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Nadar Saraswathi College of Engineering & Technology

DEPARTMENT OF ELECTRONICS AND COMMUNICATION ENGINEERING

IV YEAR / VIII SEMESTER

EC6801– WIRELESS COMMUNICATION

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MIMO SYSTEMS

UNIT 05 – MULTIPLE ANTENNA TECHNIQUES – LECTURE 01

Error Probability in Flat-Fading Channels

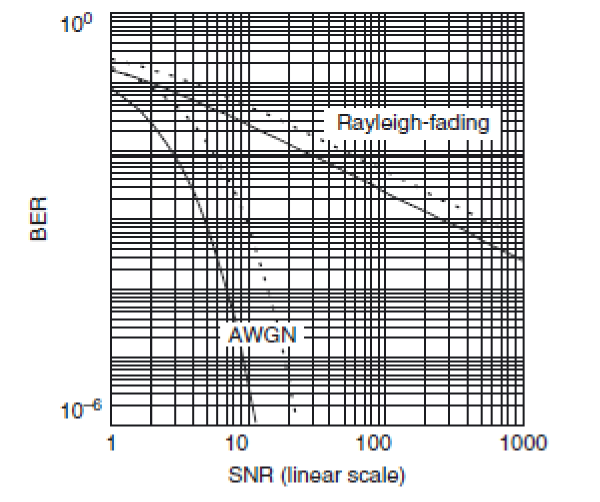
- In fading channels, the received signal power (and thus the SNR) is not constant but changes as the fading of the channel changes.
- In many cases, we are interested in the BER in a fading channel averaged over the different fading states. For a mathematical computation of the BER in such a channel, we have to proceed in three steps:
- 1. Determine the BER for any arbitrary SNR.
- 2. Determine the probability that a certain SNR occurs in the channel – in other words, determine the pdf of the power gain of the channel.
- 3. Average the BER over the distribution of SNRs.
- In an AWGN channel, the BER decreases approximately exponentially as the SNR increases: for binary modulation formats, a 10-dB SNR is sufficient to give a BER on the order of 10^{-4}, for 15 dB the BER is below 10^{-8}.
- At first glance, this is astonishing: sometimes fading leads to high SNRs, sometimes it leads to low SNRs, and it could be assumed that high and low values would compensate for each other. The important point here is that the relationship between (instantaneous) BER and (instantaneous) SNR is highly nonlinear, so that the cases of low SNR essentially determine the overall BER.

For differential detection, the BER in Rician channels can also be computed in closed form

$$\overline{BER} = \frac{1+K_r}{2(1+K_r+\overline{\gamma_B})}\exp\left(-\frac{K_r\overline{\gamma_B}}{1+K_r+\overline{\gamma_B}}\right)$$

For orthogonal signals

$$\overline{BER} = \frac{1+K_r}{(2+2K_r+\overline{\gamma_B})}\exp\left(-\frac{K_r\overline{\gamma_B}}{2+2K_r+\overline{\gamma_B}}\right)$$



Multiple Input Multiple Output Systems

- MIMO systems are systems with Multiple Element Antennas (MEAs) at both link ends.
- The MEAs of a MIMO system can be used for four different purposes: (i) beamforming, (ii) diversity, (iii) interference suppression, and (iv) spatial multiplexing (transmission of several data streams in parallel).
- The first three concepts are the same as for smart antennas.
- Having multiple antennas at both link ends leads to some interesting new technical possibilities, but does not change the fundamental effects of this approach.
- Spatial multiplexing, on the other hand, is a new concept, and has thus drawn the greatest attention. It allows direct improvement of capacity by simultaneous transmission of multiple data streams. We will show below that the (information-theoretic) capacity for a single link increases linearly with the number of antenna elements.

Spatial Multiplexing

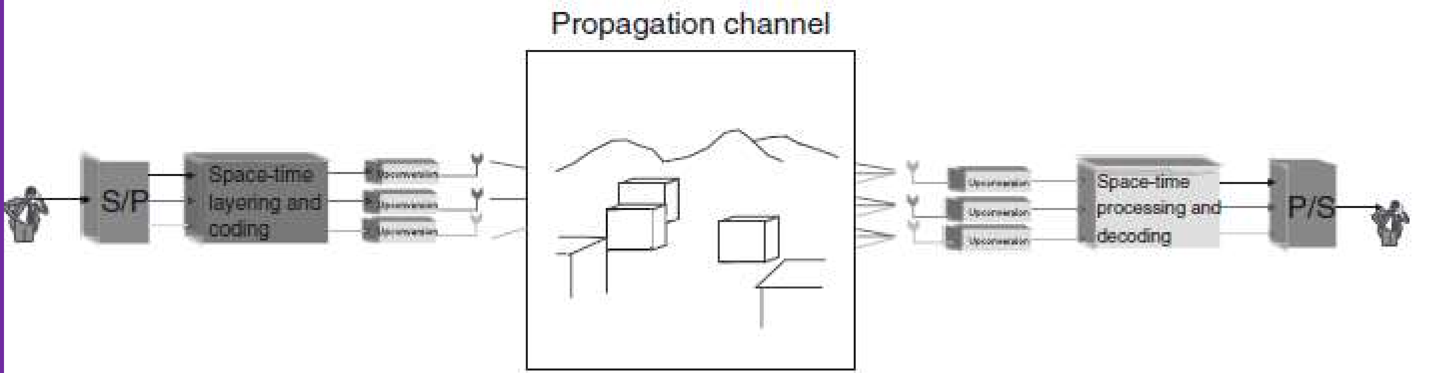
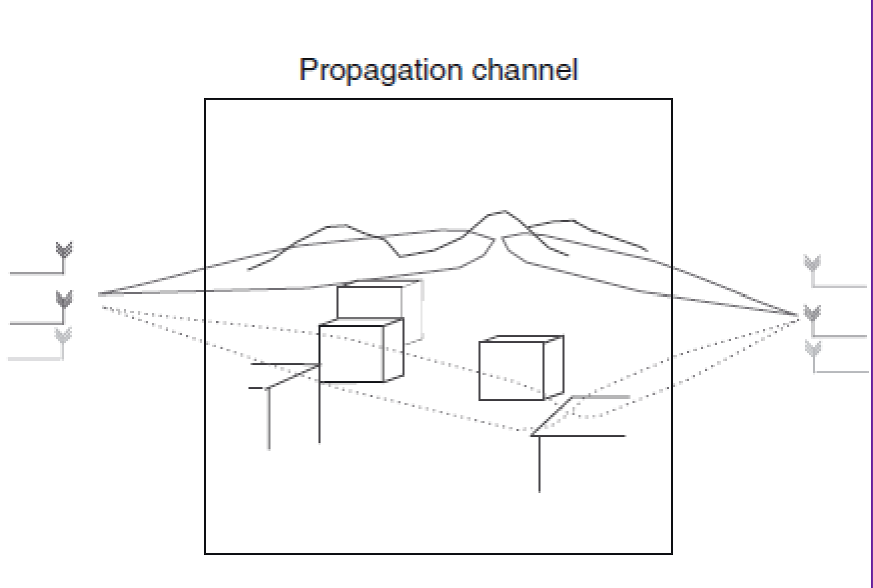


Figure 20.8 Principle behind spatial multiplexing.

- Spatial multiplexing uses MEAs at the TX for transmission of parallel data streams
- An original high-rate data stream is multiplexed into several parallel streams, each of which is sent from one transmit antenna element.
- The channel “mixes up” these data streams, so that each of the receive antenna elements sees a combination of them.
- If the channel is well behaved, the received signals represent *linearly independent combinations.*
- *In this case, appropriate signal processing at* the RX can separate the data streams.
- A basic condition is that the number of receive antenna elements is at least as large as the number of transmit data streams.
- It is clear that this approach allows the data rate to be drastically increased – namely, by a factor of min*(Nt,Nr).*



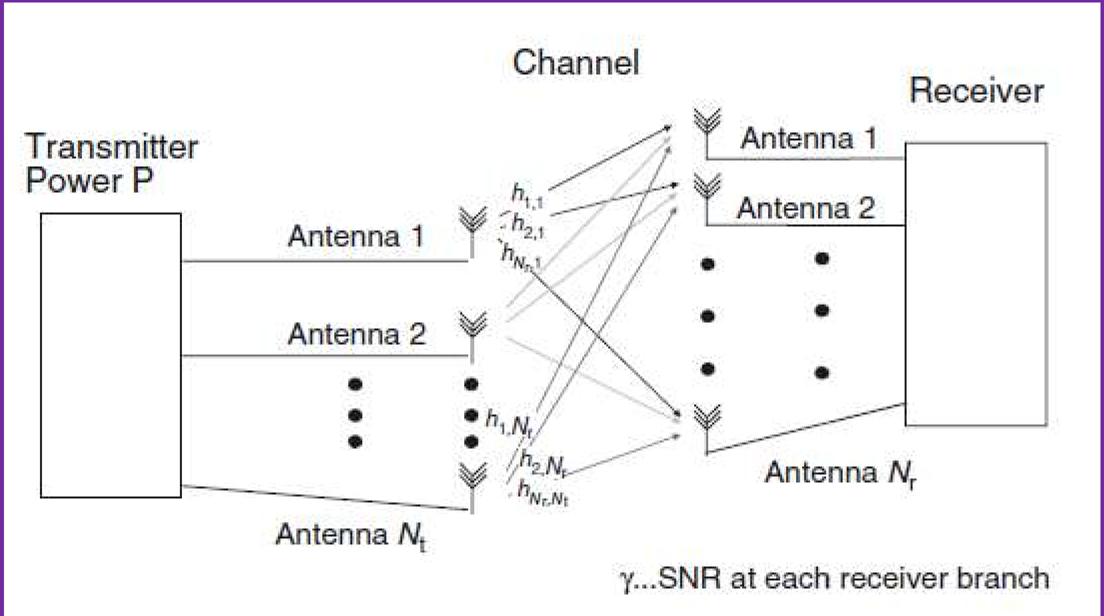
- For the case when the TX knows the channel, we can also develop another intuition
- With *Nt transmit antennas, we can form Nt different beams. We point all these* beams at different Interacting Objects (IOs), and transmit different data streams over them.
- At the RX, we can use *Nr antenna elements to form Nr beams, and also point them at different IOs.*
- *If all* the beams can be kept orthogonal to each other, there is no interference between the data streams The IOs (in combination with the beams pointing in their direction) play the same role as wires in the transmission of multiple data streams on multiple wires.
- From this description, we can also immediately derive some important principles: the number of possible data streams is limited by min*(Nt,Nr,Ns), where Ns is the number of (significant) IOs.*

System Model

- At the TX, the data stream enters an encoder, whose outputs are forwarded to *Nt transmit antennas.*
- *From the antennas, the signal is sent* through the wireless propagation channel, which is assumed to be quasi-static and frequency-flat if not stated otherwise.
- By quasi-static we mean that the coherence time of the channel is so long that “a large number” of bits can be transmitted within this time.

$$\mathbf{H} = \begin{pmatrix} h_{11} & h_{12} & \cdots & h_{1N_t} \\ h_{21} & h_{22} & \cdots & h_{2N_t} \\ \vdots & \vdots & \cdots & \vdots \\ h_{N_r1} & h_{N_r2} & \cdots & h_{N_rN_t} \end{pmatrix}$$

$$\mathbf{r} = \mathbf{H}\mathbf{s} + \mathbf{n} = \mathbf{x} + \mathbf{n}$$


Channel
Receiver
Transmitter
Power P
Antenna 1
Antenna 2
Antenna 1
Antenna 2
Antenna N_t
Antenna N_r
$h_{1,1}$
$h_{2,1}$
$h_{N_r,1}$
h_{1,N_t}
h_{2,N_t}
h_{N_r,N_t}
γ...SNR at each receiver branch

The improvement is achieved by weighting the transmit signal with a matrix T, so that the signals ˜s that are actually transmitted are

$$\tilde{s} = Ts$$

- Where, the dimension of the matrix T is Nt × NSTC and s is a vector containing the output of the
space–time encoder with dimension NSTC.
- The precoding matrix T should be chosen according to some form of CSI obtained by reciprocity or feedback.
- Note that the antenna selection and antenna grouping according to CSI is a form of MIMO precoding; we are just using specific forms of permutation matrices for T.

Beamforming

- The most simple determination of the angle of incidence can be obtained by a Fourier transform of the signal vector r.
- This gives the directions of arrival φi with an angular resolution that is determined by the size of the array, approximately 2π/Nr.
- The advantage of this method is its simple implementability (requiring only a Fast Fourier Transform (FFT)); the drawback is its small resolution.
- More exactly, the angular spectrum PBF(φ) is given as

$$P_{\mathrm{BF}}(\phi) = \frac{\boldsymbol{\alpha}^{\dagger}(\phi)\mathbf{R}_{\mathrm{rr}}\boldsymbol{\alpha}(\phi)}{\boldsymbol{\alpha}^{\dagger}(\phi)\boldsymbol{\alpha}(\phi)}$$

$$\alpha_{\mathrm{RX}}(\phi) = \begin{pmatrix} 1 \\ \exp(-jk_0 d_{\mathrm{a}}\cos(\phi)) \\ \exp(-j2k_0 d_{\mathrm{a}}\cos(\phi)) \\ \vdots \\ \exp(-j(N_r - 1)k_0 d_{\mathrm{a}}\cos(\phi)) \end{pmatrix}$$

DIVERSITY AND CAPACITY

UNIT 05 – MULTIPLE ANTENNA TECHNIQUES– LECTURE 02

Transmit Diversity

- For many situations, multiple antennas can be installed at just one link end (usually the BS).
- For the uplink transmission from the MS to BS, multiple antennas can act as receive diversity branches.

Transmitter Diversity with Channel State Information

- The first situation we analyze is the case where the TX knows the channel perfectly.
- This knowledge might be obtained from feedback from the RX, or from reciprocity principles
- In this case, we find that the noise-limited case) there is a complete equivalence between transmit diversity and receive diversity.
- In other words, the optimum transmission scheme linearly weights signals transmitted from different antenna elements with the complex conjugates of the channel transfer functions from the transmit antenna elements to the single receive antenna.
- This approach is known as *maximum ratio transmission.*

Transmitter Diversity Without Channel State Information

- In many cases, Channel State Information (CSI) is not available at the TX. We then cannot simply transmit weighted copies of the same signal from different transmit antennas, because we cannot know how they would add up at the RX.
- In order to give benefits, transmission of the signals from different antenna elements has to be done is such a way that it allows the RX to distinguish different transmitted signal components.
- One way is *delay* diversity. In this scheme, signals transmitted from different antenna elements are delayed copies of the same signal. This makes sure that the effective impulse response is delay dispersive, even if the channel itself is flat fading. So, in a flat-fading channel, we transmit data streams with a delay of 1 symbol duration (relative to preceding antennas) from each of the transmit antennas.
- The effective impulse response of the cha

$$h(\tau) = \frac{1}{\sqrt{N_t}} \sum_{n=1}^{N_t} h_n \delta(\tau - nT_s)$$

- Here , hn are gains from the nth transmit antenna to the receive antenna, and the impulse response has been normalized so that total transmit power is independent of the number of antenna elements.
- The signals from different transmit antennas to the RX act effectively as delayed MPCs.
- If antenna elements are spaced sufficiently far apart, these coefficients fade independently.
- If the channel from a single transmit antenna to the RX is already delay dispersive, then the scheme still works, but care has to be taken in the choice of delays for different antenna elements.
- The delay between signals transmitted from different antenna elements should be at least as large as the maximum excess delay of the channel.
- An alternative method is phase-sweeping diversity. In this method, which is especially useful if there are only two antenna elements, the same signal is transmitted from both antenna elements. However, one of the antenna signals undergoes a time-varying phase shift.
- This means that at the RX the received signals add up in a time-varying way

Channel State Information

1. **Full CSI at the TX (CSIT) and full CSI at the RX (CSIR):** in this ideal case, both the TX and the RX have full and perfect knowledge of the channel. This case obviously results in the highest possible capacity.
2. **Average CSIT and full CSIR**: in this case, the RX has full information of the instantaneous channel state, but the TX knows only the average CSI – e.g., the correlation matrix of **H or the** angular power spectrum. As we have discussed in Section 20.1.6, this is easier to achieve and does not require reciprocity or fast feedback; however, it does require calibration (to eliminate the non reciprocity of transmit and receive chains) or slow feedback.
3. **No CSIT and full CSIR:** this is the case that can be achieved most easily, without any feedback or calibration. The TX simply does not use any CSI, while the RX learns the instantaneous channel state from a training sequence or using blind estimation.

4. **Noisy CSI** : when we assume "full CSI" at the RX, this implies that the RX has learned the channel state perfectly. However, any received training sequence will be affected by additive noise as well as quantization noise. It is thus more realistic to assume a "mismatched RX," where the RX processes the signal based on the observed channel **Hobs, while in reality the** signals pass through channel **Htrue**

$$\mathbf{H}_{\text{true}} = \mathbf{H}_{\text{obs}} + \mathbf{\Delta}$$

5. **No CSIT and no CSIR**: it is remarkable that channel capacity is also high when neither the TX nor the RX have CSI. We can, e.g., use a generalization of differential modulation. For high SNR, capacity no longer increases linearly with m = min(Nt,Nr), but rather increases as m(1 − m/Tcoh), where m = min(Nt,NrTcoh/2), and Tcoh is the coherence time of the channel in units of symbol duration.

Capacity in Nonfading Channels

As Shannon showed, the information-theoretic (ergodic) capacity of such a channel is

$$C_{\text{shannon}} = \log_2\left(1 + \gamma \cdot |H|^2\right)$$

Let us then consider a *singular value decomposition*

$$\mathbf{H} = \mathbf{W}\boldsymbol{\Sigma}\mathbf{U}^{\dagger}$$

The received signal is then

$$\begin{aligned} \mathbf{r} &= \mathbf{H}\mathbf{s} + \mathbf{n} \\ &= \mathbf{W}\boldsymbol{\Sigma}\mathbf{U}^{\dagger}\mathbf{s} + \mathbf{n} \end{aligned}$$

Then, multiplication of the transmit data vector by matrix U and the received signal vector by W† diagonalizes the channel

$$\mathbf{W}^{\dagger}\mathbf{r} = \mathbf{W}^{\dagger}\mathbf{W}\Sigma\mathbf{U}^{\dagger}\mathbf{U}\tilde{\mathbf{s}} + \mathbf{W}^{\dagger}\mathbf{n}$$

$$\tilde{\mathbf{r}} = \Sigma\tilde{\mathbf{s}} + \tilde{\mathbf{n}}$$

The capacity of channel H is thus given by the sum of the capacities of the eigenmodes of the channel:

$$C = \sum_{k=1}^{R_{\mathrm{H}}} \log_2 \left[1 + \frac{P_k}{\sigma_{\mathrm{n}}^2}\sigma_k^2\right]$$

This capacity expression can be shown equivalent to

$$C = \log_2 \left[\det\left(\mathbf{I}_{N_r} + \frac{\overline{\gamma}}{N_t}\mathbf{H}\mathbf{H}^{\dagger}\right)\right]$$

•All transfer functions are identical – i.e., h1,1 = h1,2 = . . . = hN,N. This case occurs when all antenna elements are spaced very closely together, and all waves are coming from similar directions. In such a case, the rank of the channel matrix is unity. Then, capacity is

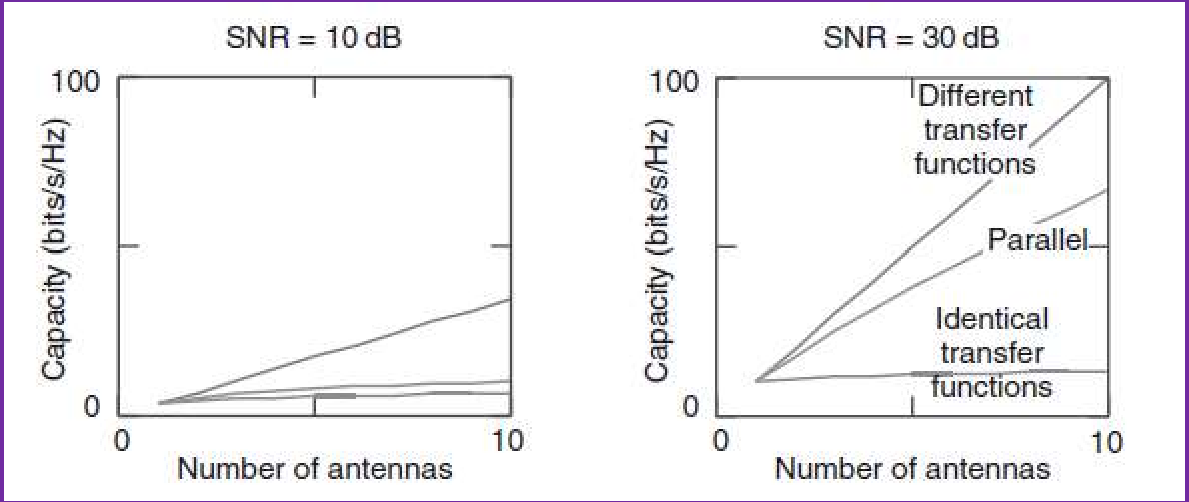
$$C_{\text{MIMO}} = \log_2(1 + N\overline{\gamma})$$

• All transfer functions are different such that the channel matrix is full rank, and has *N eigen values* of equal magnitude. This case can occur when the antenna elements are spaced far apart and are arranged in a special way. In this case, capacity is

$$C_{\text{MIMO}} = N \log_2\left(1 + \frac{\overline{\gamma}}{N}\right)$$

Parallel transmission channels – e.g., parallel cables. In this case, capacity also increases linearly with the number of antenna elements. However, the SNR per channel decreases with N, so that total capacity is

$$C_{\text{MIMO}} = N \log_2(1 + \overline{\gamma})$$



- Let us next consider the case where both the RX and TX know the channel perfectly. In such a case, it can be more advantageous to distribute power not uniformly between the different transmit antennas (or eigenmodes) but rather assign it based on the channel state.
- In other words, we are faced with the problem of optimally allocating power to several parallel channels, each of which has a different SNR.
- This is the problem and therefore the answer is : *waterfilling.*

Capacity in Flat-Fading Channels

- Because the entries of the channel matrix are random variables, we also have to rethink the concept of information-theoretic capacity. As a matter of fact, two different definitions of capacity exist for MIMO systems:

1. **Ergodic (Shannon) capacity:** this is the expected value of the capacity, taken over all realizations of the channel. This quantity assumes an infinitely long code that extends over all the different channel realizations.
2. **Outage capacity**: this is the minimum transmission rate that is achieved over a certain fraction of the time – e.g., 90% or 95%. We assume that data are encoded with a near-Shannon-limit achieving code that extends over a period that is much shorter than the channel coherence time. Thus, each channel realization can be associated with a (Shannon) capacity value. Capacity thus becomes a random variable (rv) with an associated cumulative distribution function (cdf)

No Channel State Information at the Transmitter and Perfect CSI at the Receiver

- Another practical handoff problem in microcell systems is known as cell dragging.
- Cell dragging results from pedestrian users that provide a very strong signal to the base station.
- Such a situation occurs in an urban environment when there is a line-of-sight (LOS) radio path between the subscriber and the base station.
- As the user travels away from the base station at a very slow speed, the average signal strength does not decay rapidly. Even when the user has traveled well beyond the designed range of the cell, the received signal at the base station may be above the handoff threshold, thus a handoff may not be made.
- This creates a potential interference and traffic management problem, since the user has meanwhile traveled deep within a neighboring cell.

THANK YOU

Does anyone have any questions?

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