Overview of Diversity Techniques in Wireless Communication Systems

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Presentation Outline

- Overview
- Motivation
- Diversity Techniques
- Diversity Combining Techniques
- Conclusions

Next . . .

- **Overview**
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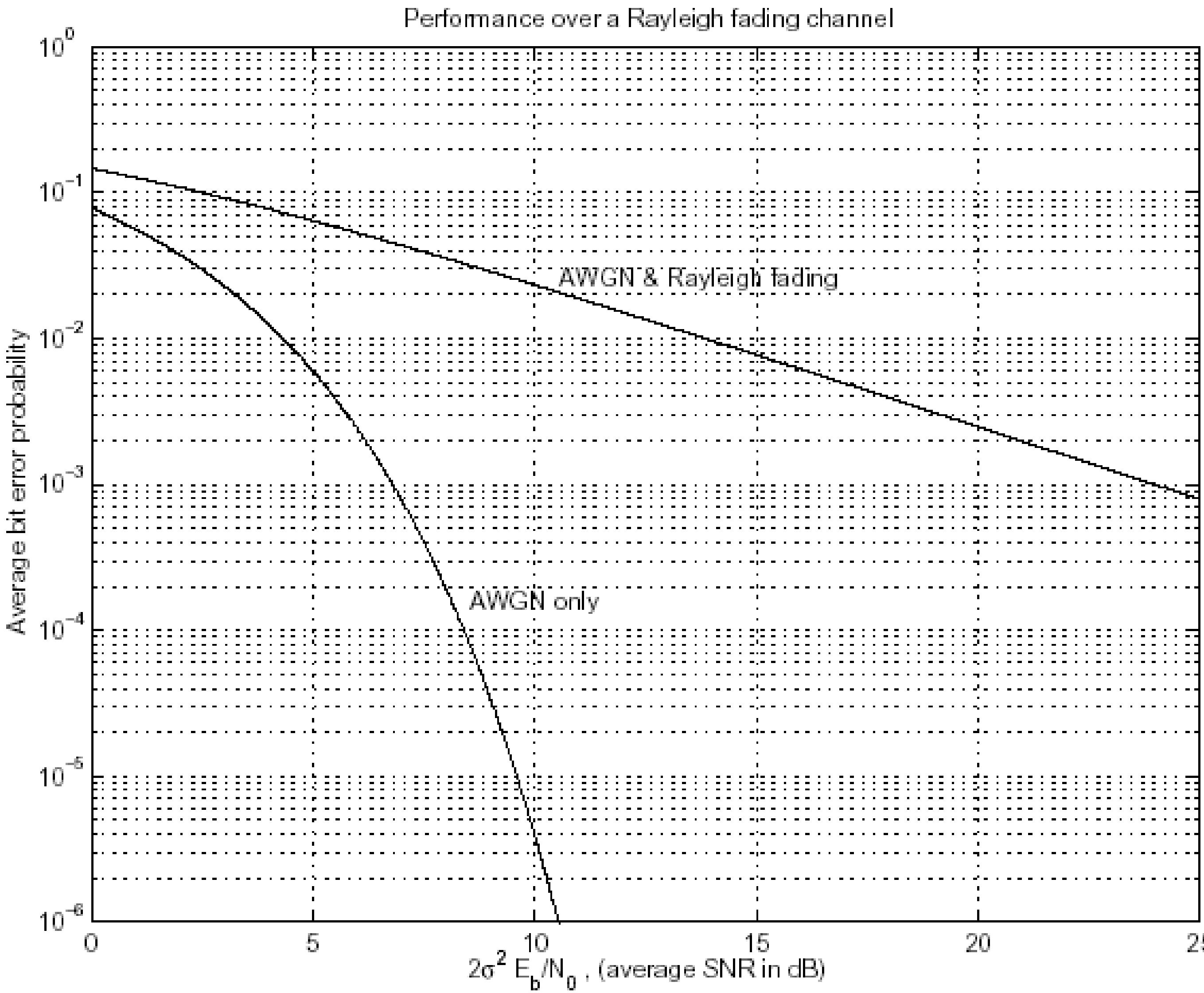
Wireless Channel Impairments

- Noise
  - Thermal noise (modeled as AWGN)
- Path Loss
  - The loss in power as the radio signal propagates
- Shadowing
  - Due to the presence of fixed obstacles in the radio path
- Fading
  - Combines the effect of multiple propagation paths, rapid movement of mobile units and reflectors

Fading

- Signal copies following different paths undergoes different
  - Attenuation
  - Distortion
  - Delays
  - Phase shifts
- System performance can be severely degraded by fading

The Effect of Flat Fading Channels



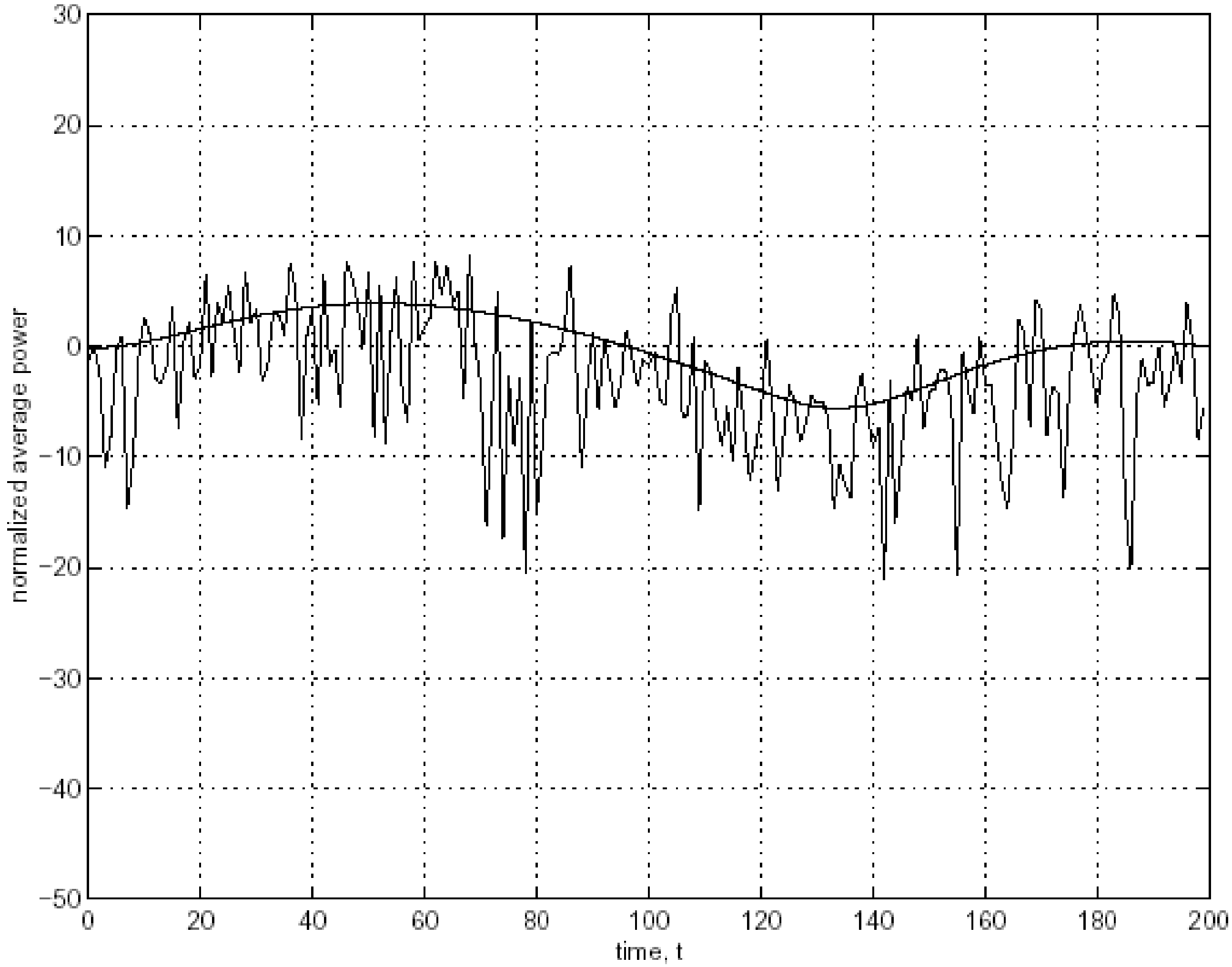
Parameters of Fading Channels

- Multipath Spread T_m
  - It tells us the maximum delay between paths of significant power in the channel
- Coherence Bandwidth $(\Delta f)_c$
  - Gives an idea of how far apart –in frequency- for signals to undergo different degrees of fading
- Coherence Time $(\Delta t)_c$
  - Gives a measure of the time duration over which the channel impulse response is essentially invariant (highly correlated)
- Doppler Spread B_d
  - It gives the maximum range of Doppler shift

Classification of Fading Channels

- Frequency non-selective
  - If the signal BW < $(\Delta f)_c$
- Frequency Selective
  - If the signal BW > $(\Delta f)_c$
- Fast Fading
  - Symbol duration < $(\Delta t)_c$
- Slow Fading
  - Symbol duration > $(\Delta t)_c$

Fast Fading vs. Slow Fading



Fading Mitigation

- The fading problem can be solved by adding a fade margin at the transmitter
  - Not a power efficient technique
- Another solution . . .
- Take the advantage of the statistical behavior of the fading channel:
  - Time correlation of the channel
  - Frequency correlation of the channel
  - Space correlation of the channel

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Basic Concept

- The basic concept: Transmit the signal via several independent diversity branches to get independent signal replicas

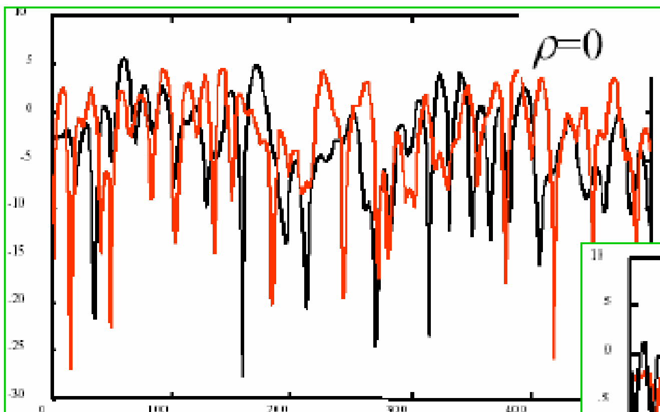
- In other words, to have diversity, we need
  - Multiple branches
  - Independent fading
  - Process branches to reduce fading probability

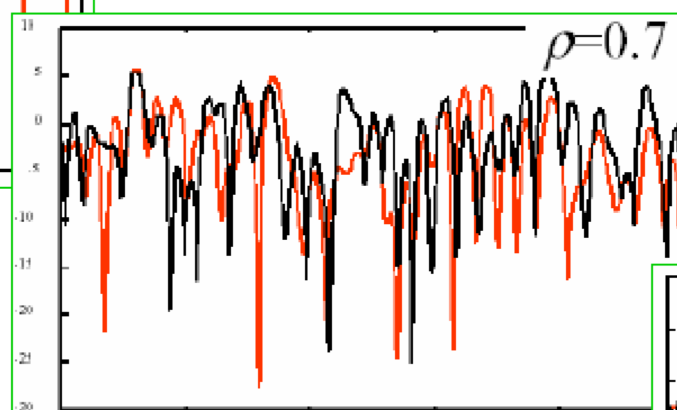
What is Diversity?

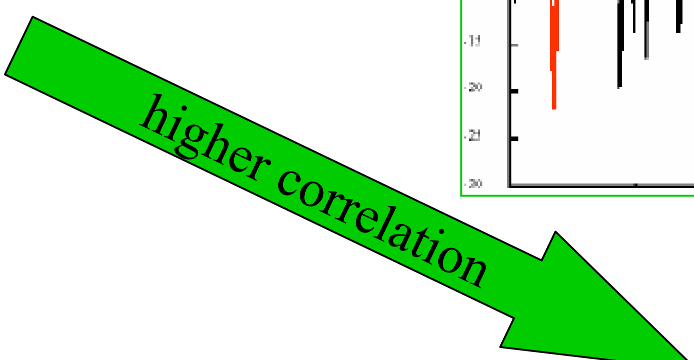
- Diversity schemes provides two or more inputs at the receiver such that the fading phenomena among these inputs are ***uncorrelated***
- If one radio path undergoes deep fade at a particular point in time, another independent (or at least highly uncorrelated) path may have a strong signal at that input
- If probability of a deep fade in one channel is p, then the probability for N channels is p^N

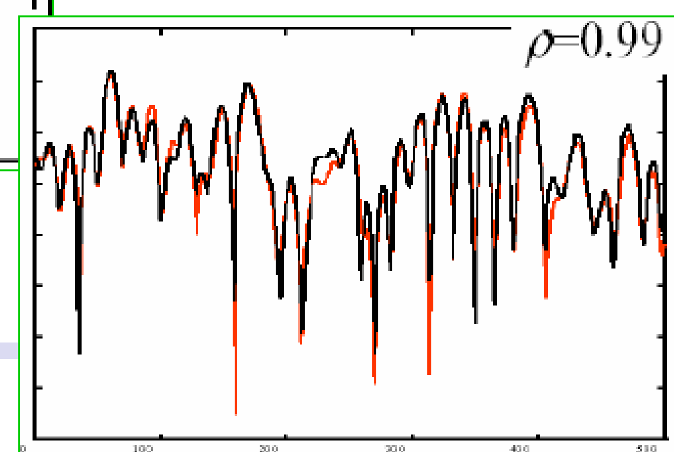
Requirements for Diversity

1. Multiple branches
2. Low correlation between branches









Diversity Techniques (1/2)

- Antenna Diversity
  - Space Diversity
    - Horizontal Space Diversity
    - Vertical Space Diversity
  - Field Component Diversity (Antenna Pattern Diversity)
  - Polarization Diversity
  - Angle Diversity (Direction Diversity)
- Frequency Diversity
- Time Diversity
- Multipath Diversity

Diversity Techniques (2/2)

- Orthogonal Transmit Diversity (OTD)
- Space-Time (S-T) Diversity
- Space-Frequency (S-F) Diversity
- Space-Time-Frequency (S-T-F) Diversity
- Open Loop Transmit Diversity (for 3G)
- Closed Loop Transmit Diversity (for 3G)

Diversity Combining Techniques

- Switching Combining
- Selection Combining
- Equal Gain Combining
- Maximal Ratio Combining

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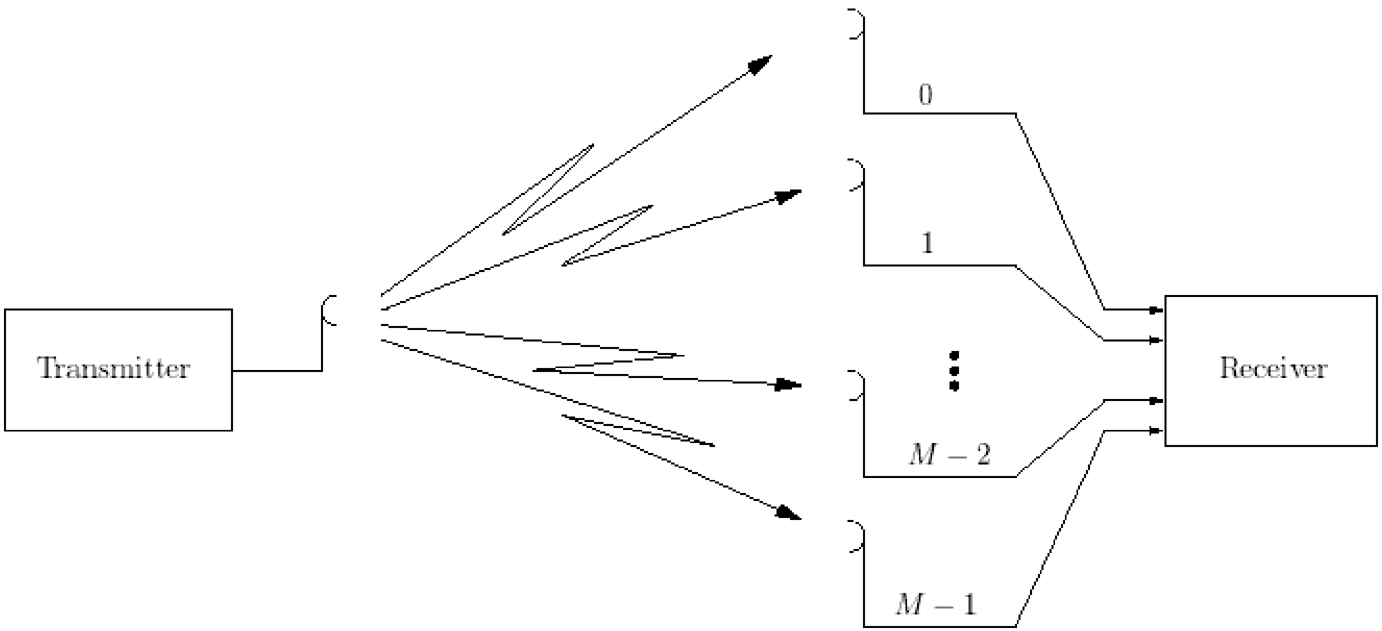
Space Diversity (1/3)

- The space correlation properties of the radio channel are used as mean of providing multiple uncorrelated copies of the same signal
- More hardware (antennas)

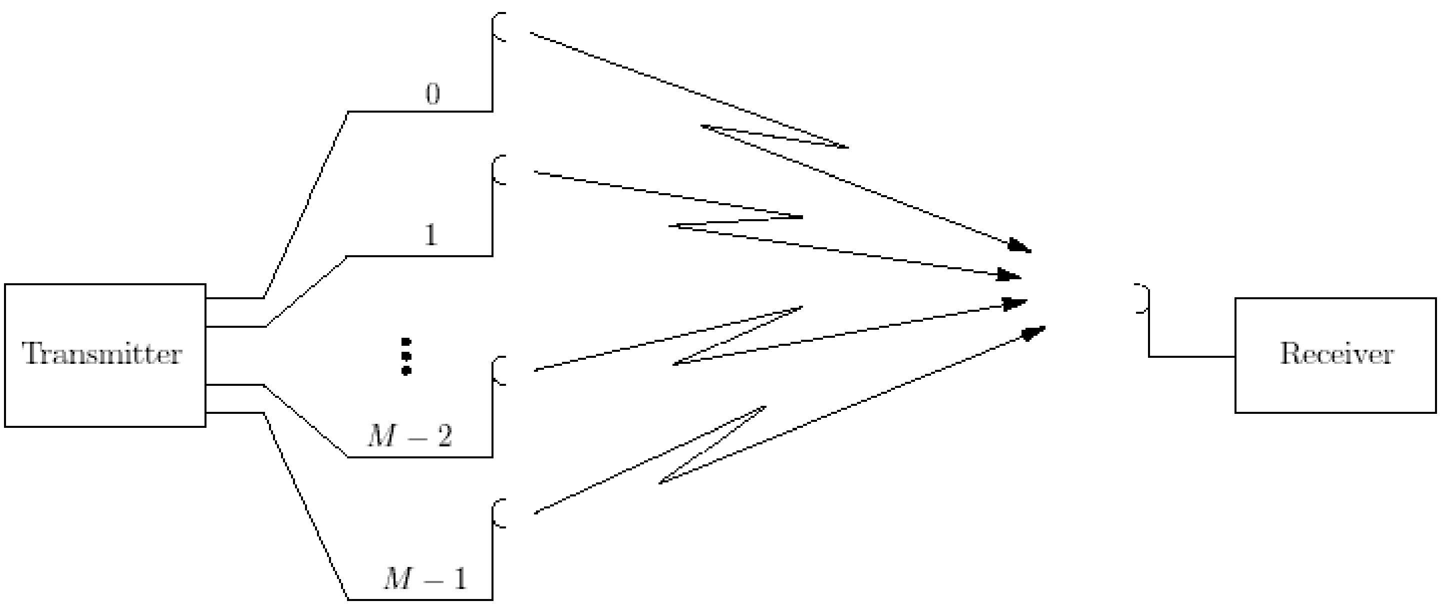
Space Diversity (2/3)

- Receiver Space Diversity
  - *M* different antennas are used at the receiver to obtain independent fading signals



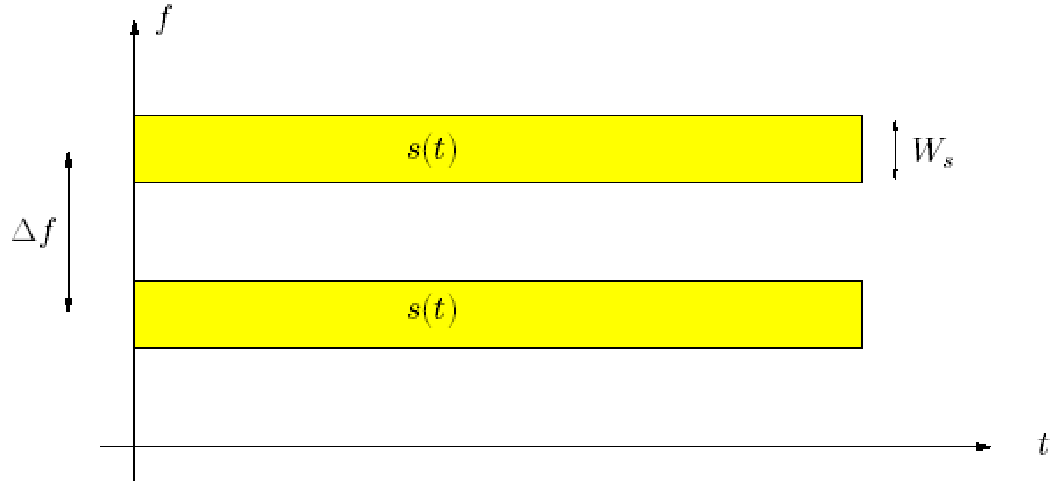
Space Diversity (3/3)

- Transmitter Space Diversity
  - *M* different antennas are used at the transmitter to obtain uncorrelated fading signals at the receiver
  - The total transmitted power is split among the antennas



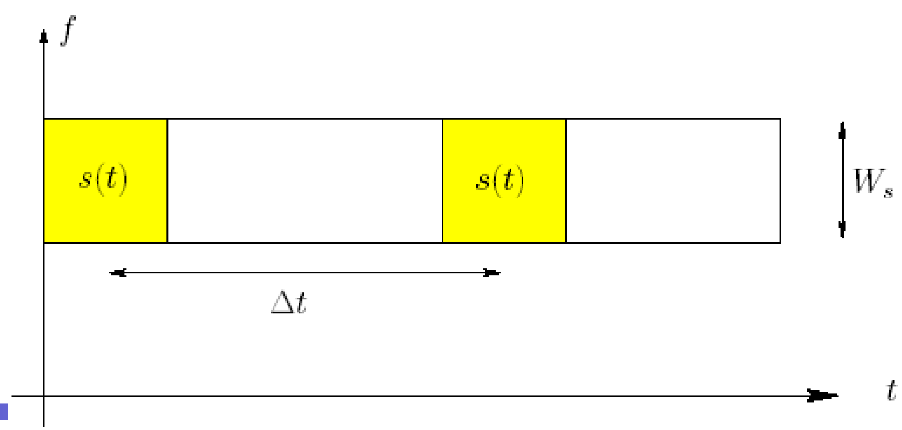
Frequency Diversity

- Modulate the signal through *M* different carriers
  - The separation between the carriers should be at least the coherent bandwidth $(\Delta f)_c$
  - Different copies undergo independent fading
- Only one antenna is needed
- The total transmitted power is split among the carriers



Time Diversity

- Transmit the desired signal in M different periods of time i.e., each symbol is transmitted M times
- The interval between transmission of same symbol should be at least the coherence time $(\Delta t)_c$
  - Different copies undergo independent fading
- Reduction in efficiency (effective data rate < real data rate)



Polarization Diversity

- Scattering shifts and decorrelates polarization
- Advantage
  - Very compact
- Disadvantage
  - Unequal branch powers
  - Less diversity gain

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Introduction

- For a slowly flat fading channel, the equivalent lowpass of the received signal of branch *i* can be written as

$$r_i(t) = A_i e^{j\theta_i} s(t) + z_i(t), \quad i = 0, 2, \ldots, M-1$$

  - Where $s(t)$ is the equivalent lowpass of the transmitted signal
    $A_i e^{j\theta_i}$ is the fading attenuation of branch *i*
    $z_i(t)$ is the AWGN

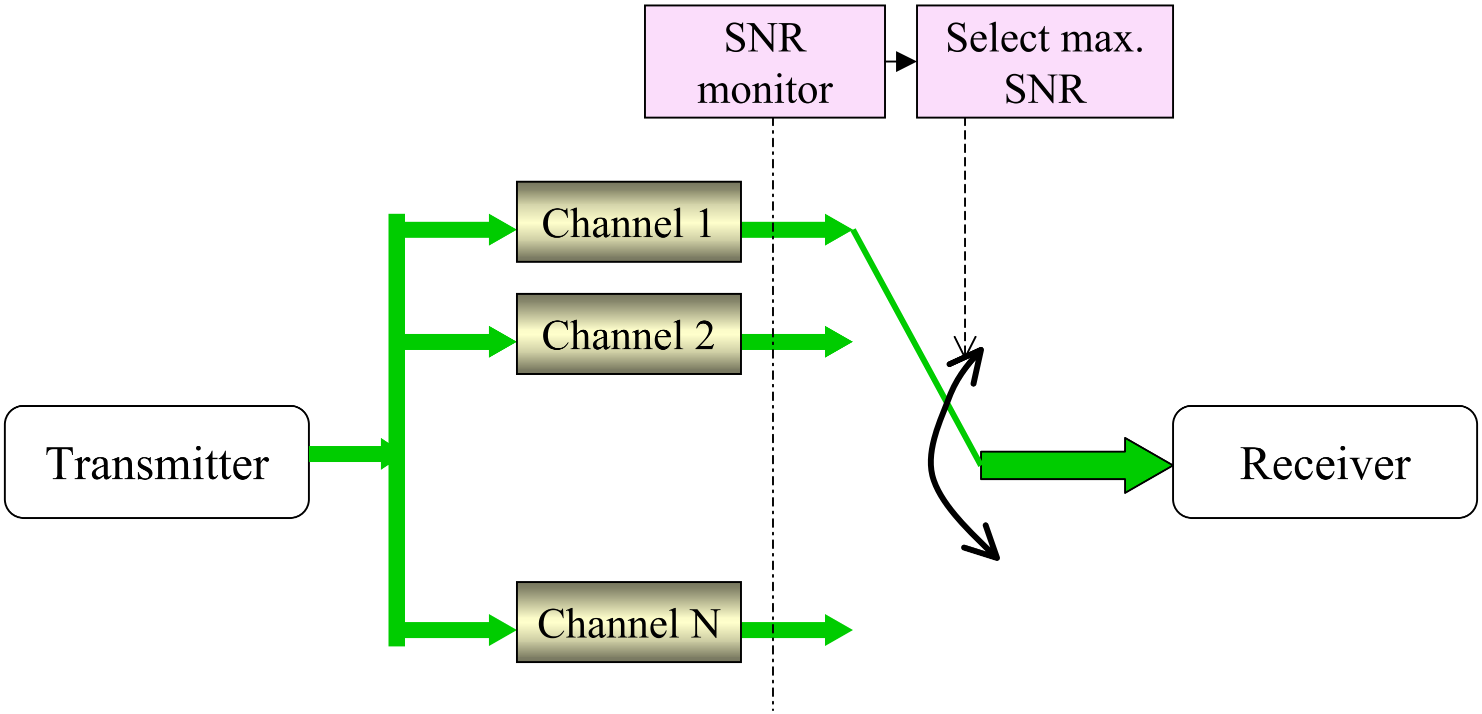
- Out of *M* branches, *M* replicas of the transmitted signal are obtained

$$\mathbf{r} = \begin{bmatrix} r_1(t) & r_2(t) & \ldots & r_{M-1}(t) \end{bmatrix}$$

- *M* is the *diversity order*

Selection Combining (SC) (1/3)

- Select the strongest signal



Selection Combining (2/3)

- The combiner output is given by

$$y(t) = Ae^{j\theta_i} s(t) + z(t), \quad \text{with } A = \max\{A_0, A_1, \ldots, A_{M-1}\}$$

- The received SNR can be written as follows:

$$\Gamma = \frac{A^2 E_b}{N_0} = \max\{\Gamma_0, \Gamma_1, \ldots, \Gamma_{M-1}\}$$

- With uncorrelated branches, the CDF of Γ is

$$P_\Gamma(\gamma) = \Pr\{\Gamma < \gamma\} = \prod_{i=0}^{M-1} P_{\Gamma i}(\gamma)$$

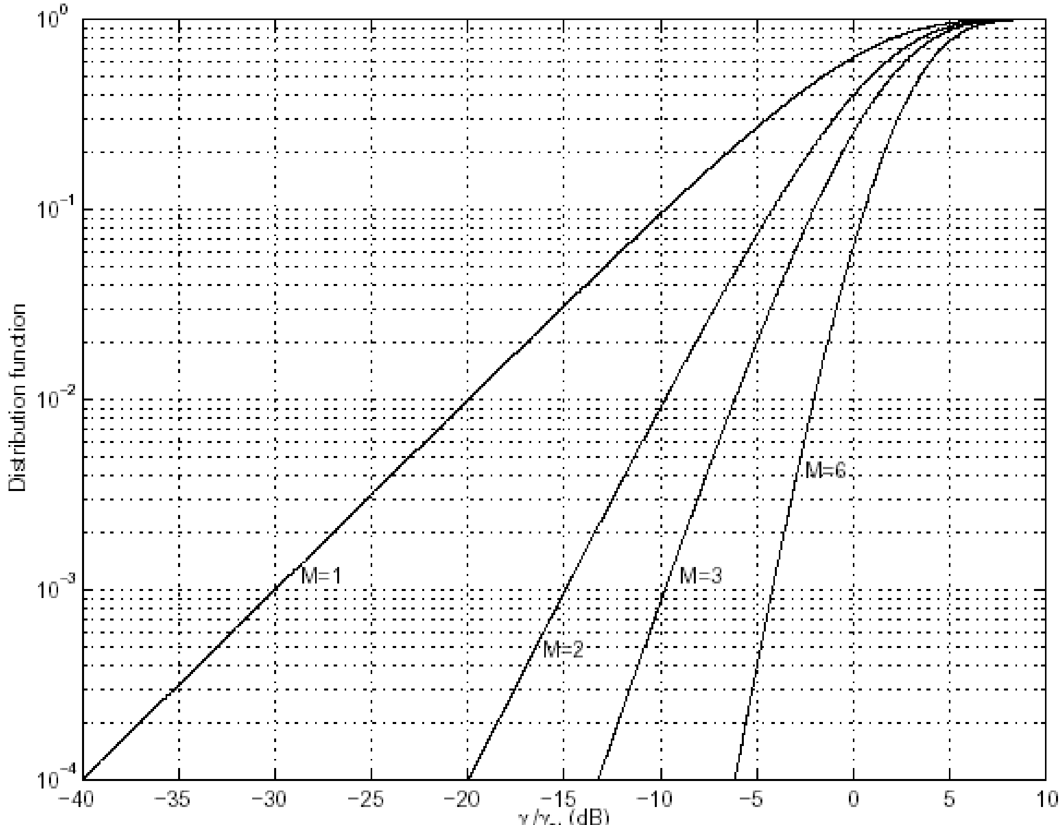
- For i.i.d branches, we have

$$P_\Gamma(\gamma) = \left[P_{\Gamma_0}(\gamma)\right]^M, \quad \text{and} \quad p_\Gamma(\gamma) = M p_{\Gamma_0}(\gamma)\left[P_{\Gamma_0}(\gamma)\right]^{M-1}$$

Selection Combining (3/3)

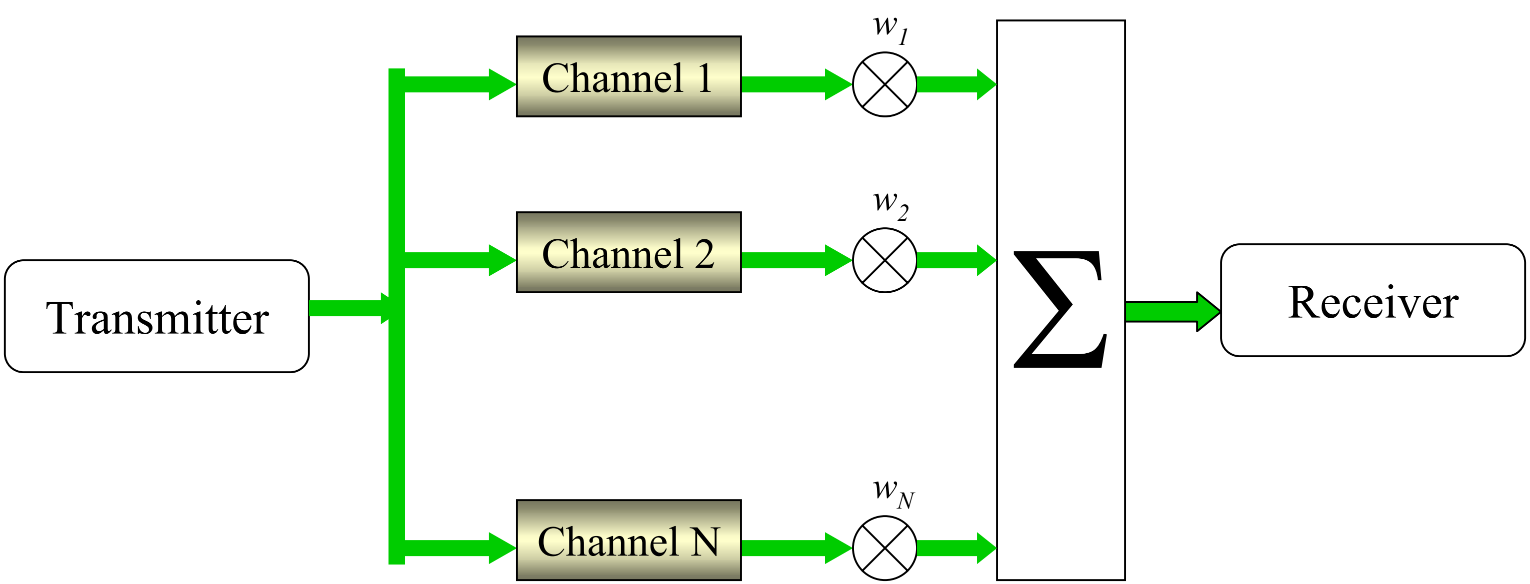
- For Rayleigh Fading channel
  - The outage probability $P_{\Gamma}(\gamma) = \left(1 - e^{-\gamma/\gamma_0}\right)^M, \quad \gamma_0 = 2\sigma^2 E_b / N_0$
  - Asymptotic behavior

$$P_{\Gamma}(\gamma) \approx \left(\frac{\gamma}{\gamma_0}\right)^M, \gamma \ll \gamma_0$$



Maximal Ratio Combining (MRC) (1/3)

- Weight branches for maximum SNR



Maximal Ratio Combining (2/3)

- The combiner output is given by $y(t) = \sum_{i=0}^{M-1} w_i r_i(t)$

- Choose the weights to be the channel gain conjugate [must be estimated]

$$y(t) = \sum_{i=0}^{M-1} A_i e^{-j\theta_i} r_i(t) = \sum_{i=0}^{M-1} A_i e^{-j\theta_i} \left[A_i e^{j\theta_i} s(t) + z_i(t) \right]$$

$$= \left(\sum_{i=0}^{M-1} A_i^2 \right) s(t) + \sum_{i=0}^{M-1} A_i e^{-j\theta_i} z_i(t)$$

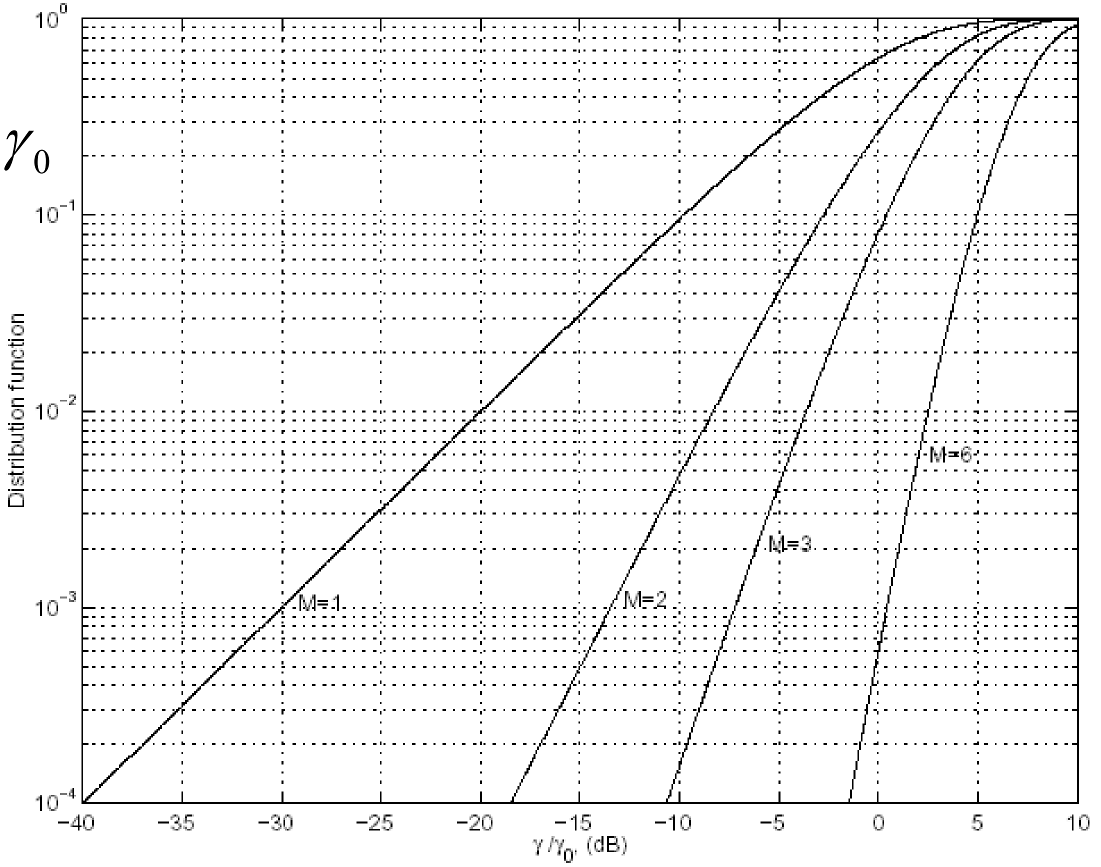
- The SNR of the combined signal is

$$\Gamma = \frac{\sum_{i=0}^{M-1} A_i^2 E_b}{N_0} = \sum_{i=0}^{M-1} \Gamma_i$$

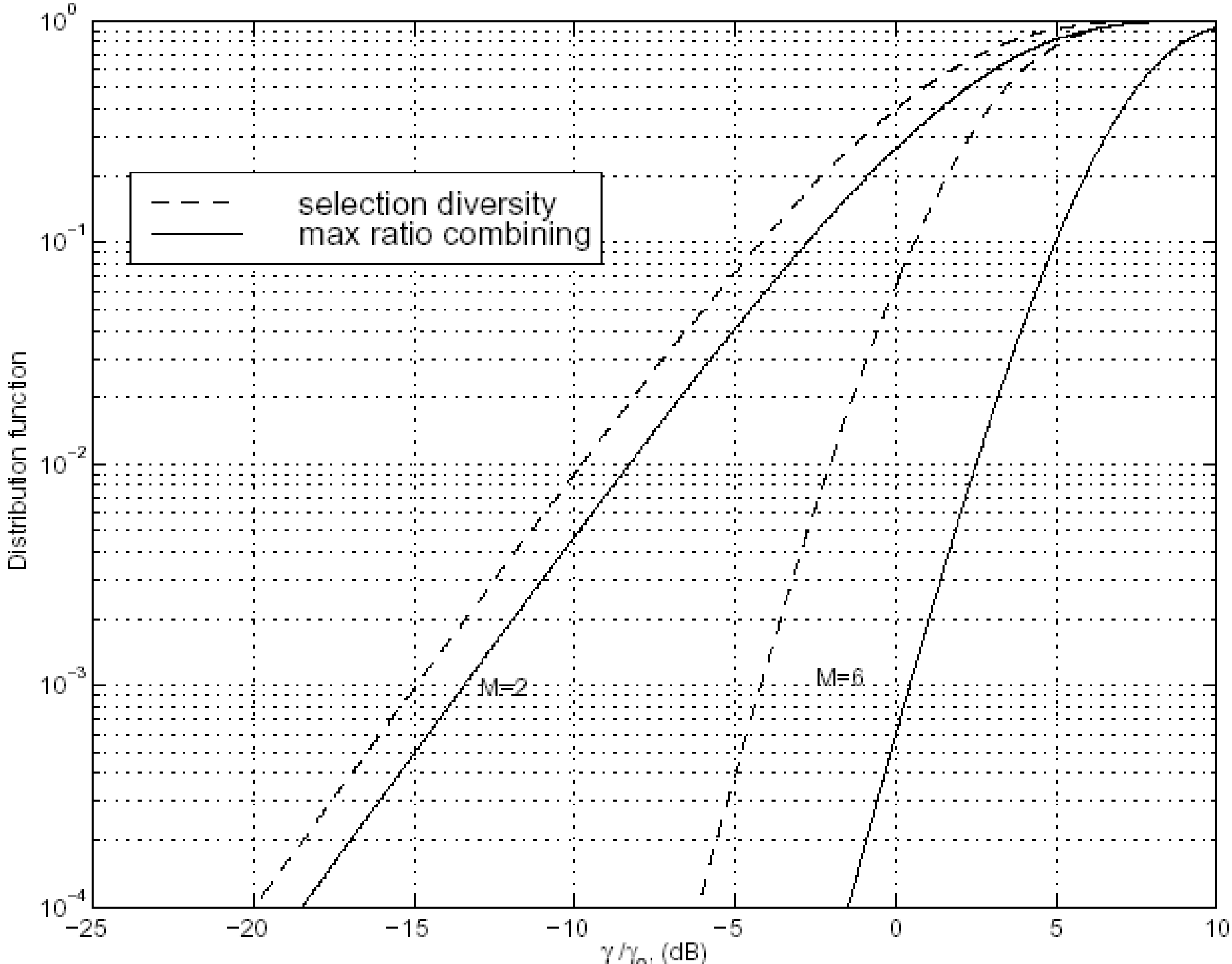
Maximal Ratio Combining (3/3)

- For Rayleigh Fading channel
  - The outage probability $P_\Gamma(\gamma) = 1 - e^{-\frac{\gamma}{\gamma_0}} \sum_{i=1}^{M} \frac{(\gamma/\gamma_0)^{i-1}}{(i-1)!}$
  - Asymptotic behavior

$$P_\Gamma(\gamma) \approx \frac{(\gamma/\gamma_0)^M}{M!}, \quad \gamma \ll \gamma_0$$



MRC vs. SC


selection diversity
max ratio combining
M=2
M=6
Distribution function
γ /γ0, (dB)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
−25
−20
−15
−10
−5
0
5
10

Equal Gain Combining (EGC) (1/2)

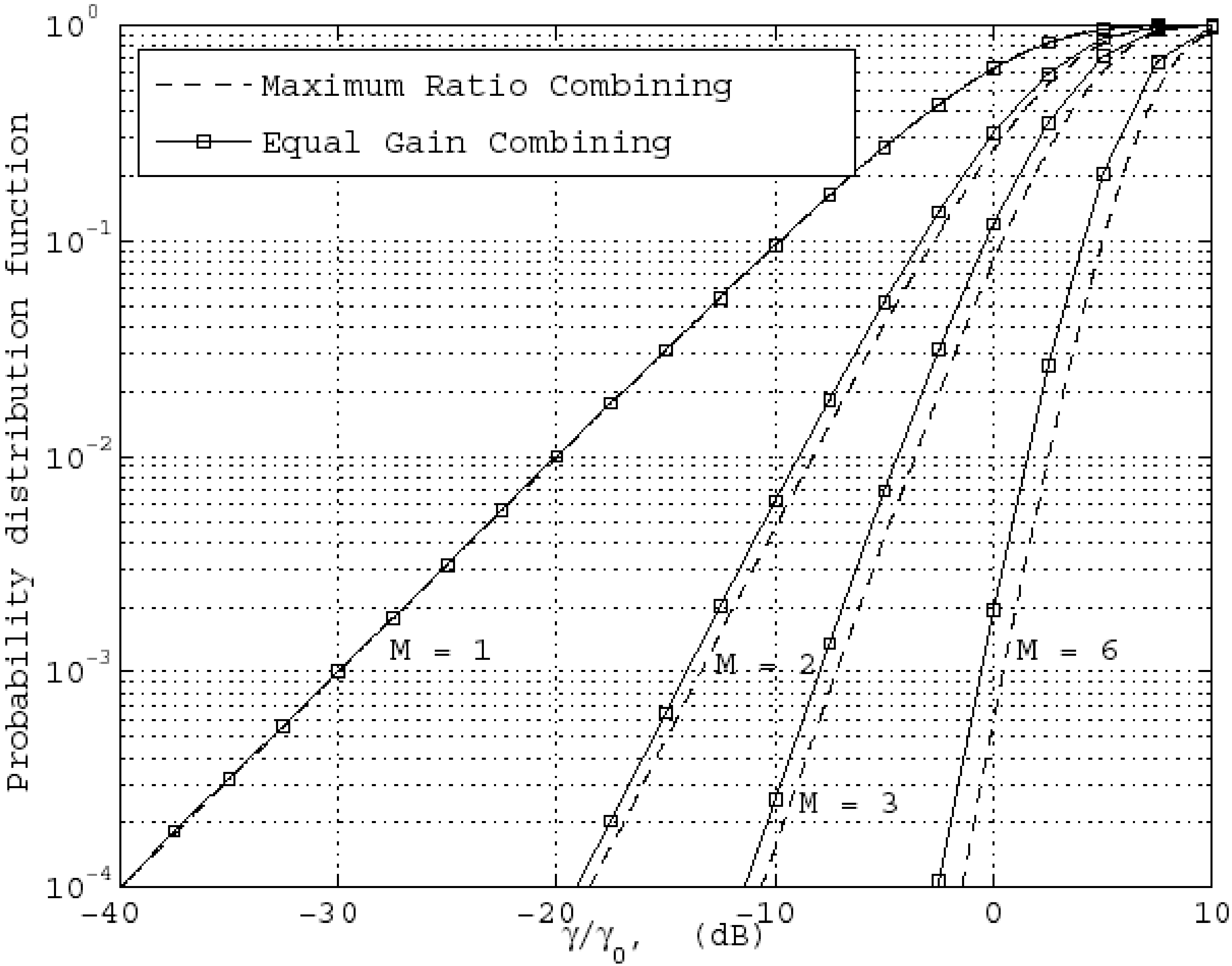
- Coherent combining of all branches with equal gain
  - A simplified version of MRC
- Basic concept
  - Each branch signal is rotated by $e^{-j\theta_i}$
  - All branch signals are then added
- The combiner output is given by

$$y(t)=\sum_{i=1}^{M} e^{-j\theta_i} r_i(t)=\left(\sum_{i=0}^{M} A_i\right) s(t)+\sum_{i=0}^{M} e^{-j\theta_i} z_i(t)$$

- The SNR is given by

$$\Gamma=\left(\sum_{i=0}^{M-1} A_i\right)^2 \frac{E_b}{MN_0}$$

Equal Gain Combining (2/2)

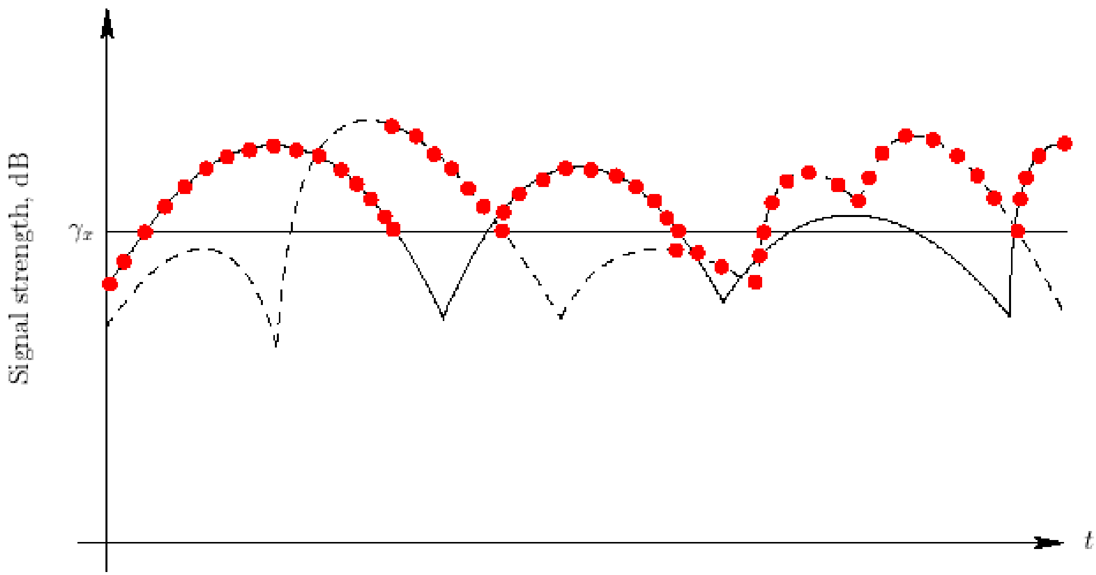


Switched Diversity Combining (SDC)

- When the signal quality of the used branch is good, there is no need to look for (to use) other branches
- Other branches are needed only when the signal quality deteriorates
- Two strategies can be used
  - Switch-and-examine strategy
  - Switch-and-stay strategy
- Switching between branches will introduce discontinuities is the combined signal

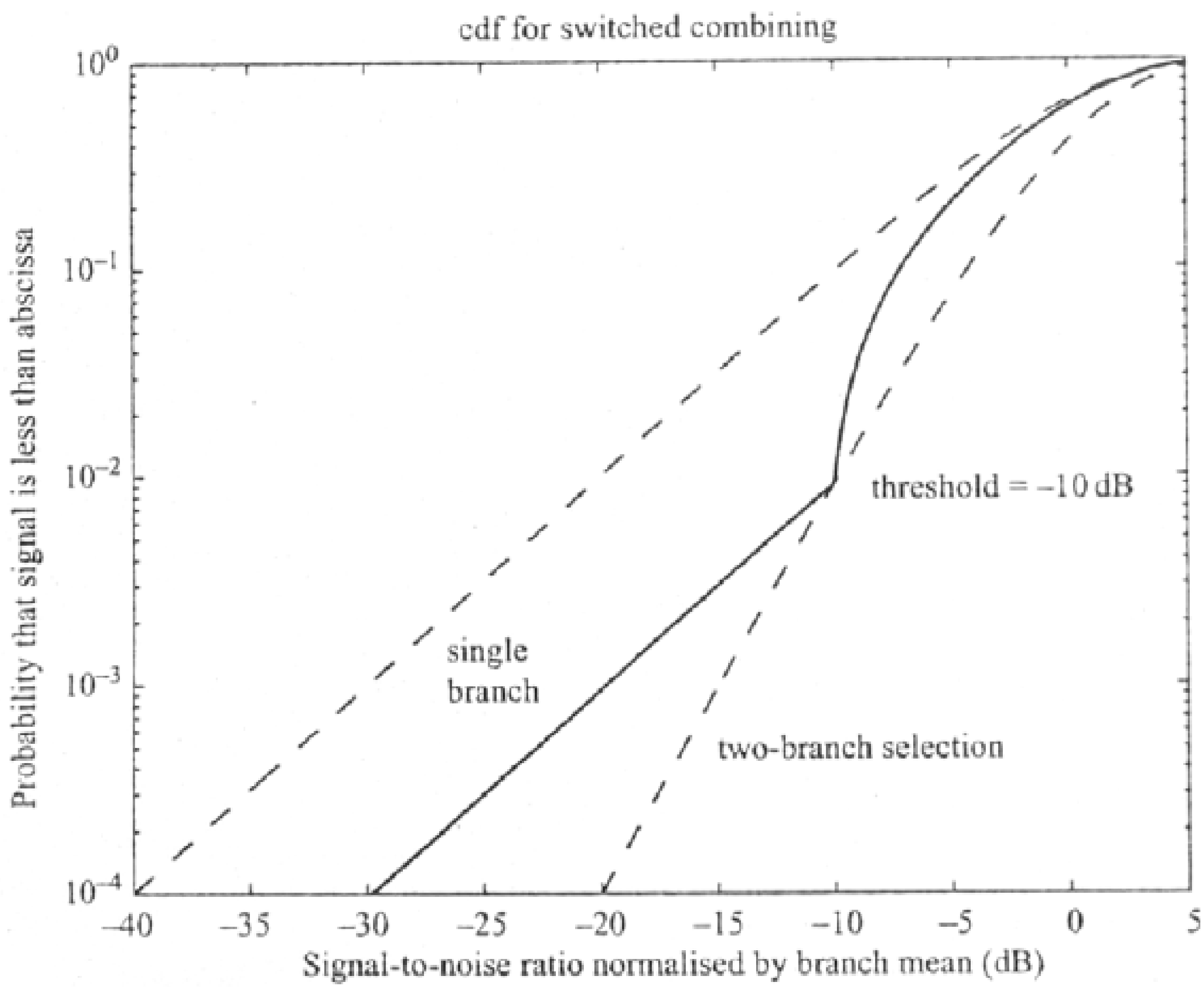
SDC: Switch-and-Stay Strategy (1/2)

- Stay with the signal branch until the envelop drops below a predefined threshold



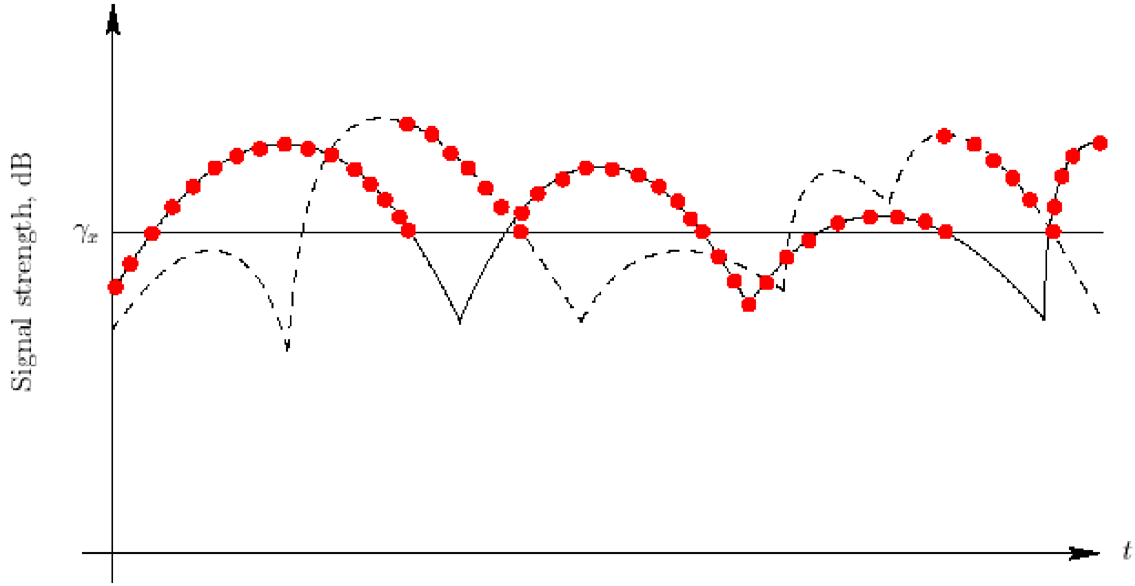
- Only one receiver is needed

SDC: Switch-and-Stay Strategy (2/2)



SDC: Switch-and-Examine Strategy

- The receiver switches to the strongest of the M-1 other signals only if its level exceeds the threshold

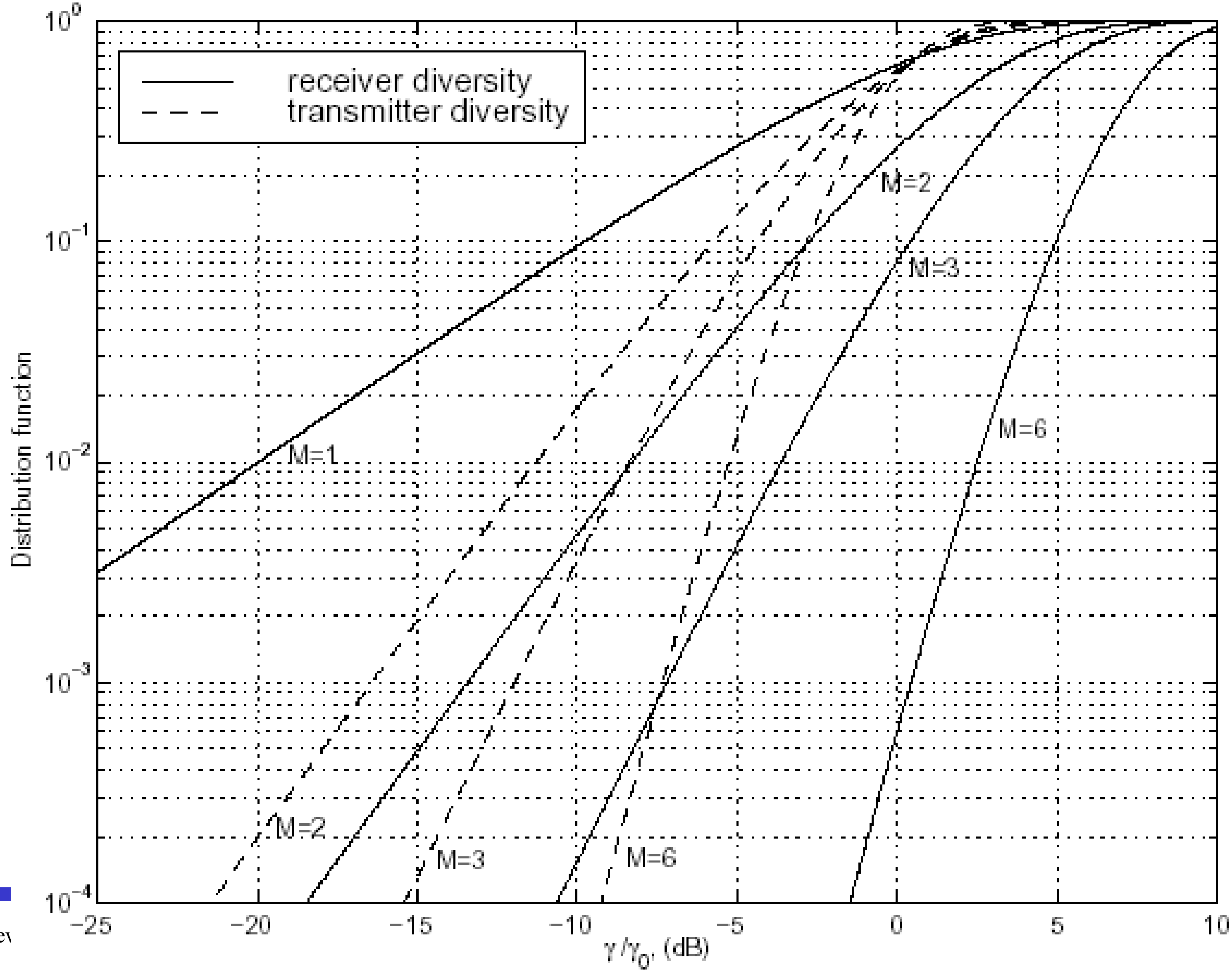


- Less signal discontinuities

Optimum Combining

- Weight branches to get maximum SNIR

Transmitter Diversity vs. Receiver Diversity

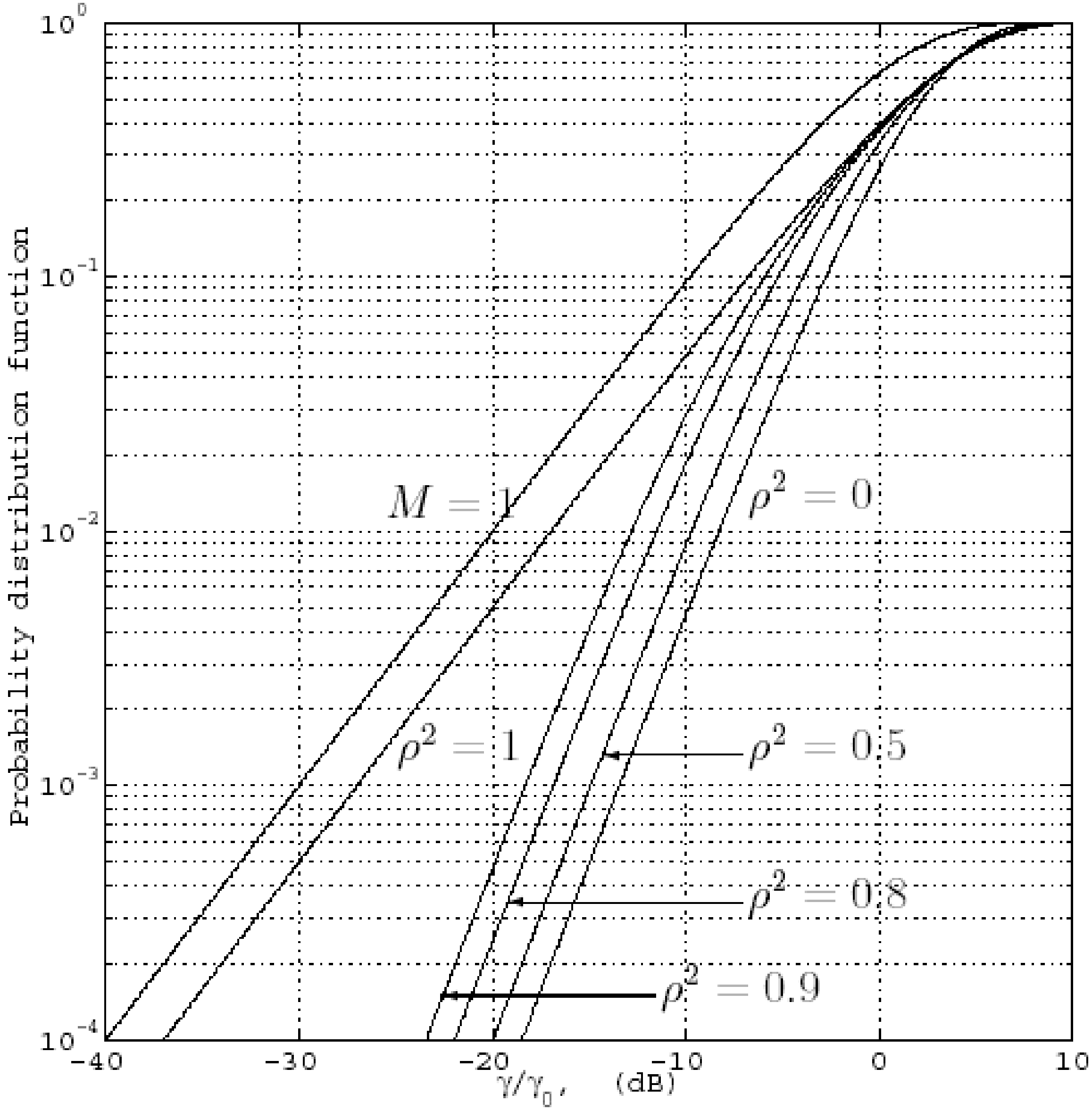


The Effect of Correlation between Branches (1/2)

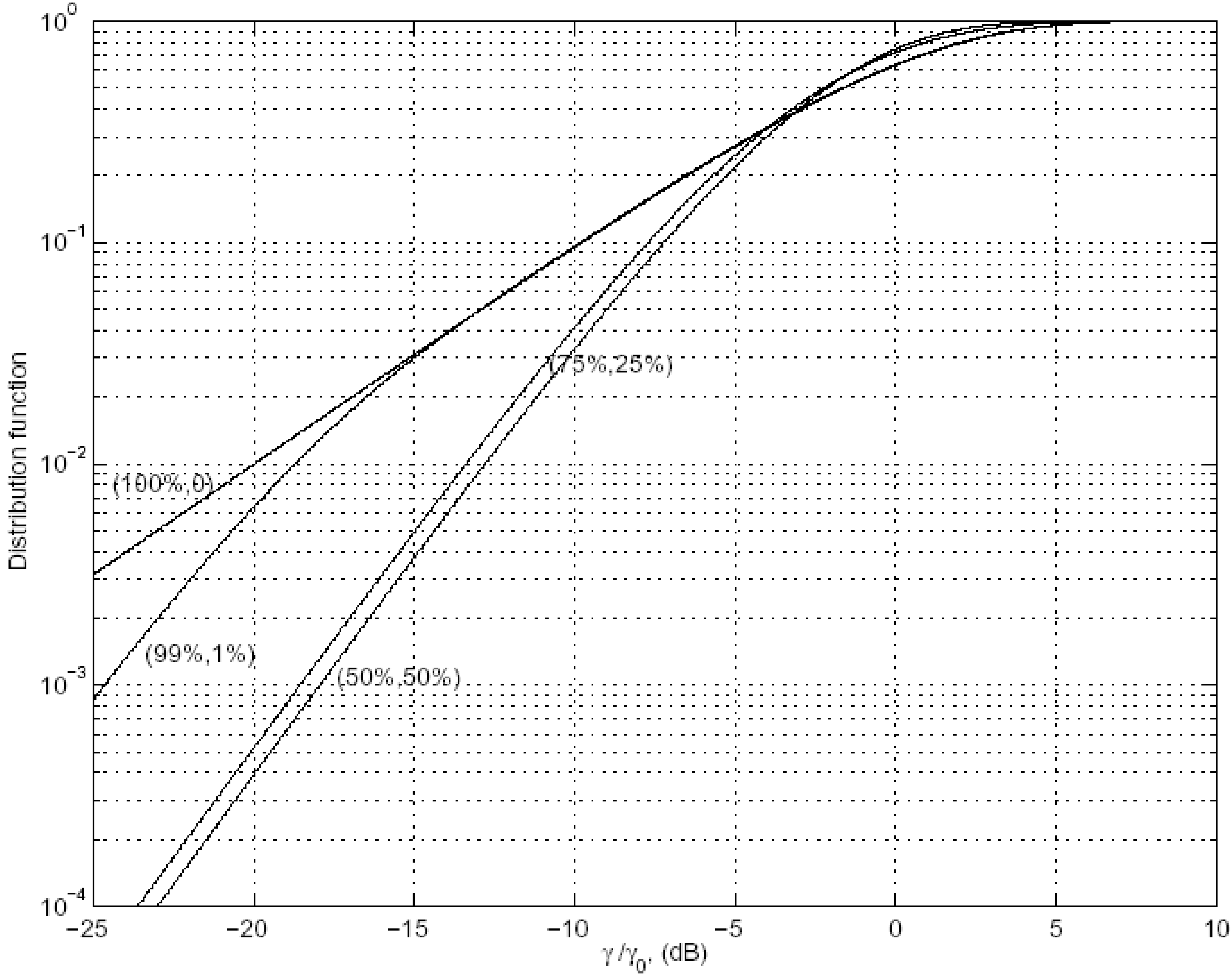
- The correlation between branches will always reduce the diversity gain
- The effect of correlation can be approximately modeled by introducing equivalent average SNR

$$\gamma_0' = \gamma_0 \left(1 - |\rho|^2\right)$$

The Effect of Correlation between Branches (2/2)



Effect of Power Unbalance between Branches



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Conclusions (1/2)

- The diversity is used to provide the receiver with several replicas of the same signal
- Diversity techniques are used to improve the performance of the radio channel without any increase in the transmitted power
- As higher as the received signal replicas are decorrelated, as much as the diversity gain

Conclusions (2/2)

- Diversity Combining
  - MRC outperforms the Selection Combining
  - Equal gain combining (EGC) performs very close to the MRC. Unlike the MRC, the estimate of the channel gain is not required in EGC
- Among different combining techniques
  - MRC has the best performance and the highest complexity
  - SC has the lowest performance and the least complexity

References

- Aalborg University, Lecture notes, URL: http://kom.aau.dk/~imr/RadioCommIII/
- Markku Juntti, et. al. ,"*MIMO Communications with Applications to 3G and 4G*", Oulu University,
- Royal Institute of Technology, Stockholm, Lecture notes, URL: http://www.s3.kth.se/radio/COURSES/RKBASIC_2E1511_2004/Downloads/LectureNotes/

Exercise

Q1. Derive an expression for average BER of DPSK in the rapidly fading Rayleigh channel when two fold diversity with *selection combining* is applied.

Hints: - The BER for DPSK is given by $P_{b_{DPSK}}(\gamma) = \frac{1}{2} e^{-\gamma}$

Thank You!

Q&A