FUNDAMENTALS OF WIRELESS COMMUNICATION

POINT-TO-POINT COMMUNICATION : KEYNOTES

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OUTLINE OF PRESENTATION

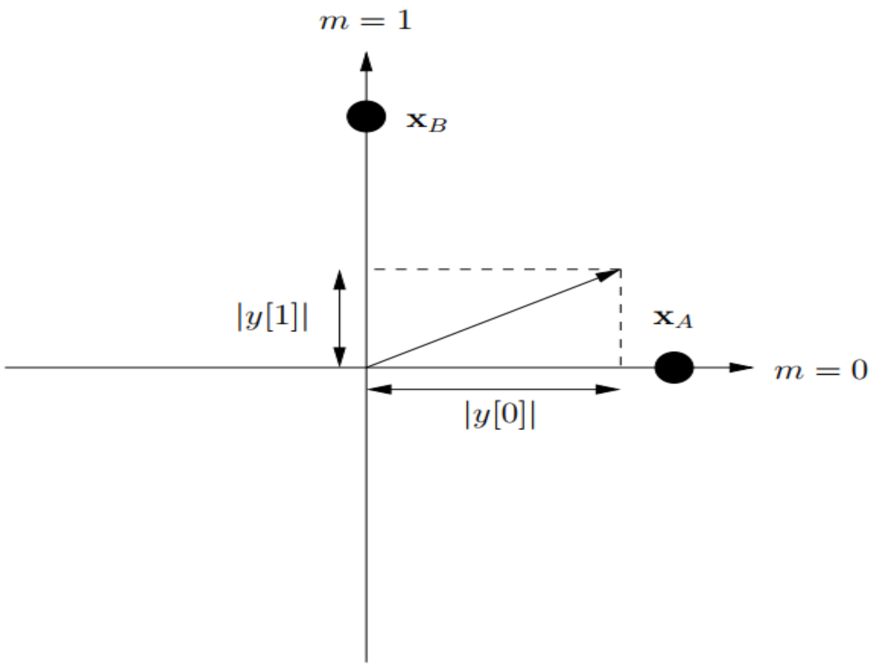
- **NON-COHERENT DETECTION**
- **COHERENT DETECTION**
- **DIVERSITY**
- **CHANNEL UNCERTAINTY**

NONCOHERENT DETECTION

- In non coherent detection the local carrier generated at the receiver not be phase locked with the carrier at the transmitter.
- First consider uncoded binary antipodal signaling (binary phase-shift-keying, BPSK)
- This signaling scheme fails completely, even in the absence of noise, since the phase of the received signal is uniformly distributed between 0 and 2π regardless of amplitudes.
- Binary antipodal signaling is binary phase modulation and it is easy to see that phase modulation in general is similarly flawed.

NONCOHERENT DETECTION

- Geometrically, we can interpret the detector as projecting the received vector y onto each of the two possible transmit vectors x_A and x_B and comparing the energies of the projections. Thus, this detector is also called an energy or a square-law detector.



NONCOHERENT DETECTION

- We can analyze the error probability of this detector. We can express the error probability of the orthogonal scheme in terms of SNR:

$$P_e = \frac{1}{2(1 + SNR)}$$

- This is a very discouraging result. To get an error probability $P_e = 10^{-3}$, one would require SNR ≈ 500 (27 dB). Stupendous amounts of power would be required for more reliable communication.

COHERENT DETECTION

- Why is the performance of the noncoherent maximum likelihood (ML) receiver on a fading channel so bad? It is instructive to compare its performance with detection in an AWGN channel without fading.
- Thus, the detection error probability decays exponentially in SNR in the AWGN channel while it decays only inversely with the SNR in the fading channel. To get an $P_e = 10^{-3}$, an SNR of about 7 dB is needed in an AWGN channel (as compared to 27 dB in the noncoherent channel).
- Compared to detection in the AWGN channel, the detection problem considered in the previous section has two differences: the channel gains h[m]'s are random, and the receiver is assumed not to know them.

COHERENT DETECTION

- Suppose now that the channel gains are tracked at the receiver so that they are known at the receiver (but still random). In practice, this is done either by sending a known sequence (called a pilot or training sequence) or in a decision directed manner, estimating the channel using symbols detected earlier.
- The accuracy of the tracking depends, of course, on how fast the channel varies.

COHERENT DETECTION

- Knowing the channel gains, coherent detection of BPSK can now be performed on a symbol-by-symbol basis.

$$P_e = \frac{1}{4SNR}$$

- Decays inversely proportional to the SNR, just as in the noncoherent orthogonal signaling scheme. There is only a 3 dB difference in the required SNR between the coherent and noncoherent schemes; in contrast, at an $P_e = 10^{-3}$, there is a 17 dB difference between the performance on the AWGN channel and coherent detection on the Rayleigh fading channel.

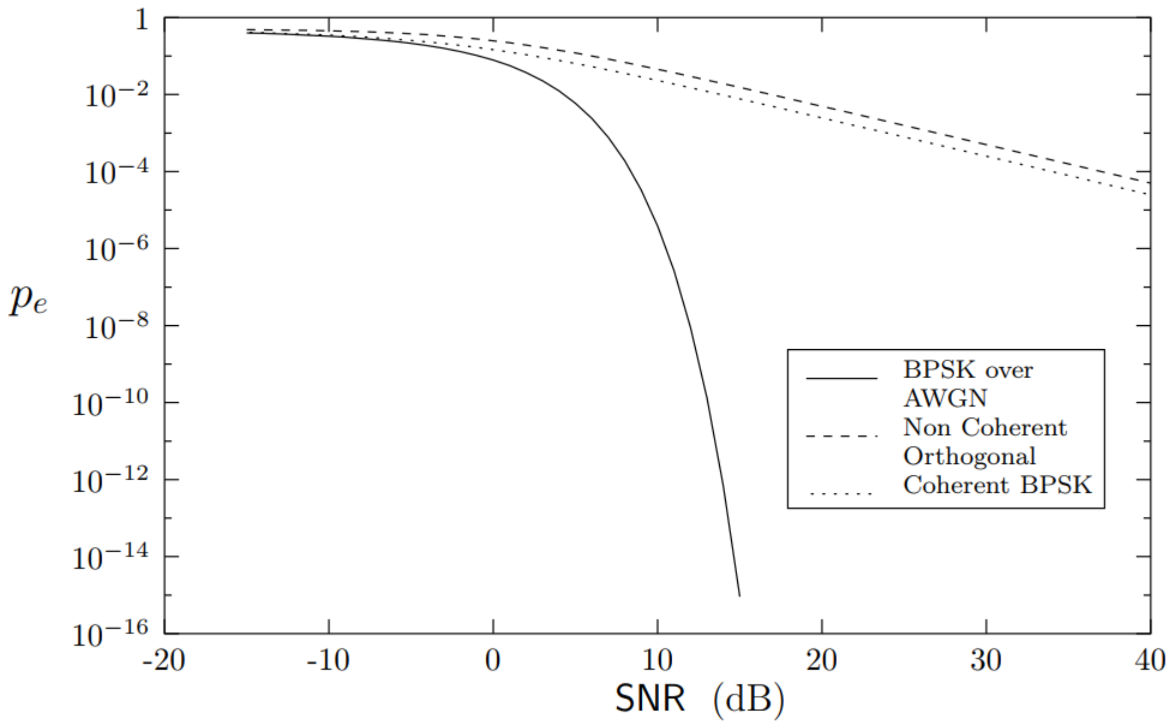
COHERENT DETECTION

- The main reason why detection in fading channel has poor performance is not because of the lack of knowledge of the channel at the receiver. It is because the channel gain is random and there is a significant probability that the channel is in a “deep fade”.

$$|h|^2 < \frac{1}{4SNR} \qquad P\{Deep\ Fade\} = \frac{1}{SNR}$$

- We conclude that high-SNR error events most often occur because the channel is in deep fade and not as a result of the additive noise being large. In contrast, in the AWGN channel the only possible error mechanism is for the additive noise to be large. Thus, the error probability performance over the AWGN channel is much better.

COHERENT DETECTION



- Performance of coherent BPSK vs noncoherent orthogonal signaling over Rayleigh fading channel vs BPSK over AWGN channel.

EXPLOITING DEGREE OF FREEDOM: BSPK TO QPSK

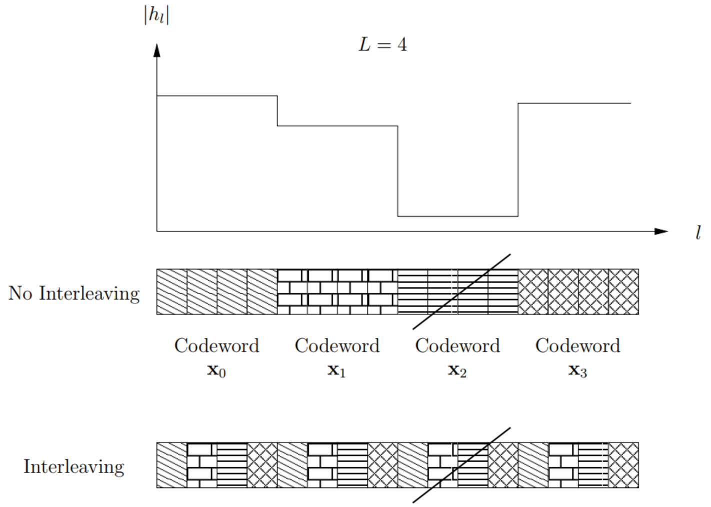
- BPSK uses only the real dimension (the I channel), while in practice both the I and Q channels are used simultaneously in coherent communication, increasing spectral efficiency.
- QPSK requires a transmit energy of $2a^2$ per symbol, while 4-PAM requires a transmit energy of $5b^2$ per symbol. Hence, for the same error probability, approximately 2.5 times more transmit energy is needed: a 4 dB worse performance.
- The loss is due to the fact that it is more energy-efficient to pack, for a desired minimum distance separation, a given number of constellation points in a higher-dimensional space than in a lower-dimensional space.

DIVERSITY

- Some schemes are spectrally more efficient than others, but from a practical point of view, they are all bad: the error probabilities all decay very slowly.
- The root cause of this poor performance is that reliable communication depends on the strength of a single signal path. There is a significant probability that this path will be in a deep fade. When the path is in a deep fade, any communication scheme will likely suffer from errors.
- A natural solution to improve the performance is to ensure that the information symbols pass through multiple signal paths, each of which fades independently, making sure that reliable communication is possible if one of the paths is strong. This technique is called diversity, and it can dramatically improve the performance over fading channels.

TIME DIVERSITY

- Diversity over time can be obtained via coding and interleaving: information is coded, and the coded symbols are dispersed over time in different coherence periods so that different parts of the codewords experience independent fades.



- The codewords are transmitted over consecutive symbols (top) and interleaved (bottom). A deep fade will wipe out the entire codeword in the former case but only one coded symbol from each codeword in the latter. In the latter case, each codeword can still be recovered from the other three unfaded symbols.

REPETITION CODING

- The simplest code is a repetition code, in which $x_l = x_1$ for $l = 1, \dots, L$. In vector form, the overall channel becomes

$$\mathbf{y} = \mathbf{h}x_1 + \mathbf{w},$$

where $\mathbf{y} = [y_1, \dots, y_L]^t$, $\mathbf{h} = [h_1, \dots, h_L]^t$ and $\mathbf{w} = [w_1, \dots, w_L]^t$.

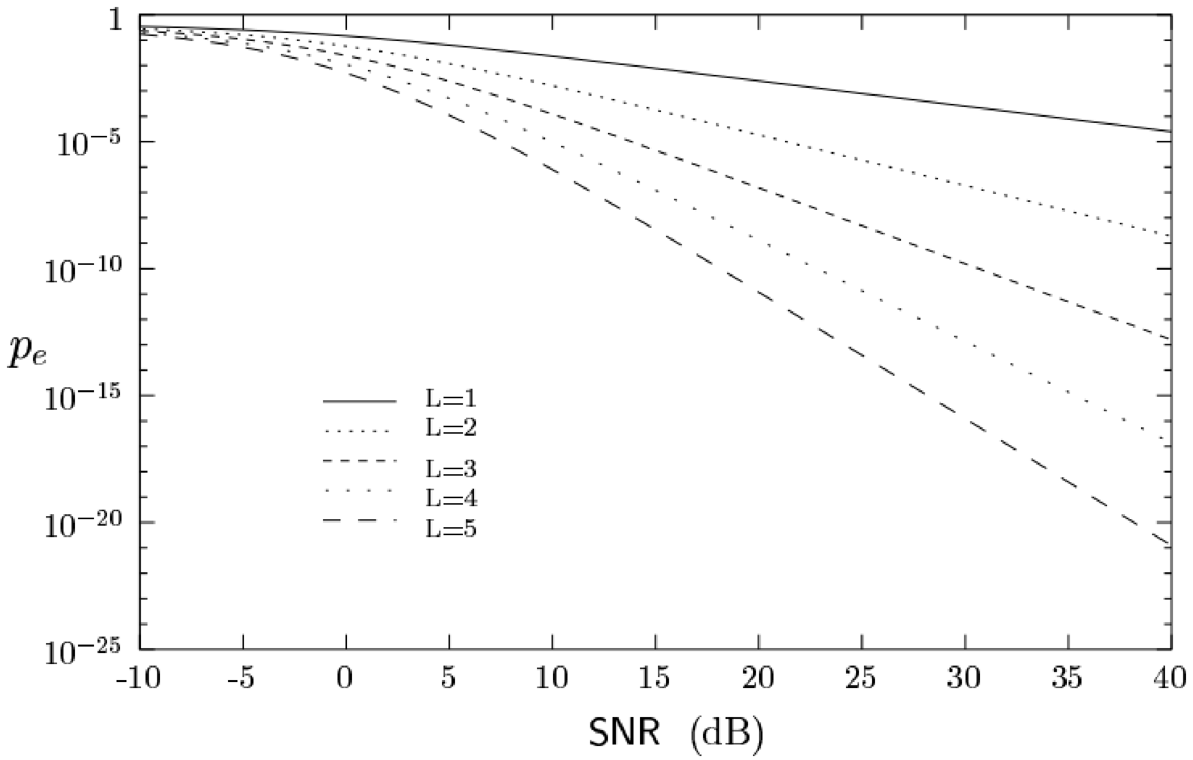
The receiver structure is a matched filter and is also called a maximal ratio combiner: it weighs the received signal in each branch in proportion to the signal strength and aligns the phases of the signals in the summation to maximize the output SNR.

This receiver structure is also called coherent combining.

REPETITIVE CODING

- The average error probability is

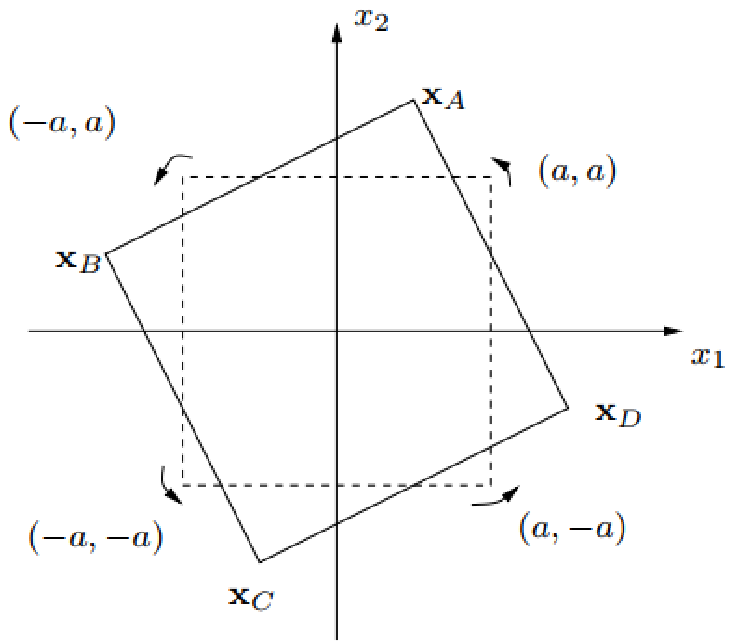
$$
\begin{aligned}
p_e &= \int_0^\infty Q\left(\sqrt{2x\mathsf{SNR}}\right) f(x)\, dx, \\
&= \left(\frac{1-\mu}{2}\right)^L \sum_{\ell=0}^{L-1} \binom{L-1+\ell}{\ell} \left(\frac{1+\mu}{2}\right)^\ell,
\end{aligned}
$$



BEYOND REPETITION CODING

- Although repetitive coding achieves a diversity gain, it does not exploit the degrees of freedom available in the channel effectively. By using more sophisticated codes, a coding gain can also be obtained beyond the diversity gain

Consider the case L = 2. A repetition code which repeats a BPSK symbol u = ±a twice obtains a diversity gain of 2 but would only transmit one bit of information over the two symbol times . Transmitting two independent BPSK symbols u1, u2 over the two times would use the available degrees of freedom more efficiently, but of course offers no diversity gain: an error would be made whenever one of the two channel gains h1, h2 is in deep fade. Hence vectors are transmitted.



BEYOND REPETITION CODING

- P $\{x_A \rightarrow x_B\}$ is the pairwise error probability of confusing x_A with x_B when x_A is transmitted and when these are the only two hypotheses. Conditioned on the channel gains h_1 and h_2 .

$$\mathbb{P}\{\mathbf{x}_A \rightarrow \mathbf{x}_B | h_1, h_2\} = Q\left(\frac{\|\mathbf{u}_A - \mathbf{u}_B\|}{2\sqrt{N_0/2}}\right) = Q\left(\sqrt{\frac{\mathsf{SNR}\left(|h_1|^2|d_1|^2 + |h_2|^2|d_2|^2\right)}{2}}\right)$$

$$\mathbb{P}\{\mathbf{x}_A \rightarrow \mathbf{x}_B\} \leq \frac{16}{|d_1 d_2|^2}\mathsf{SNR}^{-2}, \qquad \delta_{AB} := |d_1 d_2|^2,$$

- This is the squared product distance between x_A with x_B , when the average energy of the code is normalized to be 1 per symbol time. This determines the pairwise error probability between the two codewords.

ANTENNA DIVERSITY

- Antenna diversity, or spatial diversity, can be obtained by placing multiple antennas at the transmitter and/or the receiver. If the antennas are placed sufficiently far apart, the channel gains between different antenna pairs fade independently, and independent signal paths are created.
- The required antenna separation depends on the local scattering environment as well as on the carrier frequency.

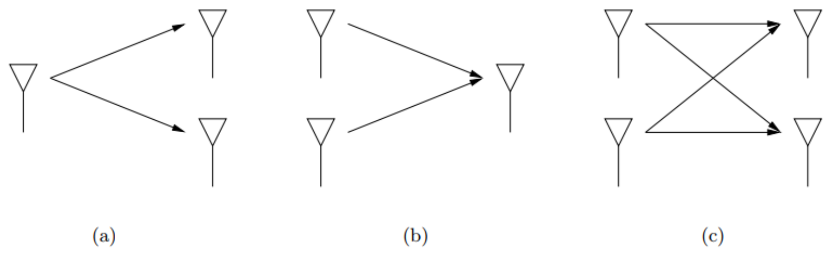


Figure 3.11: (a) Receive diversity; (b) transmit diversity; (c) transmit and receive diversity.

RECEIVE DIVERSITY

- With 1 transmit antenna and L receive antennas, then we have

$$y_\ell[m] = h_\ell[m]x[m] + w_\ell[m] \qquad \ell = 1, \ldots, L$$

- By having multiple receive antennas and coherent combining at the receiver, the effective total received signal power increases linearly with L: Increased power gain.
- By averaging over multiple independent signal paths, the probability that the overall gain is small is decreased. Hence high diversity gain.

TRANSMIT DIVERSITY

- Now consider the case when there are L transmit antennas and 1 receive antenna, the MISO channel.
- It is easy to get a diversity gain of L: simply transmit the same symbol over the L different antennas during L symbol times. At any one time, only one antenna is turned on and the rest are silent. This is simply like a repetition code, quite wasteful of degrees of freedom.
- More generally, any time diversity code of block length L can be used on this transmit diversity system: simply use one antenna at a time and transmit the coded symbols of the time diversity code successively over the different antennas. This provides coding gain over repetition codes.
- One can also design codes specifically for the transmit diversity system; Space-Time coding.

ALAMOUTI SCHEMES

- This is the transmit diversity scheme proposed in several third-generation cellular standards. Alamouti scheme is designed for 2 transmit antennas; generalization to more than 2 antennas is possible, to some extent.

- The two transmit, single receive channel is written as

$$y[m] = h_1[m]x_1[m] + h_2[m]x_2[m] + w[m],$$

- where h_i is the channel gain from transmit antenna i.

$$\begin{bmatrix} y[1] & y[2] \end{bmatrix} = \begin{bmatrix} h_1 & h_2 \end{bmatrix} \begin{bmatrix} u_1 & -u_2^* \\ u_2 & u_1^* \end{bmatrix} + \begin{bmatrix} w[1] & w[2] \end{bmatrix}.$$

We are interested in detecting u_1, u_2, so we rewrite this equation as

$$\begin{bmatrix} y[1] \\ y[2]^* \end{bmatrix} = \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix} \begin{bmatrix} u_1 \\ u_2 \end{bmatrix} + \begin{bmatrix} w[1] \\ w[2]^* \end{bmatrix}.$$

ALAMOUTI SCHEMES

- We project y onto each of the two columns to obtain the sufficient statistics

$$r_i = \|\mathbf{h}\| u_i + w_i, \qquad i = 1, 2,$$

- Thus, the diversity gain is 2 for the detection of each symbol. Compared to the repetition code, 2 symbols are now transmitted over two symbol times instead of 1 symbol, but with half the power in each symbol.

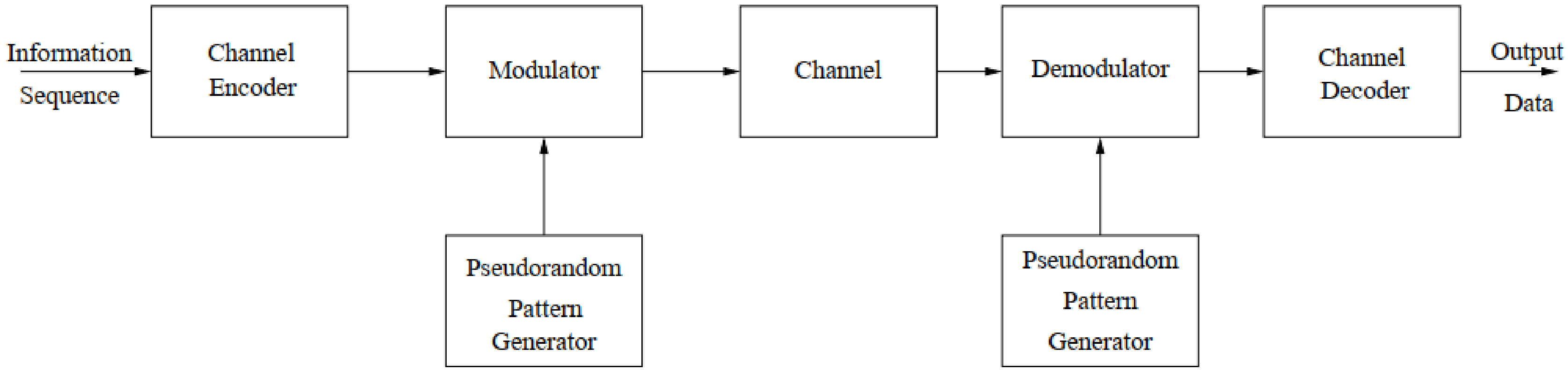
FREQUENCY DIVERSITY

- In wideband channels, however, the transmitted signal arrives over multiple symbol times and the multipaths can be resolved at the receiver. The frequency response is no longer flat, i.e., the transmission bandwidth W is greater than the coherence bandwidth Wc of the channel. This provides another form of diversity: frequency.
- Diversity is achieved by the ability of resolving the multipaths at the receiver due to the wideband nature of the channel and is thus called frequency diversity.

FREQUENCY DIVERSITY

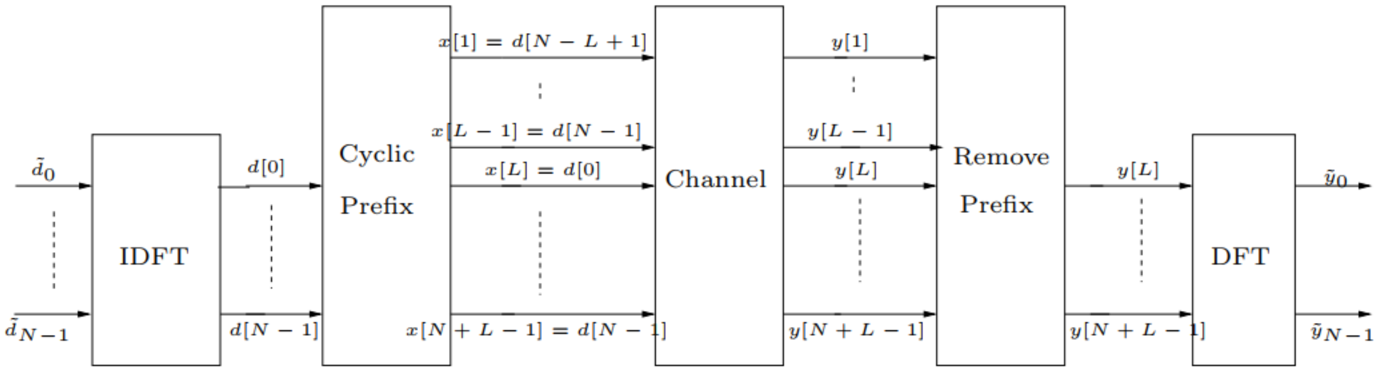
- This scheme can be thought of as analogous to the repetition codes used for both time and spatial diversity, where one information symbol is repeated L times. In this setting, if once one tries to transmit symbols more frequently, inter-symbol interference (ISI) occurs: the delayed replicas of previous symbols interfere with the current symbol.
- Approaches to dealing with the ISI while at the same time exploiting the inherent frequency diversity in the channel.
- single-carrier systems with equalization. (GSM)
- direct sequence spread spectrum (IS-95 CDMA)
- Discrete Multi-Tone (DMT) or Orthogonal Frequency Division Multiplexing (OFDM). (IEEE 802.11a)

DIRECT SEQUENCE SPREAD SPECTRUM



- Information is encoded and modulated by a pseudonoise (PN) sequence and transmitted over a bandwidth W. The data rate $R\ bits/s$ in a spread spectrum system is typically much smaller than the transmission bandwidth $W\ Hz$. The ratio W/R is sometimes called the processing gain of the system which is very high in DSSS Systems. Because the symbol rate per user is very low in a spread spectrum system, ISI is typically negligible, and equalization is not required.

Orthogonal Frequency Division Multiplexing



The data symbols modulate Nc tones or sub-carriers which occupying the bandwidth W and are uniformly separated by NWc . The data symbols on the sub-carriers are then converted (through the IDFT) to time domain. The procedure of introducing the cyclic prefix before transmission allows for the removal of ISI. The receiver ignores the part of the output signal containing the cyclic prefix (along with the ISI terms)and converts the length-Nc symbols back to the frequency domain through a DFT.

The data symbols on the sub-carriers are maintained to be orthogonal as they propagate through the channel and hence go through narrowband parallel channels. This interpretation justifies the name of OFDM for this communication scheme.

Orthogonal Frequency Division Multiplexing

- The simplicity achieved with OFDM is at a cost of underutilizing two resources, resulting in a loss of performance.
- First, the cyclic prefix occupies an amount of time which cannot be used to communicate data. A fraction of the average power is allocated to the cyclic prefix and cannot be used towards communicating data.
- OFDM schemes that put a zero signal instead of the cyclic prefix have been proposed to reduce this loss. However due to the abrupt transition in the signal, such schemes introduce harmonics that are difficult to filter in the overall signal. Further, the cyclic prefix can be used for timing and frequency acquisition in wireless applications, and this capability would be lost if a zero signal replaces the cyclic prefix.

CHANNEL UNCERTAINTY

- In fast varying channels, it may not be easy to estimate accurately the phases and magnitudes of the tap gains before they change.
- We have previously a simple coherent and noncoherent detector for fading channels without diversity. Here, we extend this to channels with diversity. When we compared coherent and noncoherent detection for channels without diversity, the difference was seen to be relatively small.
- An important question is what happens to that difference as the number of diversity paths L increases.

CHANNEL UNCERTAINTY

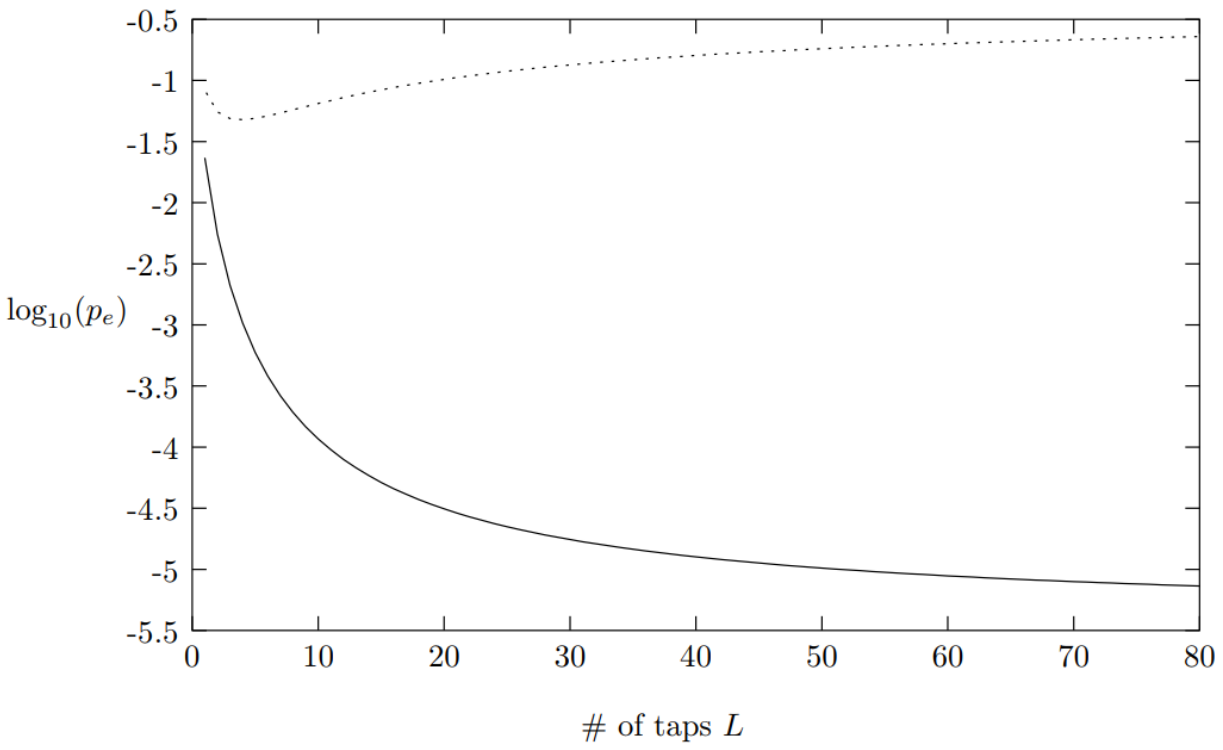


Figure 3.23: Comparison of error probability under coherent detection (solid) and noncoherent detection (dotted), as a function of the number of taps L. Here $\mathcal{E}_b/N_0 =$ 10dB.

CHANNEL UNCERTAINTY

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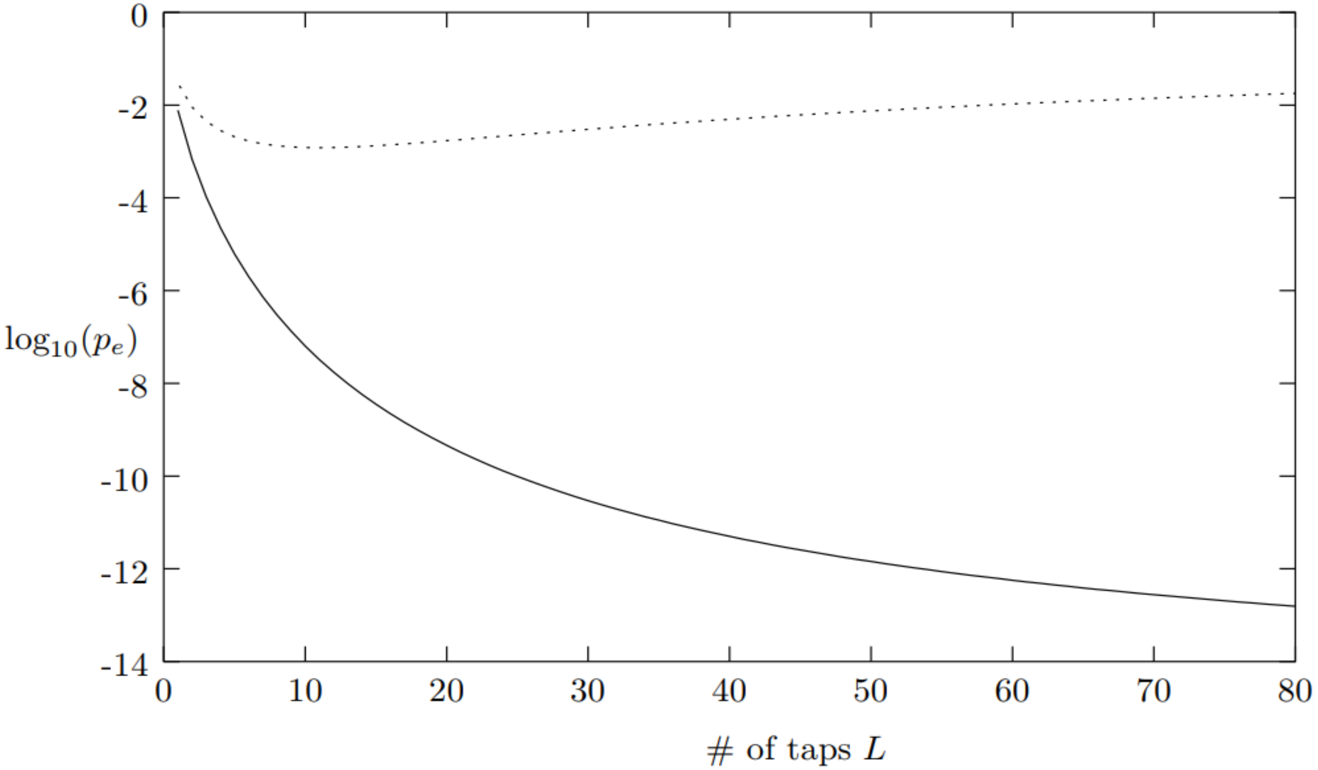


Figure 3.24: Comparison of error probability under coherent detection (solid) and noncoherent detection (dotted), as a function of the number of taps L. Here $\mathcal{E}_b/N_0 =$ 15dB.

CHANNEL ESTIMATION

- In practice, the channel taps must be estimated and tracked. There may be measurement errors which may impact the performance of the coherent combiners.
- In channel estimation, the transmitted sequence is assumed to be known at the receiver.
- In a pilot-based scheme, a known sequence (called a pilot, sounding tone, or training sequence) is transmitted and this is used to estimate the channel.
- In a decision-feedback scheme, the previously detected symbols are used to update the channel estimates.

CHANNEL ESTIMATION

- Typically, channel estimation is obtained by averaging over several such measurements. For simplicity, we assume that the channel is constant over K symbol times, and we obtain K such measurements over these symbol times. The mean-square error associated with this estimate for all branches is

$$\frac{1}{L} \cdot \frac{1}{1 + \frac{K\mathcal{E}}{LN_0}},$$

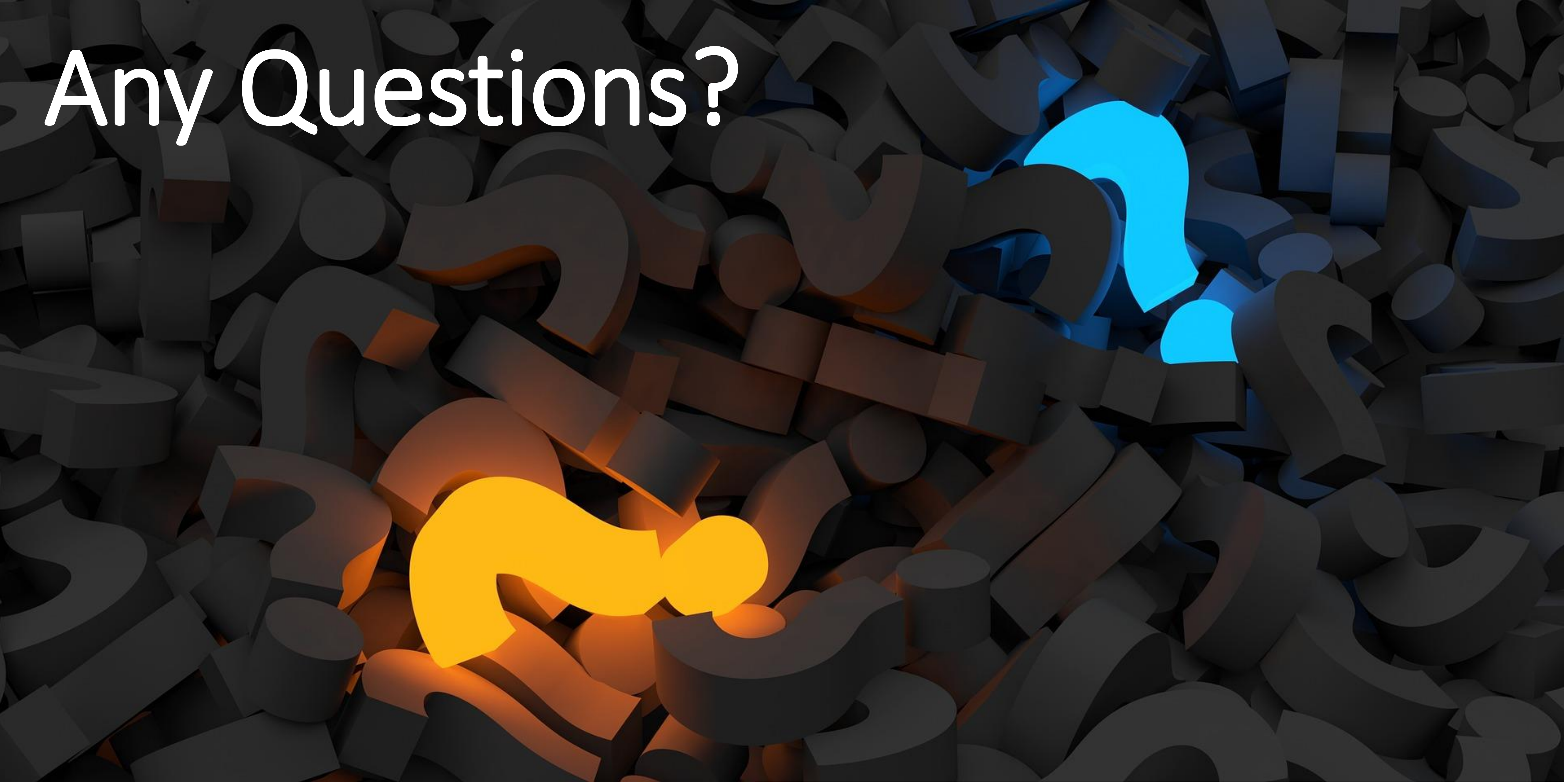
- The key parameter affecting the estimation error is

$$\mathsf{SNR}_{\mathrm{est}} := \frac{K\mathcal{E}}{LN_0}.$$

CHANNEL ESTIMATION

- Also $$\mathrm{SNR}_{\mathrm{est}} = \frac{PT_c}{LN_0}$$
- where P is the received power of the signal from which channel measurements are obtained.
- Hence, SNR_{est} can be interpreted as the signal-to-noise ratio available to estimate the channel per coherence time per tap.
- If the measurements are done in a decision-feedback mode, P is the received power of the data stream itself.
- If the measurements are done from a pilot, then P is the received power of the pilot.

Any Questions?



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