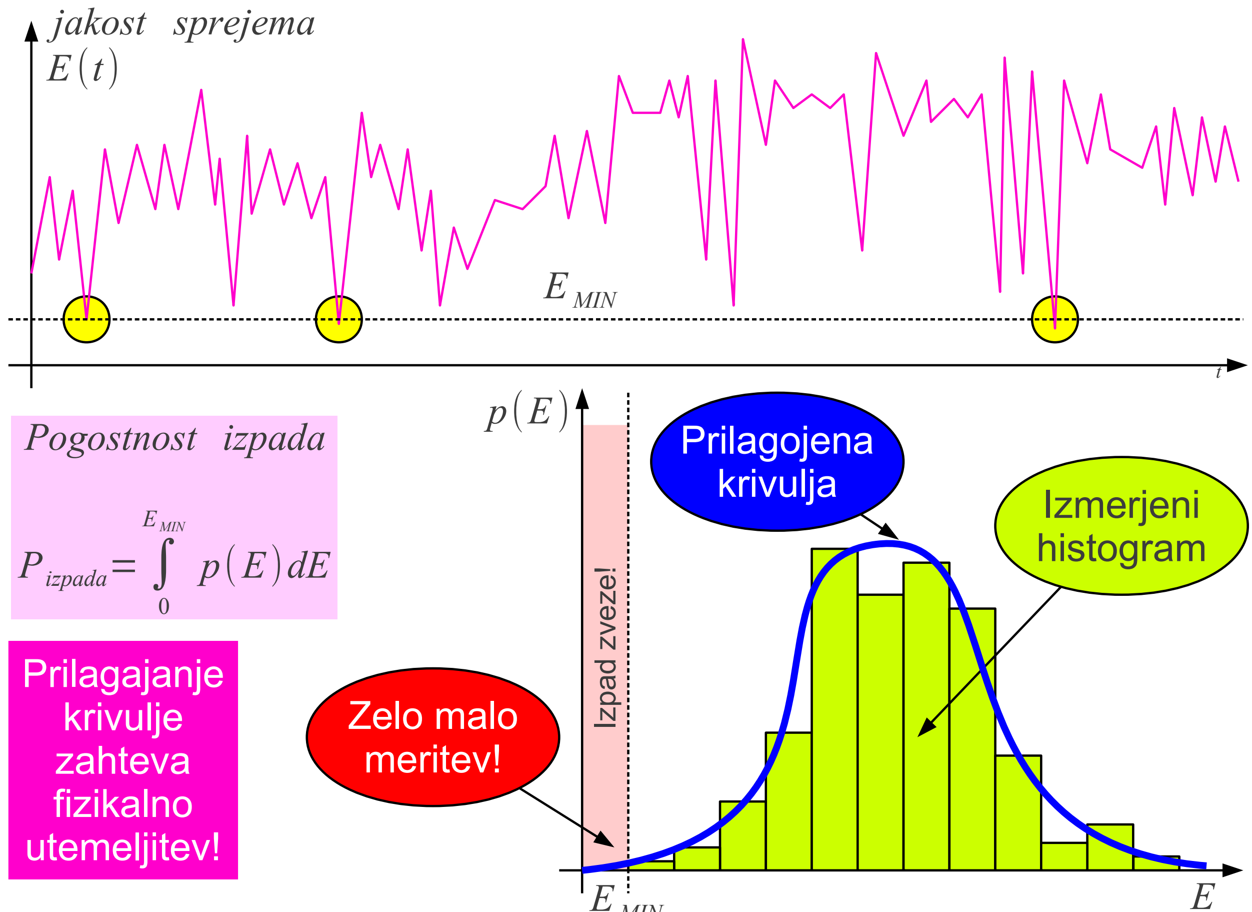
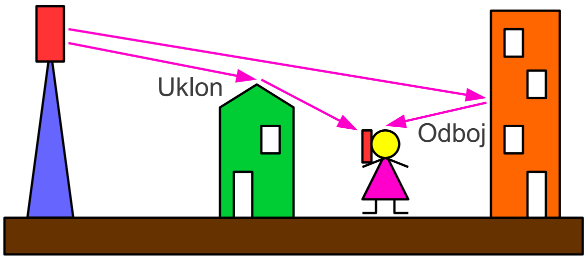
17. Večpotje v radijski zvezi

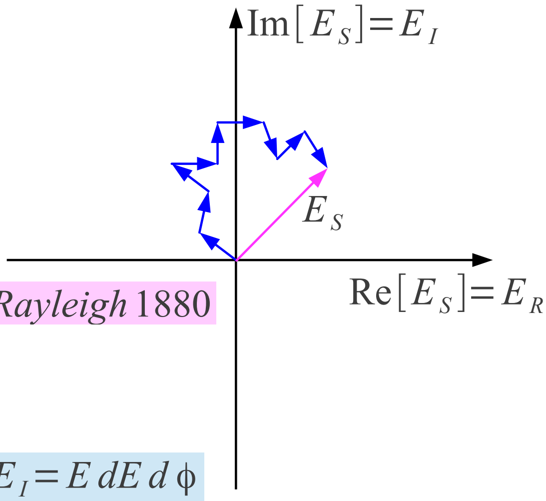
Večina nalog iz anten in razširjanje valov zahteva obravnavo v treh dimenzijah prostora. Tako skalarne kot tudi vektorske veličine so funkcije časa in vseh treh dimenzij prostora. Ozkopasovne signale $B \ll f$ radia največkrat smemo v izračunih ponazoriti s harmonskim signalom ene same krožne frekvence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

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

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

Lord Rayleigh 1880

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

$$E=|E_S|$$

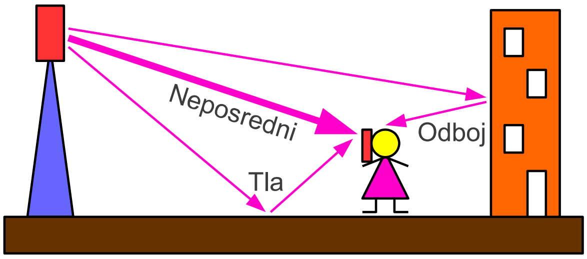
$$dE_R\,dE_I=E\,dE\,d\phi$$

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

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

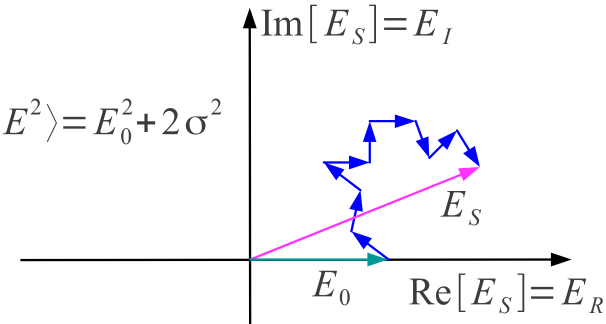
$$p(E)=\int_0^{2\pi}p(E_R,E_I)\,E\,d\phi=\int_0^{2\pi}\frac{1}{\sigma^2 2\pi}e^{-\frac{E^2}{2\sigma^2}}E\,d\phi=\frac{E}{\sigma^2}\mathrm{e}^{-\frac{E^2}{2\sigma^2}}=\frac{2E}{\langle E^2\rangle}\mathrm{e}^{-\frac{E^2}{\langle E^2\rangle}}$$

Rayleighjeva porazdelitev



Večpotje z neposrednim žarkom: Rice (E_0, σ)

en velik in mnogo naključnih malih kazalcev



$$\langle E^2 \rangle = E_0^2 + 2\sigma^2$$

Gaussova porazdelitev komponent

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

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

$$E = |E_S|$$

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

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

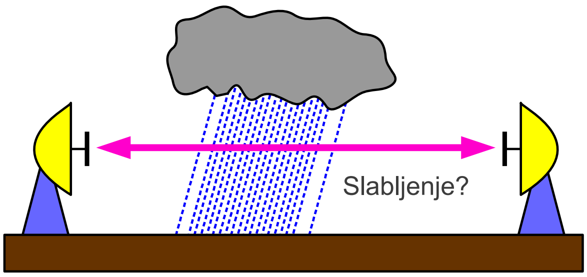
$$p(E_R, E_I) = \frac{1}{\sigma^2 2\pi} e^{-\frac{(E_R-E_0)^2+E_I^2}{2\sigma^2}} = \frac{1}{\sigma^2 2\pi} e^{-\frac{E^2+E_0^2}{2\sigma^2}} e^{\left(\frac{E_R E_0}{\sigma^2}\right)} = \frac{1}{\sigma^2 2\pi} e^{-\frac{E^2+E_0^2}{2\sigma^2}} e^{\left(\frac{E_0 E}{\sigma^2}\right)\cos\phi}$$

Stephen O. Rice 1948

$$p(E) = \int_0^{2\pi} p(E_R, E_I)\, E\, d\phi = \frac{E}{\sigma^2} \mathrm{e}^{-\frac{E^2+E_0^2}{2\sigma^2}} \mathrm{I}_0\left(\frac{E_0 E}{\sigma^2}\right)$$

$$\int_0^{2\pi} e^{\left(\frac{E_0 E}{\sigma^2}\right)\cos\phi} d\phi = 2\pi \mathrm{I}_0\left(\frac{E_0 E}{\sigma^2}\right)$$

Riceova porazdelitev



Vremenski pojavi: log-normalna $(\langle E_{dB}\rangle, \sigma_{dB})$

produkt mnogo naključnih prispevkov
brez interference večpotja

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

Francis Galton ~ 1880

Fizikalno utemeljeno?

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

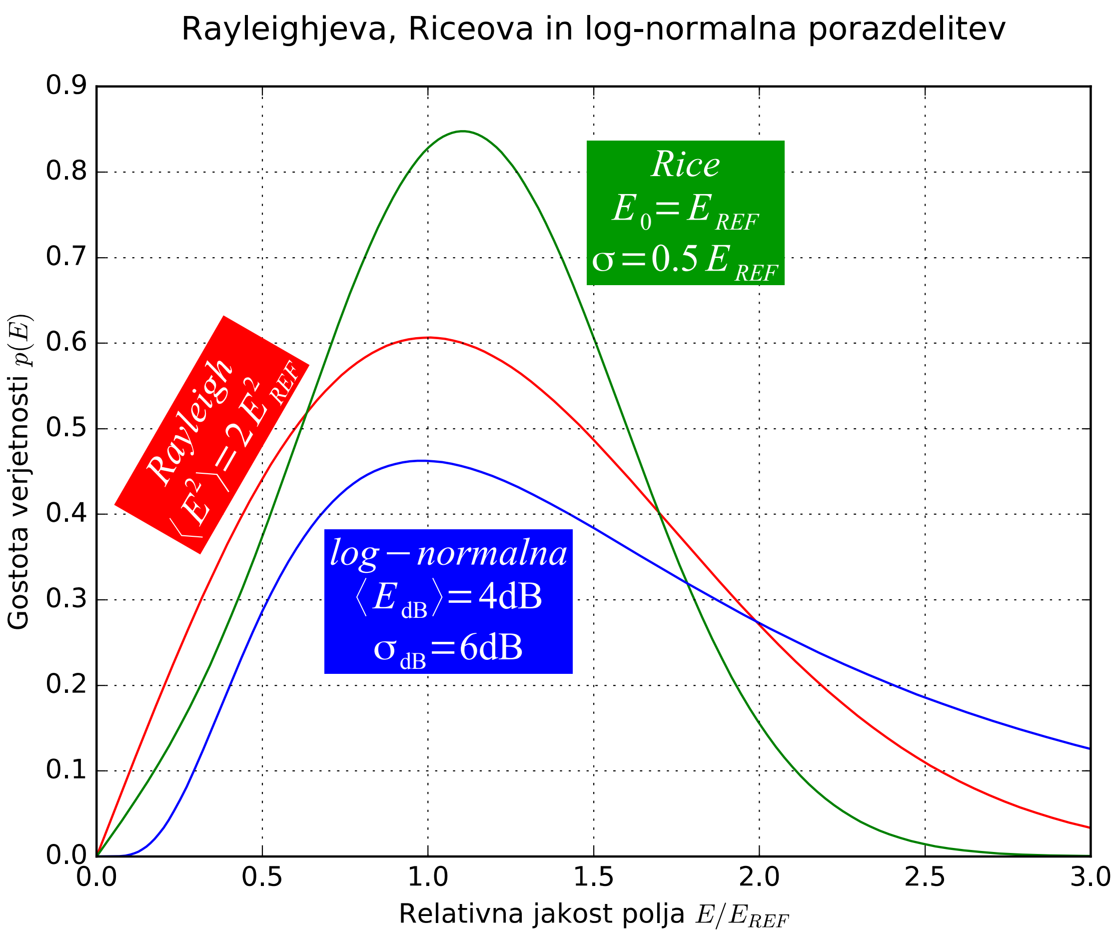
$$\sigma_{dB} = \sqrt{\left\langle \left(E_{dB} - \langle E_{dB}\rangle\right)^2 \right\rangle}$$

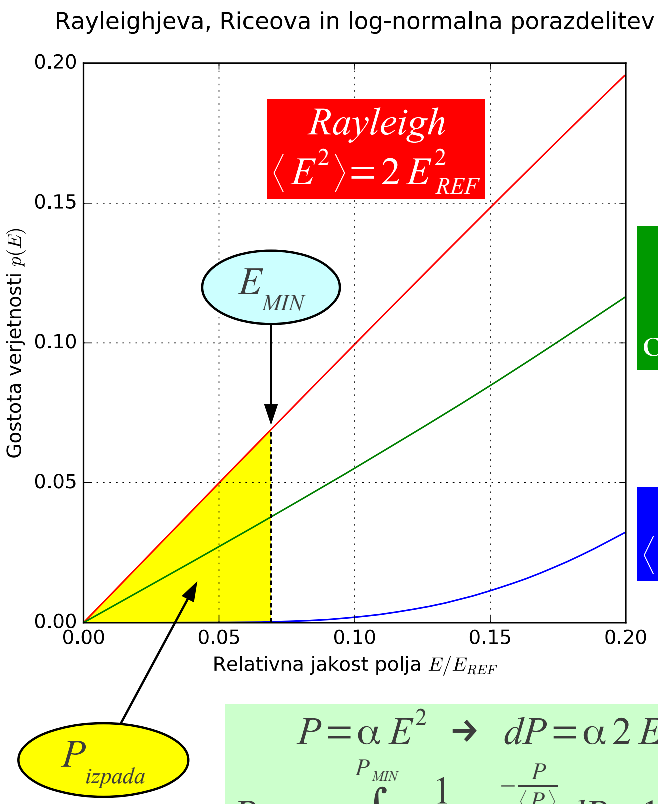
$$\frac{dE_{dB}}{dE} = \frac{20}{\ln 10}\left(\frac{E_{REF}}{E}\right)\frac{1}{E_{REF}} = \frac{20}{E\ln 10}$$

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

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

Log-normalna porazdelitev


Rayleighjeva, Riceova in log-normalna porazdelitev
Gostota verjetnosti $p(E)$
Relativna jakost polja E/E_{REF}
Rice
$E_0 = E_{REF}$
$\sigma = 0.5\,E_{REF}$
Rayleigh
$\langle E^2 \rangle = 2E^2_{REF}$
$log - normalna$
$\langle E_{dB} \rangle = 4dB$
$\sigma_{dB} = 6dB$
0.0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
0.5
1.0
1.5
2.0
2.5
3.0



Rice
$E_0 = E_{REF}$
$\sigma = 0.5\, E_{REF}$

log−normalna
$\langle E_{dB} \rangle = 4\mathrm{dB} \quad \sigma_{dB} = 6\mathrm{dB}$

Pošten račun: Rayleigh

$$P_{izpada} = \int_0^{E_{MIN}} p(E)\, dE$$

$$P_{izpada} = \int_0^{E_{MIN}} \frac{2E}{\langle E^2 \rangle} e^{-\frac{E^2}{\langle E^2 \rangle}} dE$$

$$P_{izpada} = 1 - e^{-\frac{E^2_{MIN}}{\langle E^2 \rangle}}$$

$$P = \alpha E^2 \rightarrow dP = \alpha\, 2E\, dE$$

$$P_{izpada} = \int_0^{P_{MIN}} \frac{1}{\langle P \rangle} e^{-\frac{P}{\langle P \rangle}} dP = 1 - e^{-\frac{P_{MIN}}{\langle P \rangle}}$$

$$P_{MIN} \ll \langle P \rangle \rightarrow P_{izpada} \approx \frac{P_{MIN}}{\langle P \rangle}$$

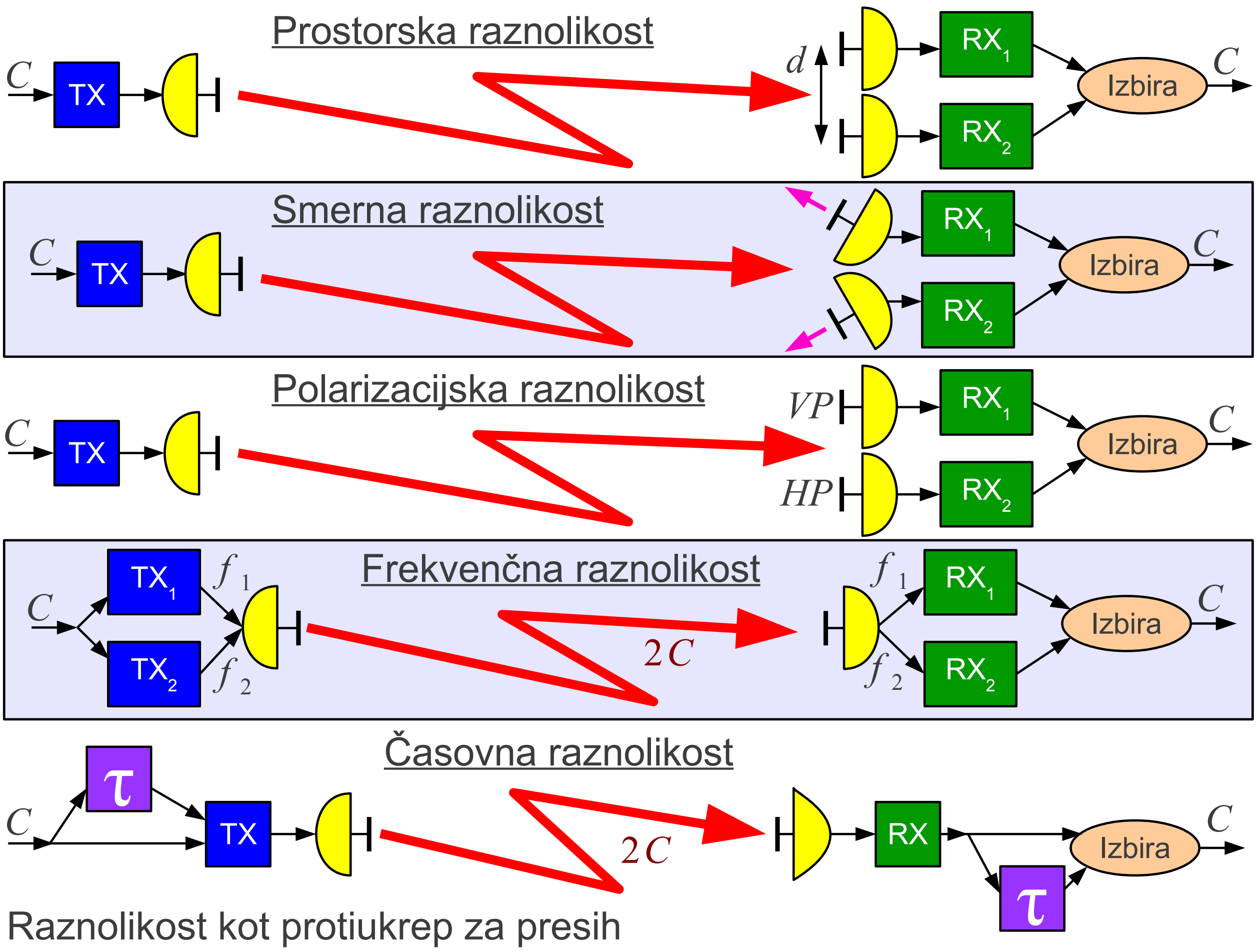
Zgled: mobilni telefon

$$\langle P \rangle = -90\mathrm{dBm} = 1\mathrm{pW}$$

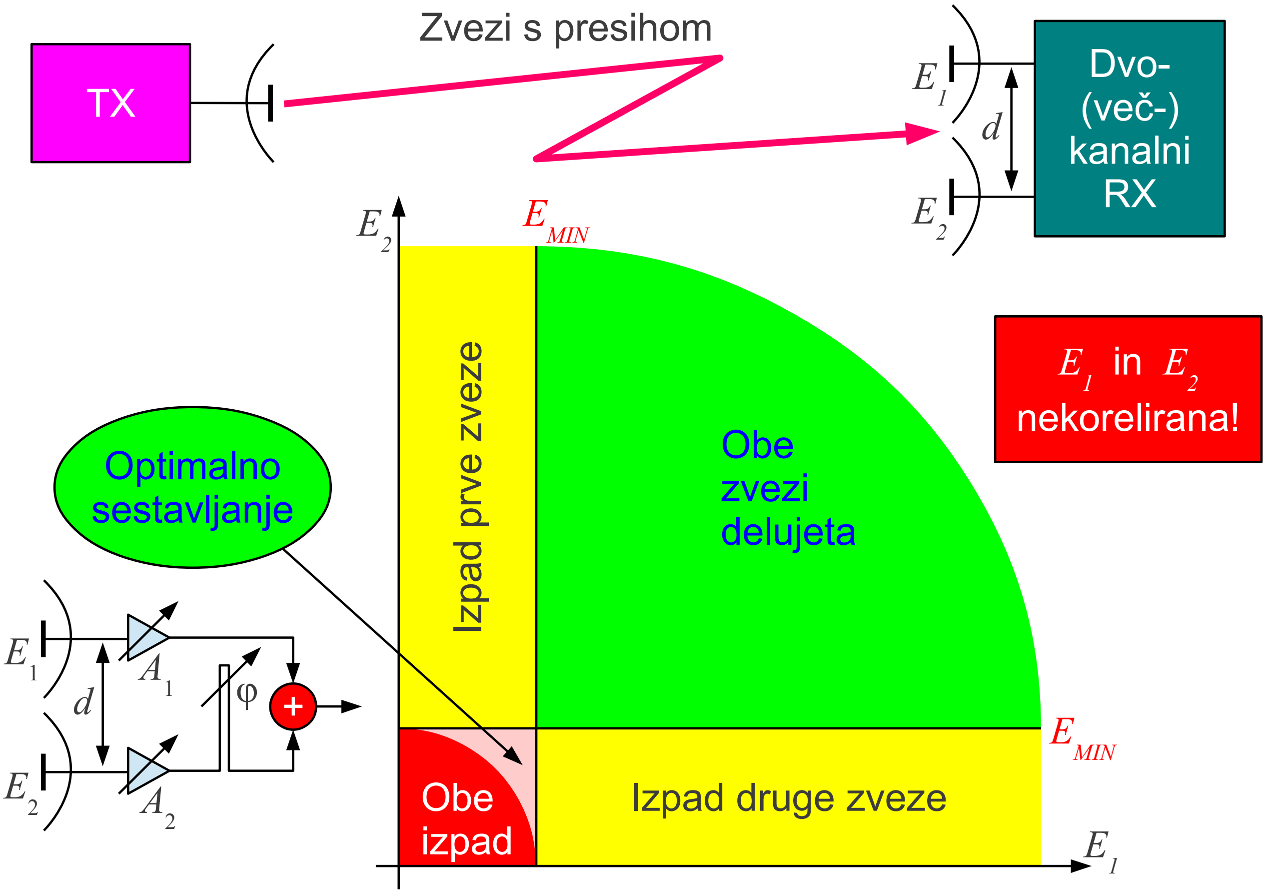
$$P_{MIN} = -105\mathrm{dBm} = 0.032\mathrm{pW}$$

$$P_{izpada} \approx 0.032 \approx 3\%$$

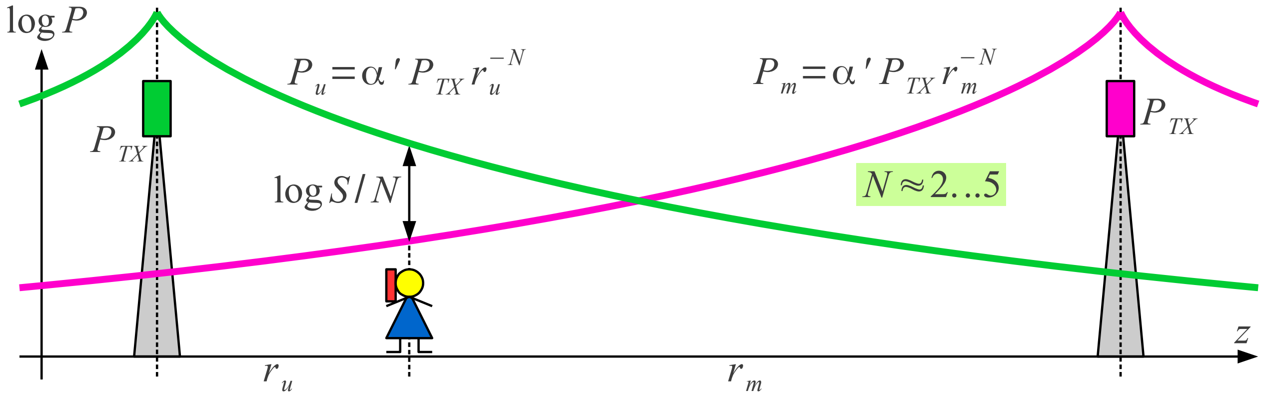
Izračun verjetnosti izpada zveze



Raznolikost kot protiukrep za presih



Pogostnost izpada pri nekoreliranem sprejemu



Mestno okolje brez vidljivosti

$$3 \leq N \leq 5$$

$$P_{RX} = P_{TX} G_{TX} G_{RX} \alpha(\lambda) h_{TX}^2 h_{RX}^2 d^{-N}$$

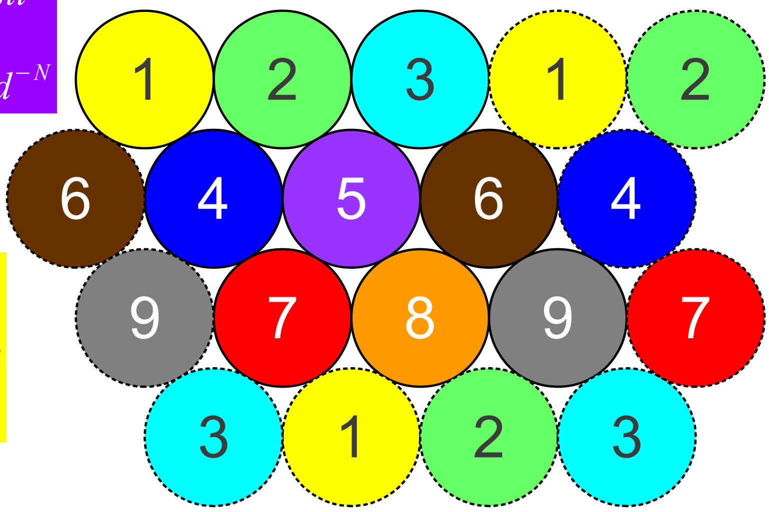
$$S/N = \frac{P_u}{P_m} = \left(\frac{r_m}{r_u}\right)^N$$

Primer: $N = 4$

$$S/N = 28\mathrm{dB} = 625$$

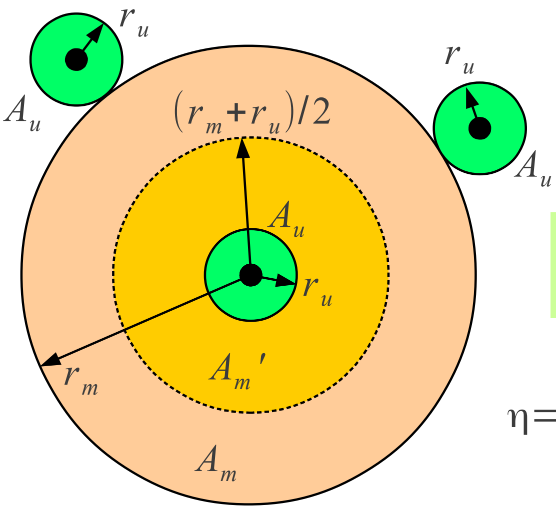
z rezervo presiha!

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



Ponovna uporaba spektra

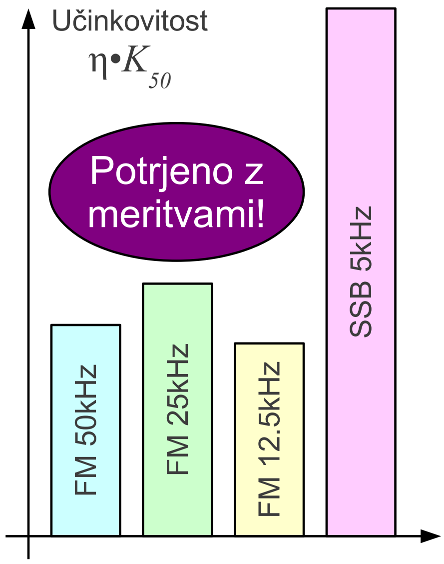
Modulacija	K_{50}	Koleb Δf	$m=\Delta f/B_u$	$3m^2$	r_m/r_u	η	$\eta \cdot K_{50}$	Ocena
FM 50kHz	1	±15kHz	5	75	1.08	0.929	0.929	FM prag?
FM 25kHz	2	±6kHz	2	12	1.70	0.549	1.098	Dober!
FM 12.5kHz	4	±1.5kHz	0.5	0.75	3.40	0.207	0.827	Slab!
SSB 5kHz	10	$B_R=B_u=3$kHz		1	3.16	0.231	2.309	Presluh?



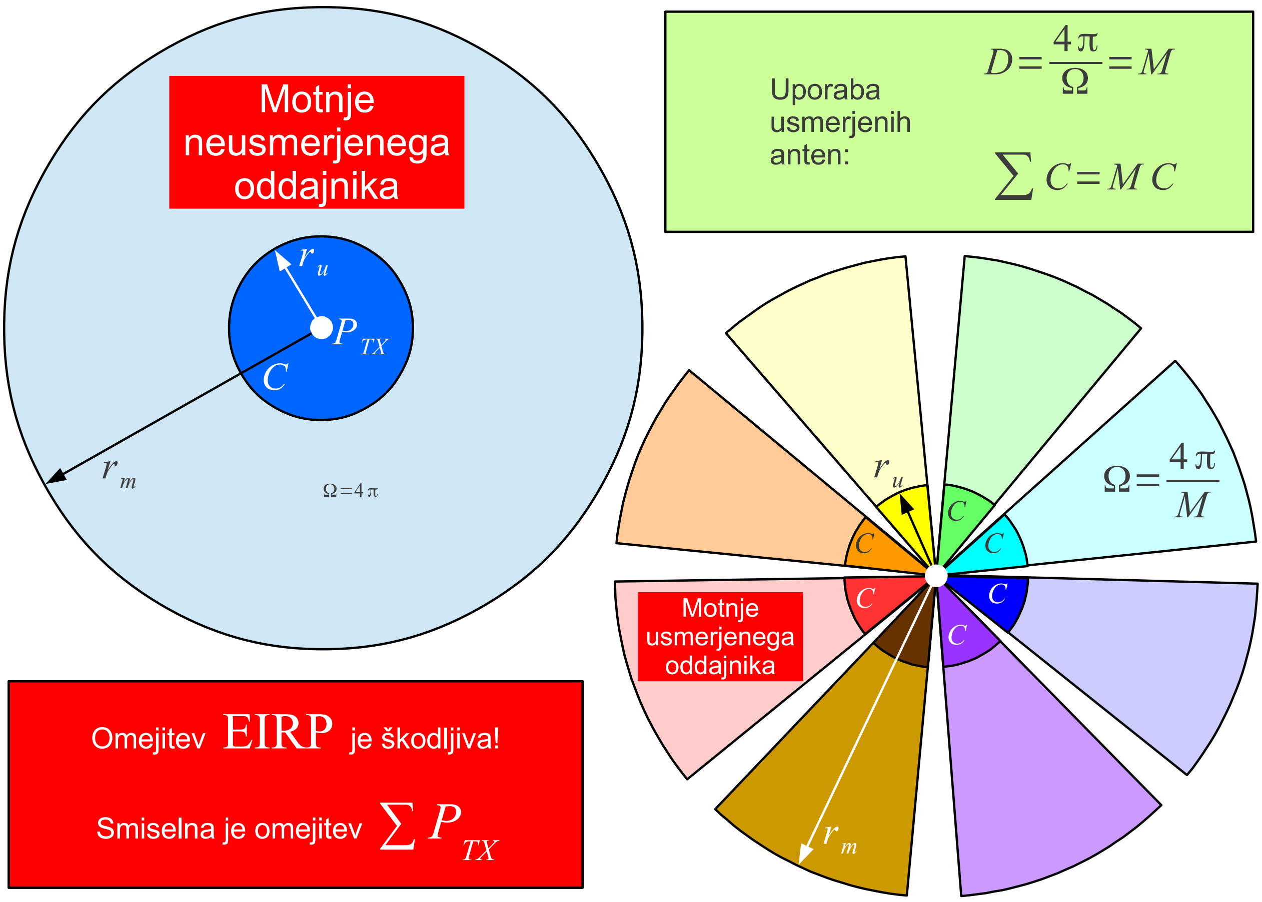
Primer:
$N=4$
$S/N=100$

$$\frac{r_m}{r_u}=\sqrt[N]{\frac{S/N}{3m^2}}$$

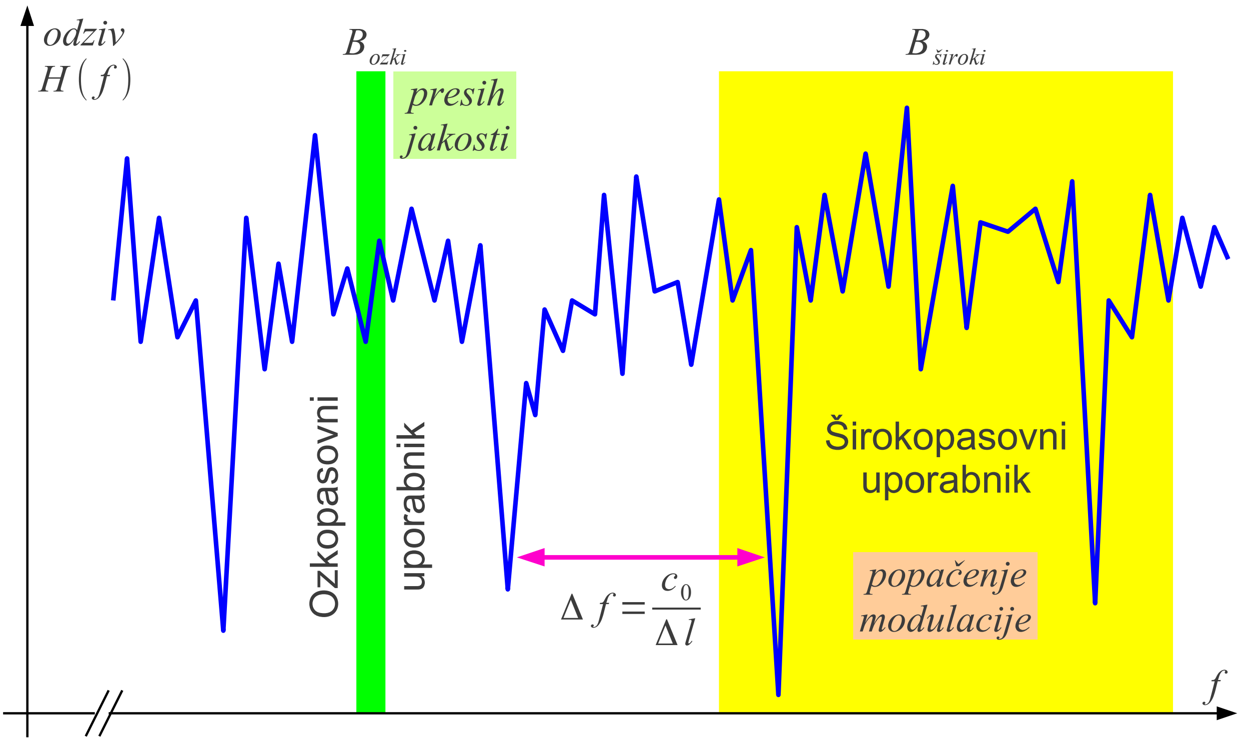
$$\eta=\frac{A_u}{A_m'}=\left(\frac{2}{1+\frac{r_m}{r_u}}\right)^2$$



Izbira učinkovite modulacije



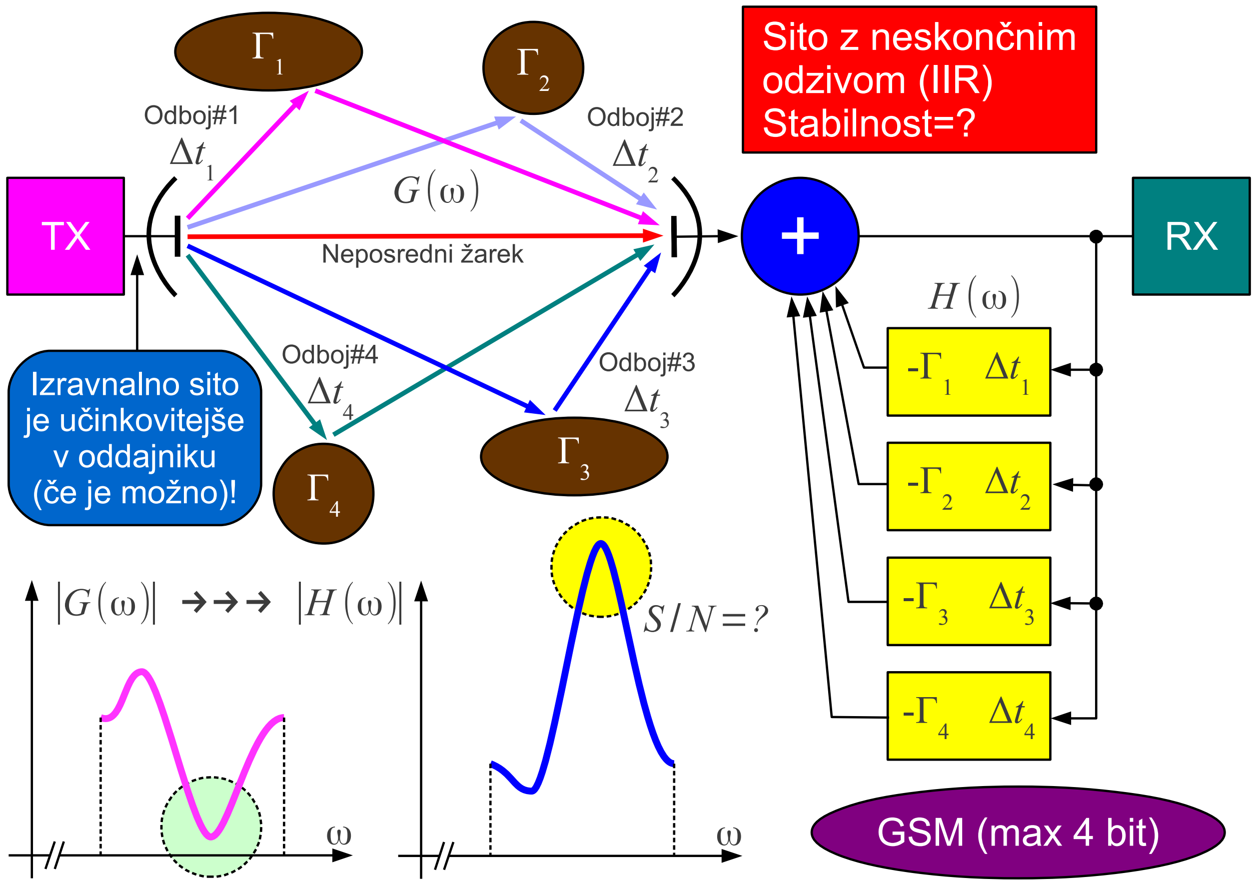
Povečanje zmogljivosti z usmerjenimi antenami



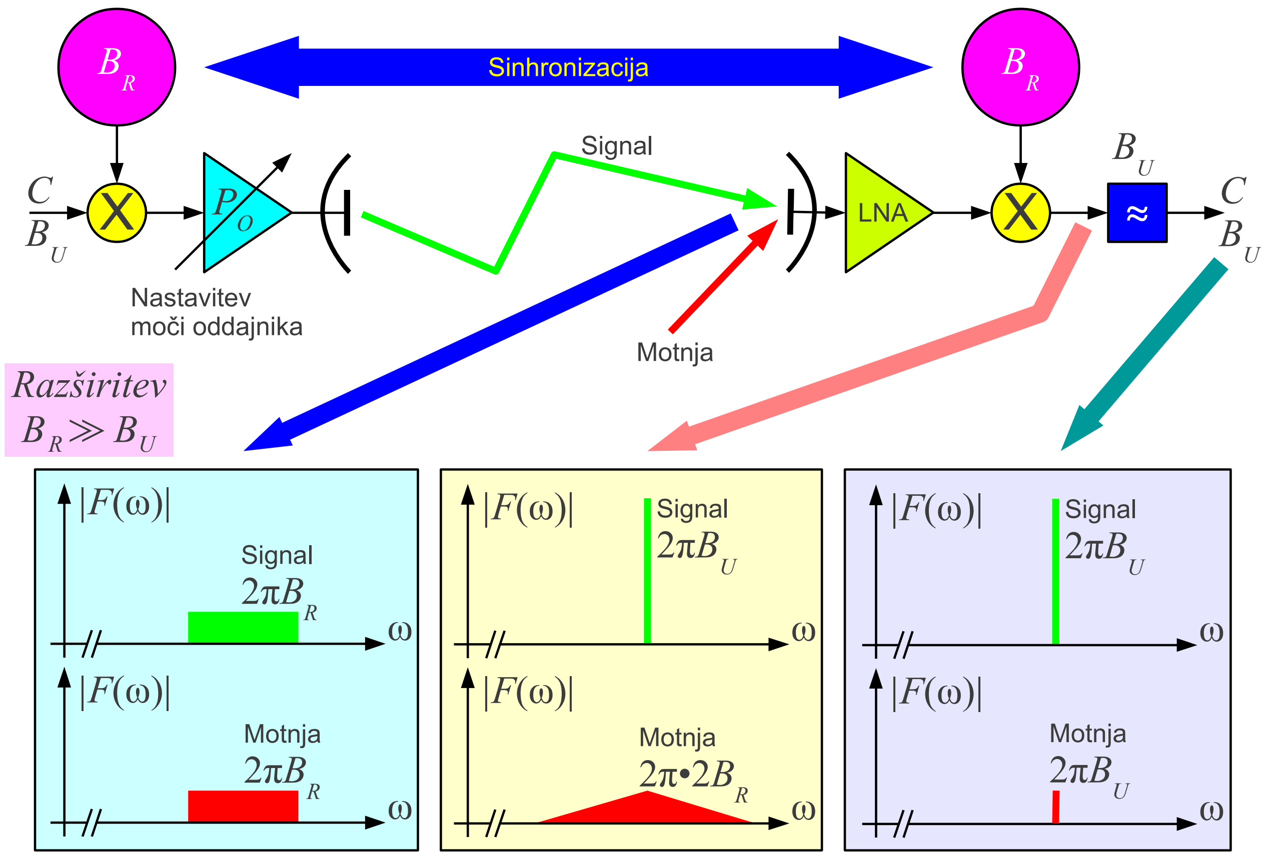
$B_{ozki} \ll \Delta f \ll B_{široki}$

Mestno okolje $f_0 \approx 450\text{MHz}$
$\Delta l = 200\text{m}...1.5\text{km}$
$\Delta f = 1.5\text{MHz}...200\text{kHz}$

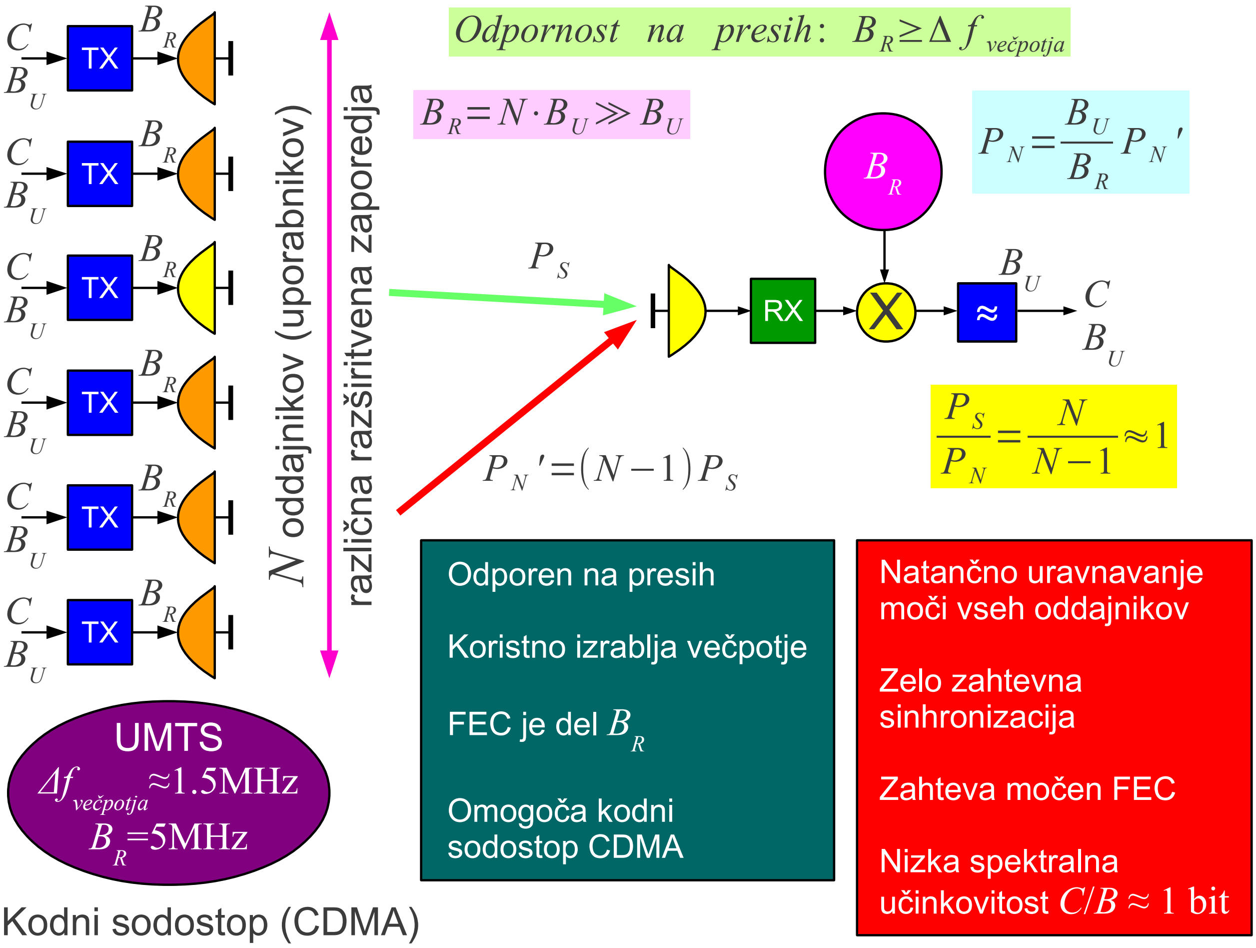
Večpotje v frekvenčnem prostoru



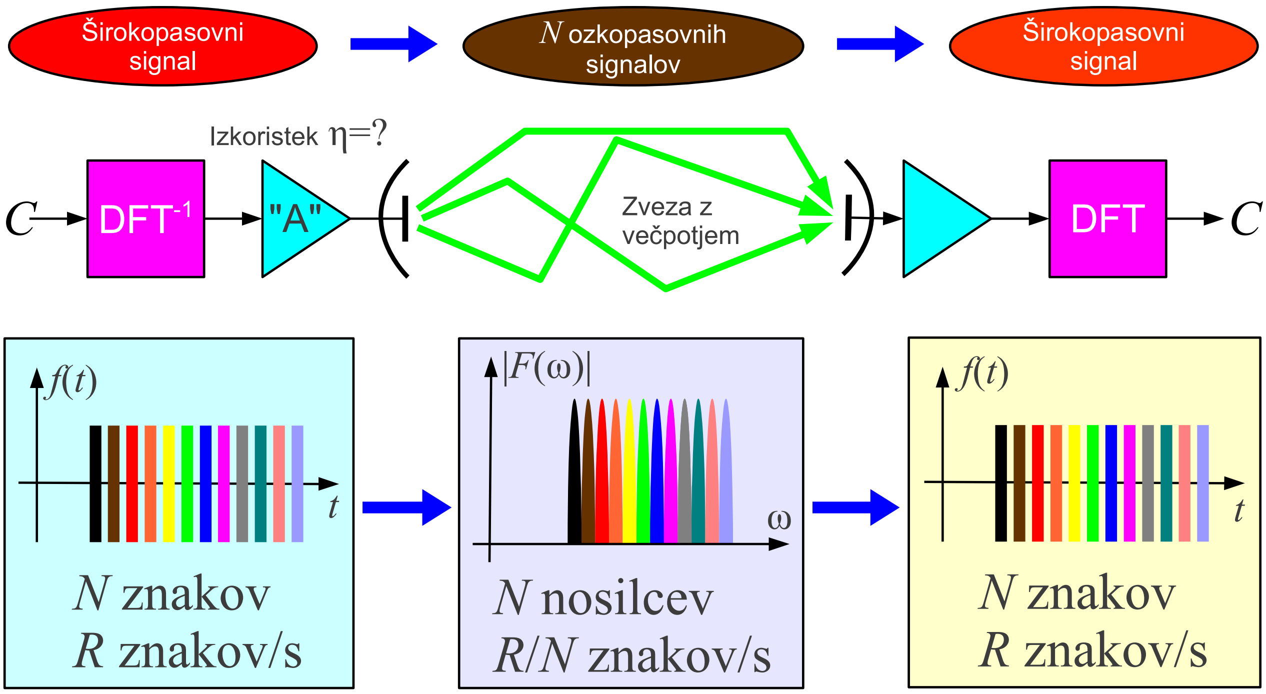
Odpravljanje popačenja večpotja z izravnalnim sitom



Razširjeni spekter (Spread spectrum)



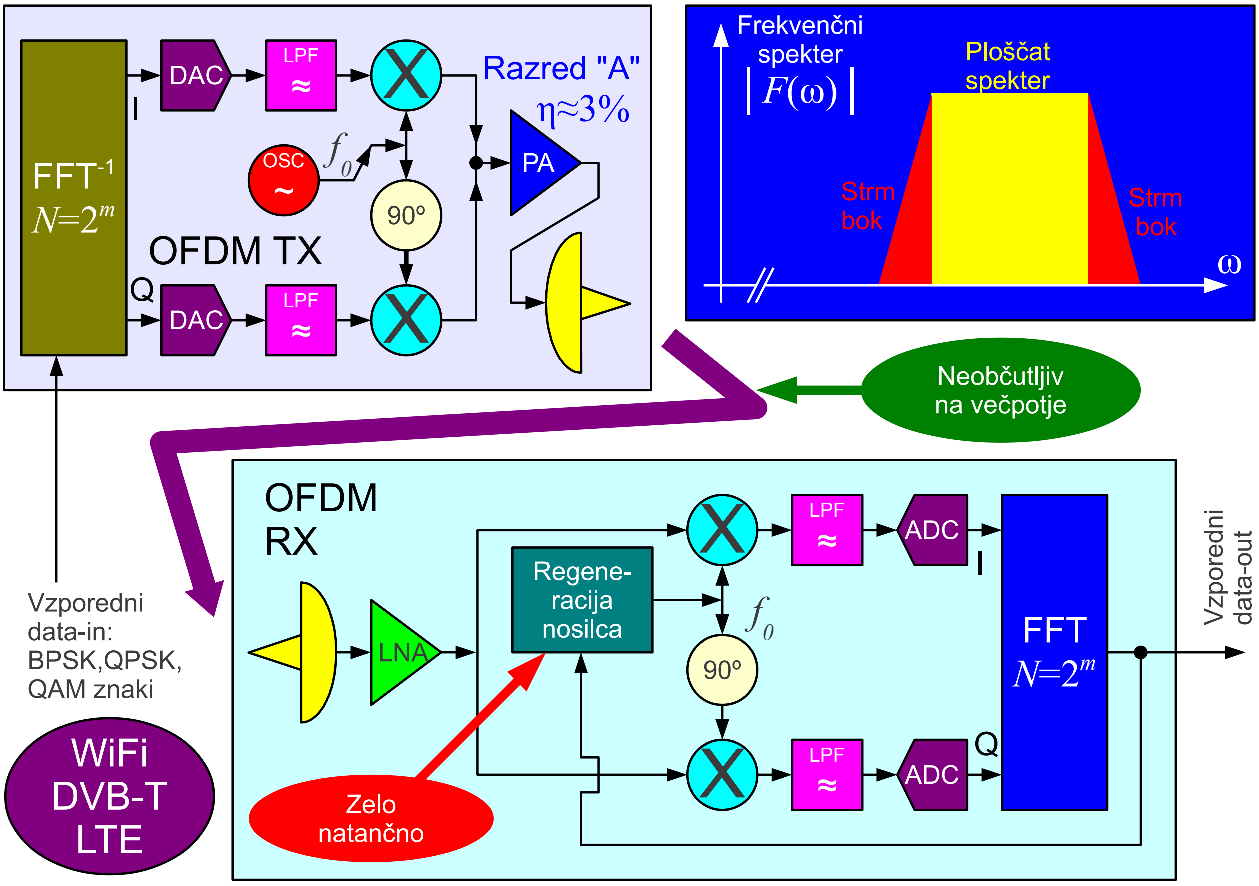
Kodni sodostop (CDMA)



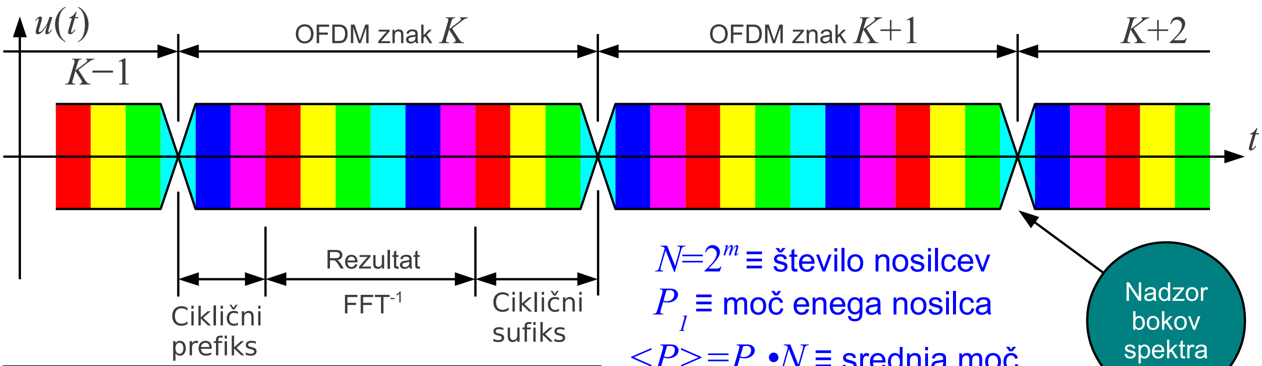
~1950 analogni večtonski modem za ionosferske zveze

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

Večtonski modem kot protiukrep za popačenje večpotja



Orthogonal Frequency-Division Multiplex (OFDM)



$N=2^m$ ≡ število nosilcev

P_1 ≡ moč enega nosilca

$<P>=P_1 \cdot N$ ≡ srednja moč

$P_{MAX}=P_1 \cdot N^2$ ≡ vršna moč

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

Nastavljiva odpornost na $\Delta t_{večpotja}$

Skoraj pravokoten frekvenčni spekter

Zadošča šibek FEC

Spektralni izkoristek C/B dosega teoretske vrednosti BPSK, QPSK, QAM

Omogoča enofrekvenčna omrežja SFN (Single-Frequency Network)

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

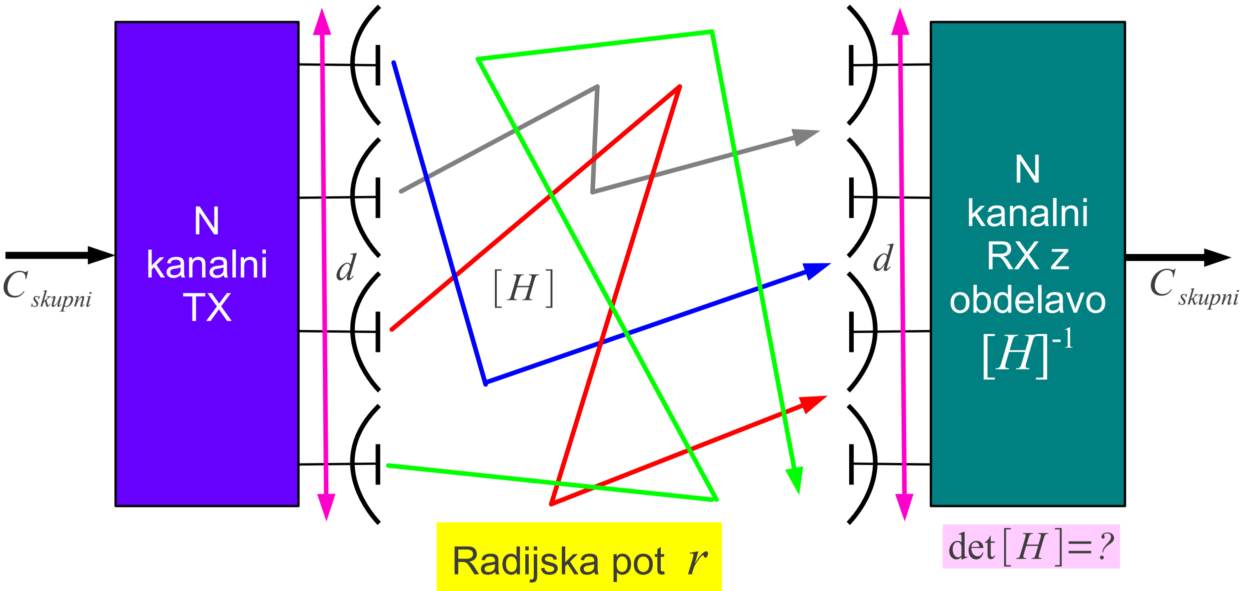
FFT zahteva $N \cdot \log_2 N$ računskih operacij

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

Lastnosti OFDM



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: $C/B \approx 10$ bit

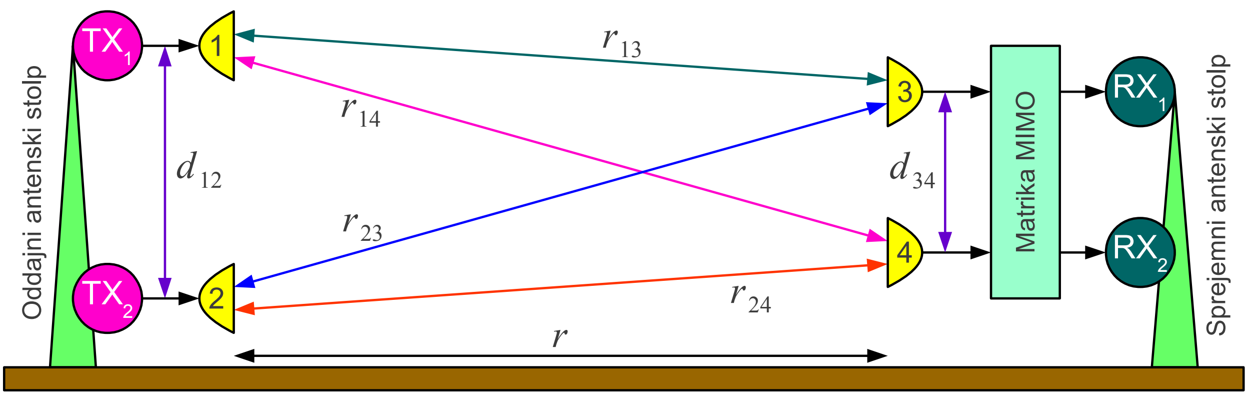
(–) zahteva N oddajnih anten in N sprejemnih anten

(+) 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 ≡ 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:

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

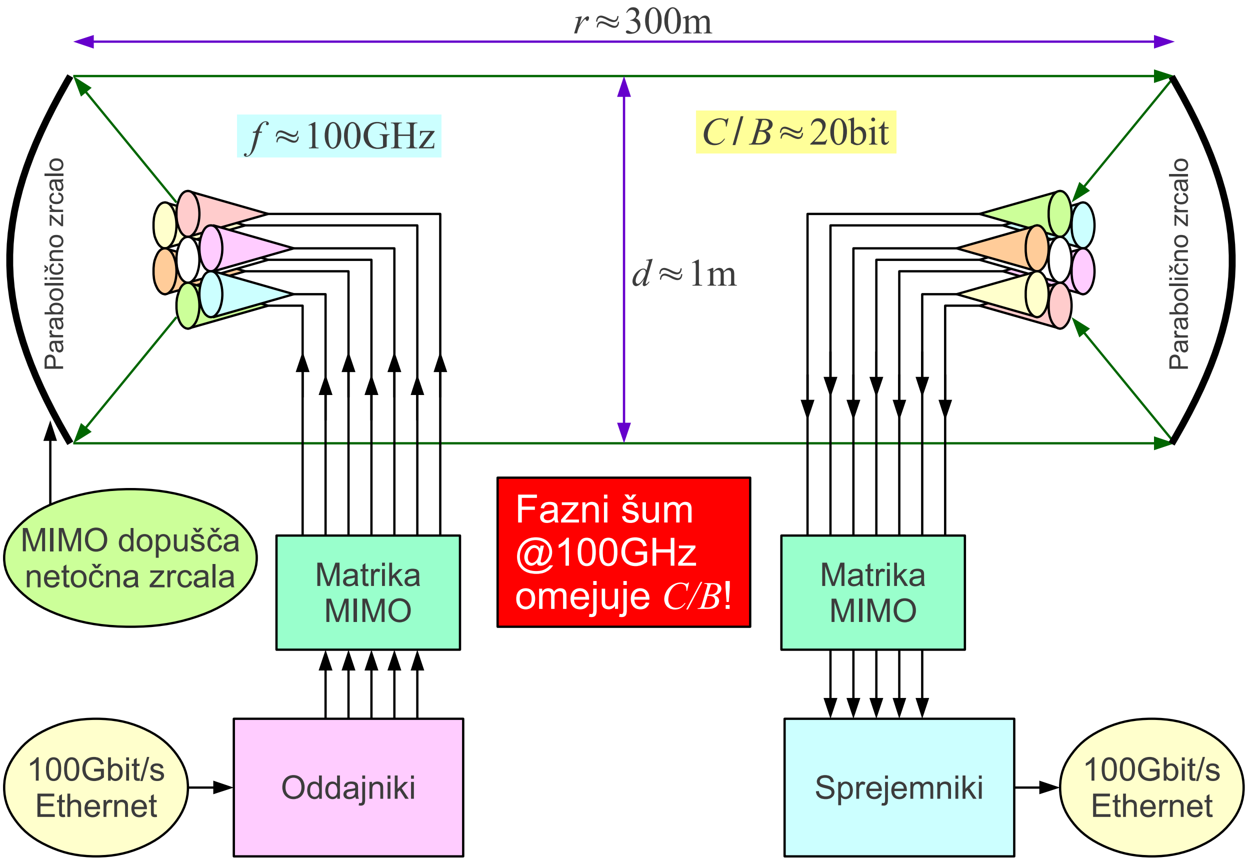
$\lambda=c_0/f=2\text{cm}$

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

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

Preizkus:

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



Visokozmogljiva zveza na kratko razdaljo

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