COURSE 10
MOBILE RADIO CHANNEL

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CONTENT

- Mobile radio channel characterization
  - Radio channels, fading, channel models
- Types of diversity characteristic of radio transmissions
  - Frequency, time, space diversity etc.
- Signal combination techniques
  - Selection combining, maximum ratio combining, equal gain combining

MOBILE RADIO CHANNEL

- Mobile radio channel characterization involves at least three components:
  - Average attenuation (or average signal level) at the point where the mobile is located
    - Characterizes large-scale fading
  - Multiple propagation due to environmental reflections
    - Determines the frequency selectivity of the radio channel
  - Fast/slow variable flat fading due to mobile movement
    - Caused by the Doppler effect

RADIO CHANNEL MODELING

- A radio channel, in general, is described by the average attenuation transmitter-receiver
- The average attenuation with respect to the transmitter can be computed based on theoretical or empirical models:
  - Theoretical models:
    - Attenuation in free space
    - The two-ray model
    - The four-ray model
  - Empirical models:
    - The Okumura-Hata model
    - The Lee model
    - The COST 231 model Walfisch-Ikegami – (improved Hata model)

RADIO CHANNEL MODELING

- General model for computing the average attenuation:

$$a_m(d)[dB] = a_s(d_0)[dB] + 10n\lg(d/d_0) + X_\sigma[dB]$$

  - d – distance between the transmitter and the mobile terminal
  - d_0 – reference distance (1km for large cells, 100m for micro-cells, 1m for indoor)
  - n – attenuation change slope (depends on frequency, antenna height, propagation conditions):
    - n = 2 for free space propagation
    - n < 2 for indoor LOS
    - n >> 2 if there are obstacles in the propagation path

RADIO CHANNEL MODELING

- $a_s(d_0)$ can be computed based on theoretical or empirical formulas
  - In case of free space propagation is:

$$a_s(d_0) = (4\pi d_0/ \lambda)^2$$

  - λ – wavelength
- X_σ – is a Gaussian variable with 0 mean and dispersion σ given in dB
  - The dispersion of this variable is dependent on the propagation conditions and the geometry of the site
  - The dispersion gives the deviations of the average due to variations in the propagation conditions

RADIO CHANNEL MODELING

- Attenuation for the free space propagation model

$$L_{FS}[dB] = 20lg(d) + 20lg(f) + 92.45$$

  - d – distance between transmitter and mobile terminal in km
  - f – frequency in GHz

- It is used for LOS connections

RADIO CHANNEL MODELING

- Attenuation for the two-ray model

$$L_{TR}[dB] = 40lg(d) + 10lg(Gh_t^2h_r^2)$$

  - d – distance between the transmitter and the mobile terminal
  - $G = G_tG_r$, G_t – emitter antenna gain, G_r – receiver antenna gain
  - h_t – emitter antenna height, h_r – receiver antenna height
- The received signal has 2 components:
  - LOS component
  - Multipath component (a single reflected wave)

RADIO CHANNEL MODELING

- COST Hata model for urban environment

$$L_U[dB] = 69.55 + 26.16\lg(f) - 13.82\lg(h_B) - C_H + [44.9 - 6.55\lg(h_B)]\lg(d)$$

- For small towns: $C_H = 0.8 + (1.1\lg(f) - 0.7)h_M - 1.56\lg(f)$
- For large cities:

$$C_H = 8.29(\lg(1.54h_M))^2 - 1.1 \text{ for } 150 \leq f \leq 200 \text{ MHz}$$

$$C_H = 3.2(\lg(11.75h_M))^2 - 4.97 \text{ for } 200 < f \leq 1500 \text{ MHz}$$

  - h_B – base station antenna height (m), h_M – mobile station antenna height (m)
  - f – frequency (MHz), d – distance (km), C_H – antenna height correction factor
- It is used for large cells, at frequencies of 150-1500 MHz
- It is considered that the base stations are located on the roofs of the buildings

RADIO CHANNEL MODELING

- COST 231 model – extended Hata

$$L_{CH}[dB] = 46.3 + 33.9\lg(f) - 13.82\lg(h_B) - C_H + [44.9 - 6.55\lg(h_B)]\lg(d) + C$$

C_H = 0dB for medium size cities and suburban areas

C = 3dB for metropolitan areas

  - h_B – base station antenna height (m), h_M – mobile station antenna height (m)
  - f – frequency (MHz), d – distance (km), C_H – antenna height correction factor

- It is used for small and large macro-cells, at frequencies of 1500-2000 MHz

RADIO CHANNEL MODELING

- COST 231 – Walfisch-Ikegami model: differentiates between LOS and NLOS cases, it is used for small macro- and micro-cells

$$L_{LOS}[dB] = 46.2 + 26\lg(d) + 20\lg(f)$$

$$L_{NLOS} = L_0 + L_{rts} + L_{msd} \text{ for } L_{rts} + L_{msd} > 0$$

$$L_{NLOS} = L_0 \text{ for } L_{rts} + L_{msd} \leq 0$$

- Free space loss: $L_0 = 32.4 + 20\lg(d) + 20\lg(f)$
- Rooftop to street diffraction loss: $L_{rts} = -16.9 - 10\lg(w) + 10\lg(f) + 20\lg(\Delta h_m) + L_{ori}$
  - w – road width, f – frequency, d – distance
  - $\Delta h_m = h_{cl} - h_m$, where h_{cl} is the building height, h_m terminal height

RADIO CHANNEL MODELING

- ○ Street orientation loss

$$L_{ori} = -10 + 0.354\varphi \text{ for } 0° \leq \varphi < 35°$$

$$L_{ori} = 2.5 + 0.075(\varphi - 35) \text{ for } 35° \leq \varphi < 55°$$

$$L_{ori} = 4 + 0.114(\varphi - 55) \text{ for } 55° \leq \varphi \leq 90°$$

- ○ φ – angle between incidences coming from base station and road

❑ Multiscreen loss: $L_{msd} = L_{bsh} + k_a + k_d lg(d) + k_f lg(f) - 9lg(b)$

$$L_{bsh} = 18lg(1 + \Delta h_b) \text{ for } h_b > h_{cl}$$

$$L_{bsh} = 0 \text{ for } h_b \leq h_{cl}$$

- ○ $\Delta h_b = h_b - h_{cl}$, h_b – base station height, h_{cl} – building height, d – distance between buildings

RADIO CHANNEL MODELING

$k_a = 54$ for $h_b > h_{cl}$

$k_a = 54 – 0.8\Delta h_b$ for $d \geq 5km$, $h_b \leq h_{cl}$

$k_a = 54 – 0.8\ \Delta h_b d/0.5$ for $d < 5km$, $h_b = h_{cl}$

$k_d = 18$ for $h_b > h_{cl}$

$k_d = 18 - 15\Delta h_b/h_{cl}$ for $h_b \leq h_{cl}$

$k_f = -4 + 0.7(f/925 – 1)$ for medium size cities, suburban areas

$k_f = -4 + 1.5(f/925 – 1)$ for metropolitan areas

2.4GHZ CHANNEL MODELS

RMS Delay spread	Câștig cale 1 (0dB)	Câștig cale 2 (-4dB)	Câștig cale 3 (-8dB)	Câștig cale 4 (-12dB)	Câștig cale 5 (-16dB)	Câștig cale 6 (-20dB)
0ns	0ns	0	0	0	0	0
10ns	0ns	10.167	20.333	30.5	40.667	50.833
20ns	0ns	20.5	41	61.5	82	102.5
30ns	0ns	30.667	61.333	92	122.667	153.333
40ns	0ns	41	82	123	164	205
50ns	0ns	51.167	102.333	153.5	204.667	255.833

5GHZ CHANNEL MODELS

Suburban macro		Urban macro		Urban micro	
Putere [dB]	Întârziere [µs]	Putere [dB]	Întârziere [µs]	Putere [dB]	Întârziere [µs]
-3	0	-3	0	-4.55	0
-5.22	0.01	-5.22	0.01	-6	0.01
-6.98	0.025	-6.98	0.03	-6.98	0.015
-5.6682	0.14	-5.2204	0.36	-6.98	0.03
-7.8882	0.15	-7.4404	0.37	-5.8161	0.285
-9.6482	0.165	-9.2004	0.385	-7.2661	0.29
-9.2147	0.06	-4.7184	0.25	-8.2461	0.295
-11.4347	0.07	-6.9384	0.26	-8.2461	0.31
-13.1947	0.09	-8.6984	0.28	-7.2701	0.205
-13.4132	0.4	-8.1896	1.04	-8.7201	0.2
-15.6332	0.41	-10.4096	1.045	-9.7001	0.22
-17.3932	0.43	-12.1696	1.065	-9.7001	0.23
-19.4735	1.38	-12.0516	2.73	-8.8473	0.665
-21.6935	1.39	-14.2716	2.74	-10.2973	0.67
-23.4535	1.41	-16.0316	2.76	-11.2773	0.675
-25.1898	2.83	-15.5013	4.6	-11.2773	0.685
-27.4098	2.835	-17.7213	4.61	-10.564	0.805
-29.1698	2.855	-19.4813	4.625	-12.014	0.81
				-12.994	0.82
				-12.994	0.835
				-12.9806	0.925
				-14.4306	0.935
				-15.4106	0.94
				-15.4106	0.96

FADING CLASSIFICATION

- Based on the multipath delay spread:
  - Flat fading
    - Signal bandwidth < Channel bandwidth; Delay distribution < Symbol period
  - Frequency selective fading
    - Signal bandwidth > Channel bandwidth; Delay distribution > Symbol period
- Based on Doppler spread:
  - Fast fading
    - Coherence time < symbol period; the variations of the channel are faster than the variations of the baseband signal
  - Slow fading
    - Coherence time > symbol period; the variations of the channel are slower than the variations of the baseband signal

FLAT FADING

- All frequency components are affected in the same way
  - It is caused by the combination of the Doppler effect and the sum of reflected waves with identical delays
  - The sum of these waves causes a parasitic amplitude modulation of the received signal
- The channel model is WSSUS
  - Wide Sense Stationary Uncorrelated Scattering – the channel variation are random over time
- Basic parameters:
  - Doppler frequency: $f_d = v/\lambda = v/(c/f_c) = vf_c/c$
  - Doppler shift: $f_i = \cos(\gamma_i)f_d$
    - v – speed of the terminal, c – speed of light, γ_i – incidence angle

FLAT FADING

- In the case of an isotropic emitter that emits an unmodulated sine signal with an envelope power of σ_g^2, the Doppler spectrum is given by:

$$S_g(f) = \frac{\sigma_g^2}{\pi f_d} \frac{1}{\sqrt{1 - \left(\frac{f}{f_d}\right)^2}}$$

- The power of a scatterer γ is given by: $P(\gamma) = \sigma_g^2/2\pi$
- The autocorrelation function of the received envelope is given by:

$$r_g(\tau) = \int_{-f_d}^{f_d} S_g(f) e^{j2\pi f\tau} df = \frac{\sigma_g^2}{2\pi} \int_{-\pi}^{\pi} e^{j2\pi f_d \tau \cos(\gamma)} = \sigma_g^2 J_0(2\pi f_d \tau) = \mathrm{E}[g(t) g^*(t-\tau)]$$

FLAT FADING

- The coherence time is the time interval in which the channel transfer function remains constant
  - In the case of flat fading the channel acts as an amplifier with complex amplification
  - Coherence time: time interval τ in which the autocorrelation function does not fall below $x\sigma_g^2$
  - Empirical computation formulas:

$$t_{c-0.5} = \frac{1}{f_d}$$

$$t_{c-0.9} = \frac{1}{16\pi f_d}$$

$$t_c = \sqrt{\frac{9}{16\pi f_d^2}} = \frac{0.423}{f_d}$$

FLAT FADING

- The Rayleigh distribution of the channel gain value implies the lack of a dominant wave

$$p(r,\theta) = \frac{r}{2\pi\sigma_g^2} e^{-\frac{r^2}{2\sigma_g^2}} \Rightarrow \begin{cases} p(r) = \frac{r}{2\pi\sigma_g^2} e^{-\frac{r^2}{2\sigma_g^2}} \text{ Rayleigh distribution} \\ p(\theta) = \frac{1}{2\pi} \text{ Normal distribution} \end{cases}$$

- If there is a dominant wave the channel is distributed Rice

$$p(r) = \frac{r}{2\pi\sigma_g^2} e^{-\frac{a_0^2+r^2}{2\sigma_g^2}} I_0\left(\frac{r a_0}{\sigma_g^2}\right)$$

  - a_0 – gain on the dominant wave, $I_0(x)$ – modified Bessel function of first kind and order 0

FLAT FADING

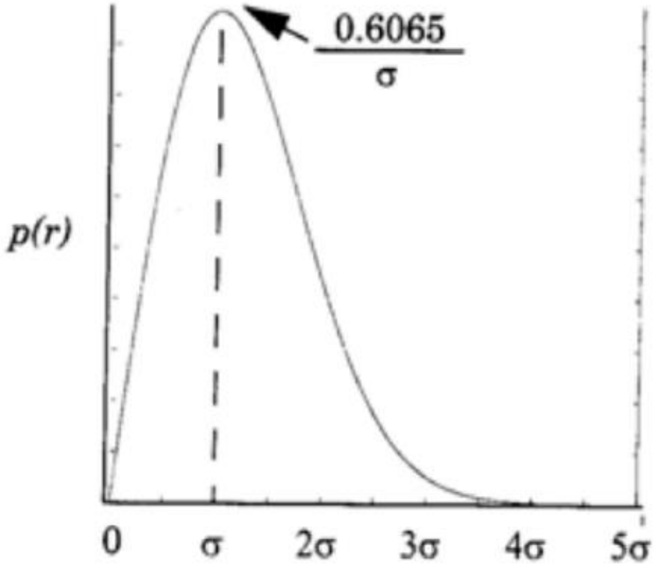


Fig. 1.a Alura funcției p.d.f. de tip Rayleigh

$$K(dB) = 10 \cdot \lg \frac{a_0^2}{2\sigma^2}$$

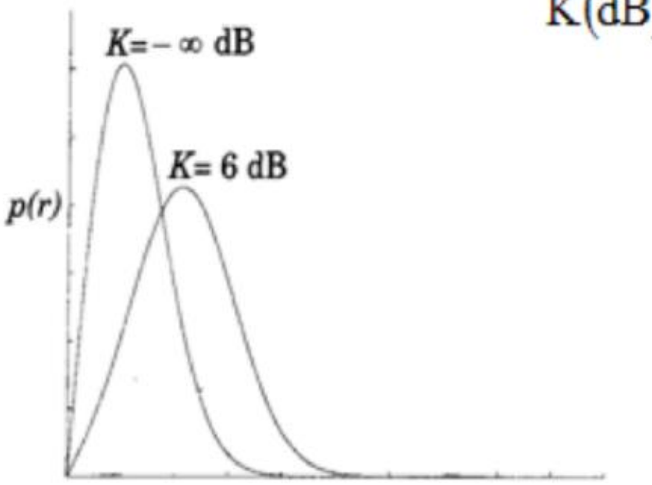


Fig. 1.b Alura funcției p.d.f. de tip Rice;
K=-∞ corespunde distribuției Rayleigh

- ❑ In the situation where the number of incoming waves is small the channel amplification distribution is of Nakagami type

FREQUENCY SELECTIVE FADING

- From the point of view of multipath propagation, the radio channel can be described as an invariant filter in time – if the speed of the mobile is considered 0
- Due to the motion and multipath propagation, a variable filter in time will be obtained and the channel will be selective in both frequency and time
- The time response g(t) and the frequency characteristics G(f) of the channel are given by:

$$g(t) = \sum_i a_i e^{-j\varphi_i} \delta(t - \tau_i) = \sum_i \bar{A}_i \, \delta(t - \tau_i)$$

$$G(f) = \sum_i \bar{A}_i \, e^{-j 2\pi f \tau_i}$$

  - a_i – the amplification of the propagation path; φ_i – the phase shift of the propagation path

FREQUENCY SELECTIVE FADING

- The autocorrelation function of the frequency characteristic is given by:

$$r_G(f-\Delta f)=\frac{1}{2}E[G(f)G^*(f-\Delta f)]=E\left[\sum_i\sum_k \bar{A}_i\bar{A}_k^* e^{-j2\pi f(\tau_i-\tau_k)}e^{-j2\pi\Delta f\tau_k}\right]$$

- If the received waves are uncorrelated, then the following simplification can be made:

$$\frac{1}{2}E\left[\sum_i\sum_k \bar{A}_i\bar{A}_k^*\right]=\frac{1}{2}E\left[\sum_i \bar{A}_i\bar{A}_i^*\right]=\sigma_i^2$$

- In this case the frequency autocorrelation function becomes:

$$r_G(\Delta f)=\sum_k \sigma_k^2 e^{-j2\pi\Delta f\tau}=\int_0^\infty P(\tau)e^{-j2\pi\Delta f\tau}d\tau$$

  - ○ P(τ) – the power-delay profile of the channel

FREQUENCY SELECTIVE FADING

- τ^2_{rms} represents the delay spreads inserted by the channel

$$\tau^2_{rms} = \frac{1}{\sigma_g^2}\int_0^{\infty}(\tau - \tau_m)^2 P(\tau)d\tau$$

  - τ_m – average value of the delays
  - σ_g^2 – average power of the received signal

$$\tau_m = \frac{1}{\sigma_g^2}\int_0^{\infty}\tau P(\tau)d\tau$$

  - The channel coherence band represents the frequency band in which the channel can be considered constant
  - Represents the band in which the correlation function is above $x\sigma_g^2$
  - Empirical computation formulas: $B_{c-0.9}=1/(50\ \tau_{rms})$; $B_{c-0.5}=1/(5\ \tau_{rms})$; $B_c=0.276/\ \tau_{rms}$

DIVERSITY TECHNIQUES

- Diversity techniques together with signal combining techniques are a way to improve the performance of fading radio transmissions
  - The basic idea of these techniques is to transmit copies of the signal over independent channels
    - Signal replicas are affected differently by fading
    - If the channels and fading are uncorrelated the effects introduced on different channels are compensated

FREQUENCY DIVERSITY

- The signal is transmitted on different carriers
- The signal replicas must be transmitted on channels affected differently by fading
  - This type of diversity is used to combat frequency selective fading
  - The carriers must be separated at least by the width of the coherence band
  - At reception, the signal replicas are combined before the decision block
  - It is the most inefficient method of diversity – it requires additional frequency and power resources.

TIME DIVERSITY

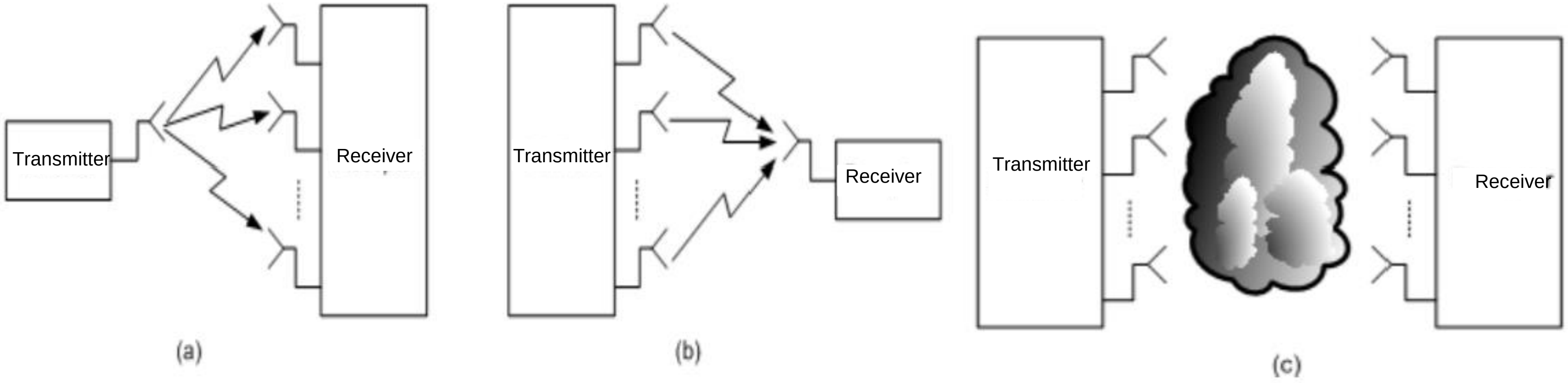
- ❑ It is obtained by transmitting signal replicas at different time intervals
- ❑ The interval between successive transmissions must be at least the channel coherence time in order that the replicas to be affected differently by the channel
  - ○ At reception, the signal replicas are combined before the decision block
  - ○ This type of diversity can be achieved through techniques such as repetition coding
  - ○ This type of diversity can be used to combat fast fading
  - ○ Low efficiency; can only be used for static users

SPACE DIVERSITY

- Space diversity is the most common form of diversity
- It consists of the use of several antennas for both transmission and reception:
  - The antennas must be spaced far enough apart to ensure a low correlation between the transmitted signals
    - The separation should be at least λ/2, but larger spacing is usually required
      - Separation from 10-30 λ for a correlation factor of 0.7
  - It can be used to combat both frequency- and/or time-selective fading
  - It is necessary to know the status of the channel

SPACE DIVERSITY

- Depending on the distribution of the antennas, spatial diversity is of 3 types:
  - Transmission diversity – MISO systems (a)
  - Reception diversity – SIMO systems (b)
  - Diversity both in transmission and reception – MIMO systems (c)



OTHER TYPES OF DIVERSITY

- Polarization diversity
  - Two orthogonally polarized antennas are used (for transmission or reception)
  - Orthogonal polarization presents uncorrelated fading
    - The scattering angle relative to each polarization is random
    - Only two branch polarization is possible
    - 3dB power loss
    - Alternative solution for spatial diversity
- Diversity of arrival angle
  - Directional antennas are required
  - Refracted signals from different directions are affected by independent fading

OTHER TYPES OF DIVERSITY

- Multipath diversity
  - Related to multipath propagation
  - Replicas of the transmitted signal are provided by the multiple propagation paths provided by the channel
- Multi-user diversity
  - Is related to the dynamic allocation of resources and the exploitation of diversity in frequency and time
  - It is characteristic of the OFDMA access method
  - A scheduling algorithm which allocates high throughput to users with better physical resources is needed
  - It ensures a maximum rate from the point of view of the cell, but does not ensure "fairness" between users

SIGNAL COMBINING

- They allow the use of diversity forms provided by the radio channel
- General expression of a replica of the signal received on channel i:

$$r_i(t) = A_i e^{j\varphi_i} s(t) + z_i(t),\ i = 1,2,\ ...,\ M$$

  - $s(t)$ – transmitted signal
  - $z_i(t)$ – additive noise on channel i
  - $A_i e^{j\varphi_i}$ – models the fading that affects signal replica i
  - M – number of replicas transmitted

SELECTION COMBINING

- Selects the strongest received replica
- The signal at the output of the combination block is:

$$y_{SC}(t) = ae^{j\varphi}s(t) + z(t),\ a = \max(a_1,a_2,\ldots,a_M)$$

- The instantaneous signal-to-noise ratio of the signal obtained from the combination is:

$$\rho_{SC} = a^2E_b/N_0 = \max(\rho_1,\rho_2,\ldots,\rho_M)$$

- The average signal-to-noise ratio is:

$$\Gamma = 2\sigma^2E_b/N_0 = \rho_0,\ a^2 = 2\sigma^2$$

- The cumulative distribution of the SNR of a signal affected by Rayleigh fading is:

$$P_\Gamma(\rho) = 1 - e^{-\rho/\rho 0} = P(\Gamma < \rho)$$

SELECTION COMBINING

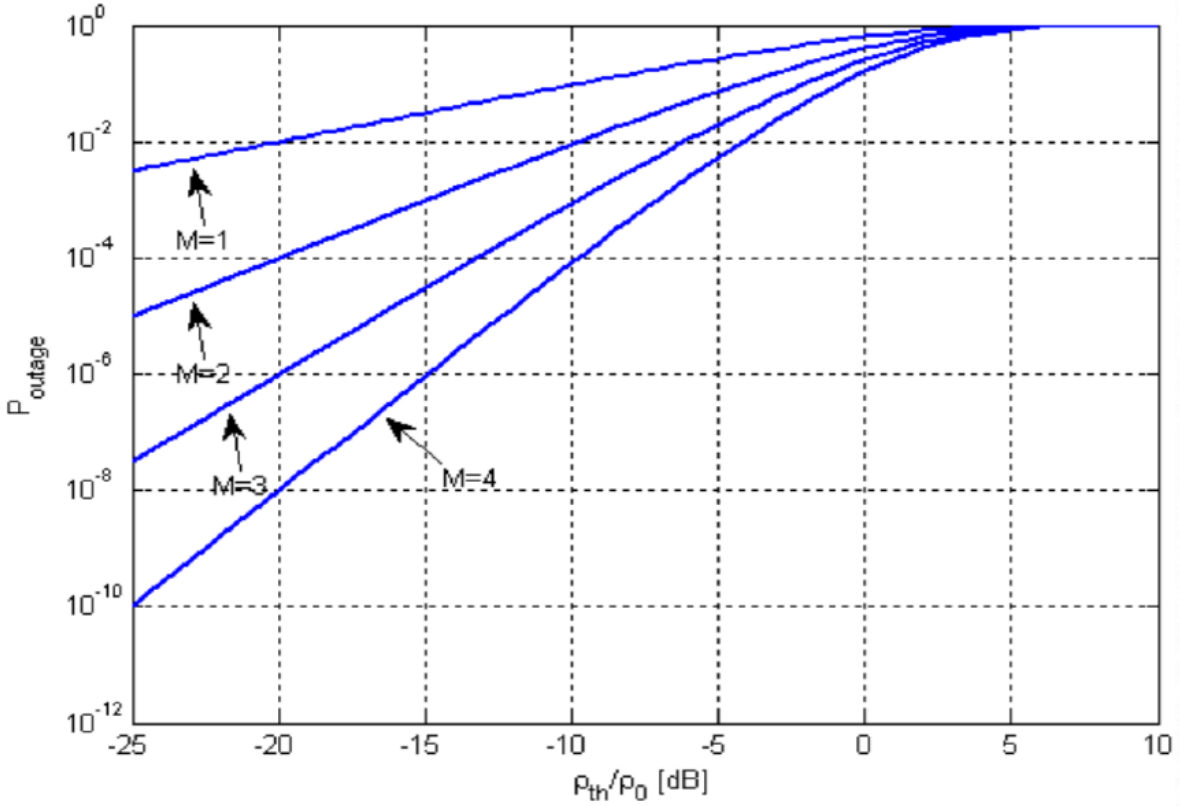
- Outage probability
  - The “outage” event is defined as the event that occurs when the noise-signal ratio falls below a certain threshold, called the “outage” threshold
  - The probability with which the "outage" event occurs is called the "outage“ probability:

$$P_{outage}^{\rho_{th}} = \prod_{i=1}^{M} P_{\Gamma_i}(\rho_{th}) = \prod_{i=1}^{M} (1 - e^{-\frac{\rho_{th}}{\rho_{i0}}})$$

    - ρ_{th} is the outage threshold
    - ρ_{0i} is the average SNR of the i-th replica of the signal

SELECTION COMBINING

- Variation of the “outage” probability depending on the number of signal replicas



MAXIMUM RATIO COMBINING

- This type of combination weights the signal replicas to maximize the signal-to-noise ratio of the obtained signal
- The combined signal can be written:

$$y_{MRC}(t) = \sum_{i=1}^{M} w_i r_i(t) = \sum_{i=1}^{M} w_i\left(a_i e^{j\varphi_i} s(t) + z_i(t)\right)$$

- Weights w_i are chosen according to the quality of channel i
  - A good channel estimate is necessary for each replica
  - Instantaneous SNR obtained after combining:

$$\rho_{MRC} = \frac{\left(\sum_{i=1}^{M} |w_i a_i|\right)^2 E_b}{N_0 \sum_{i=1}^{M} |w_i|^2}$$

MAXIMUM RATIO COMBINING

- ❑ The weights are chosen to maximize the SNR obtained after combining
- ❑ Weighting coefficients can be computed based on Cauchy-Schwartz inequality:

$$\left(\sum_{i=1}^{M} |w_i a_i|\right)^2 \leq \sum_{i=1}^{M} |w_i|^2 \sum_{i=1}^{M} |a_i|^2$$

- ❑ The SNR is maximized when the above inequality is equality
  - ○ The weights are chosen as the conjugate of the gain of each channel, the phase correction is also made
- ❑ The signal at the output of the combiner becomes:

$$y_{EGC}(t) = \sum_{i=1}^{M} a_i e^{-j\varphi} \left(a_i e^{j\varphi} s(t) + z_i(t) = \sum_{i=1}^{M} a_i^2 s(t) + \sum_{i=1}^{M} a_i e^{-j\varphi} z_i(t)\right.$$

MAXIMUM RATIO COMBINING

- ❑ The SNR of the obtained signal is:

$$\rho_{MRC} = \frac{\sum_{i=1}^{M} a_i^2 E_b}{N_0} = \sum_{i=1}^{M} \rho_i$$

- ❑ If the replicas of the received signal are affected by Rayleigh fading (independent on each channel), the SNR of the signal obtained from the combining has a Gamma distribution
  - ○ The scaling parameter of the distribution is equal to the inverse of the average SNR ($1/\rho_0$)
  - ○ The shape parameter is equal to the number of received replicas of the signal (M)
  - ○ The relation holds only if the random variables that model the SNR on each propagation path have the same mean

MAXIMUM RATIO COMBINING

- The cumulative distribution function for the SNR obtained from the combining is:

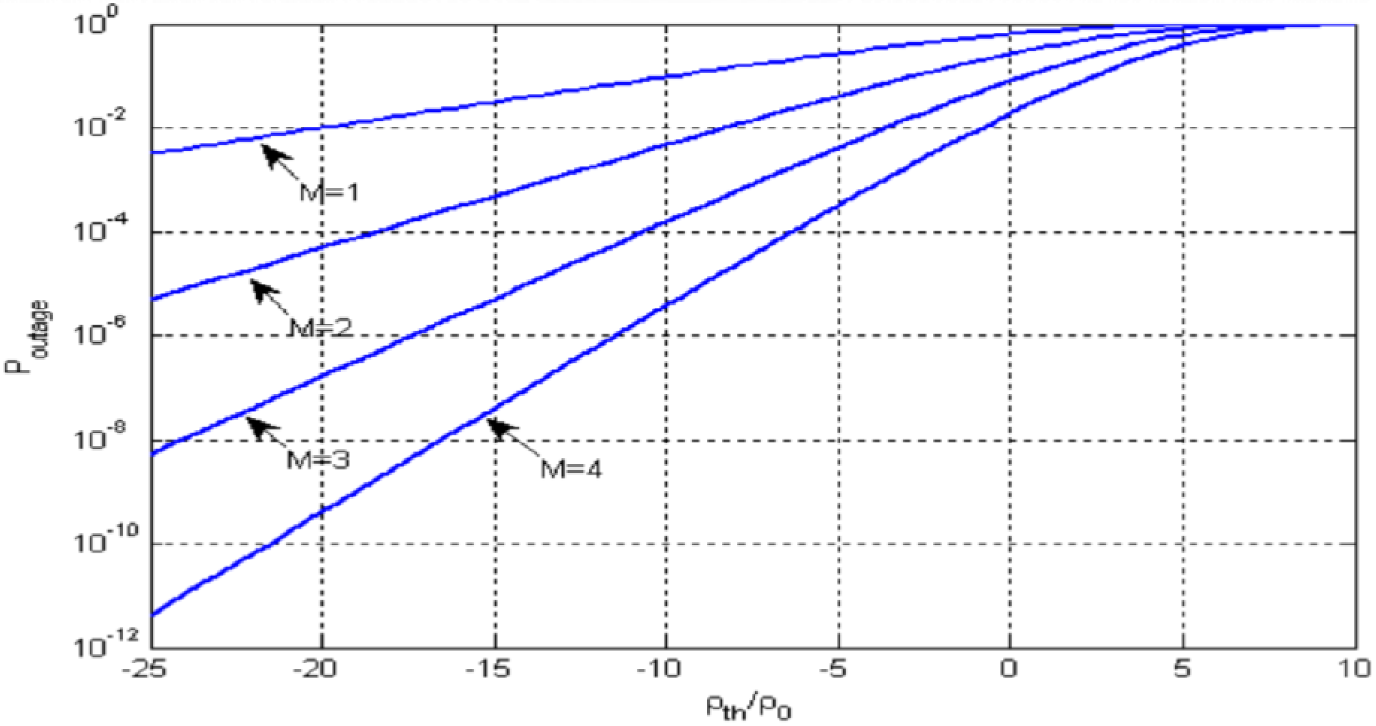
$$P_{\Gamma_{MRC}}(\rho) = CDF_{GAMMA}(\rho, M, \rho_0^{-1}) = 1 - e^{-\frac{\rho}{\rho_0}} \sum_{i=0}^{M-1} \frac{(\rho/\rho_0)^i}{i!}$$

- The probability of "outage" is given by the cumulative distribution function having as argument the "outage" threshold:

$$P_{outage}^{\rho_{th}} = P_{\Gamma_{MRC}}(\rho_{th}) = 1 - e^{-\frac{\rho_{th}}{\rho_0}} \sum_{i=0}^{M-1} \frac{(\rho_{th}/\rho_0)^i}{i!}$$

MAXIMUM RATIO COMBINING

- ❑ Variation of the "outage" probability depending on the number of signal replicas



EQUAL GAIN COMBINING

- ❑ This type of combination does not weight the amplitude of the different signal replicas
    - ○ Only the phase is corrected to prevent the signal replicas from being eliminated
- ❑ The signal obtained after the combination is:

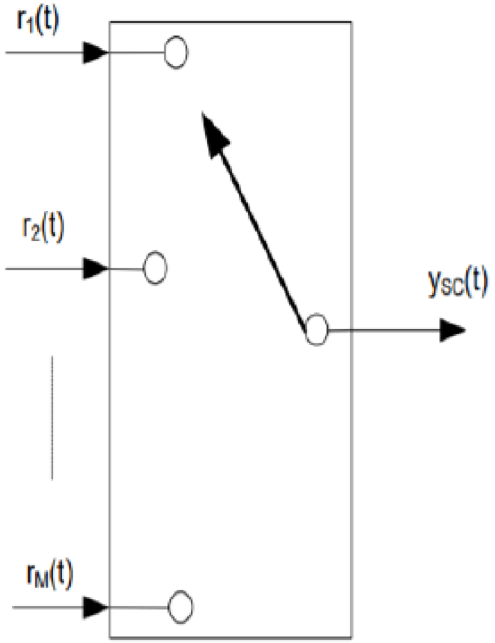
$$y_{EGC}(t) = \sum_{i=1}^{M} e^{-j\varphi}\left(a_i e^{j\varphi} s(t) + z_i(t)\right) = \sum_{i=1}^{M} a_i s(t) + \sum_{i=1}^{M} e^{-j\varphi} z_i(t)$$

- ❑ The SNR of the signal obtained after the combination is:

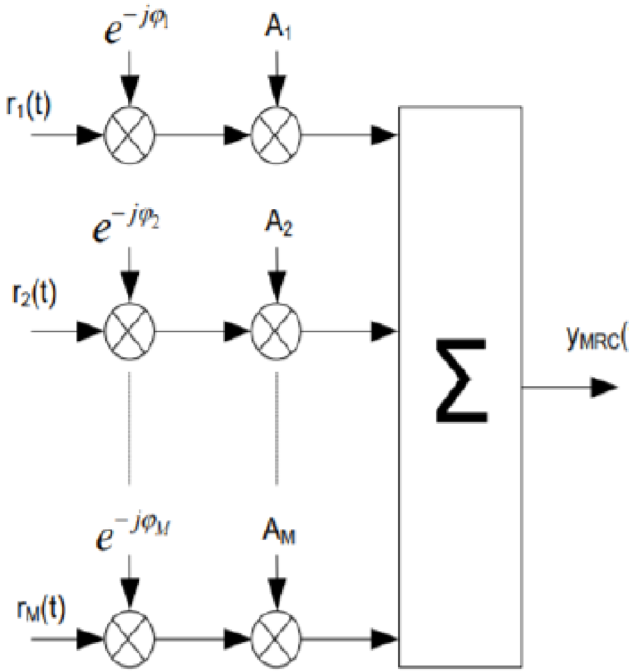
$$\rho_{egc} = \frac{\left(\sum_{i=1}^{M} a_i\right)^2 E_b}{M N_0}$$

SIGNAL COMBINATION TECHNIQUES

Selection combining



Maximum ratio combining



Equal gain combining