Overview of Diversity Techniques in Wireless Communication Systems

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Presentation Outline

- Overview
- Motivation
- Diversity Techniques
- Diversity Combining Techniques
- Conclusions
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
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 $\text{BW} < (\Delta f)_c$

- Frequency Selective
  - If the signal $\text{BW} > (\Delta f)_c$

- Fast Fading
  - Symbol duration $< (\Delta t)_c$

- Slow Fading
  - Symbol duration $> (\Delta t)_c$
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
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 provide 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

\[ \rho = 0 \] 
\[ \rho = 0.7 \] 
\[ \rho = 0.99 \]

higher correlation
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
Overview
Motivation
Diversity Techniques
Diversity Combining Techniques
Conclusions
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
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)
Next . . .

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- Diversity Techniques
- Diversity Combining Techniques
- Conclusions
Introduction

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

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

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

![Diagram showing Selection Combining (SC) process]

- Transmitter
  - Channel 1
  - Channel 2
  - Channel N

- SNR monitor
- Select max. SNR

- Receiver
Selection Combining (2/3)

- The combiner output is given by
  \[ y(t) = Ae^{j\theta_i} s(t) + z(t), \quad \text{with} \quad A = \max \{ A_0, A_1, \ldots, A_{M-1} \} \]

- 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 \( \Gamma \) is
  \[ P_{\Gamma_i}(\gamma) = \Pr \{ \Gamma < \gamma \} = \prod_{i=0}^{M-1} P_{\Gamma_i}(\gamma) \]

- 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
    \[ P_\Gamma (\gamma) = (1 - e^{-\gamma / \gamma_0})^M, \quad \gamma_0 = 2\sigma^2 E_b / N_0 \]
  - Asymptotic behavior
    \[ P_\Gamma (\gamma) \approx \left( \frac{\gamma}{\gamma_0} \right)^M, \quad \gamma \ll \gamma_0 \]
Maximal Ratio Combining (MRC) (1/3)

- Weight branches for maximum SNR

![Diagram of MRC](image)

Transmitter → Channel 1 (w₁) → Receiver
Transmitter → Channel 2 (w₂) → Receiver
Transmitter → Channel N (wₙ) → Receiver

Σ
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 $P_{\Gamma}(\gamma) = 1 - e^{-\frac{\gamma}{\gamma_0}} \sum_{i=1}^{M} \frac{\left(\frac{\gamma}{\gamma_0}\right)^{i-1}}{(i-1)!}$
  - Asymptotic behavior

$$P_{\Gamma}(\gamma) \approx \left(\frac{\gamma}{\gamma_0}\right)^{M} \frac{M!}{M!}, \quad \gamma \ll \gamma_0$$
MRC vs. SC

![Graph showing comparison between selection diversity and max ratio combining](image-url)
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 in 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
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