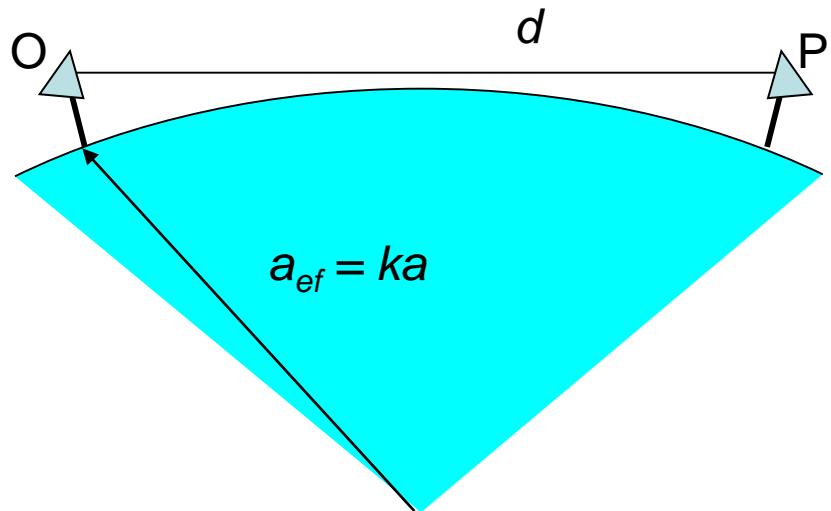


FAKULTET ELEKTROTEHNIKE, STROJARSTVA I BRODOGRADNJE SPLIT

Mjerenja u bežičnim sistavima

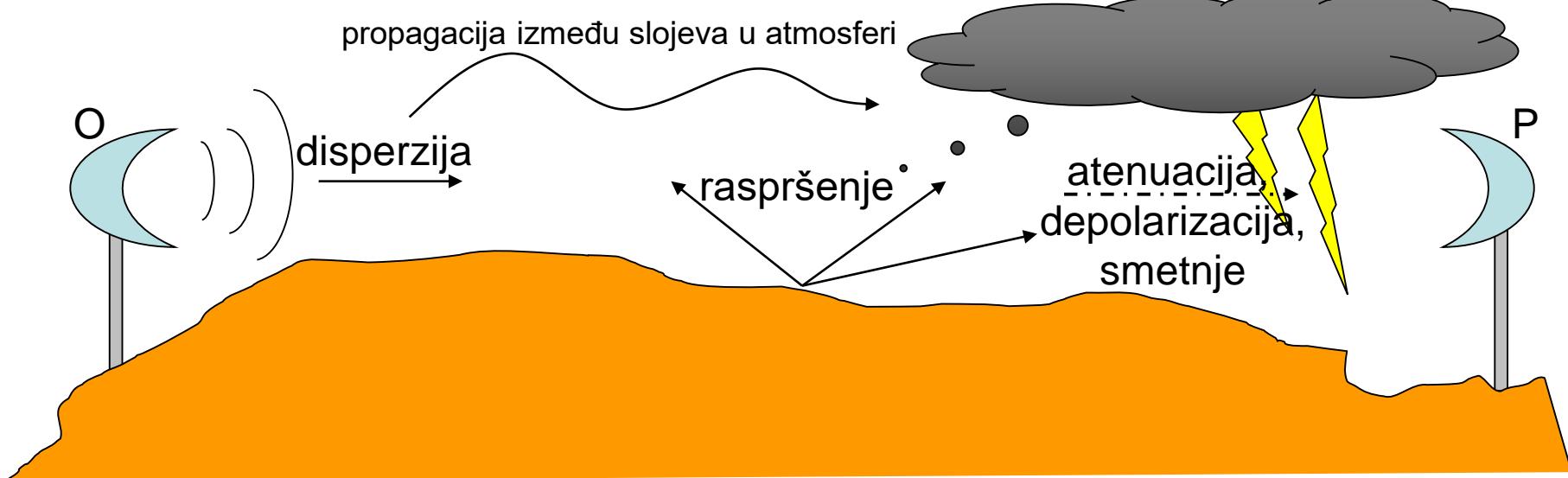
Zoran Blažević

1. Parametri fiksnih radio-linkova



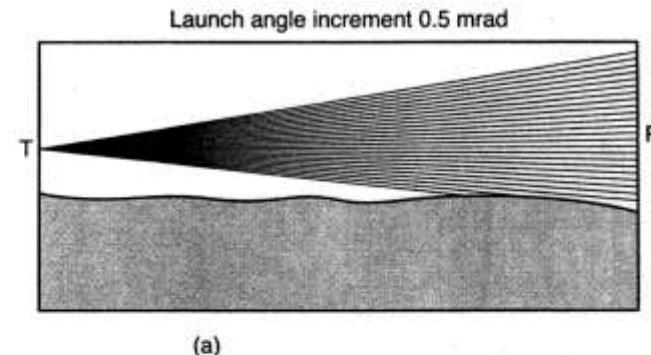
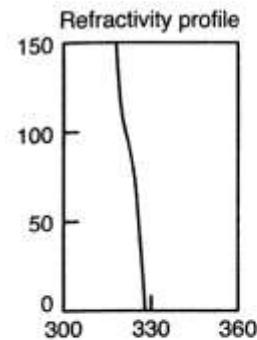
$$k = \frac{1}{1 + a \frac{dN}{dh} \cos \alpha}$$

Za standardnu atmosferu i komunikaciju blizu površine Zemlje:
 $k = 4/3$, $dN/dh = -40$ N-jed/km

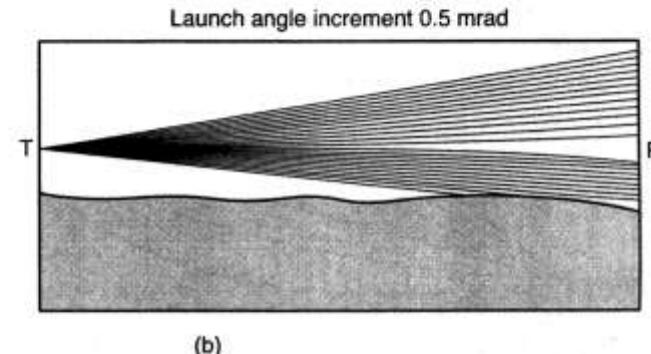
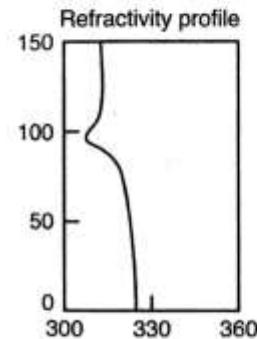


Sporo-promjenjivi feeding

a) "clear-sky" scenarij (čiste atmosfere):



b) defokusiranje (širenje radio-zrake):



c) "high-low" scenarij:

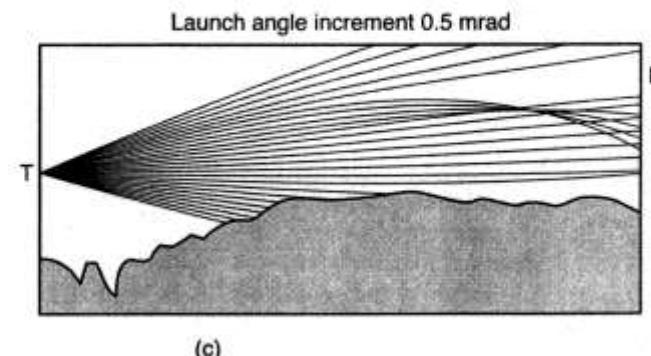
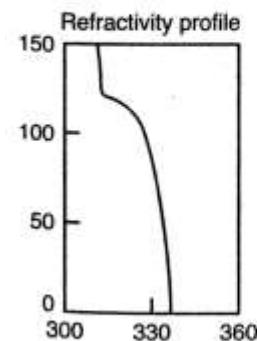
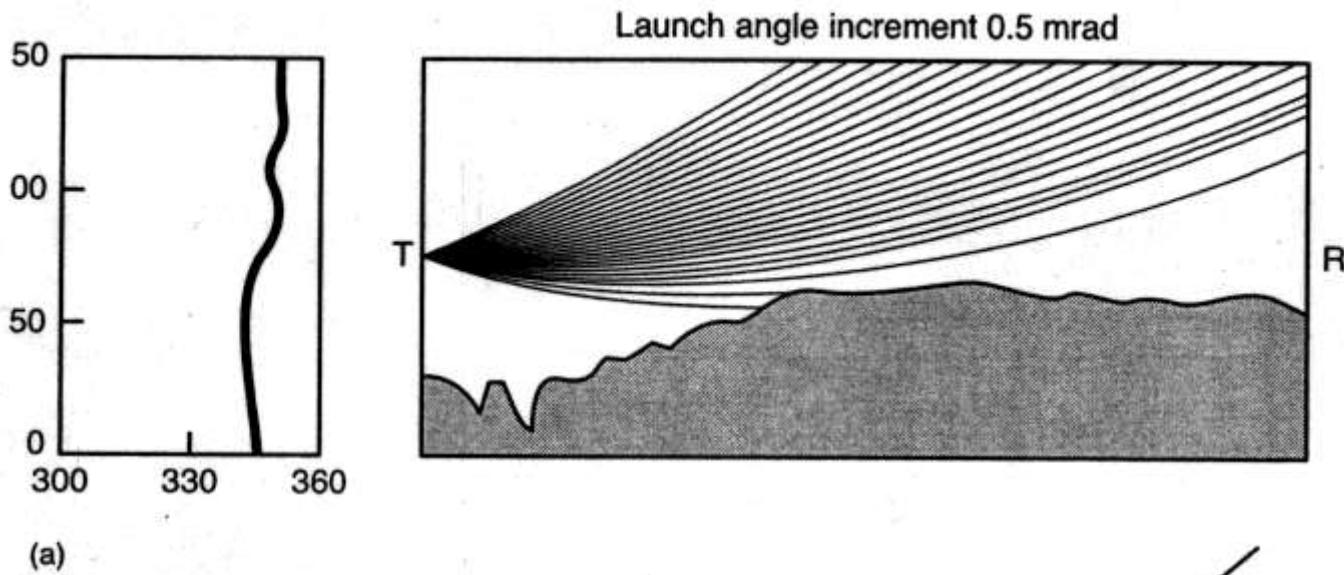


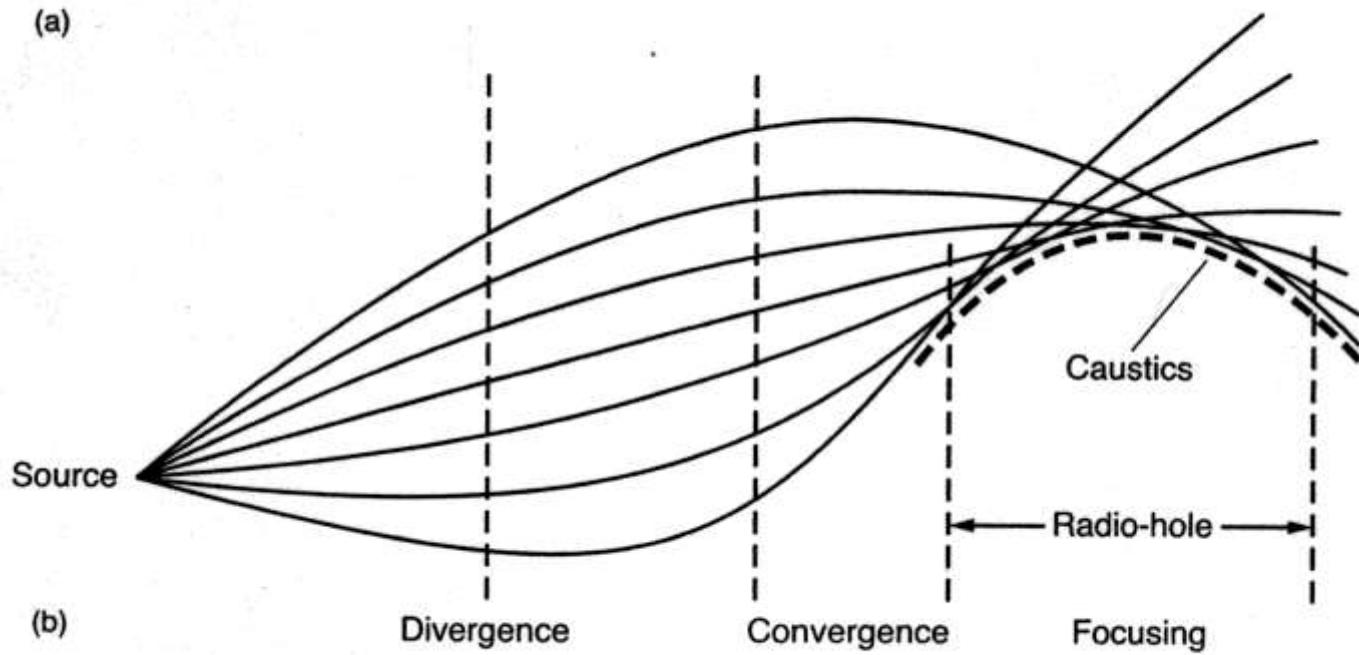
FIGURE 2.5 Ray-tracing diagrams for a range of refractivity profiles: (a) clear-sky situation, (b) defocusing event, and (c) high-low situation.

d) opstrukcija uslijed tla u subrefraktivnoj troposferi:



(a)

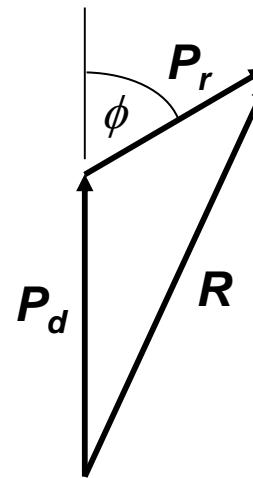
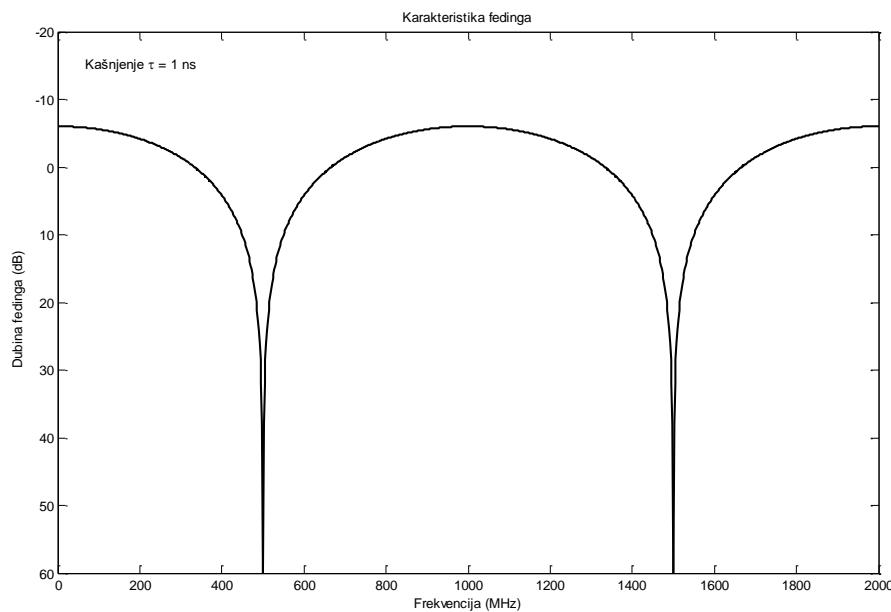
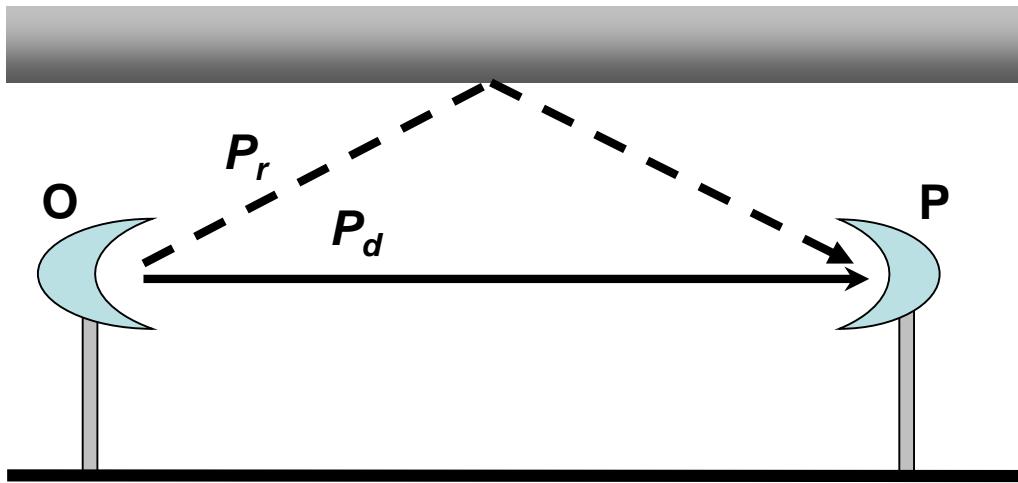
e) "radio-jama:"



(b)

FIGURE 2.6 (a) Ray-tracing diagrams for a subrefractive profile. (b) Graphic representation of certain refractivity concepts. (From CCIR Report 718-3 by kind permission of the ITU.)

Frekvencijski selektivan feeding



$$\phi = 2\pi c \tau$$

$$R^2 = P_d^2 + P_r^2 + 2P_d P_r \cos \phi$$

Efekt fedinga na performase fiksnih radijskih veza

- **Analogni sustavi velikog kapaciteta:** većinom su uskopojasni i nisu osjetljivi na distorziju izazvanu višestaznom propagacijom (osim u slučaju dubokih višestaznih ureza koji mogu povećati interferenciju susjednih kanala-ACI), te je jedini faktor koji doprinosi degradaciji performansi sustava **dubina fedinga**. Granica pri kojoj SNR degradira do stupnja u kojem je sustav neupotrebljiv naziva se **sistemska granica ravnog fedinga**.
- **Digitalni sustavi:** granica ravnog fedinga definira se na isti način kao i kod analognih sustava, osim što se kao parametar koji određuje performanse sustava uzima BER. Međutim, za razliku od analognih sustava, digitalni sustavi visokog kapaciteta su širokopojasni, tako da ravni feding uzrokuje tek nešto više od pojačane osjetljivosti sustava na višestazni, frekvencijski selektivan feding. Granica širine pojasa kanala pri kojoj digitalni radio signal postaje podložan distorziji uslijed frekvencijski selektivnog fedinga naziva se **koherentni pojas kanala**. Iznos koherentnog pojasa je, u pravilu, u visokoj korelaciji sa standardnom devijacijom kašnjenja (rasipanjem kašnjenja), koja se dobije iz karakteristike impulsnog odziva kanala.

Mjerenje Riceovog K-faktora kod fiksnih radijskih linkova

$$p(r; K) = \frac{r}{\sigma^2} e^{-\frac{r^2}{2\sigma^2}} e^{-K_f} I_0\left(\frac{\mu}{\sigma^2} \sqrt{2K}\right)$$

- Riceova distribucija

σ_f^2 - varijanca signala uslijed fedinga

σ_n^2 - varijanca signala uslijed šuma

A - amplituda izravne komponente (konstantna veličina)

$$K_f = \frac{A^2}{2\sigma_f^2}$$

- Riceov K-faktor uslijed fedinga

$$\rho = \frac{A^2}{2\sigma_n^2}$$

- omjer signal-šum (SNR)

$$K_{mj} = \frac{A^2}{2(\sigma_n^2 + \sigma_f^2)}$$

- ukupni mjereni Riceov K-faktor

$$K_f = \frac{K_n K_{mj}}{K_n - K_{mj}}$$

$$\text{Kalibracija mjernog sustava: } K_n = \frac{A^2}{2\sigma_n^2} = \rho$$

Prije mjerjenja Riceovog K-faktora potrebno je izvršiti kalibraciju u cilju eliminacije šuma iz mjerenih rezultata. Pri tome treba ispuniti uvjet $\rho = K_n \gg K_f$.

2. Parametri mobilnih sustava

- Klasifikacija propagacijskog okoliša: gubici propagacije, stupanj radio-sjene (gušenje izravnog vala uslijed transmisije)-urbani, suburban i ruralni (otvorene sredine); unutrašnjost zgrada i ostalih objekata (zatvorene sredine);
- Ćelijski radijski sustavi (zemaljski-obično male i srednje ćelije, satelitski-makroćelije, zatvoreni prostori-pikoćelije): faktor reupotrebe frekvencije
- Uskopojasni sustavi: prosječno trajanje fedinga (AFD), brzina prelaska razine (LCR)
- Širokopojasni sustavi: rasipanje kašnjenja, koherentni pojas kanala (gornja granica brzine prijenosa), koherentno vrijeme kanala (donja granica brzine prijenosa i ovisi o brzini promjene propagacijskih uvjeta u radio-kanalu)

- Gubici propagacije: $L^{[\text{dB}]} = -10 \log G_R = -10 \log \frac{P_P}{P_0}$ (izotropne antene)
- Stupanj radio-sjene u dB: (obično normalne razdiobe)

$$L_S^{[\text{dB}]} = 10 \log \frac{P_P}{P_{FS}}; \quad P_{FS} = P_o \left(\frac{\lambda}{4\pi d} \right)^2$$

- Brzina prelaska granice fedinga (LCR): $N(R) = \int_0^{\infty} r p(R, r) dr$ (f_m – maksimalni Dopplerov pomak)

$$N(R) = \sqrt{\frac{\pi}{\sigma^2}} R f_m e^{-\frac{R^2}{2\sigma^2}}$$

- Prosječno trajanje fedinga (AFD) za razinu $r = R$:

$$T(R) = \frac{P(r \leq R)}{N(R)}$$

$$T(R) = \frac{R}{2\sqrt{\pi} f_m \sigma} \left[\exp\left(-\frac{R^2}{2\sigma^2}\right) - 1 \right] \approx \frac{1}{2\sqrt{\pi}} \frac{\lambda}{v} \frac{R}{\sigma}$$

Statistički parametri kanala COST 207

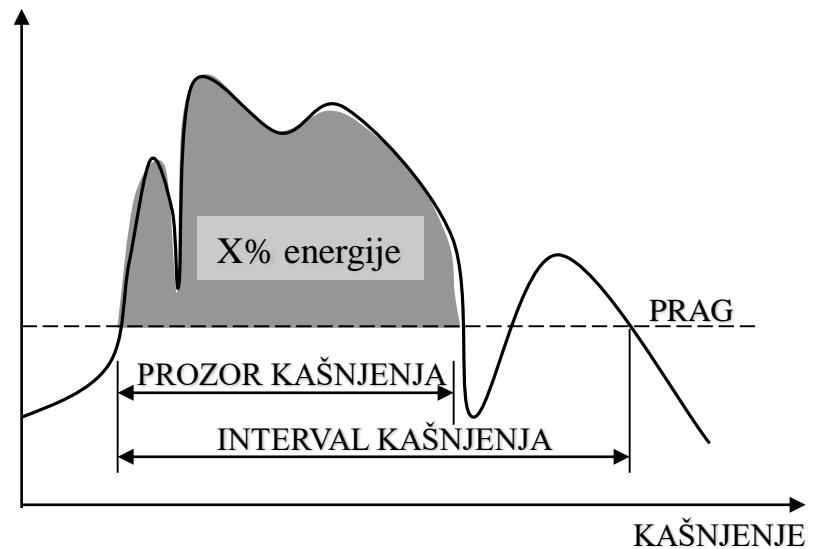
- prosječno prekoračenje kašnjenja

$$\mu_\tau(t) = \int_0^\infty \tau P_h(\tau, t) d\tau; \quad P_h(\tau, t) = |h(\tau, t)|^2$$

- standardna devijacija ili rasipanje kašnjenja

$$\sigma_\tau(t) = \sqrt{\int_0^\infty [\tau - \mu_\tau(t)]^2 P_h(\tau, t) d\tau}$$

- prozor kašnjenja



- interval kašnjenja
(maksimalno prekoračenje kašnjenja)

Koherentni pojas kanala

$$A_c(\Delta f) = \Im[\mathbf{h}(\tau) \cdot \mathbf{h}^*(\tau)] = \Im[|\mathbf{h}(\tau)|^2]$$

$$|A_c(\Delta f = B_c)| = C \cdot P, \quad C - \text{korelacijski prag}$$

$$B_c \triangleq \frac{1}{\sigma_\tau} \quad \text{- koherentni pojas}$$

$$\sigma_\tau = \sqrt{\int_0^\infty (\tau - \mu)^2 |\mathbf{h}(\tau)|^2 d\tau} \quad \text{- rasipanje kašnjenja (standardna devijacija kašnjenja)}$$

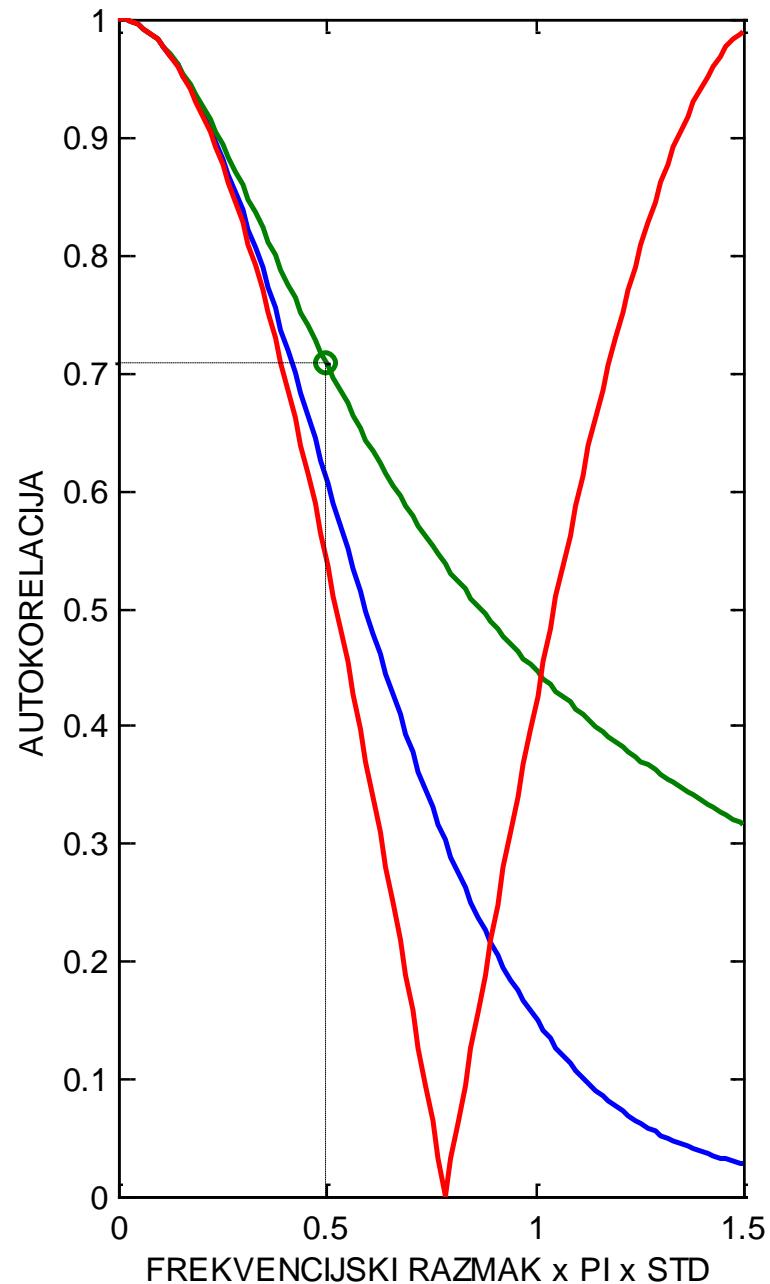
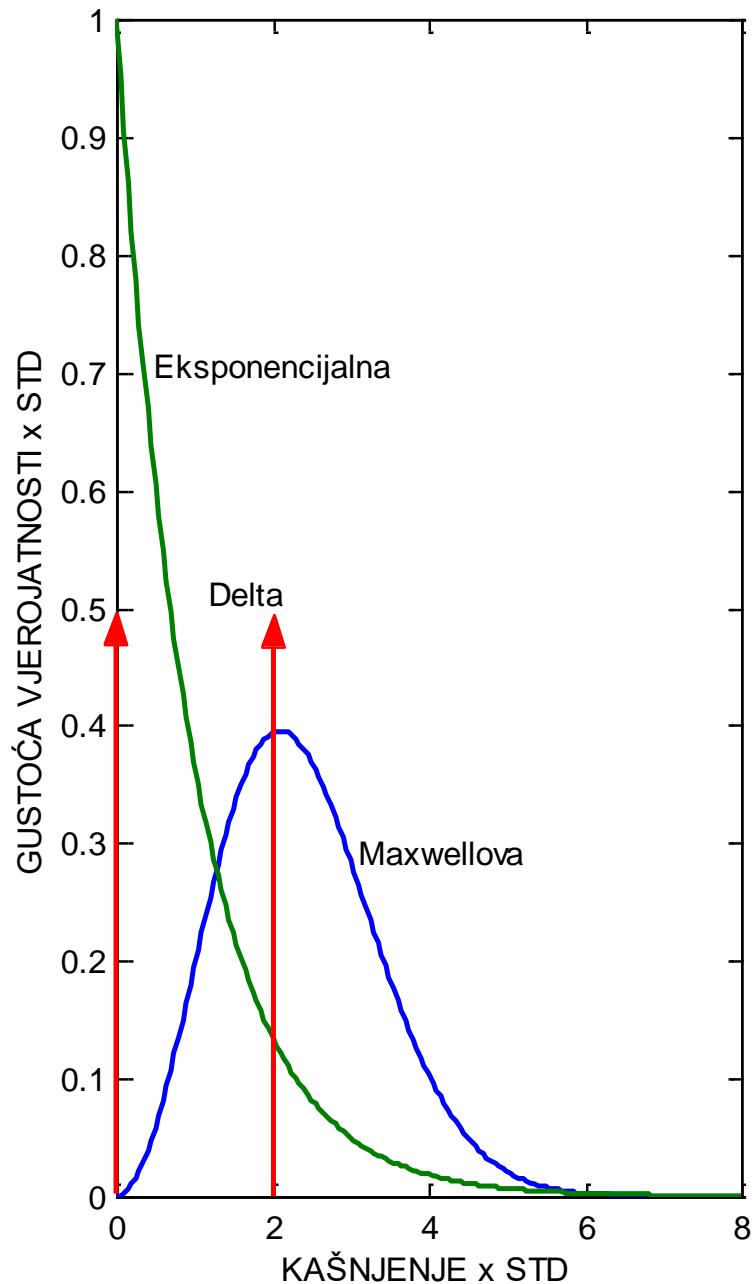
$$\mu_\tau = \int_0^\infty \tau |\mathbf{h}(\tau)|^2 d\tau \quad \text{- prosječno prekoračenje kašnjenja}$$

$$P_h(\tau) = |\mathbf{h}(\tau)|^2 = \frac{1}{\sigma_\tau} \exp\left(-\frac{\tau}{\sigma_\tau}\right) \quad \text{- čest oblik karakteristike prosječnog profila snage}$$

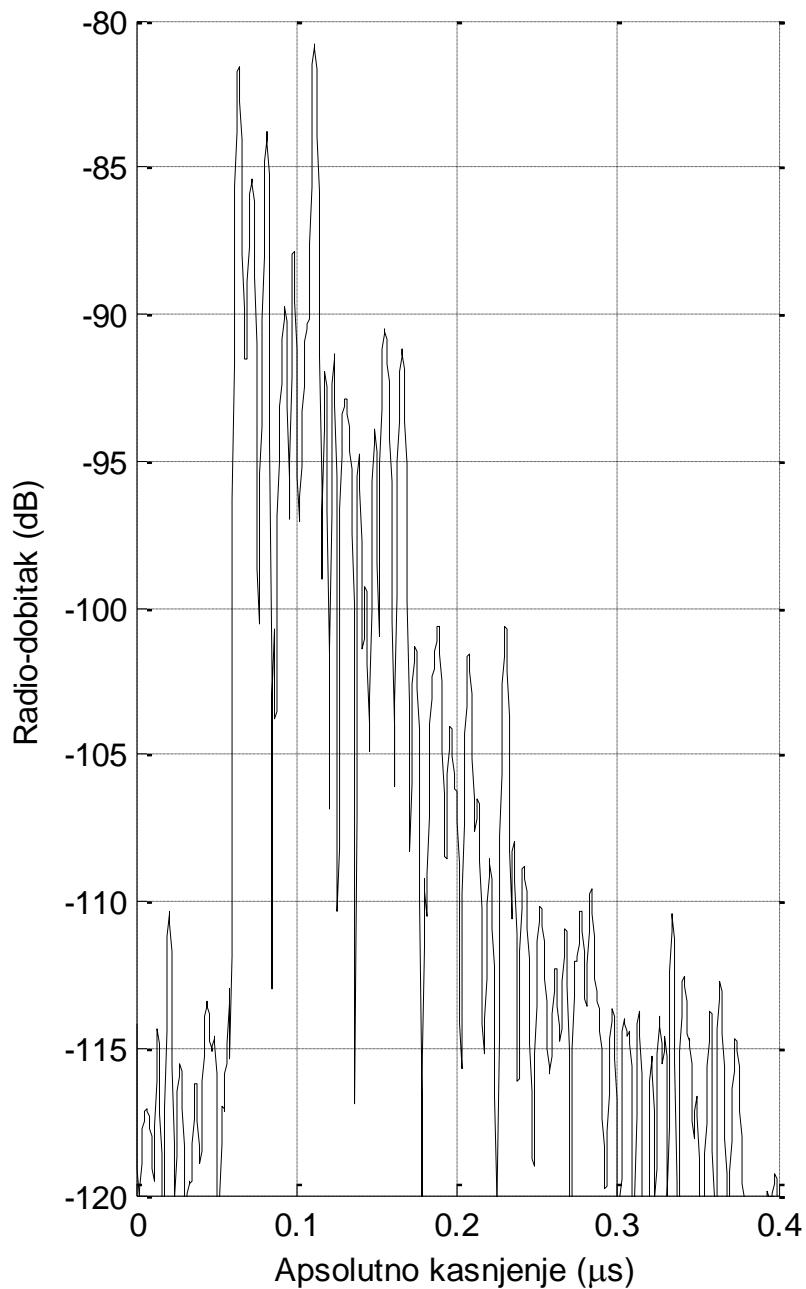
$$A_c(\Delta f) = \Im[P_h(\tau)] = \frac{1}{1 - j2\pi\sigma_\tau \cdot \Delta f} \Rightarrow |A_c(\Delta f)| = \frac{1}{\sqrt{1 + (2\pi\sigma_\tau \cdot \Delta f)^2}};$$

$$|A_c(\Delta f)| \Big|_{\Delta f = B_c} = C, \quad C = \frac{1}{\sqrt{2}} \Rightarrow \boxed{B_c = \frac{1}{2\pi\sigma_\tau}}$$

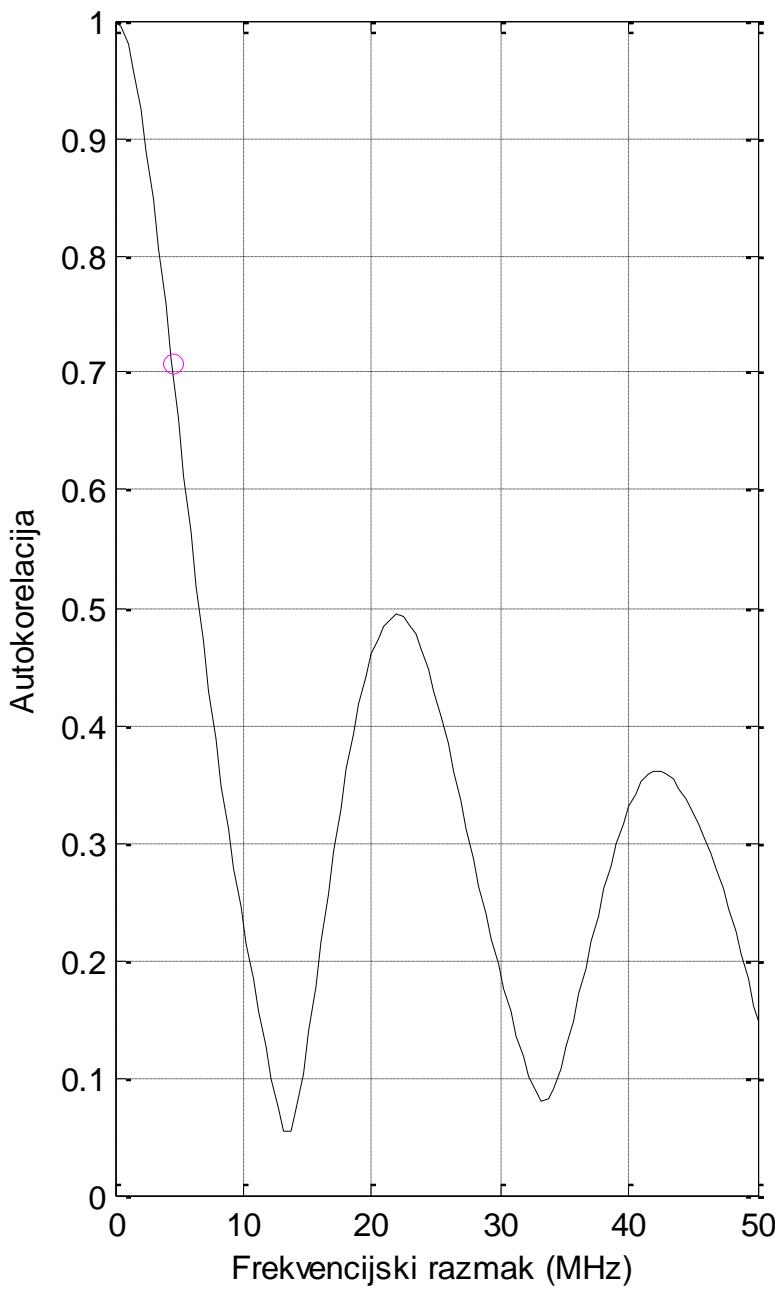
$$P_h(\tau) = \delta(\tau) + \delta(t - T) \Rightarrow B_c = \frac{\arccos C}{2\pi\sigma_\tau} \quad \text{- minimalni koherentni pojas za WSS sustave}$$



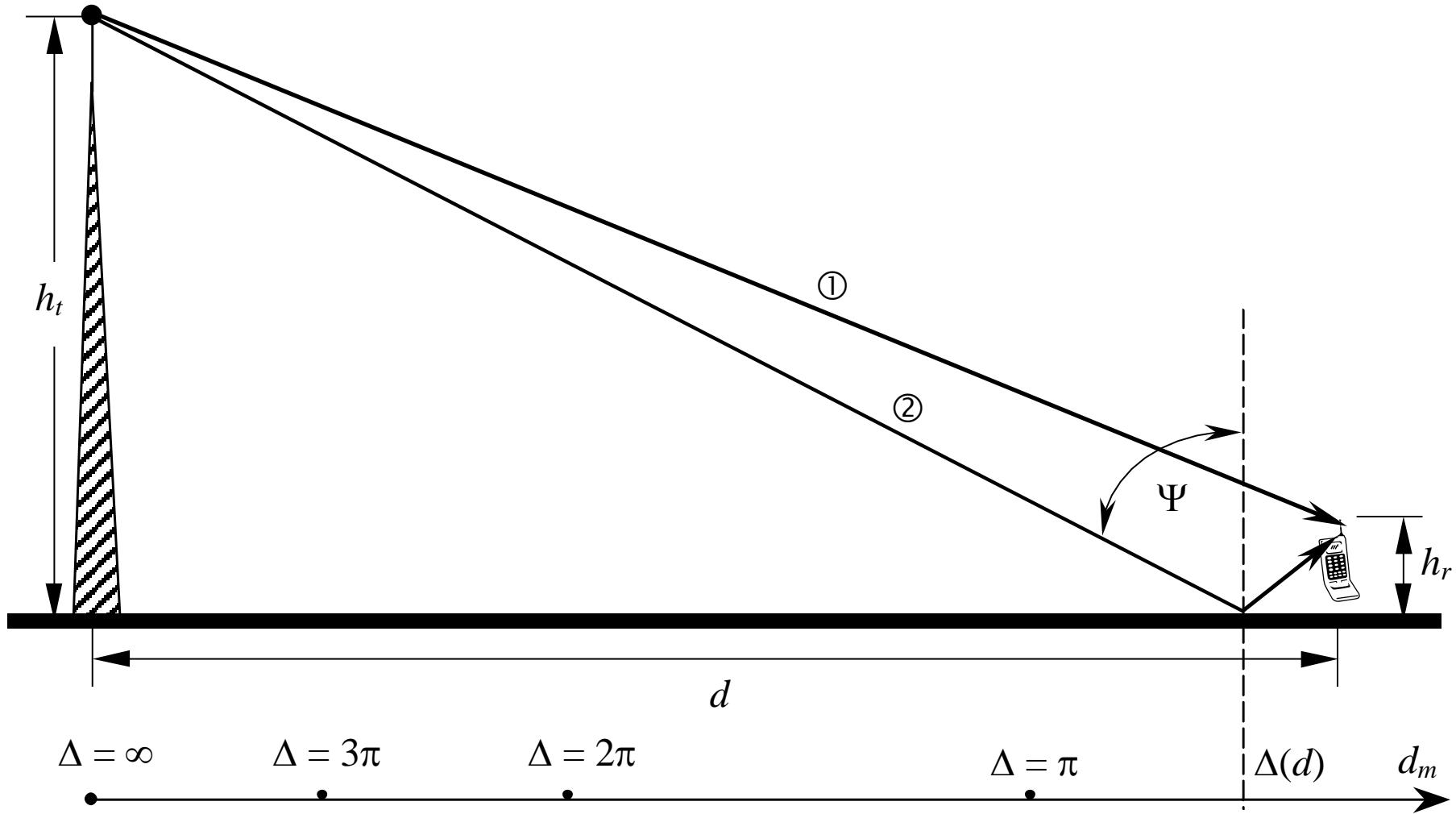
PROFIL SNAGE



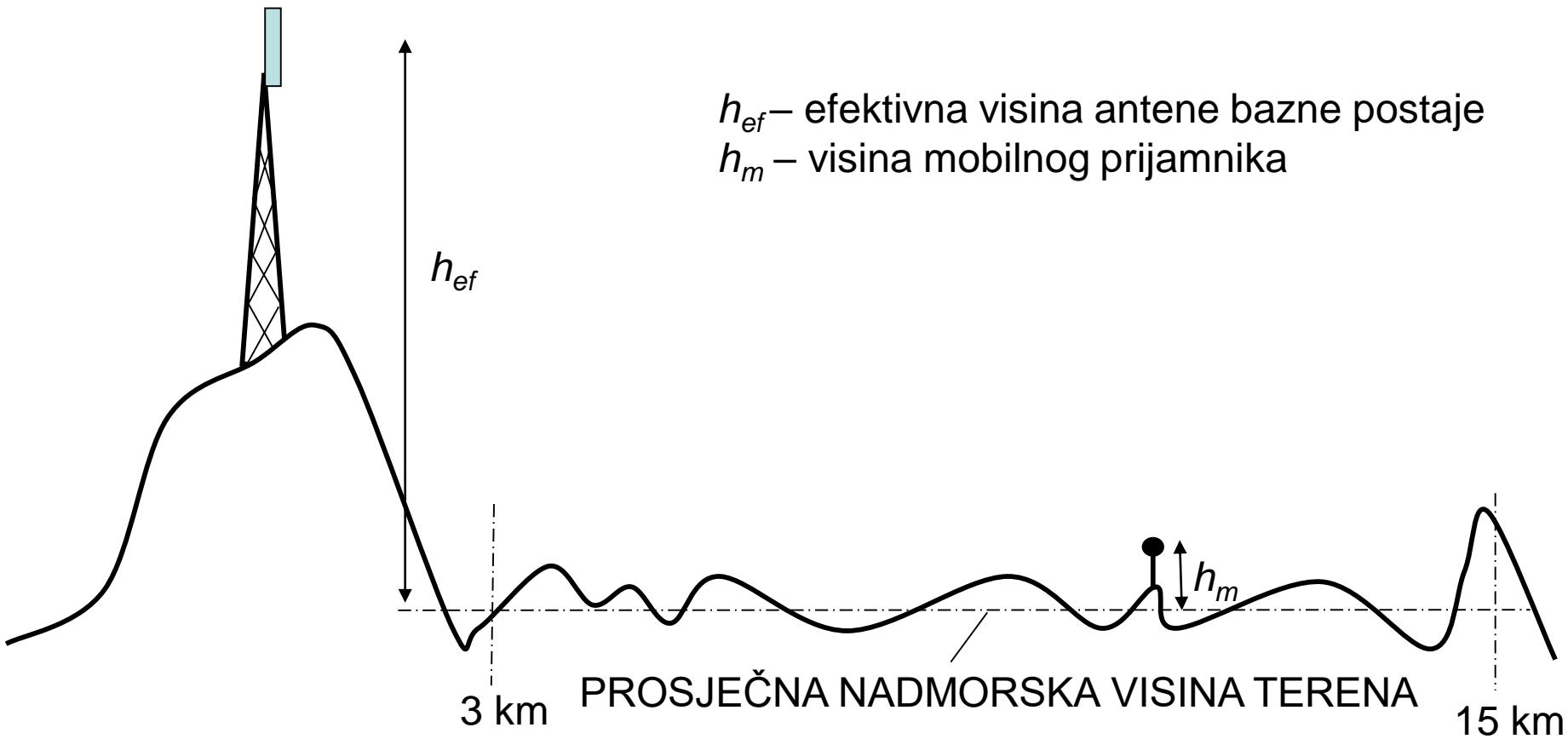
AUTOKORELACIJA



Gubici propagacije refleksijom



Efektivna visina antene



– gubici propagacije:

$$L = \frac{P_o}{P_p} = \frac{P_o}{|E_d + E_r|^2} = \frac{P_o}{P_o \left(\frac{\lambda}{4\pi d} \right)^2 \left| 1 + \mathbf{R} \frac{d_1}{d_2} e^{-jk(d_2-d_1)} \right|^2}; \quad E_1 = \frac{\lambda}{4\pi(1m)} \sqrt{P_o}$$

$$L^{[\text{dB}]} = -20 \log \left[\frac{\lambda}{4\pi d} \left| 1 + \mathbf{R}_{h,v} \frac{d_1}{d_2} e^{-jk(d_2-d_1)} \right| \right] = -20 \log \frac{\lambda}{4\pi d} - 20 \log |1 + C e^{-j\Delta}|$$

– razlika u fazi između izravnog i vala reflektiranog od tla:

$$\begin{aligned} \Delta_m &= k(d_2 - d_1) = k \left[\sqrt{d^2 + (h_t + h_r)^2} - \sqrt{d^2 + (h_t - h_r)^2} \right] = \\ &= kd \left[\sqrt{1 + \left(\frac{h_t + h_r}{d} \right)^2} - \sqrt{1 + \left(\frac{h_t - h_r}{d} \right)^2} \right] \cong kd \left[\left(1 + \frac{1}{2} \left(\frac{h_t + h_r}{d} \right)^2 \right) - \left(1 + \frac{1}{2} \left(\frac{h_t - h_r}{d} \right)^2 \right) \right] = \\ &= \frac{2kh_t h_r}{d} = \frac{4\pi h_t h_r}{\lambda d} \end{aligned}$$

– položaj ekstrema polja: $d_m = \frac{4h_t h_r}{m\lambda}, \quad m = 1, 2, 3, \dots$

$$\frac{d_1}{d_2} \approx 1, \mathbf{R}_{h,v} \approx -1, d \geq d_{m=1} \Rightarrow L^{[\text{dB}]} = -20 \log \frac{h_t h_r}{d^2} \Rightarrow P_p \approx \frac{1}{d^4}$$

Okumura-Hata empirijski model za predviđanje gubitaka propagacije

L_H – empirijska procjena gubitaka propagacije u dB

f_c – frekvencija nosioca u MHz, opseg 150 – 1500 MHz

h_l – efektivna visina antene bazne postaje u m, opseg 30 – 200 m

h_m – visina pokretne antene u m, opseg 1 – 10 m

R – udaljenost između bazne i mobilne postaje u km, opseg 1 – 20 km

$a(h_m)$ – faktor korekcije

$$L_{Hu} = 69.55 + 26.16 \log f_c - 13.82 \log h_l - a(h_m) + (44.9 - 6.55 \log h_l) \log R$$

$$a(h_m) = (1.1 \log f_c - 0.7) h_m - (1.56 \log f_c - 0.8) \quad \text{- mali i srednji gradovi}$$

$$a(h_m) = \begin{cases} 8.29 \log^2(1.54 h_m) - 1.1, & f_c \leq 200 \text{ MHz} \\ 3.2 \log^2(11.75 h_m) - 4.97, & f_c \geq 400 \text{ MHz} \end{cases} \quad \text{- veliki gradovi}$$

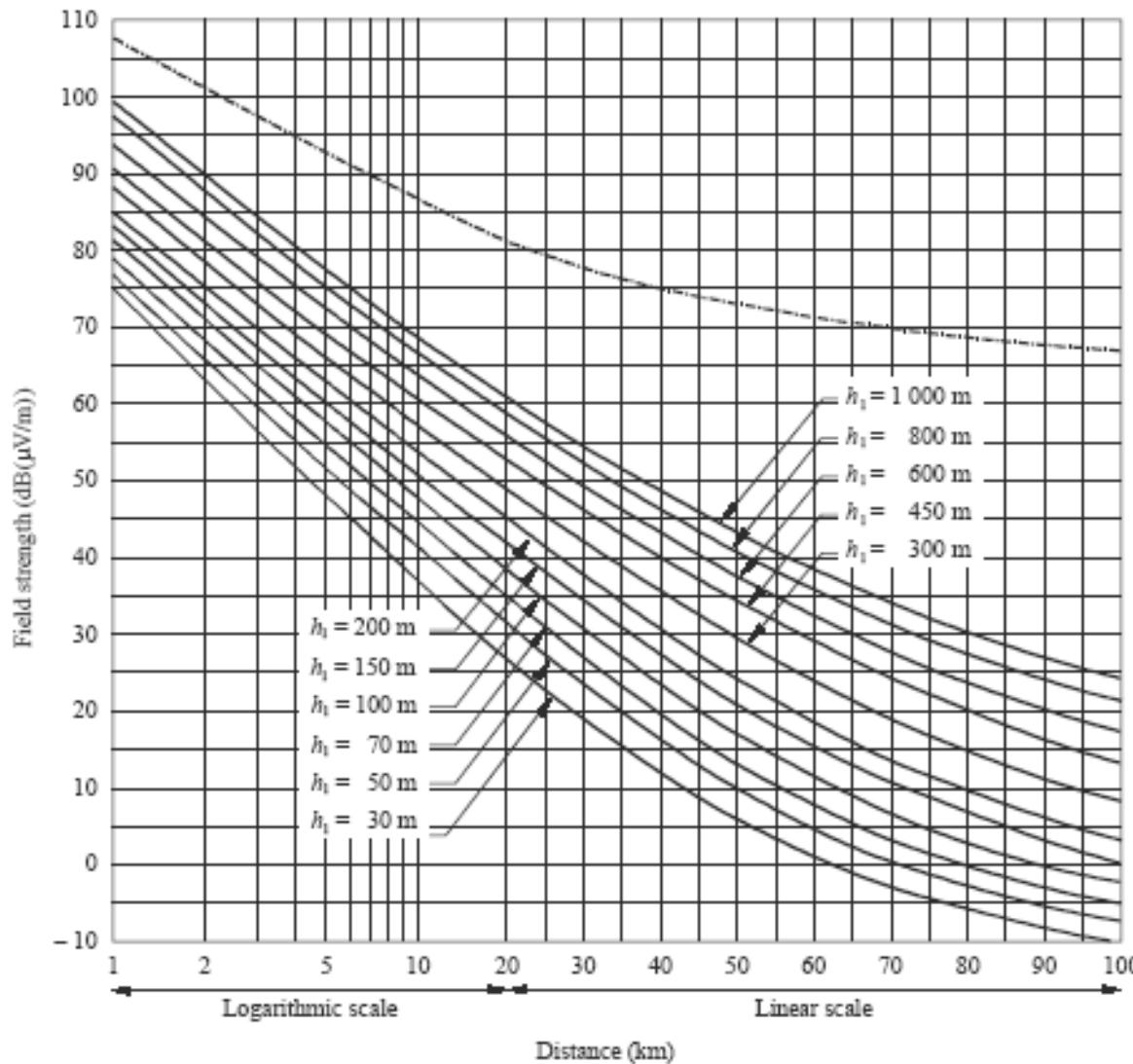
$$L_{Hsu} = L_{Hu} - 2 \log^2 \left(\frac{f_c}{28} \right) - 5.4 \quad \text{- suburbane sredine}$$

$$L_{Hr} = L_{Hu} - 4.78 \log^2 f_c + 18.33 \log f_c - 40.94 \quad \text{- ruralne sredine}$$

Za frekvencije nosioca f_c između 1.5 – 2 GHz:

$$L_H = 46.3 + 33.9 \log f_c - 13.82 \log h_l - a(h_m) + (44.9 - 6.55 \log h_l) \log R + C_m$$

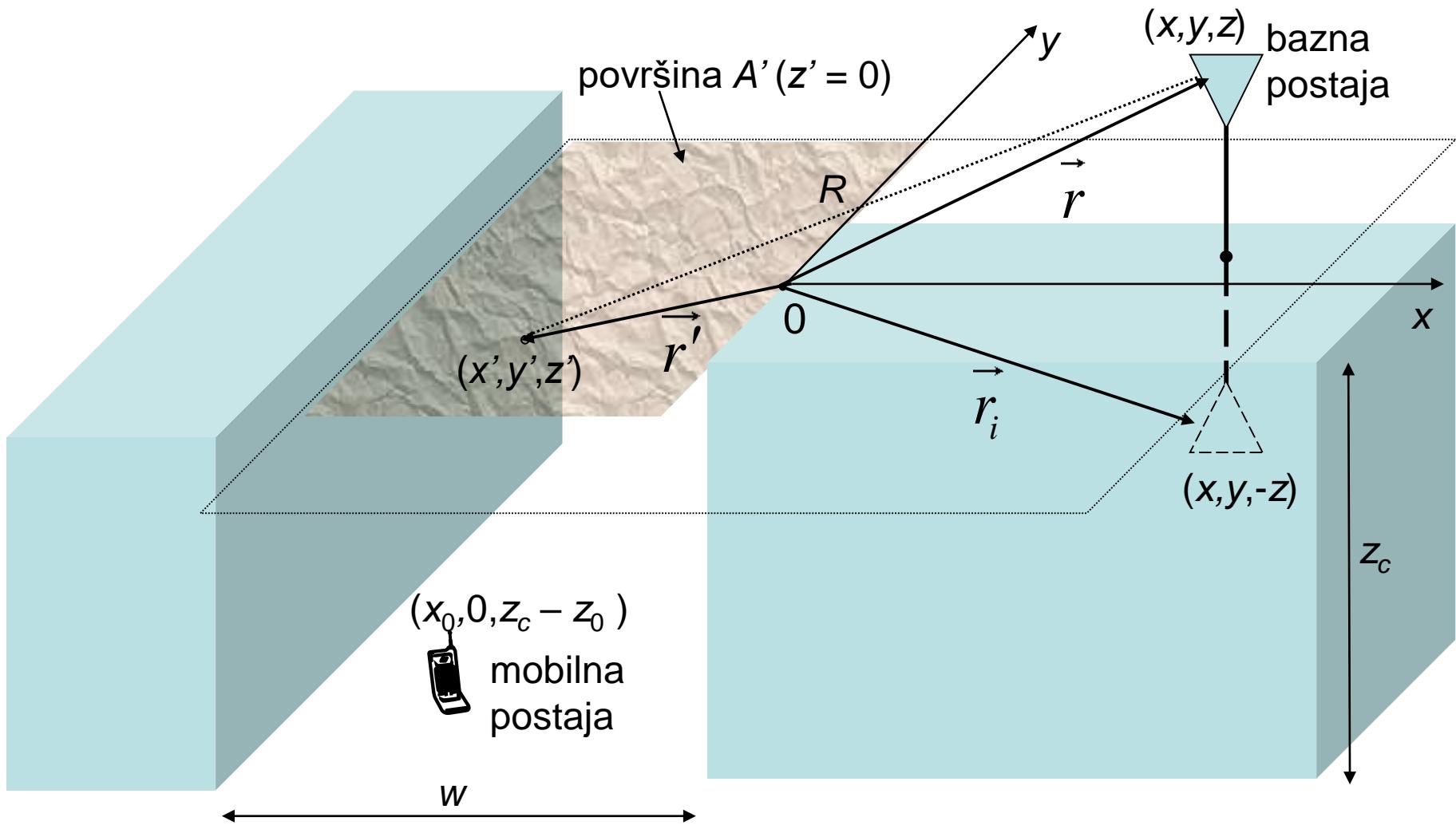
$$C_m = \begin{cases} 0 \text{ dB za srednje gradove i suburbana središta s umjerenom vegetacijom} \\ 3 \text{ dB za metropole} \end{cases}$$



Frequency $\approx 900 \text{ MHz}$; urban area; 50% of the time;
50% of the locations; $h_2 = 1.5 \text{ m}$

----- Free space

Fizikalni stohastički model



$$\Delta U + k^2 U = 0$$

$$U(\vec{r}) = \iint_{A'} \left[U(\vec{r}') \nabla \mathbf{G}(\vec{r}, \vec{r}') - \mathbf{G}(\vec{r}, \vec{r}') \nabla U(\vec{r}') \right] dA'$$

$$\mathbf{G}(\vec{r}, \vec{r}') = \frac{e^{jk|\vec{r}' - \vec{r}|}}{4\pi|\vec{r}' - \vec{r}|} + \mathbf{R}_{h,v} \frac{e^{jk|\vec{r}' - \vec{r}_i|}}{4\pi|\vec{r}' - \vec{r}_i|}$$

- Greenova funkcija u točki odašiljača

$$z \square x \Rightarrow \mathbf{R}_{h,v} \square -1 \Rightarrow \mathbf{G}(\vec{r}, \vec{r}') = 0 \Rightarrow U(\vec{r}) = \int_{-\infty}^{+\infty} dy' \int_{-\infty}^{+\infty} dx' U(x', y', 0) \frac{\partial \mathbf{G}}{\partial z'} \Big|_{z'=0}$$

$$R = |\vec{r}' - \vec{r}| = |\vec{r}' - \vec{r}_i| = \sqrt{(x - x')^2 + (y - y')^2 + (z - z')^2}$$

$$x \square x', y', z', y, z \Rightarrow R \approx (x - x') + \frac{x'^2 + (y - y')^2 + (z - z')^2}{2x}$$

- veza između Greenove funkcije na površini A ($z' = 0$) i G. funkcije u ishodištu:

$$\mathbf{G}_e = \mathbf{G}(x, 0, z | 0, 0, z') \Rightarrow \frac{\partial \mathbf{G}}{\partial z'} \Big|_{z'=0} = \frac{\partial \mathbf{G}_e}{\partial z'} \Big|_{z'=0} \exp \left(jkx' + \frac{jk(y - y')^2 + jkx'^2}{2x} \right)$$

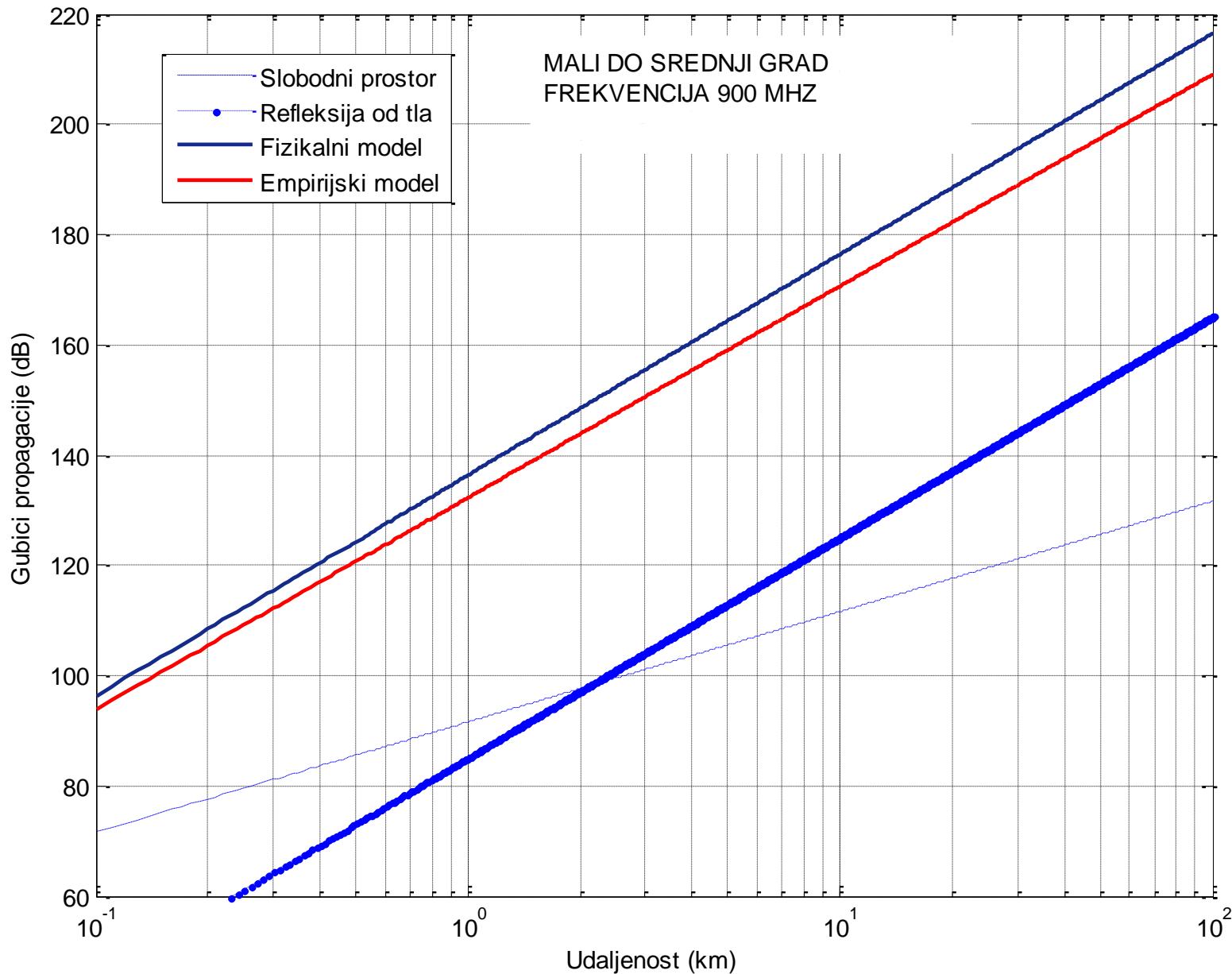
$$P_p = \lambda^2 \left\langle |U(r)|^2 \right\rangle = \lambda^2 \left\langle \left| \frac{\partial \mathbf{G}_e}{\partial z'} \right|_{z'=0}^2 \right\rangle \frac{P_o w \pi}{4k^2 \sqrt{(z_c - z_0)^2 + \left(x_0 - \frac{w}{2} \right)^2}}$$

- snaga u točki prijama

$$P_p = L_0 L_{lok} P_o \Rightarrow \begin{cases} L_{lok} = -\frac{w \pi}{4k^2 \sqrt{(z_c - z_0)^2 + \left(x_0 - \frac{w}{2} \right)^2}} & \text{- gubici lokalnog okoliša} \\ z \square x \Rightarrow L_0 = \left\langle \left| \frac{\partial \mathbf{G}_e}{\partial z'} \right|_{z'=0}^2 \right\rangle \approx \frac{z^2}{\lambda^2 x^4} & \text{- gubici propagacije preko velikih udaljenosti} \end{cases}$$

$$G_R = \frac{P_p}{P_o} = \left(\frac{\lambda}{4\pi} \right)^2 \frac{z^2 w \pi}{\sqrt{(z_c - z_0)^2 + \left(x_0 - \frac{w}{2} \right)^2}} \frac{1}{x^4}$$

- radio-dobitak



Turinov model

- Turinov model je model namijenjen statističkoj karakterizaciji širokopojasnog radio kanala u urbanim sredinama, pri čemu se pretpostavlja log-normalna razdioba amplituda i modificirana Poissonova razdioba vremenskih intervala između trenutaka pristizanja uzastopnih zraka.

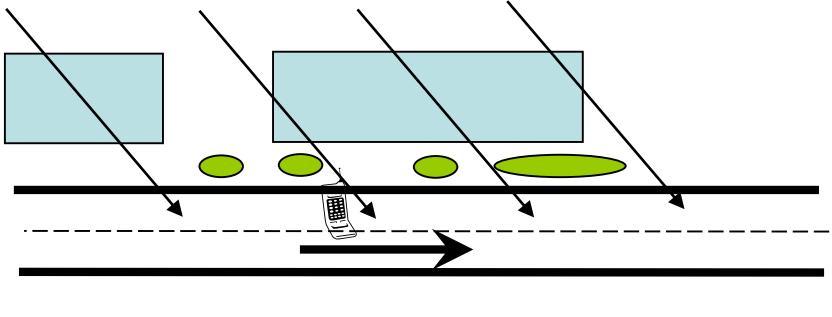
$$\mathbf{h}(t) = \sum_{k=0}^{\infty} S^{f_k} a_k \delta(t - t_k) e^{j\theta_k} + n(t) \text{ - impulsni odziv kanala}$$

$20 \log S^{f_k} a_k = 20 f_k \log S + 20 \log a_k$ - radio-dobitak k-tog primljenog impulsa u dB

$$p(\tau_k | \tau_{k-1}) = \lambda e^{-\lambda(\tau_k - \tau_{k-1})} \text{ - uvjetna vjerojatnost pojavljivanja zrake}$$

- θ_k – fazni pomak: uniformna razdioba u intervalu $[0, 2\pi]$
- a_k – log-normalna varijabla s prosjekom μ_k i varijancom σ_k^2
- S – log-normalna varijabla s prosjekom μ i varijancom σ^2
- $a_k S^{f_k}$ – log-normalna varijabla s prosjekom $f_k \mu + \mu_k$ i varijancom $f_k^2 \sigma^2 + \sigma_k^2$
- f_k, λ - empirijski parametri (iz mjerena)
- a_k, θ_k, S su nezavisne slučajne varijable
- Logaritamski radio-dobici pojedinog primljenog impulsa su linearno zavisni (svaki od njih sadrži linearni član $20 \log S$)

Suzuki model za urbane sredine



$$\mathbf{E} = r e^{j\psi} = \sum_{n=1}^N A_n e^{j\phi_n}$$

$$x = \operatorname{Re}(\mathbf{E}) = r \cos \psi = \sum_{n=1}^N A_n \cos \phi_n$$

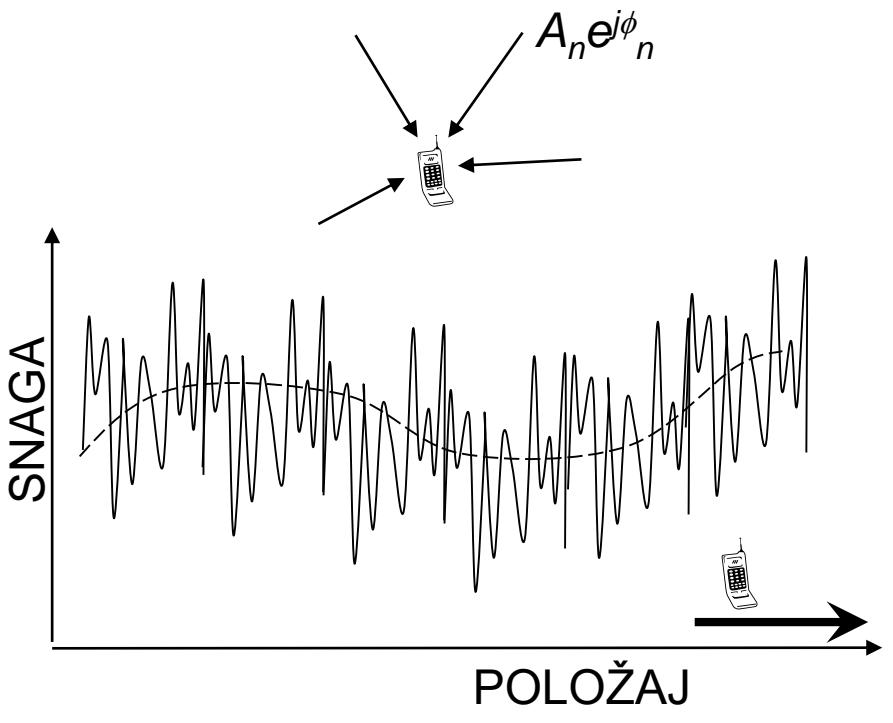
$$y = \operatorname{Im}(\mathbf{E}) = r \sin \psi = \sum_{n=1}^N A_n \sin \phi_n$$

$$r = \sqrt{x^2 + y^2} \stackrel{\text{CGT}}{\Rightarrow} p_r(r) = \frac{r}{b_0^2} e^{-\frac{r^2}{2b_0^2}}$$

$$r(t) = l(t)s(t) \Rightarrow s = \frac{r}{l} \Rightarrow p(s) = \frac{1}{l} p\left(\frac{r}{l}\right)$$

$$p(r) = p(s)p(l) \Rightarrow p(r) = \int_0^\infty \frac{1}{l} p_r\left(\frac{r}{l}\right) p_l(l) dl$$

$$p(r) = \underbrace{\int_0^\infty \frac{r}{l^2} e^{-\frac{r^2}{2l^2}}}_{\text{Rayleigh}} \underbrace{\frac{1}{\sqrt{2\pi}l\sigma} e^{-\frac{(\ln l - \mu)^2}{2\sigma^2}}}_{\text{Log-normal}} dl$$



Rayleighov feding

- x i y nezavisne slučajne varijable normalne distribucije s jednakim varijancama i prosjekom nula:

$$f_{XY}(x, y) = f_X(x)f_Y(y) = \frac{1}{2\pi\sigma^2} \exp\left(-\frac{x^2 + y^2}{2\sigma^2}\right)$$

- prijelaz na polarne koordinate:

$$f_{R\theta}(x, y) = |J| f_{XY}(x, y)$$

$$|J| = |J(r, \theta)| = \begin{vmatrix} \frac{\partial x}{\partial r} & \frac{\partial x}{\partial \theta} \\ \frac{\partial y}{\partial r} & \frac{\partial y}{\partial \theta} \end{vmatrix}$$

- Jakobijan

$$\begin{aligned} x = r \cos \theta \\ y = r \sin \theta \end{aligned} \Rightarrow |J| = \begin{vmatrix} \cos \theta & -r \sin \theta \\ \sin \theta & r \cos \theta \end{vmatrix} = r \quad \& \quad r^2 = x^2 + y^2 \Rightarrow f_{R\theta}(r, \theta) = \frac{r}{2\pi\sigma^2} \exp\left[-\left(\frac{r}{\sqrt{2}\sigma}\right)^2\right]$$

$$f_R(r) = \int_0^{2\pi} f_{R\theta}(r, \theta) d\theta \Rightarrow \boxed{f_R(r) = \frac{r}{\sigma^2} \exp\left[-\left(\frac{r}{\sqrt{2}\sigma}\right)^2\right]}$$

- Rayleighova PDF

CDF envelope:

$$P_R(R) = P(r \leq R) = \int_0^R p(r) dr$$

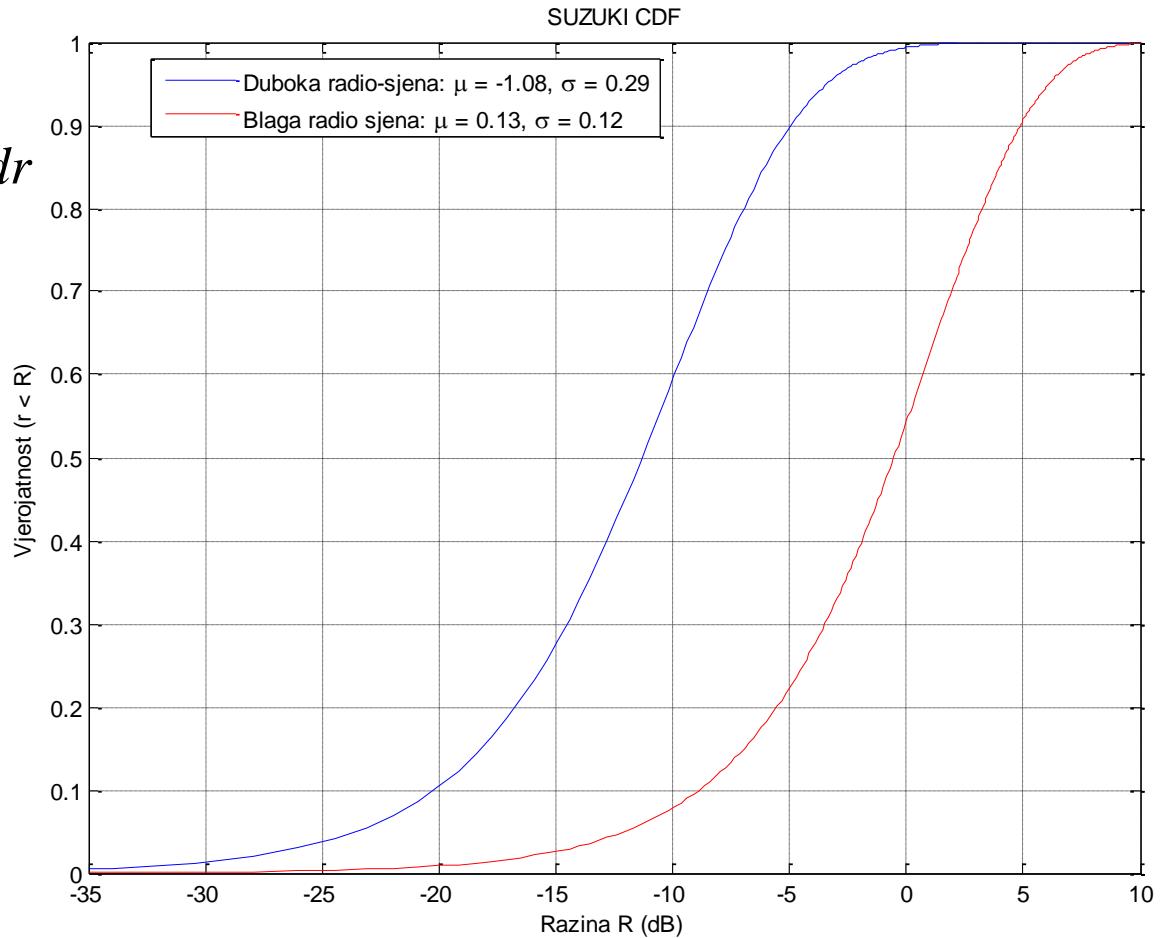
Vjerojatnost pogreške na simbolu:

$$P_e = \int_0^\infty P(e|r) p_r(r) dr$$

$$BER = f(P_e)$$

PDF snage signala:

$$w = r^2 \Rightarrow r = \sqrt{w}$$



$$p(w) = p[r(w)] \frac{dr}{dw} \Rightarrow p_w(w) = \frac{1}{2\sqrt{w}} p_r(\sqrt{w}) \Rightarrow p_w(w) = \frac{1}{2l_0^2} e^{-\frac{w}{2l_0^2}}$$

$$p(w) = \int_0^\infty \frac{1}{2l_0^2} e^{-\frac{w}{2l_0^2}} \frac{1}{\sqrt{2\pi}\sigma l_0} e^{-\frac{(\ln l_0 - \mu)^2}{2\sigma^2}} dl_0$$

Satelitski sustavi

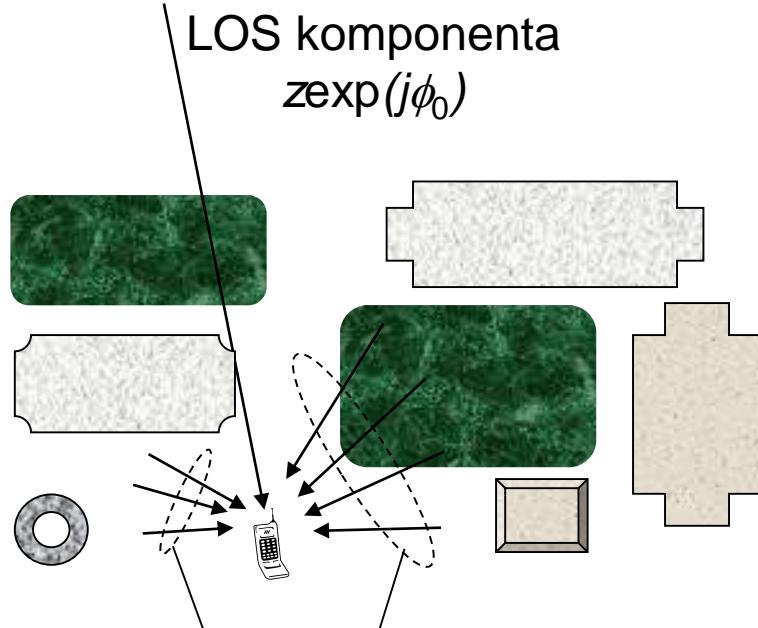
- Orbite: LEO (1km), MEO (4-5km), HEO (20km), GEO (40km)
- Komunikacijski sustavi
- Sustavi za radio-pozicioniranje (GPS, GLONASS, Galileo) (frekvencije 2.45 GHz, 5.8 GHz)
- Satelitski sustavi za bežični prijenos energije (SPS) (frekvencije 2.45 GHz, 5.8 GHz)
- Svaki od ovih sustava ima različite zahtjeve radio-kanala. Komunikacijski sustavi i radio-pozicioniranje zahtijevaju zadovoljavajući SNR na mjestu prijama i što manje rasipanje kašnjenja. Sustavi za radio-pozicioniranje mogu biti osjetljivi na atmosfersku refrakciju te stupanj zasjenjenja izravnog vala (Riceov K-faktor) zbog pogreške pseudo-udaljenosti koju te pojave mogu izazvati. Sustavi za prijenos energije kao i ostali fiksni linkovi osjetljivi su na snagu u točki prijama. Međutim, veoma važan podatak je raspršenje EM vala u atmosferi te karakteristike antena (uz precizno prilagođenje) zbog značajne prenošene snage, tako da je osnovni zahtjev stabilnost linka.

Statistički modeli satelitskog radio kanala

- Dva tipa modela: Loo-model i Suzuki-model, te različiti hibridi na osnovu tih modela
- **Loo-model:** signal se sastoji od sporo-promjenjive komponente fedinga koja slijedi log-normalnu distribuciju a na koju se zbraja brzo-promjenjiva komponenta Rayleighove razdiobe (difuzna komponenta i sporo-promjenjiva komponenta izravnog vala su statistički zavisne)
- **Suzuki-model:** signal trpi Rayleighov brzi feding u lokalnom području, čija se srednja vrijednost mijenja s položajem u širem području po log-normalnoj distribuciji (brzo-promjenjiva i sporo-promjenjiva komponenta statistički su nezavisne varijable)

Loo-model

- Primljeni signal je suma log-normalnog fazora koji opisuje ponašanje izravnog vala i Rayleighovog fazora koji opisuje difuznu višestaznu komponentu.



difuzna komponenta
 $w \exp(j\phi)$

$$E(t) = r(t) e^{j\theta(t)}$$

$$re^{j\theta} = ze^{j\phi_0} + we^{j\phi}, \quad z, w > 0$$

$$p(r) = \int_0^{\infty} p(r, z) dz = \int_0^{\infty} p(r|z) p(z) dz$$

$$p(r|z) = \frac{r}{b_0^2} I_0\left(\frac{rz}{b_0^2}\right) e^{-\frac{r^2+z^2}{2b_0^2}}$$

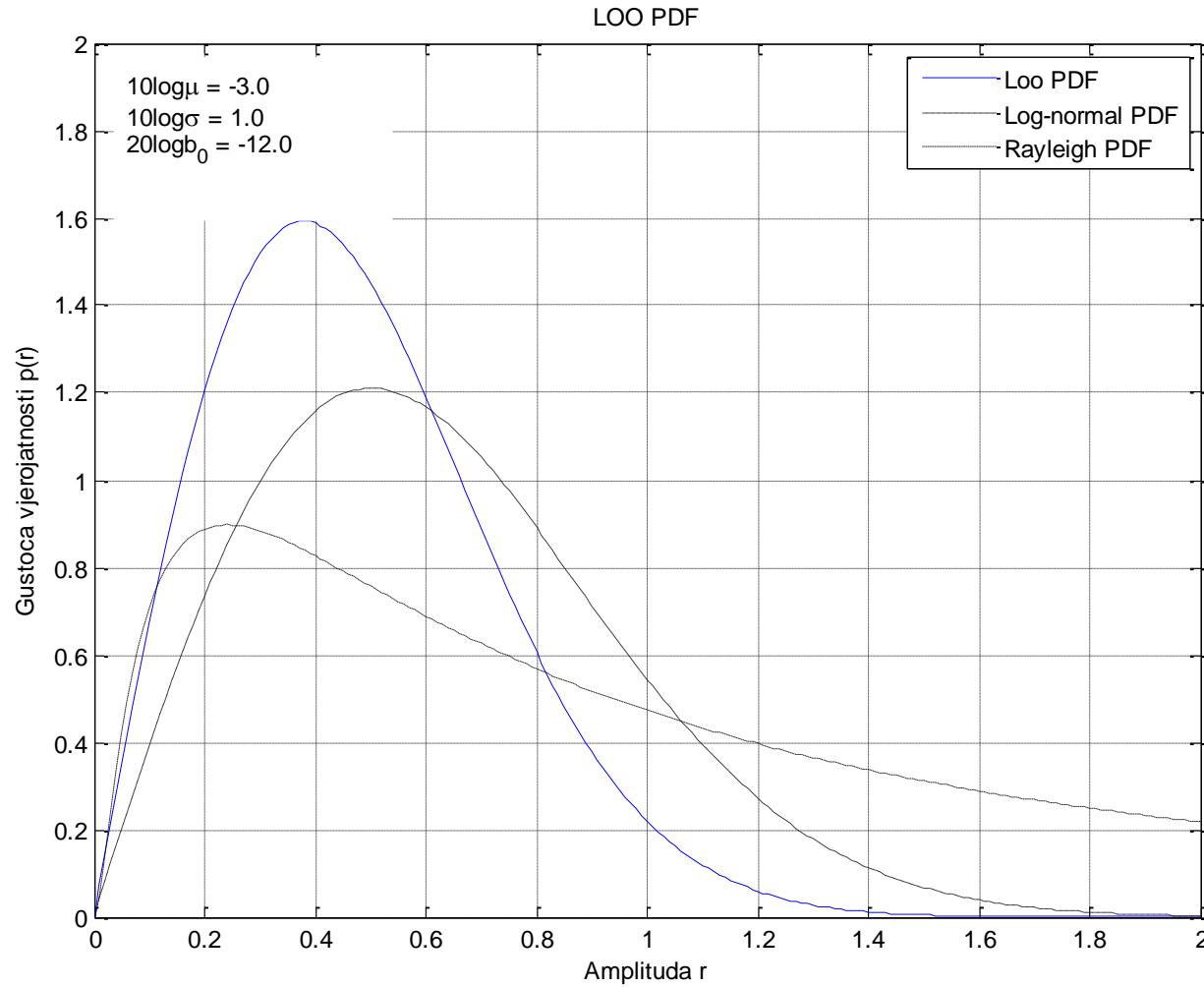
$$p(z) = \frac{1}{z\sqrt{2\pi\sigma_0^2}} e^{-\frac{(\ln z - \mu)^2}{2\sigma_0^2}}$$

$$p(r) = \frac{r}{\sqrt{2\pi\sigma_0^2 b_0^2}} \int_0^{\infty} \frac{1}{z} I_0\left(\frac{rz}{b_0^2}\right) e^{-\frac{(\ln z - \mu)^2}{2\sigma_0^2} - \frac{r^2+z^2}{2b_0^2}} dz$$

σ_0^2 – varijanca (prosječna snaga) izravne komponente

b_0^2 – varijanca (prosječna snaga) višestazne komponente

$$p(r) = \begin{cases} \frac{1}{r\sqrt{2\pi}\sigma_0} e^{-\frac{(\ln r - \mu)^2}{2\sigma_0^2}}, & r \geq b_0 \text{ - log-normalna (velike amplitude envelope)} \\ \frac{r}{b_0} e^{-\frac{r^2}{2b_0^2}}, & r \leq b_0 \text{ - Rayleighova (male amplitude envelope)} \end{cases}$$



Loo model LCR i AFD

\dot{r} - kombinirana brzina promjene envelope signala

\dot{x} - brzina promjene envelope uslijed višestaznog prijama sa STD = b_2 i AVG = 0

\dot{y} - brzina promjene envelope uslijed zasjenjenja sa STD = σ_2 i AVG = 0

$$\dot{r} = \dot{x} + \dot{y}$$

- korelirani Gaussov slučajni proces dviju varijabli \dot{x}, \dot{y} :

$$p(\dot{x}, \dot{y}) = \frac{1}{2\pi b_2 \sigma_2 (1-\rho^2)} \exp \left[\frac{1}{2(1-\rho^2)} \left(\frac{\dot{x}^2}{b_2^2} - 2\rho \frac{\dot{x}\dot{y}}{b_2 \sigma_2} + \frac{\dot{y}^2}{\sigma_2^2} \right) \right]$$

$$\rho(\dot{x}, \dot{y}) = \frac{\langle \dot{x}\dot{y} \rangle - \langle \dot{x} \rangle^2 \langle \dot{y} \rangle^2}{\sqrt{[\langle \dot{x}^2 \rangle - \langle \dot{x} \rangle^2][\langle \dot{y}^2 \rangle - \langle \dot{y} \rangle^2]}} \text{ - koeficijent korelacije}$$

$$\dot{x} = \dot{r} - \dot{y} \Rightarrow p(\dot{r}) = \int_{-\infty}^{+\infty} p(\dot{r} - \dot{y}, \dot{y}) d\dot{y}$$

$$p(\dot{r}) = \frac{1}{2\pi(1-\rho^2) \sqrt{b_2^2 + 2\rho b_2 \sigma_2 + \sigma_2^2}}$$

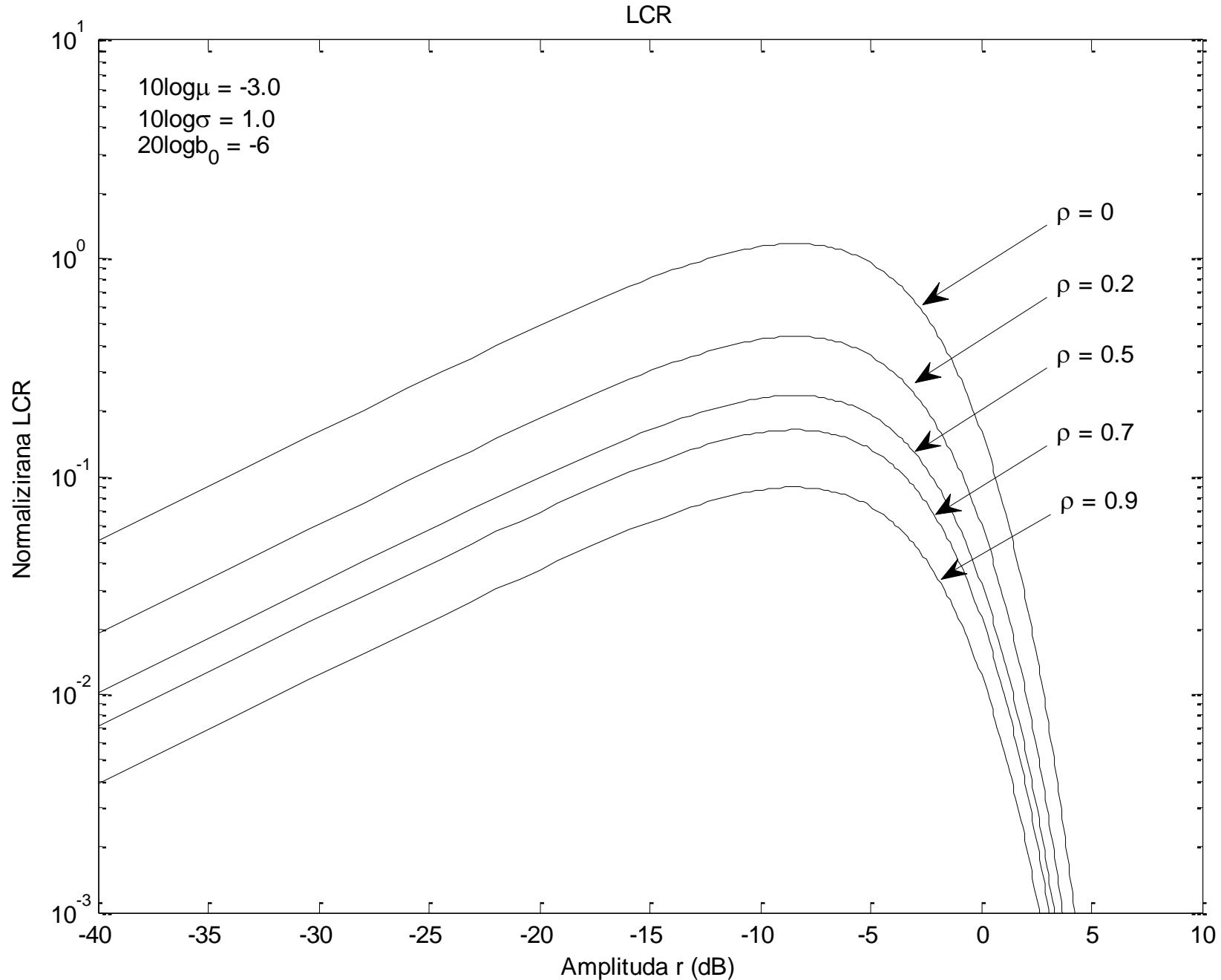
Da se pokazati da su r, \dot{r} nezavisne varijable, pa vrijedi:

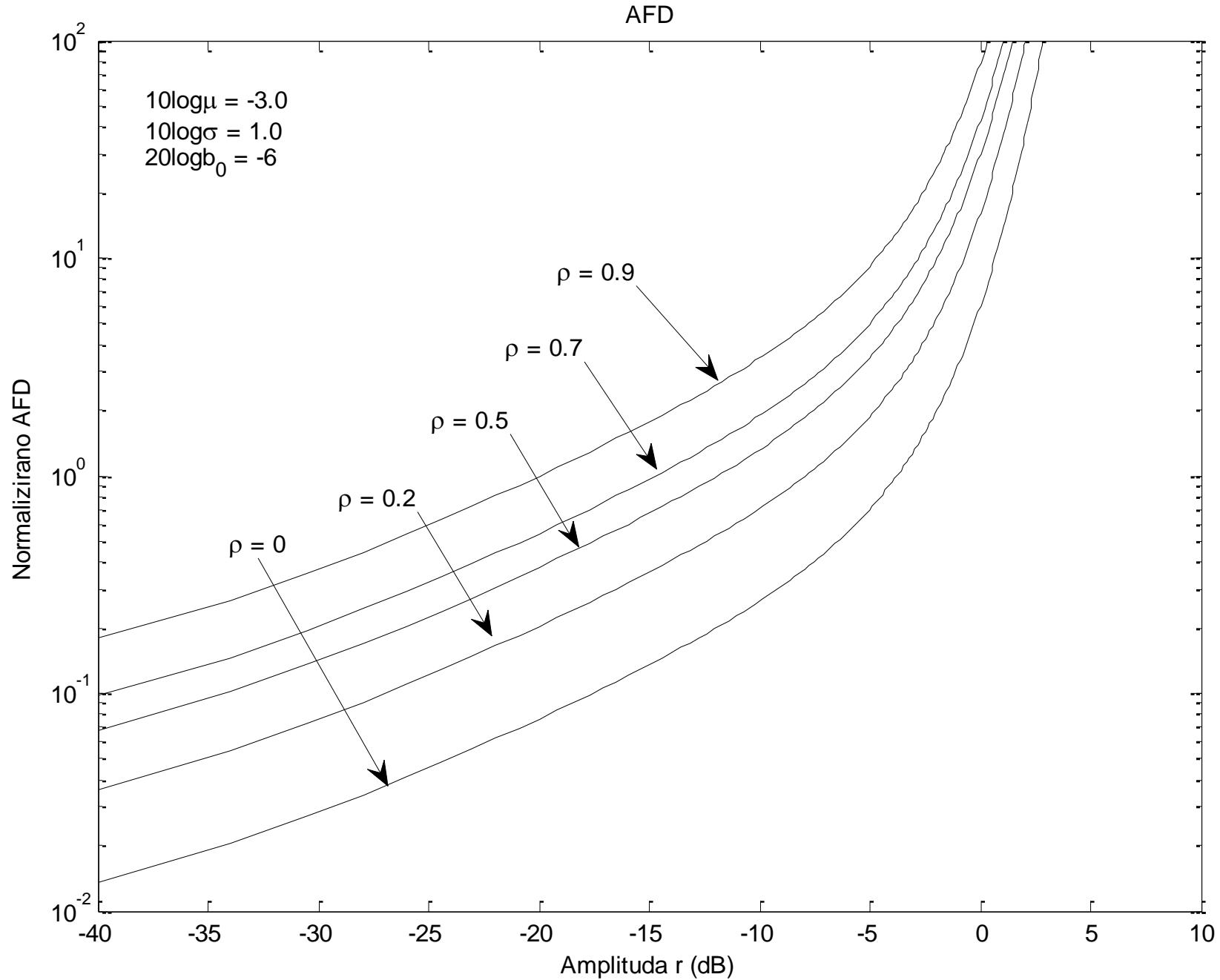
$$p(r, \dot{r}) = p(r)p(\dot{r}) \Rightarrow N_R = \int_0^\infty \dot{r} p(r, \dot{r}) d\dot{r} = p(r) \int_0^\infty \dot{r} p(\dot{r}) d\dot{r}$$

Pod pretpostavkom da je spektar fedinga uslijed zasjenjenja i višestazne propagacije simetričan i Gaussov:

$$\left. \begin{aligned} b_2 &= b_0 (2\pi f_m)^2 \\ \sigma_2 &= \sigma_0 (2\pi f_m)^2 \end{aligned} \right\} \Rightarrow N'_R = \frac{N_R}{f_m} = \sqrt{2\pi(1-\rho^2)} b_0 \frac{\sqrt{b_0^2 + 2\rho b_0 \sigma_0 + \sigma_0^2}}{b_0(1-\rho^2) + 4\rho b_0 \sigma_0} p(r) \quad \text{- normalizirana LCR}$$

$$T_N = \frac{1}{N'_R} \int_0^R p(r) dr \quad \text{- normalizirano AFD}$$

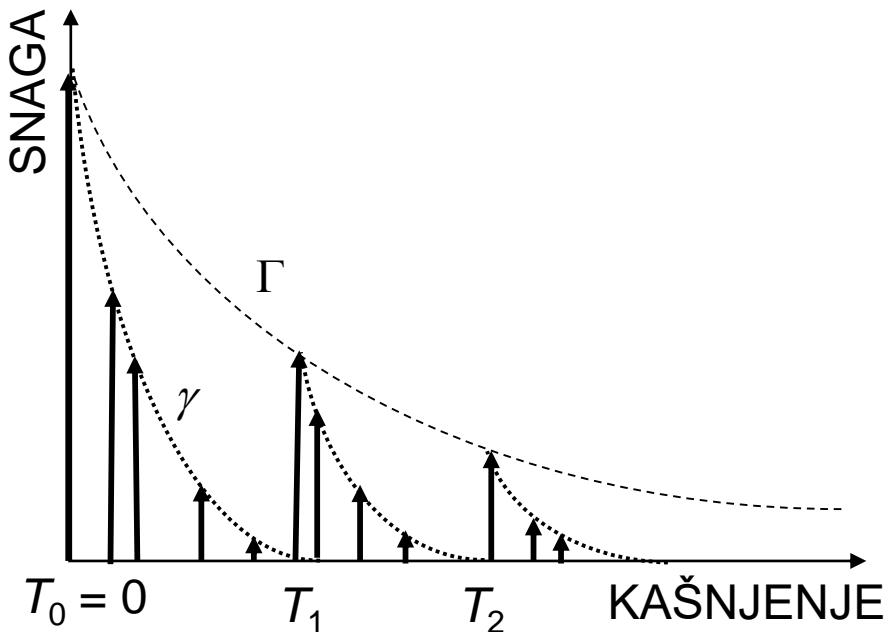




Unutrašnji prostori

- Za razliku od propagacije u otvorenim prostorima gdje značajan utjecaj ima konfiguracija terena između antena, propagacija u unutrašnjim prostorima poput zgrada, tvorničkih hala ili velikih centara ovisi o strukturi građevine i građevnim materijalima. Signal na svom putu do prijamnika trpi atenuaciju kroz zidove i vrata, refleksiju, ogib o rubove zidova i namještaja te raspršenje od objekata malih električnih dimenzija.
- Ukoliko je prijamnik i predajnik u istoj prostoriji nagib gubitaka propagacije je često između 1.5 – 1.8 (manji od 2 za slobodni prostor), a ukoliko ne postoji optička vidljivost (antene u različitim prostorijama) tada se on kreće obično između 3 – 4.
- Za opisivanje statističkih parametara kanala za zatvorene prostore često se koristi Saleh-Valenzuela model, zasnovan na modifikaciji i nadogradnji Turinova modela.

Saleh-Valenzuela model



$$P_h(t) = |\mathbf{h}(t)|^2 \quad - \text{razdioba snage}$$

$$\mathbf{h}(t) = \sum_{l=0}^{\infty} \sum_{k=0}^{\infty} g_{kl} e^{j\phi_{kl}} \delta(t - T_l - \tau_{k,l})$$

$$\overline{g_{kl}^2} = \overline{g^2(T_l, \tau_{kl})} = \overline{g_{00}^2} \cdot e^{-T_l/\Gamma} e^{-\tau_{kl}/\gamma}$$

$$p(T_l | T_{l-1}) = \Lambda e^{-\Lambda(T_l - T_{l-1})}$$

$$p(\tau_{k,l} | \tau_{k-1,l}) = \lambda e^{-\lambda(\tau_{k,l} - \tau_{k-1,l})}$$

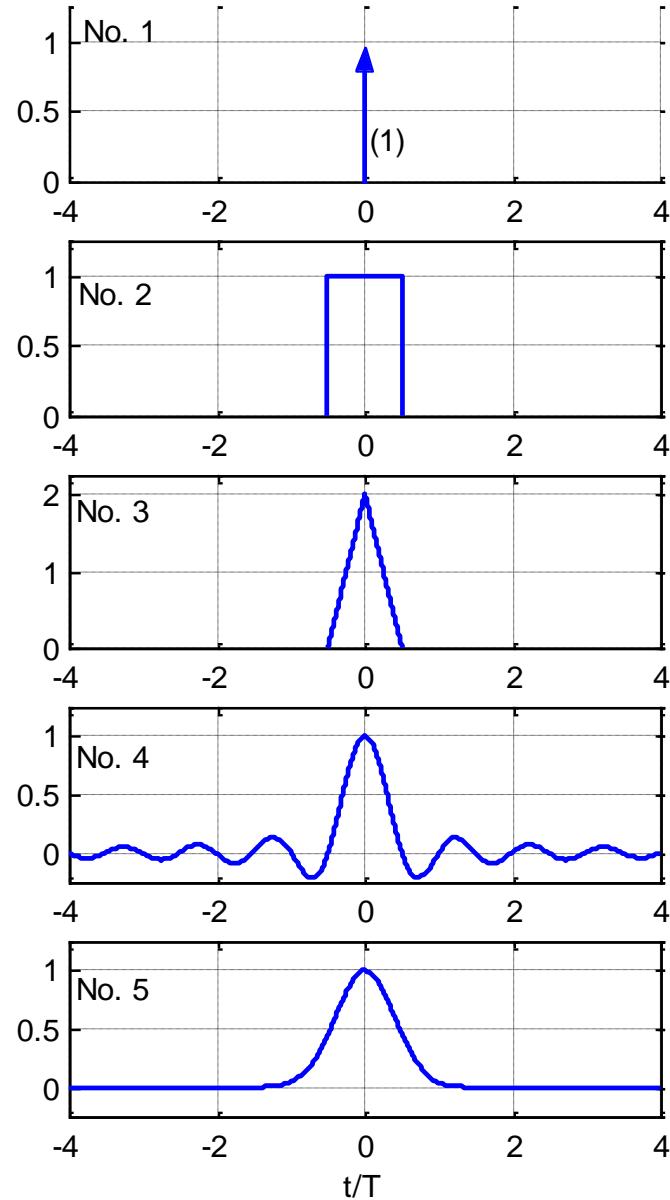
- Dvostruki Poissonov proces brzinom pojavljivanja klastera Λ i zraka unutar klastera λ s eksponencijalnim opadanjem snage klastera i snage unutar klastera. Broj klastera N_C u pojedinom odzivu se također uzima kao Poissonova varijabla
- Za potpun statistički opis zatvorenog okoliša potrebno je mjeranjima odrediti, osim zakona gubitaka snage, pet parametara: N_C , Λ , λ , Γ , γ .
- Klasteriranje impulsa u zatvorenim prostorima, osim u vremenskoj dimenziji, može se opaziti i u prostornoj dimenziji mjereći vrlo usmjerrenom antenom snagu koju prijamnik upija iz pojedinih smjerova u horizontalnoj ravnini (proširenji SV-model).

Mjerenja propagacijskog kanala

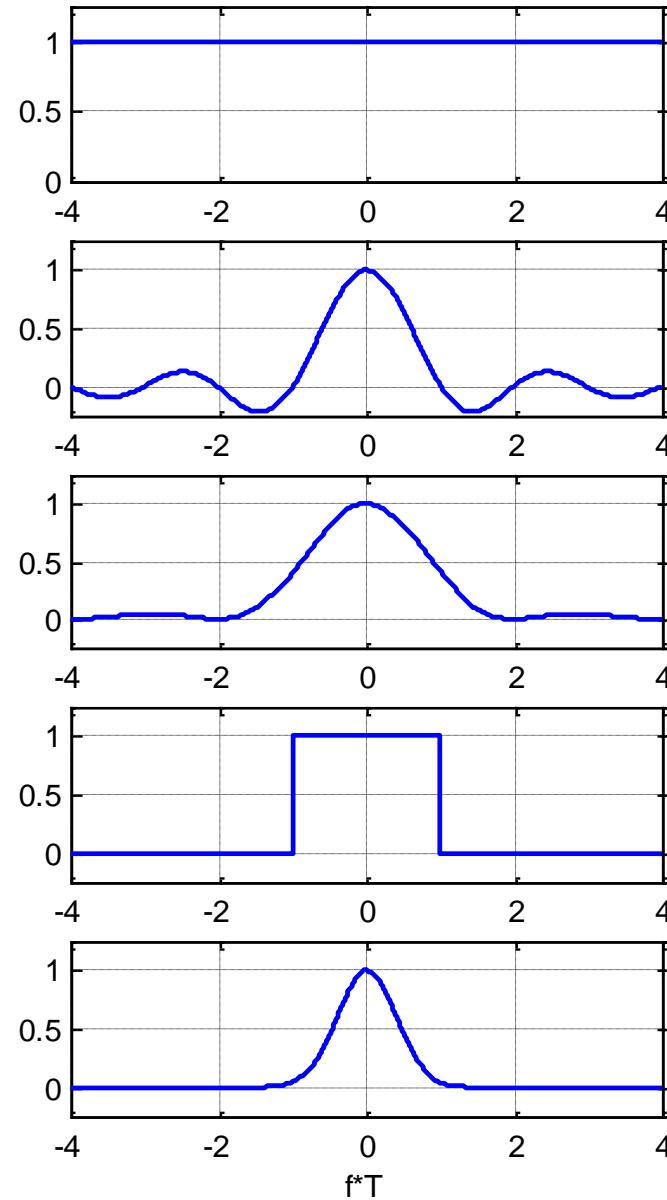


No.	Test impuls	Vremenska domena	Frekvencijska domena
1.	Delta impuls	$x(t) = \delta(t)$	$X(f) = 1$
2.	Pravokutni impuls	$x(t) = \begin{cases} 1/T, & t \leq T/2 \\ 0, & \text{inače} \end{cases}$	$X(f) = \text{sinc}(fT)$
3.	Trokutasti impuls	$x(t) = \begin{cases} 2(-2 t/T + 1), & t \leq T/2 \\ 0, & \text{inače} \end{cases}$	$X(f) = \text{sinc}^2(fT/2)$
4.	Impuls sinc(x)	$x(t) = \text{sinc}(2t/T)$	$X(f) = \begin{cases} 1, & f \leq 1/T \\ 0, & \text{inače} \end{cases}$
5.	Gaussov impuls	$x(t) = \exp[-\pi(t/T)^2]$	$X(f) = \exp[-\pi(fT)^2]$

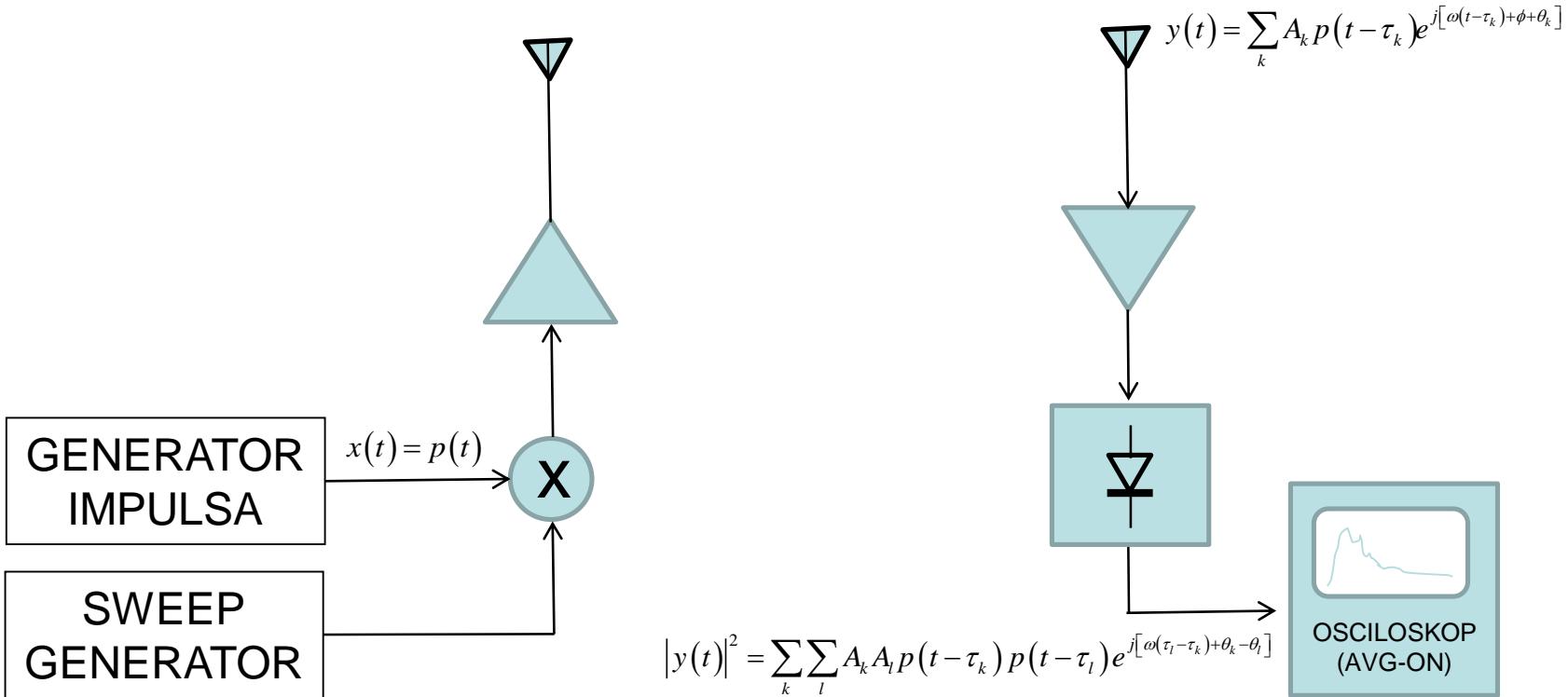
VREMENSKA DOMENA



FREKVENCIJSKA DOMENA



Pulsno mjerjenje u vremenskoj domeni



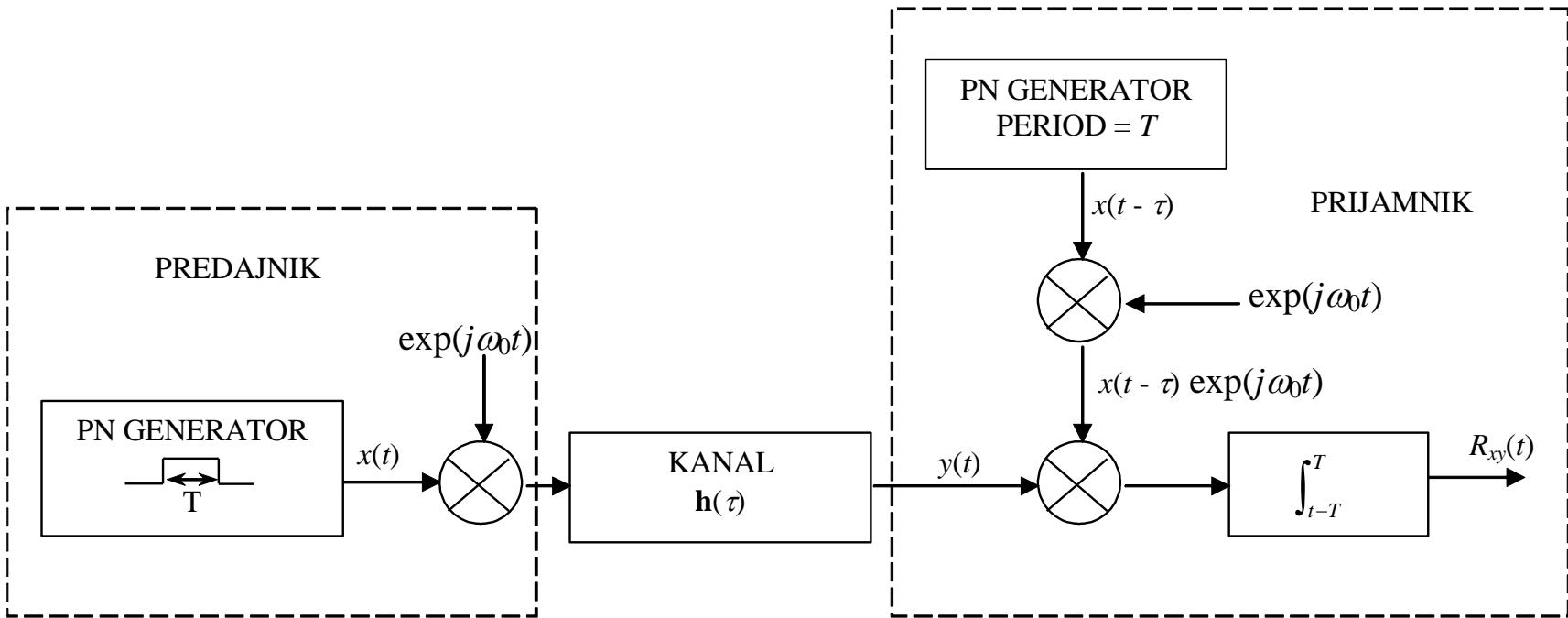
Ako se impulsi međusobno ne preklapaju na ulazu u osciloskop imamo:

$$|y(t)|^2 = \sum_k A_k^2 p^2(t - \tau_k)$$

Ako su faze θ uniformne razdiobe tada je matematičko očekivanje s obzirom na fazu jednako valnom obliku na izlazu kvadratičnog detektora u slučaju kada nemamo preklapanja impulsa:

$$E_\theta \{ |y(t)|^2 \} = \sum_k A_k^2 p^2(t - \tau_k)$$

WPMs mjerni sustav



$$N_{PN} = 1023 \text{ chip} \& f_c = 250 \text{ MHz} \Rightarrow T = \frac{1}{f_c} = 4 \text{ ns} \Rightarrow T_{WPMs} = N_{PN}T = 4,092 \mu\text{s}; \Delta\tau_R = \frac{1}{4}T = \frac{1}{4f_c} = 1 \text{ ns} \Rightarrow N_{IFFT} = \frac{T_{WPMs}}{\Delta\tau_R} = 4092 \square 4096$$

$$\Delta f = \frac{1}{N_{IFFT}\Delta\tau_R} = 0,244140625 \text{ MHz} \Rightarrow B_{IFFT} = \frac{1}{\Delta\tau_R} = N_{IFFT} (\Delta f) = 4f_c = 1 \text{ GHz}$$

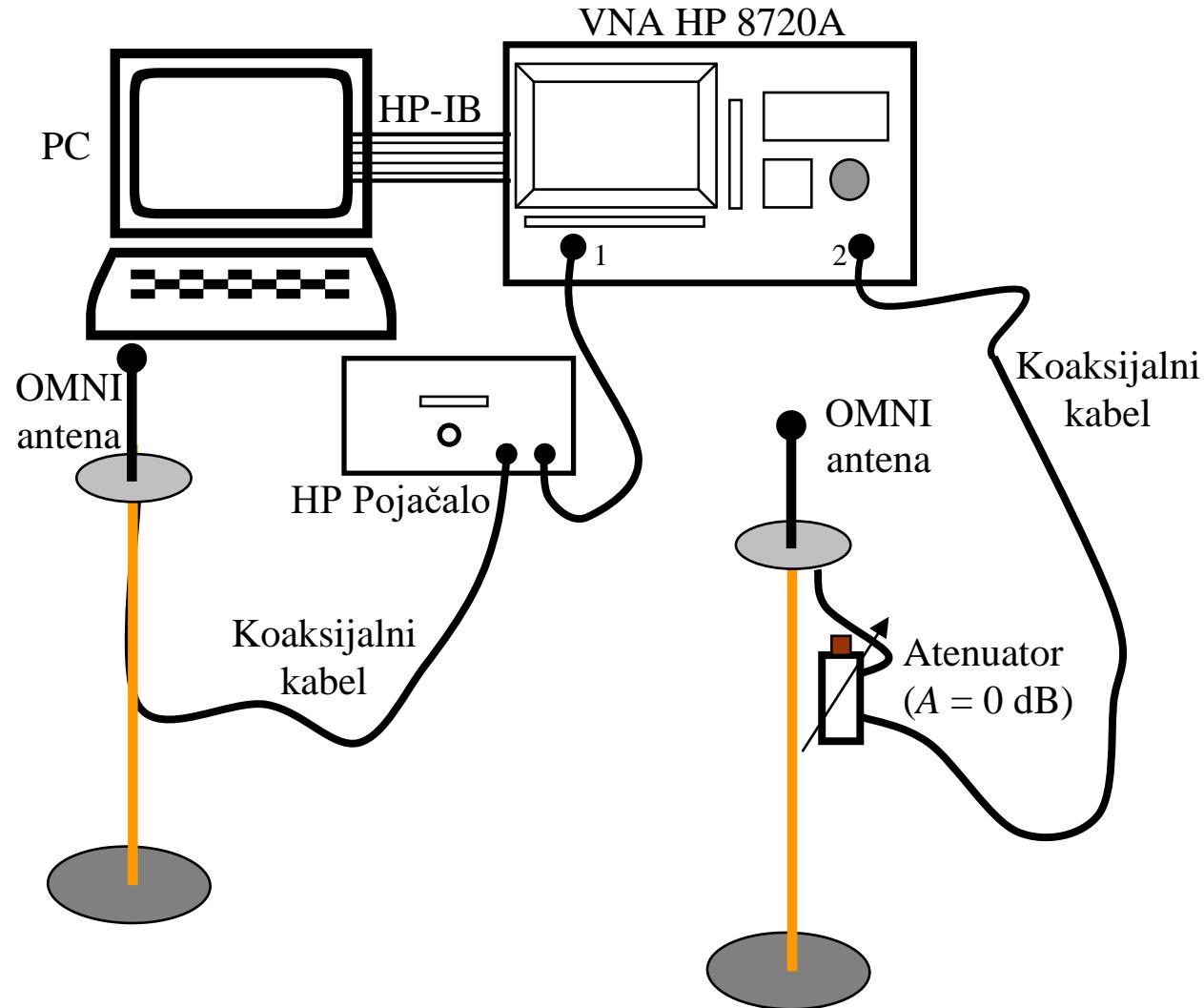
$$L_\tau(\tau; f_c) = -20 \log \frac{R_{xy}(t; f_c)}{R_{xx\max}(f_c)} = -20 \log \frac{|\hat{\mathbf{h}}(\tau; f_c)|}{R_{xx\max}(f_c)}$$

$$L_{WB}(f_c) = 10 \log \frac{\int_{-\infty}^{+\infty} |X(f; f_c)|^2 df}{\int_{-\infty}^{+\infty} |X(f; f_c) \mathbf{H}(f; f_c)|^2 df}$$

$$X(f) = \begin{cases} \operatorname{sinc}^2 \frac{f}{f_c}, & |f| < f_c \\ 0, & \text{inace} \end{cases}$$

$$R_{xx}(t) = \left[1 + 2 \sum_{n=1}^{\frac{N}{4}-1} X(n\Delta f) \cos(2\pi n \Delta f t) \right] \Delta f$$

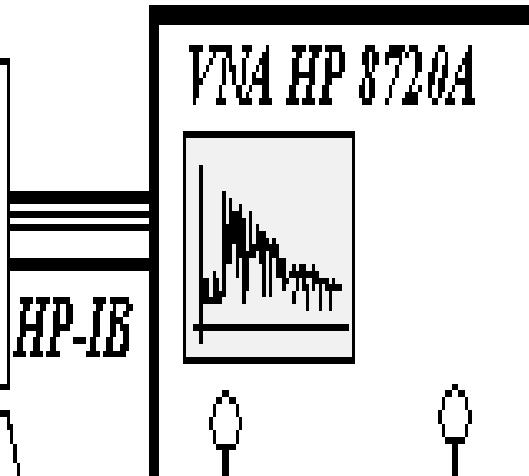
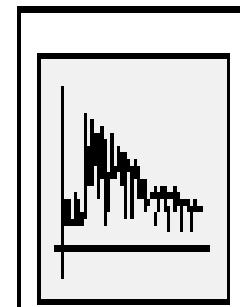
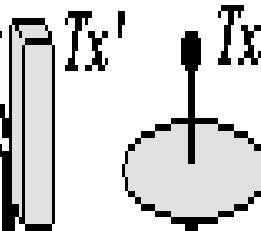
VNA mjerni sustav



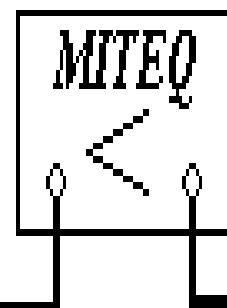
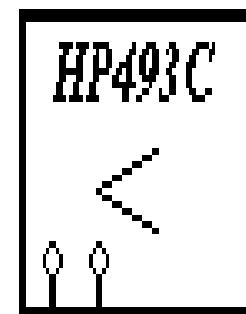
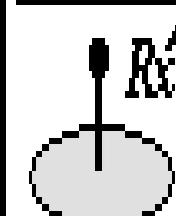
Primjer statističke karakterizacije kanala

- 4 kat FESB-a, stara zgrada
- Frekvencija 2400 MHz, širina pojasa $B = 400$ MHz
- Visine antena 1.7 m
- Broj VNA točaka: $N_{VNA} = 801$,
- Razina bočnih latica impulsa: SSL = −44 dB
(normalni prozor)
- Vremenski opseg: $T_{\max} = 400$ ns
- Vremenska rezolucija:
 - teoretska: $\Delta f = B/(N_{VNA} - 1) = 500$ kHz, $\Delta t = 1/B = 2.5$ ns
 - mjerna: 4.8 ns (zbog primijenjenog normalnog prozora)
 - ekran: $T_{\max}/(N_{VNA} - 1) = 0.5$ ns

DIRECTIONAL ANTENNA
ANDREW DB973G90-SR



OMNI ANTENNA
MAXRAD BMAXC24505



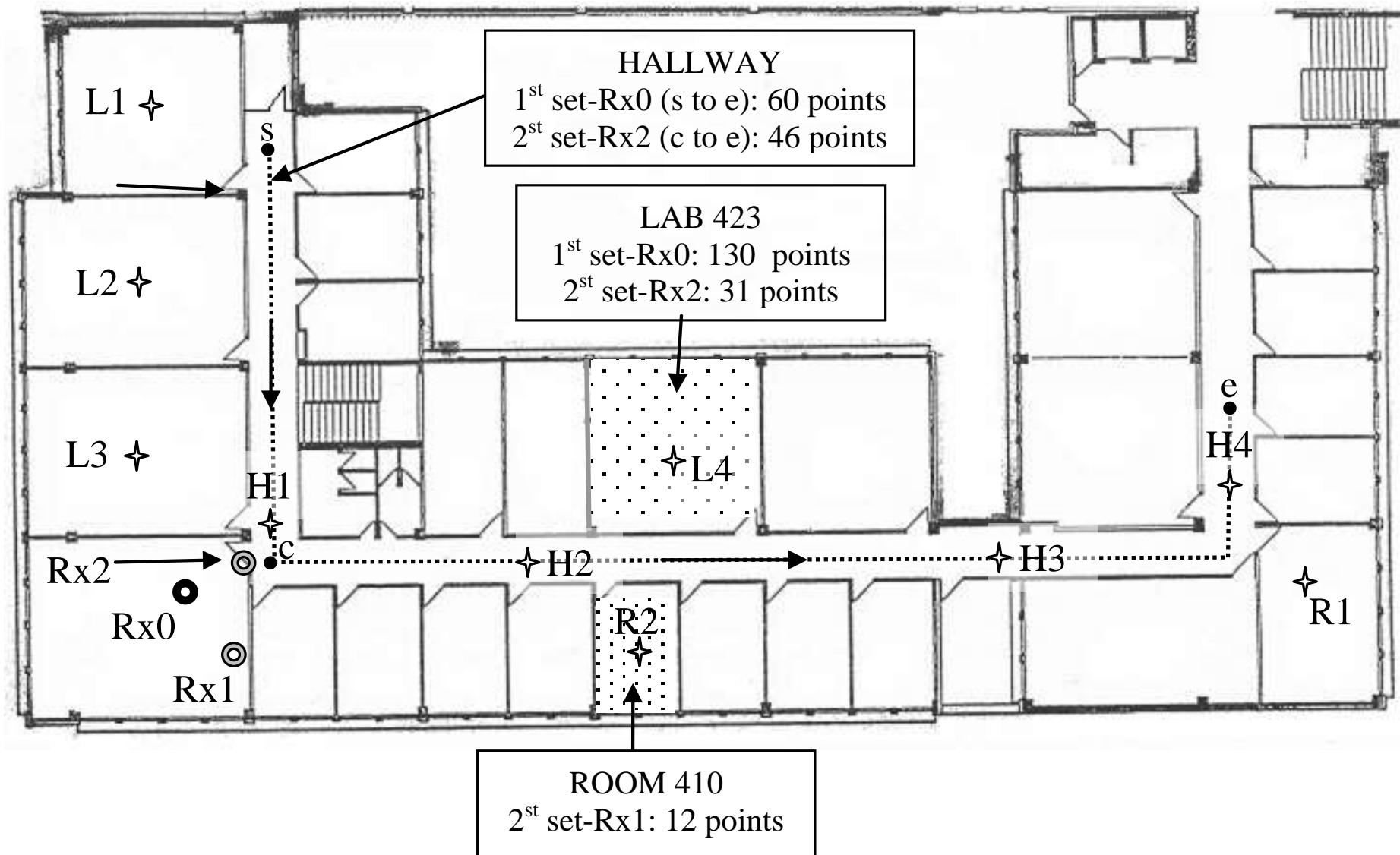
SHORT COAXIAL CABLE

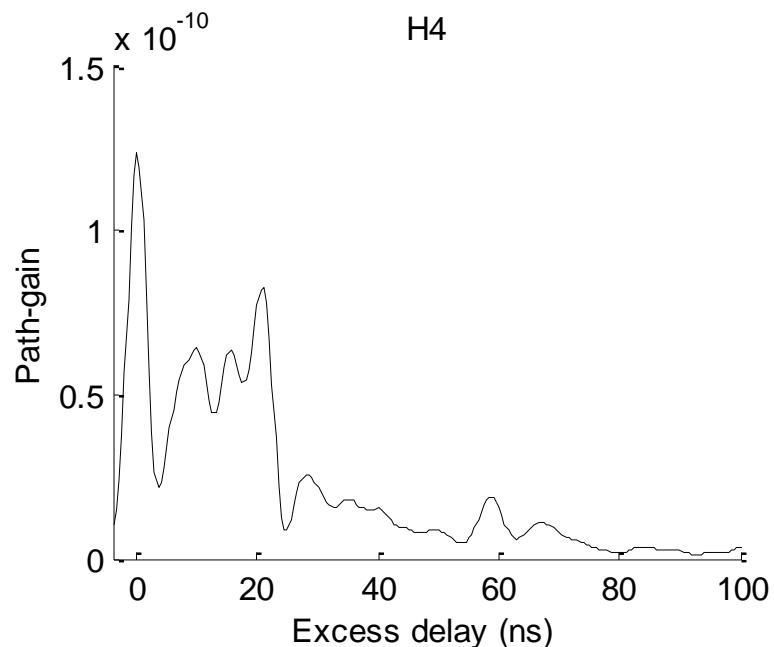
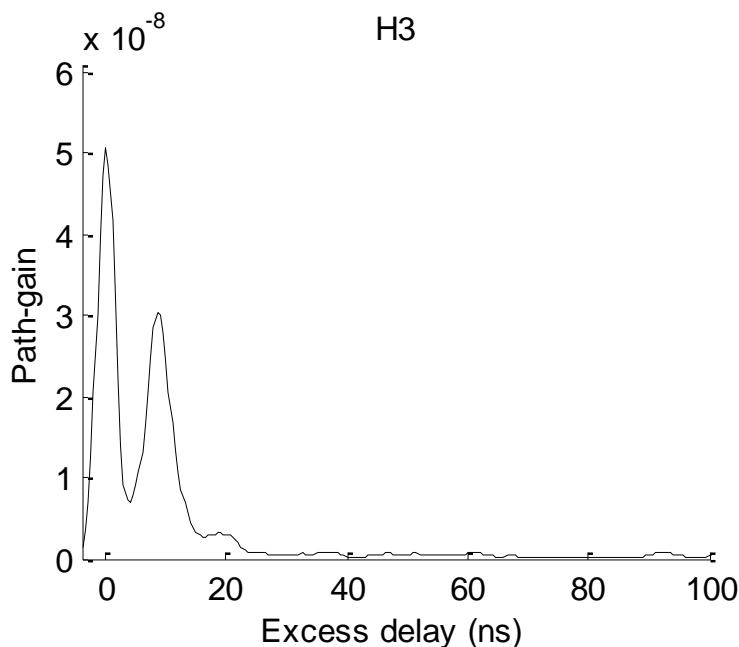
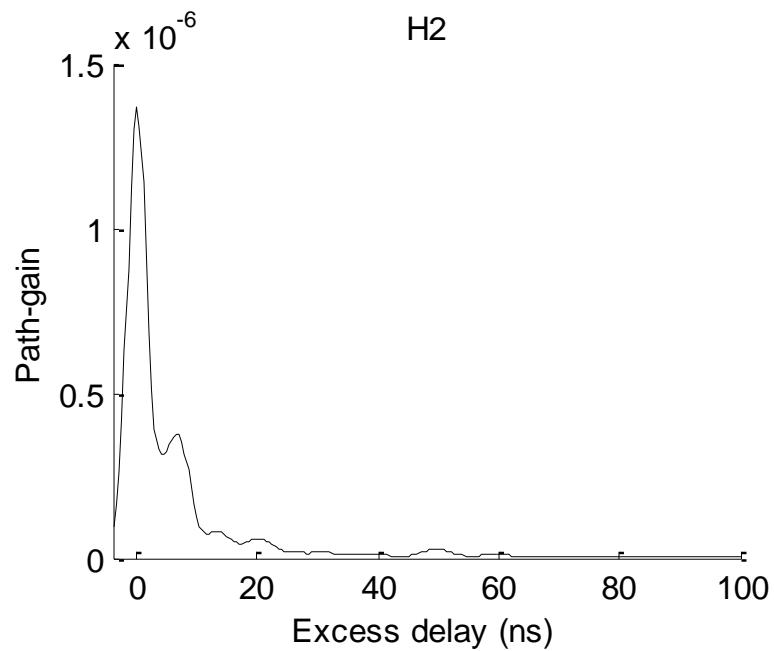
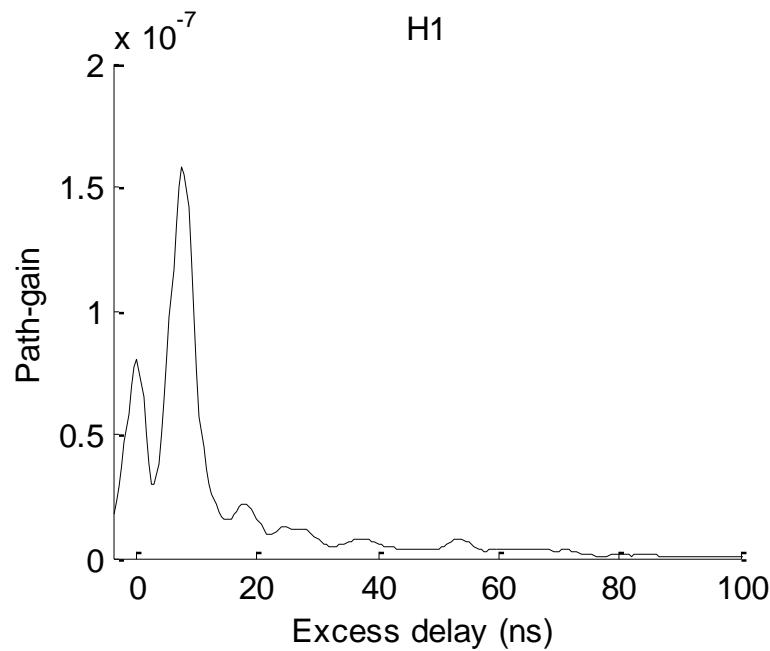


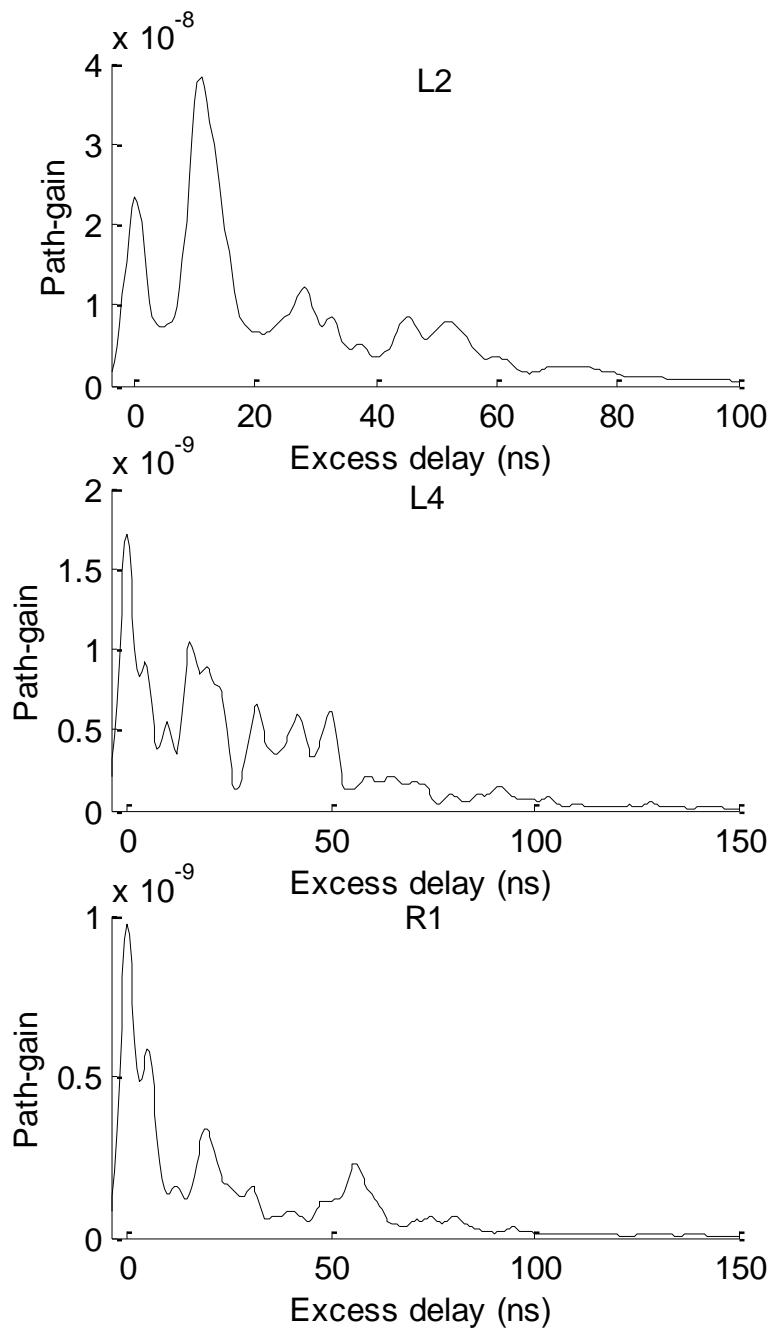
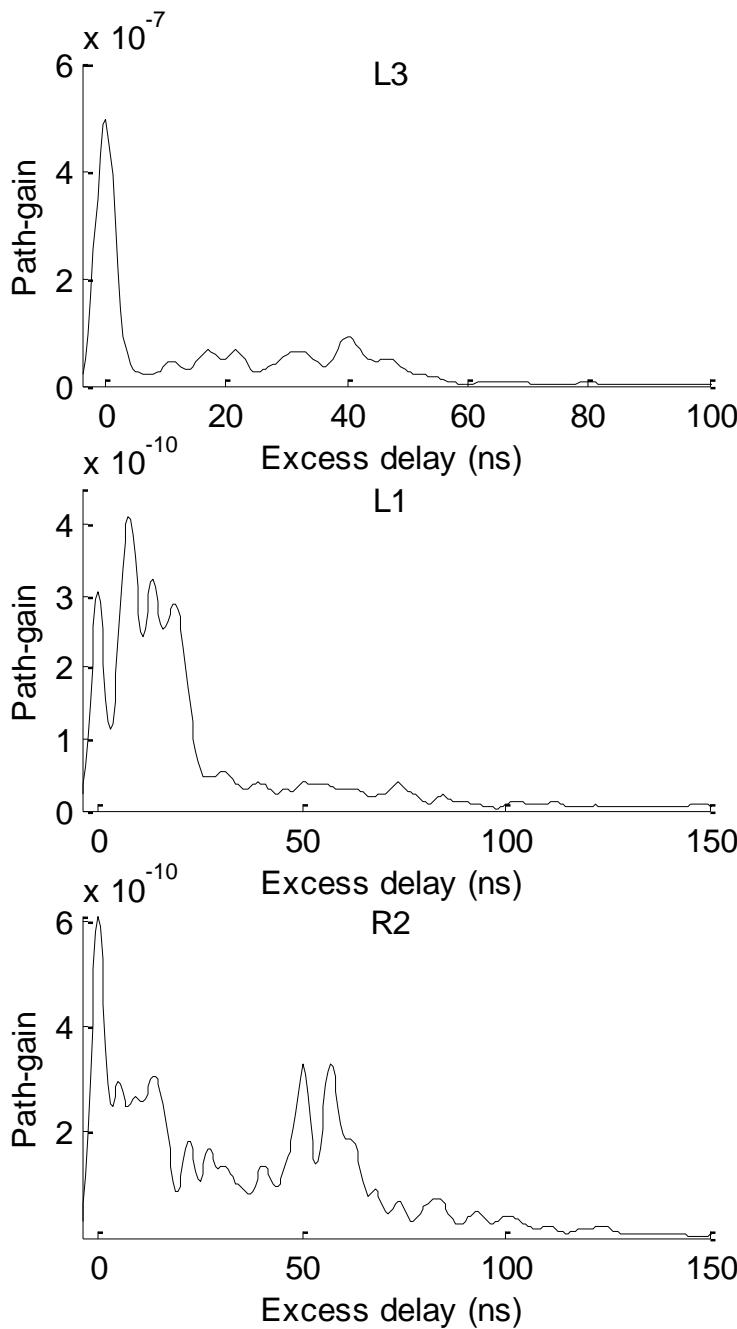
LONG COAXIAL CABLE approx. 60m

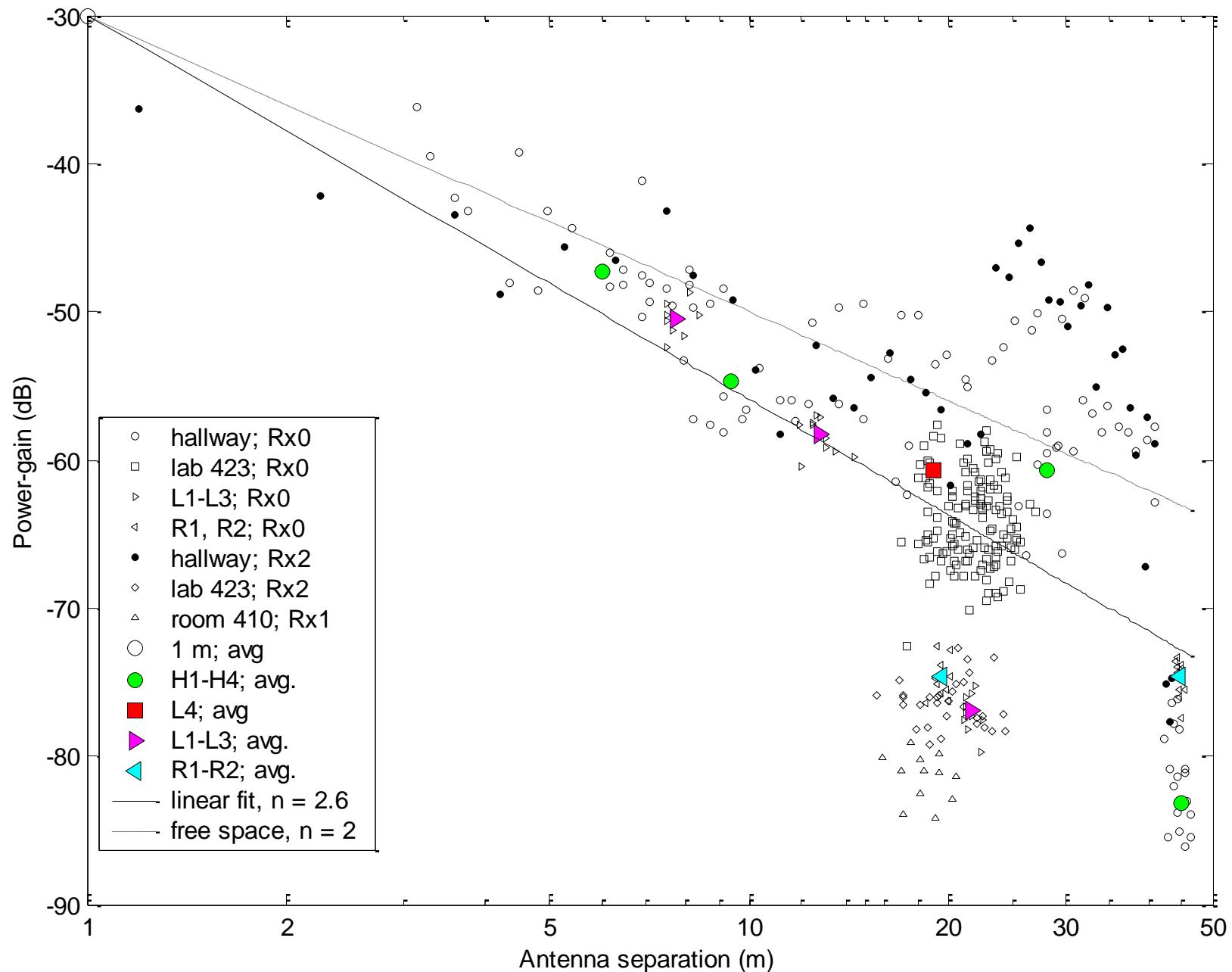
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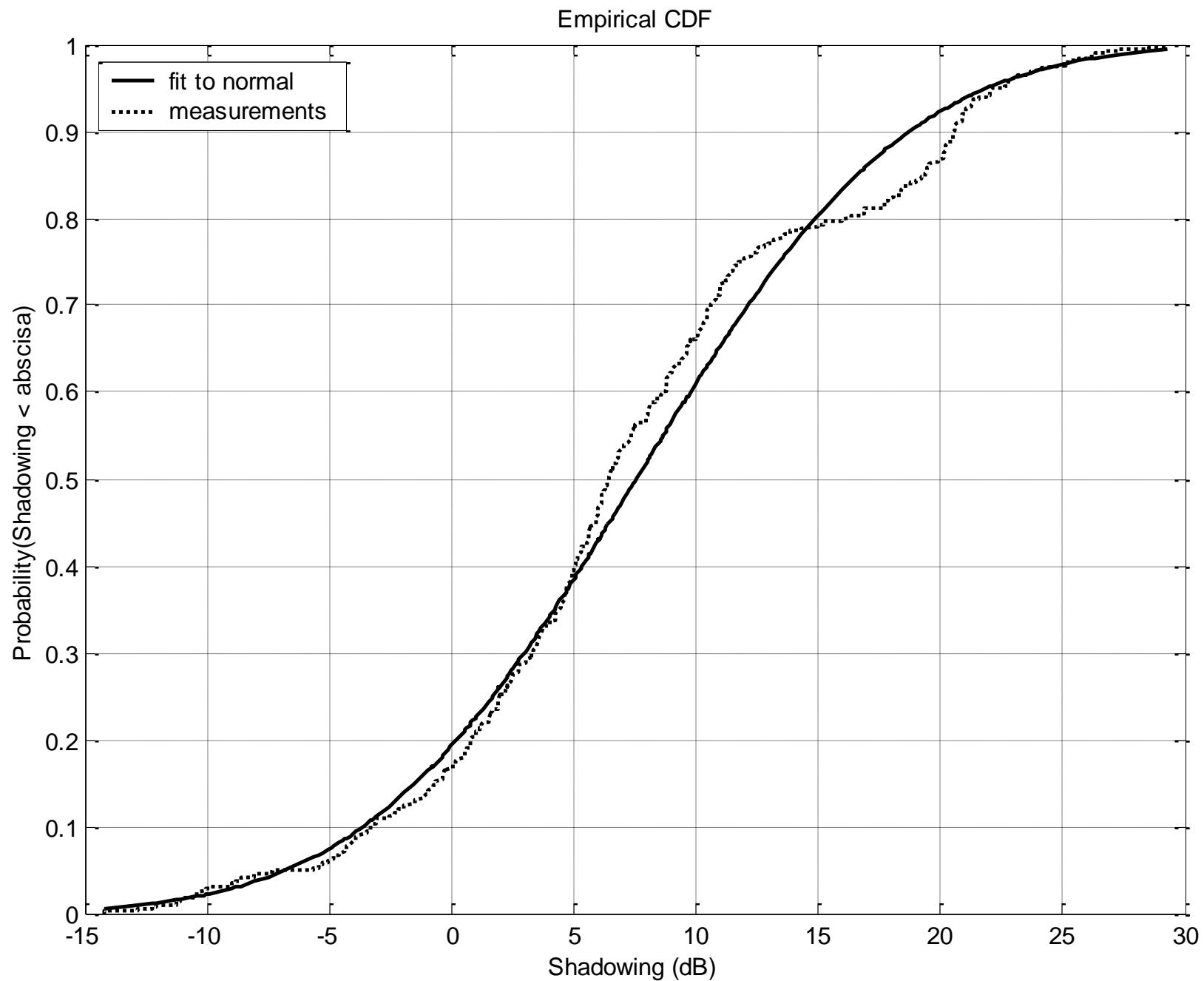
- Receiver (Rx)
- ★ Transmitter (Tx)

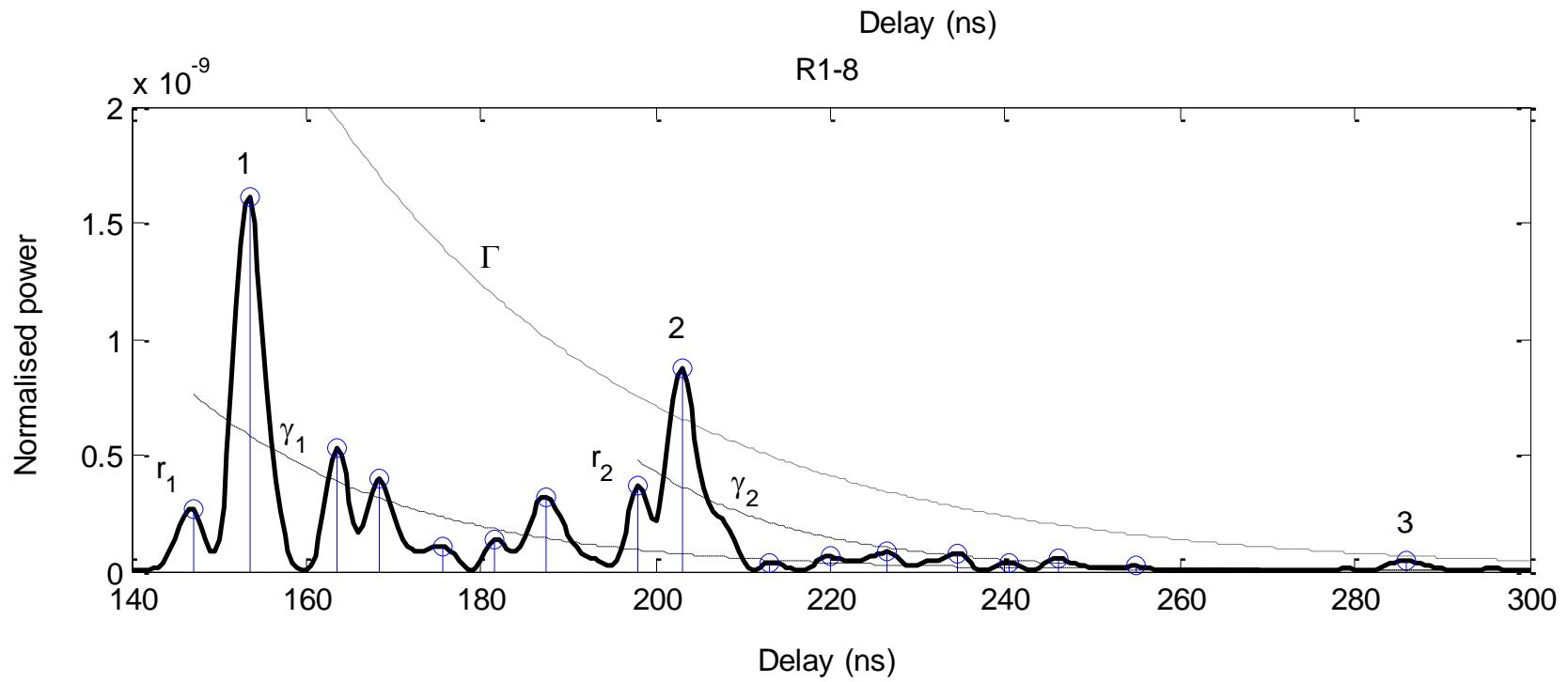
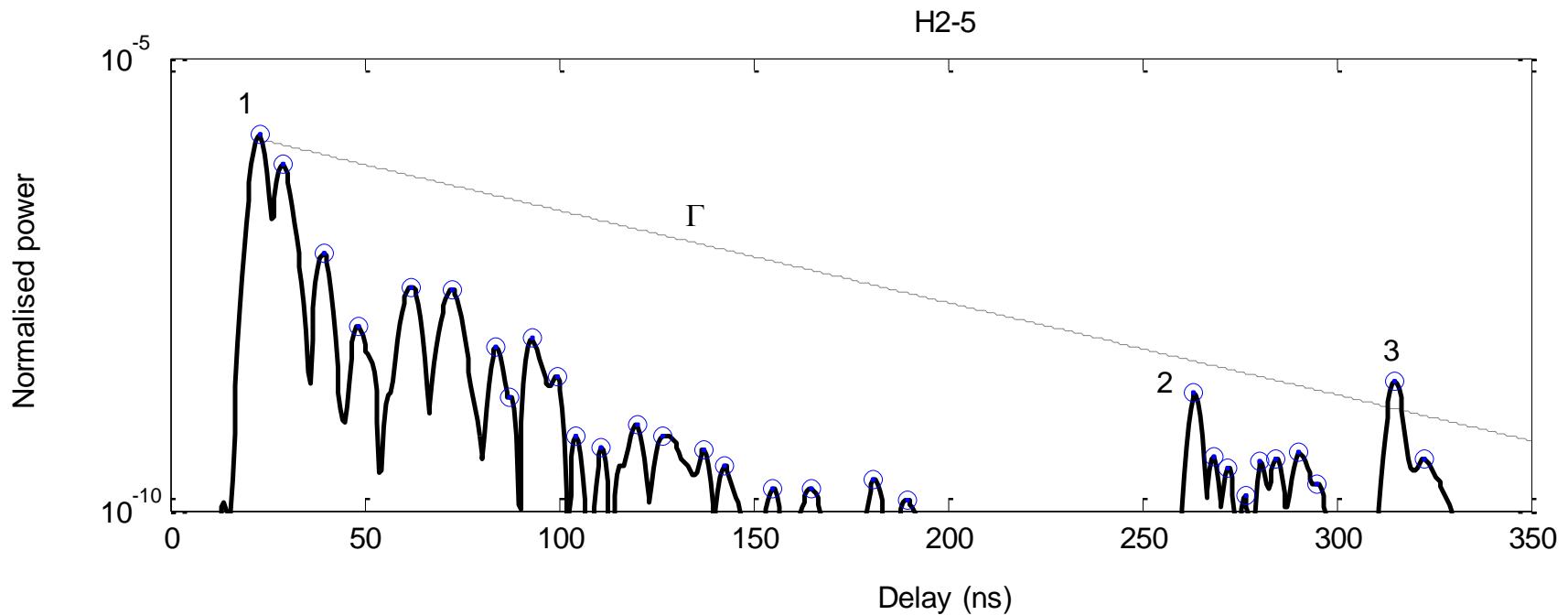


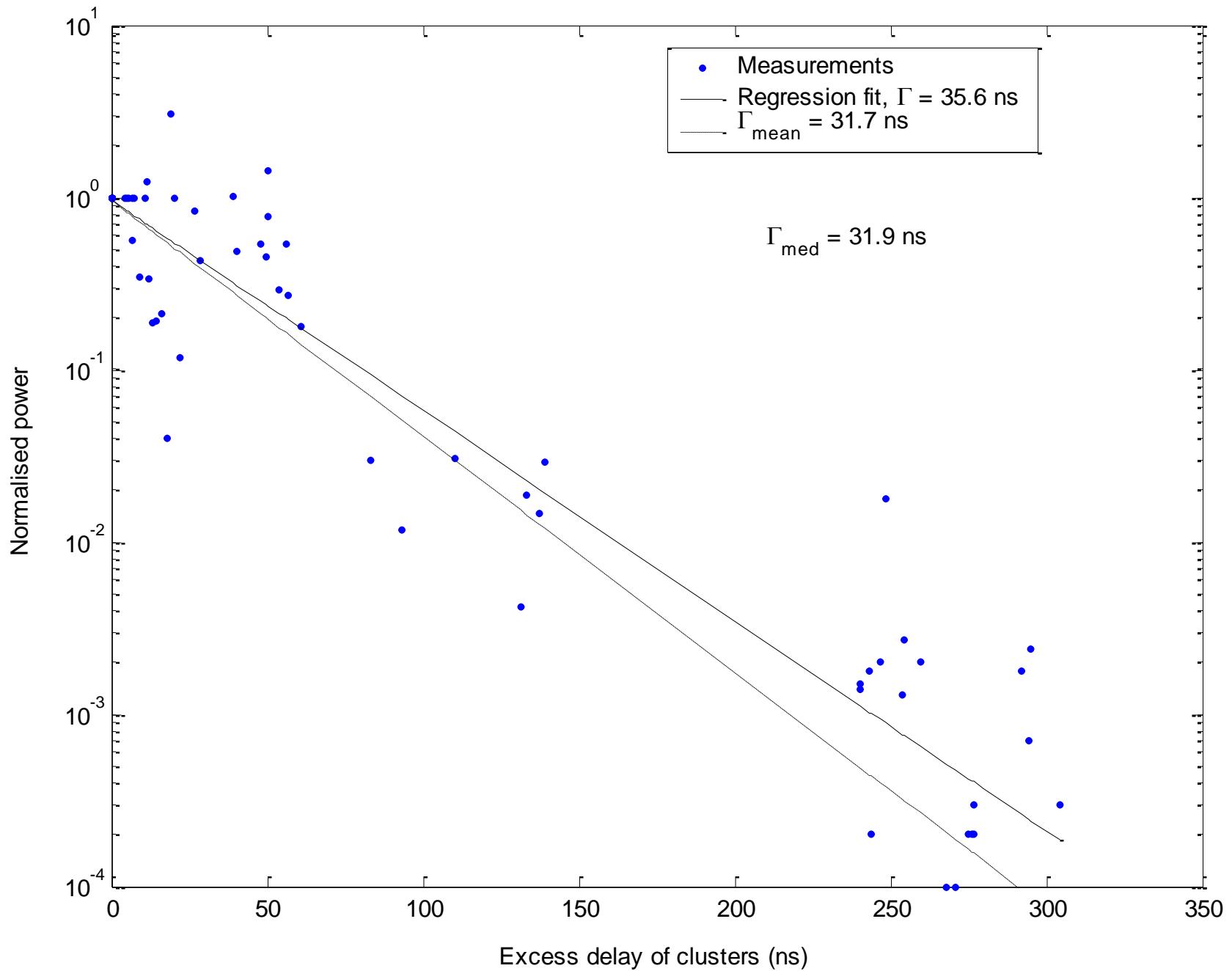


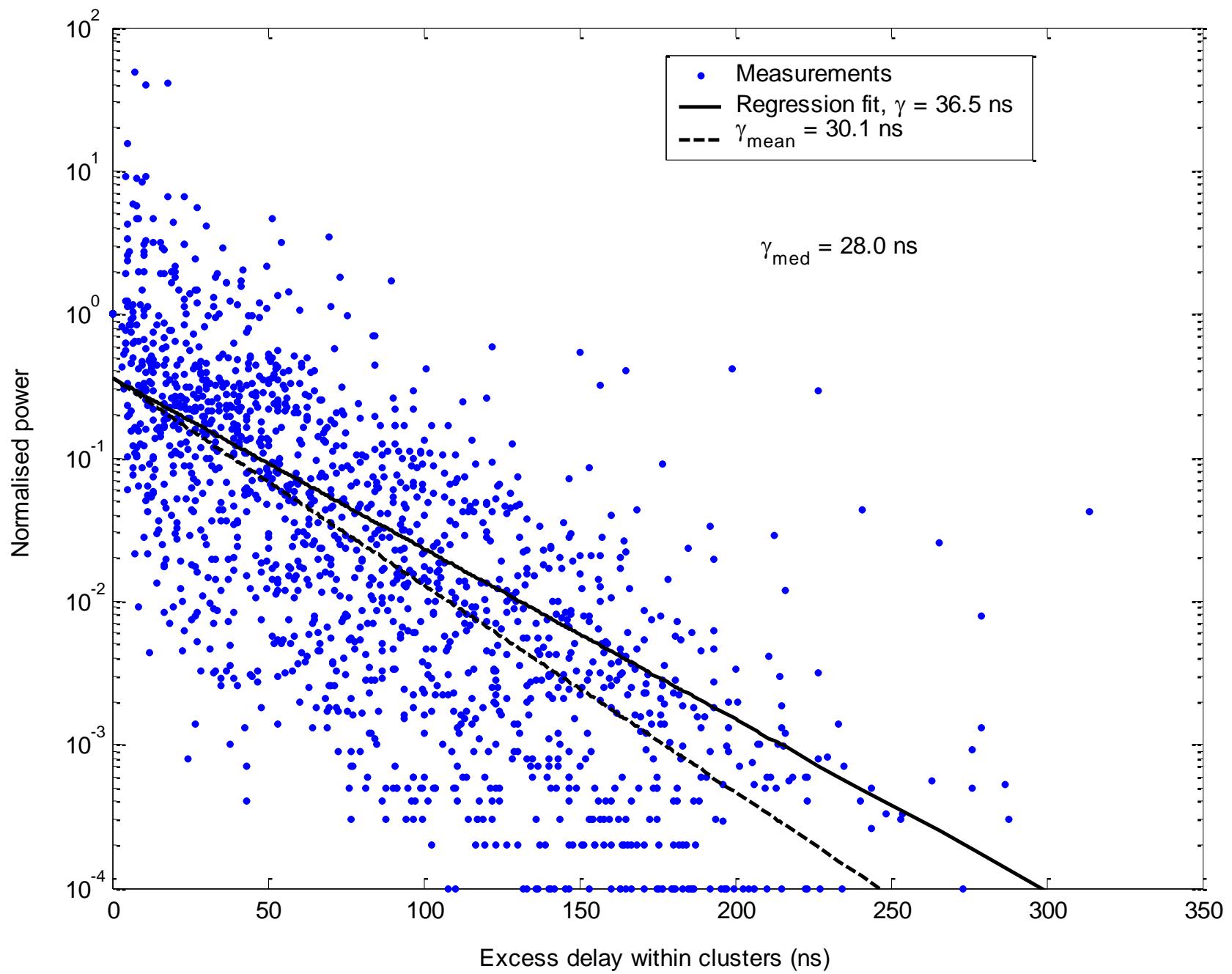


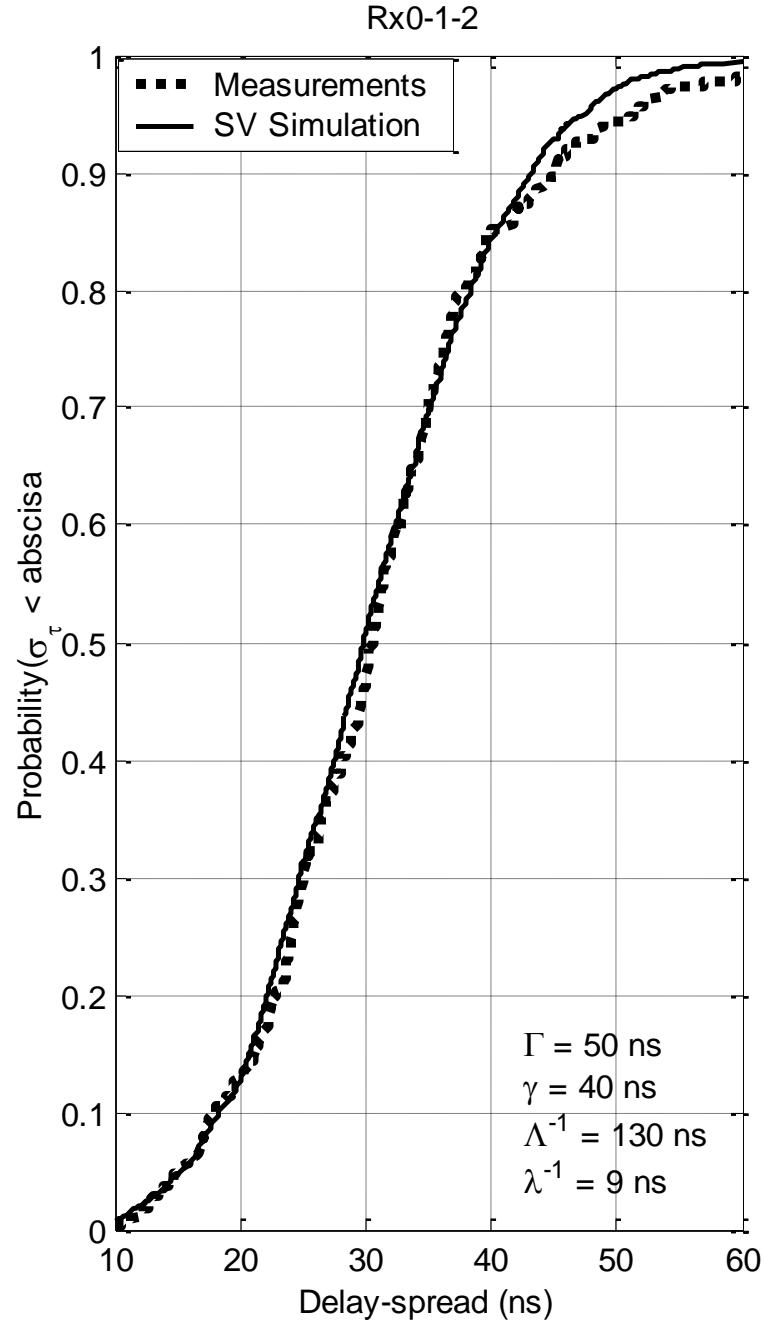
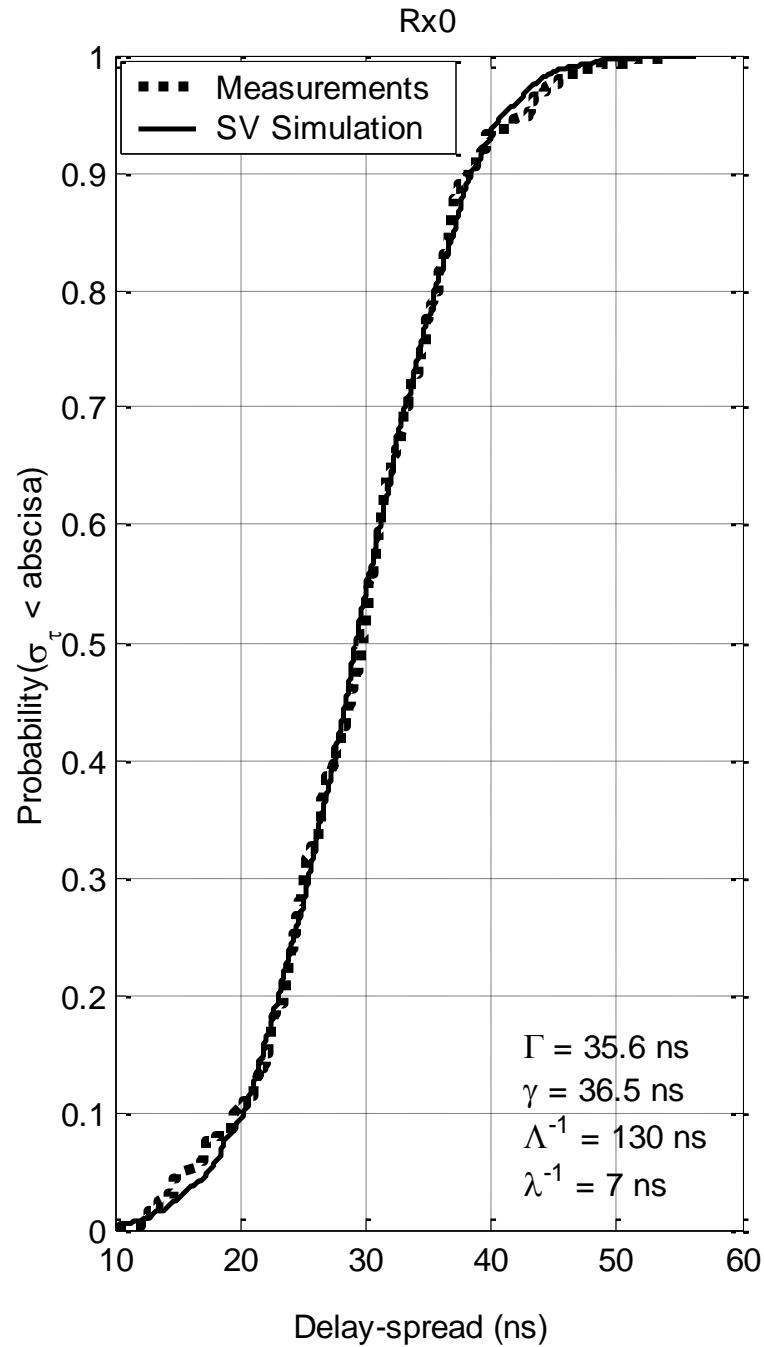


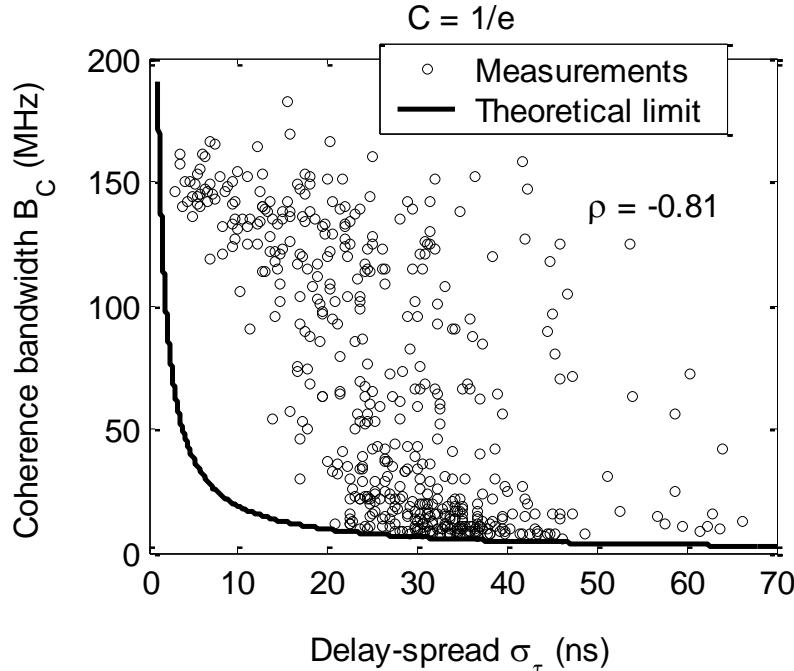
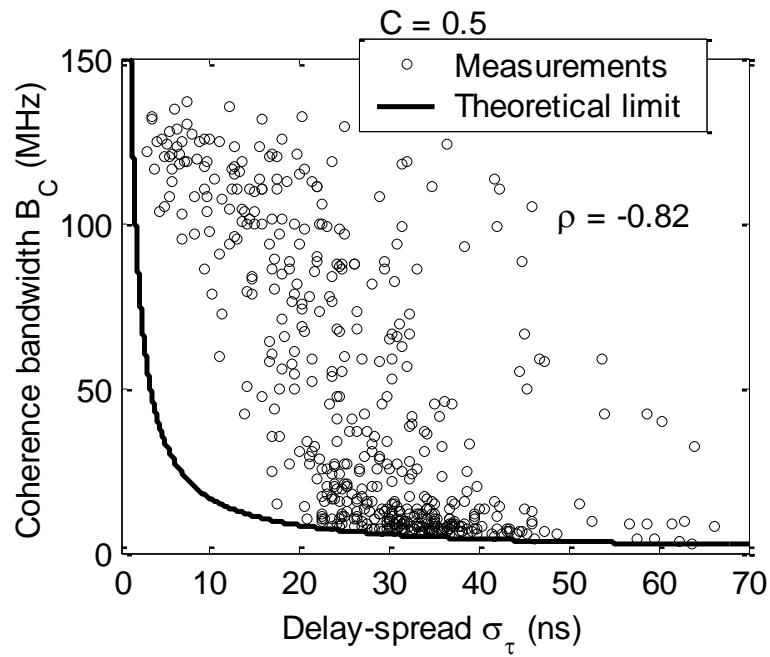
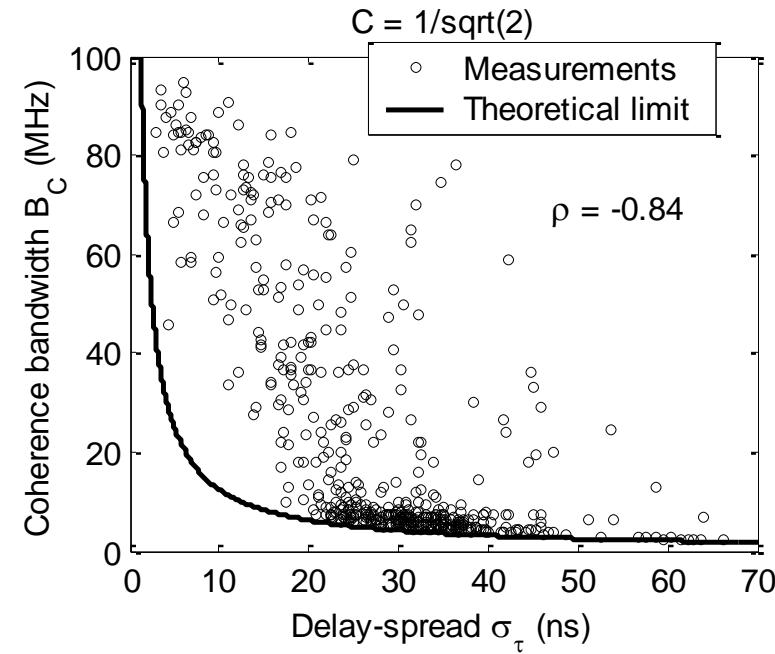
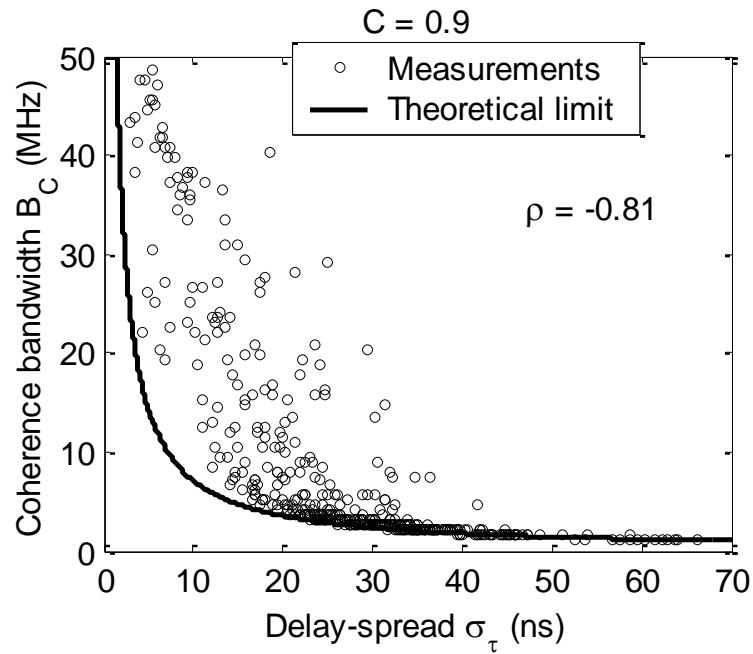


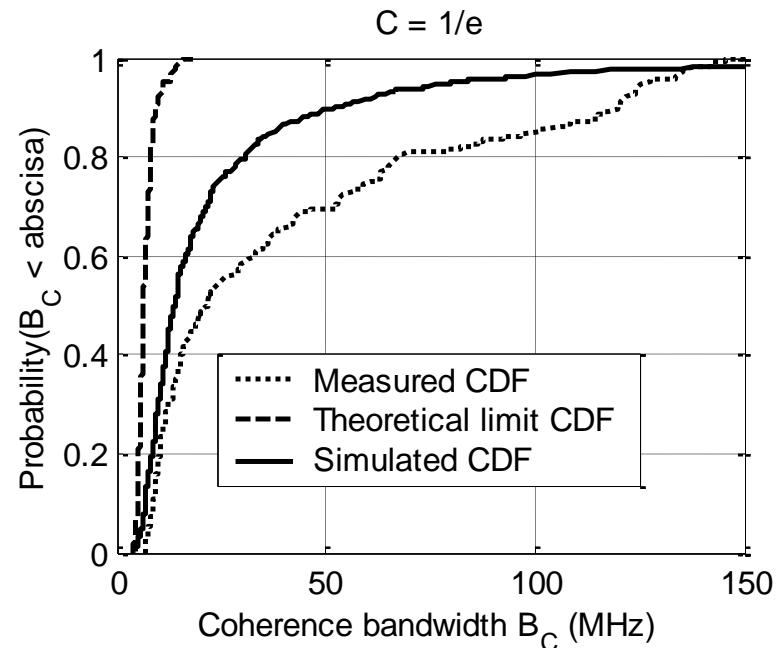
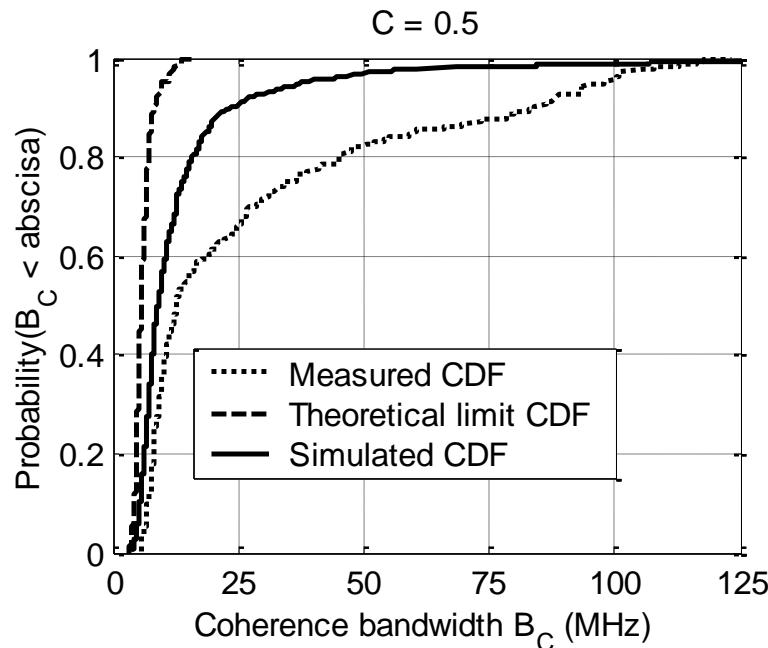
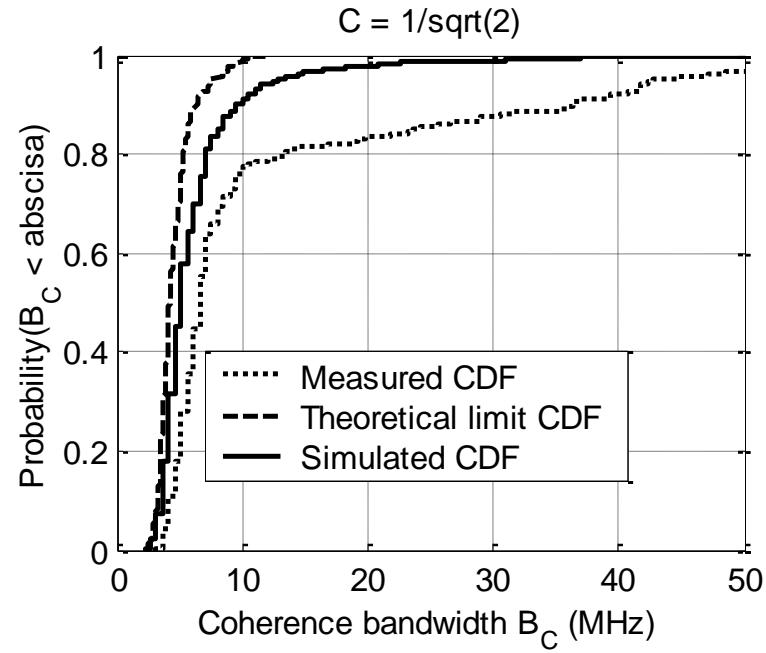
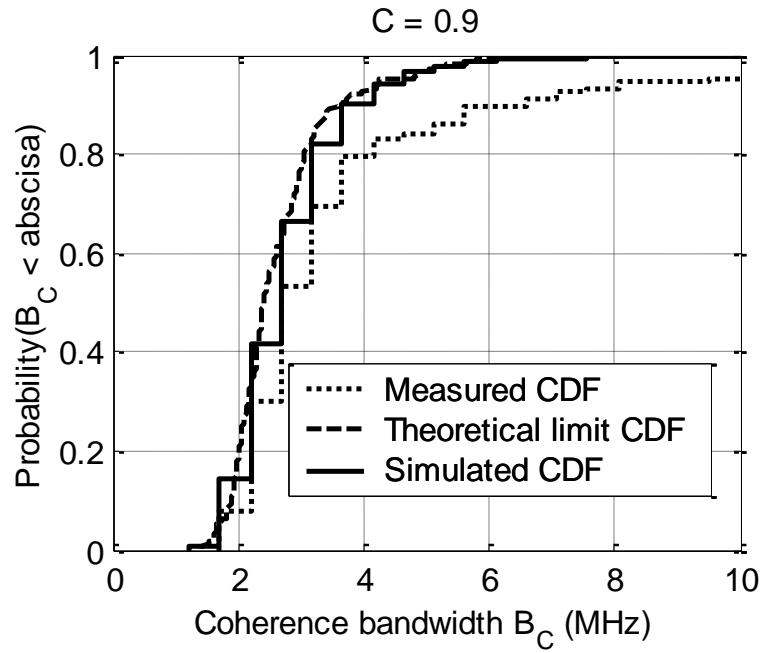












Zaključci mjerenja

- Parametri kanala:
 - $N_C = 1.5$; $\Lambda^{-1} = 130$ ns; $\lambda^{-1} = (7 - 9)$ ns
 - $\Gamma = (30 - 50)$ ns; $\gamma = (30 - 40)$ ns
 - nagib gubitaka snage $n = 2.6$ ($n \in [2.6, 3.1]$)
- Log-normalna CDF stupnja radio-sjene (barem u trendu)
- Maksimalno rasipanje kašnjenja je između 60 – 65 ns.
- Očekivano visoka negativna korelacija ($|\rho| > 0.8$) između rasipanja kašnjenja i koherentnog pojasa kanala. Vrijednosti koherentnog pojasa kanala ne prelaze ispod Fleurijeve granice.
- Nije primjećena nikakva korelacija između nagiba opadanja snage unutar klastera γ i vremena dolaska klastera T_f .
- Predviđanje iznosa koherentnog pojasa dobiveno SV modelom je pesimistično, bez obzira na korelacijski prag. Vrijednosti nisu ispod Fleurijeve granice.

Dodatak

Centralni granični teorem

- Promotrimo sumu:

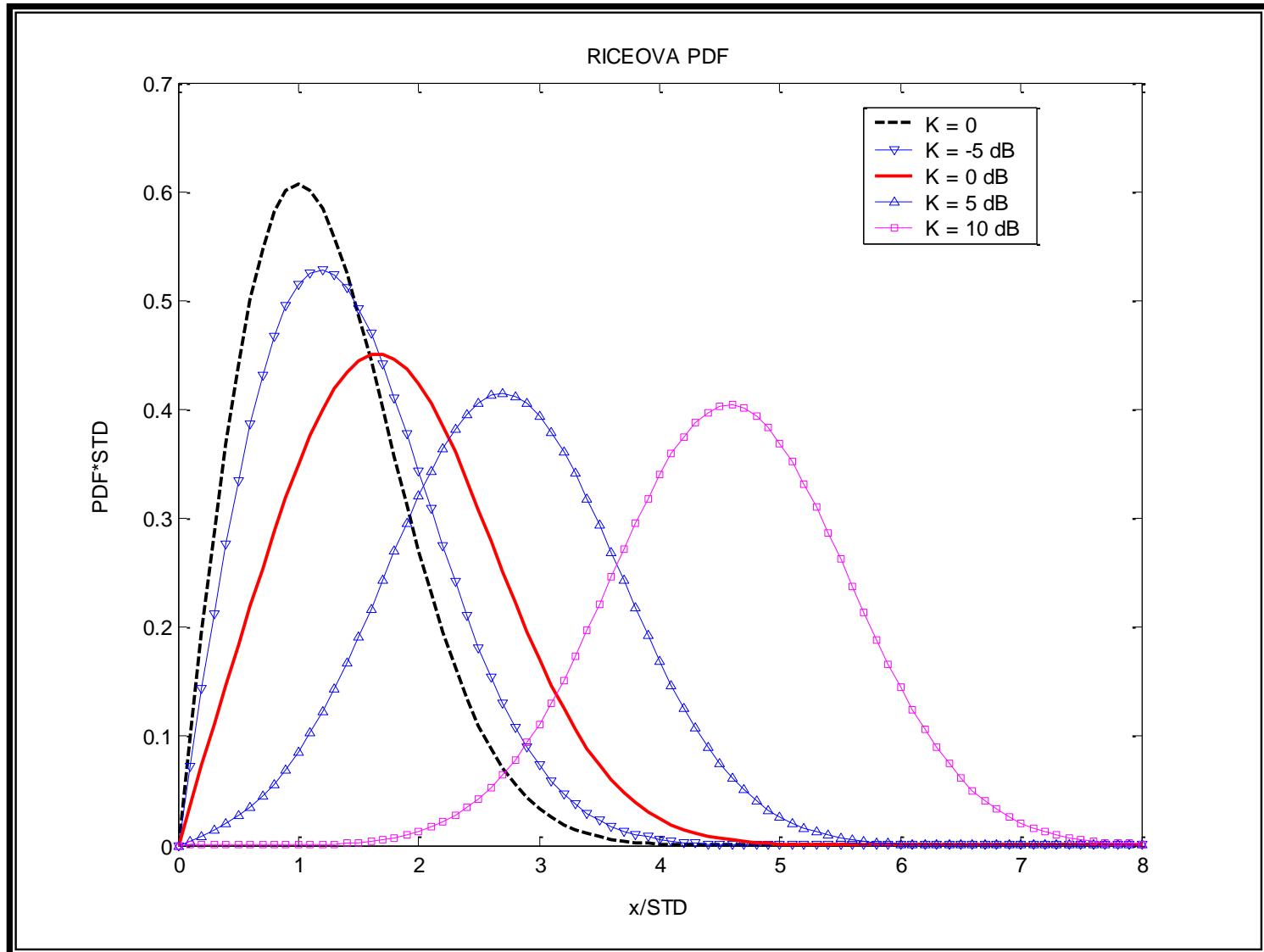
$$X = X_1 + X_2 + \dots + X_n,$$

gdje su X_1, X_2, \dots, X_n nezavisne slučajne varijable koje imaju istu distribuciju, ne nužno normalnu, s prosjekom μ i varijancom σ^2 .

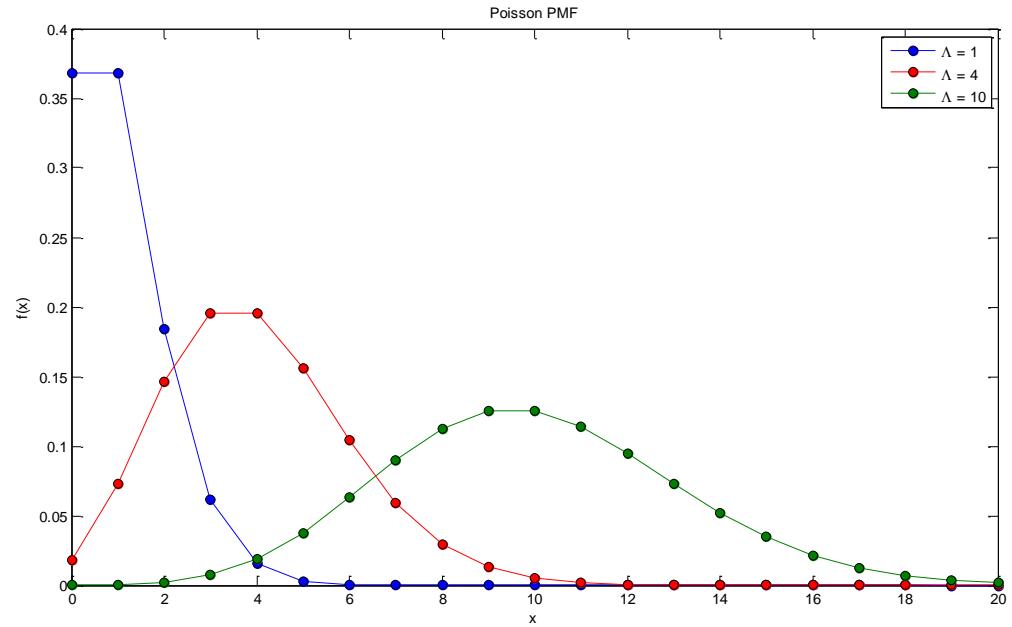
Za veliki n distribucija slučajne varijable X teži normalnoj razdiobi, s prosjekom $n\mu$ varijancom $n\sigma^2$.

Riceova i Rayleighova PDF

$$p(x; K) = \frac{x}{\sigma^2} \exp\left[-\left(\frac{x}{\sqrt{2}\sigma}\right)^2\right] \exp(-K) I_0\left(\frac{a}{\sigma} \sqrt{2K}\right) \Rightarrow p(x; K=0) = \frac{x}{\sigma^2} \exp\left[-\left(\frac{x}{\sqrt{2}\sigma}\right)^2\right], \quad x > 0$$



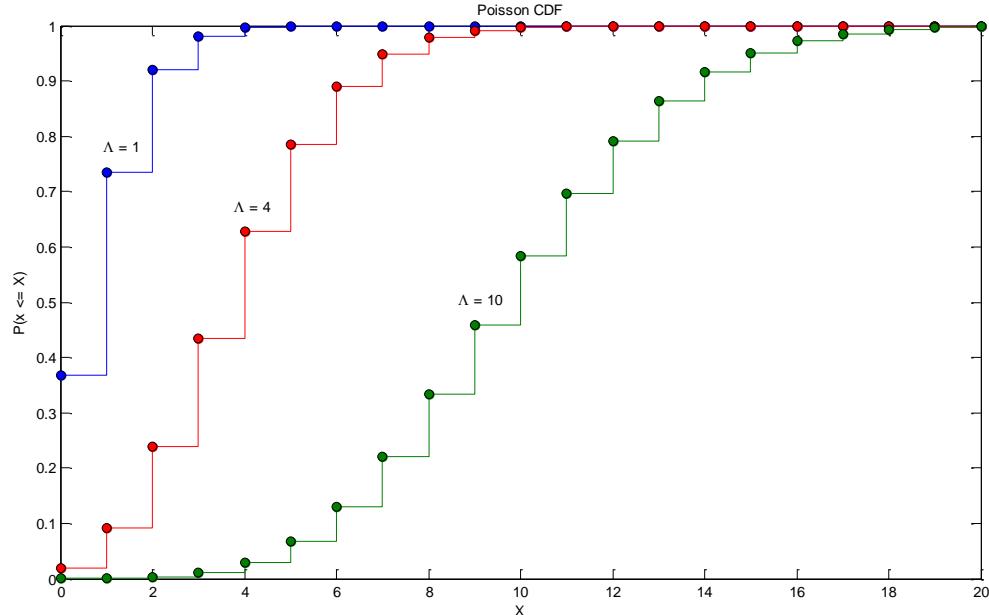
Poissonova distribucija vjerojatnosti



PMF: $f(x) = \frac{\Lambda^x e^{-\Lambda}}{x!}, \quad \Lambda > 0$

CDF: $P(x \leq X) = \sum_{x=0}^X f(x)$

$P(x \leq X) = e^{-\Lambda} \sum_{x=0}^X \frac{\Lambda^x}{x!} = \frac{\Gamma(X+1, \Lambda)}{X!}$



Prosjek i varijanca: $\mu = \sigma^2 = \Lambda$

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* Napomena: Sve popisane reference su na raspolaganju na zahtjev studenta.