Wireless Communication: Concepts, Techniques, and Models

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Outline

- Digital communication over radio channels
- Channel capacity
- MIMO: diversity and parallel channels
- Wideband systems: CDMA, OFDMA

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Digital communication over radio channels

- Modulation and detection
- Channel coding
- Delay, path loss, shadowing, and fading

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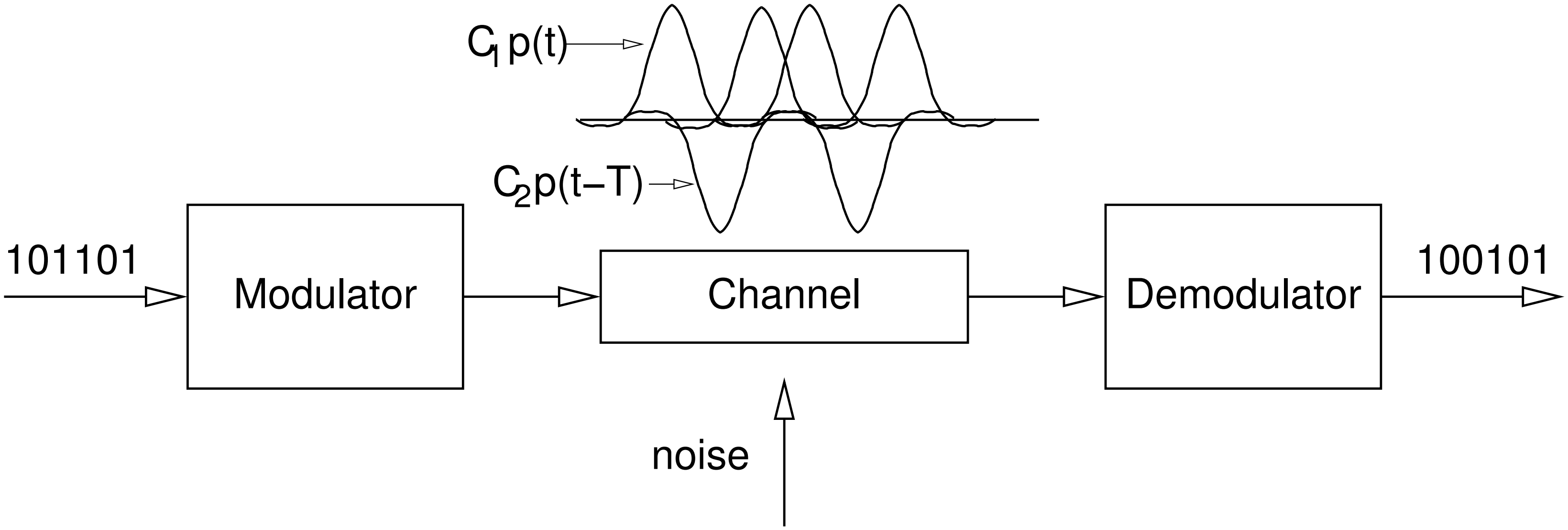
Modulation and detection



Modulation

- modulating a sequence of *pulses* by the given bit stream

- pulse p(t): also called baseband pulse
  - Chosen such that its spectrum occupies the frequencies (-W/2, W/2), where W is the bandwidth of the radio spectrum allocated for the wireless communication
  - For T=1/W, it is possible to define p(t) such that
    - p(t) is bandlimited to (-W/2,W/2);
    - p(t-kT), $k \in \{\ldots,-3,-2,-1,0,1,2,3,\ldots\}$, constitute an orthorgonal set, that is,

      $\int_{-\infty}^{\infty} p(t)p(t-k\mathrm{T})\mathrm{d}t = 0$; and
    - $\int_{-\infty}^{\infty} p^2(t)\mathrm{d}t = 1$, that is, the energy of the pulse is 1
  - The pulses are repeated every T seconds

Binary modulation and detection

- Each pulse in the pulse train is multiplied by a symbol from the symbol set $\{-\sqrt{E_s}, \sqrt{E_s}\}$
  - Bit 1: use symbol $\sqrt{E_s}$
  - Bit 0: use symbol $-\sqrt{E_s}$
- Let C_k be the symbol into which the k-th bit is mapped. When the pulses are repeated every T seconds, the modulated pulse stream can be written as

$$X(t) = \sum_{k=-\infty}^{\infty} C_k \, p(t - kT)$$

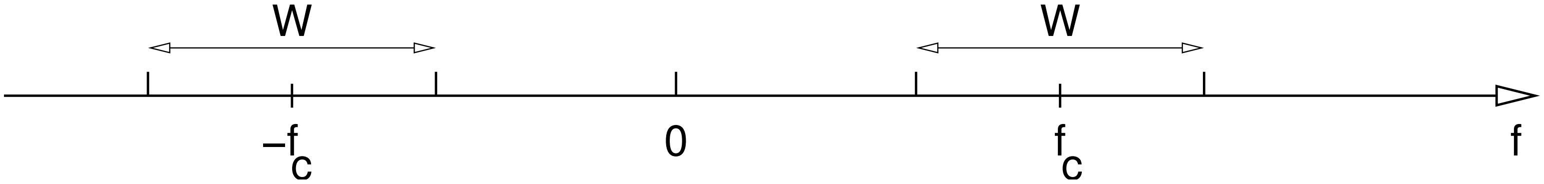
  - The following operation will recover C_k

$$C_k = \int_{-\infty}^{\infty} X(t)\, p(t-kT)\,\mathrm{d}t$$

- Before transmission, the baseband signal X(t) is translated to the allocated radio spectrum with central frequency f_c by multiplying it with a sinusoid

$$S(t) = \sqrt{2}\sum_{k=-\infty}^{\infty} C_k\, p(t-kT)\cos(2\pi f_c t)$$

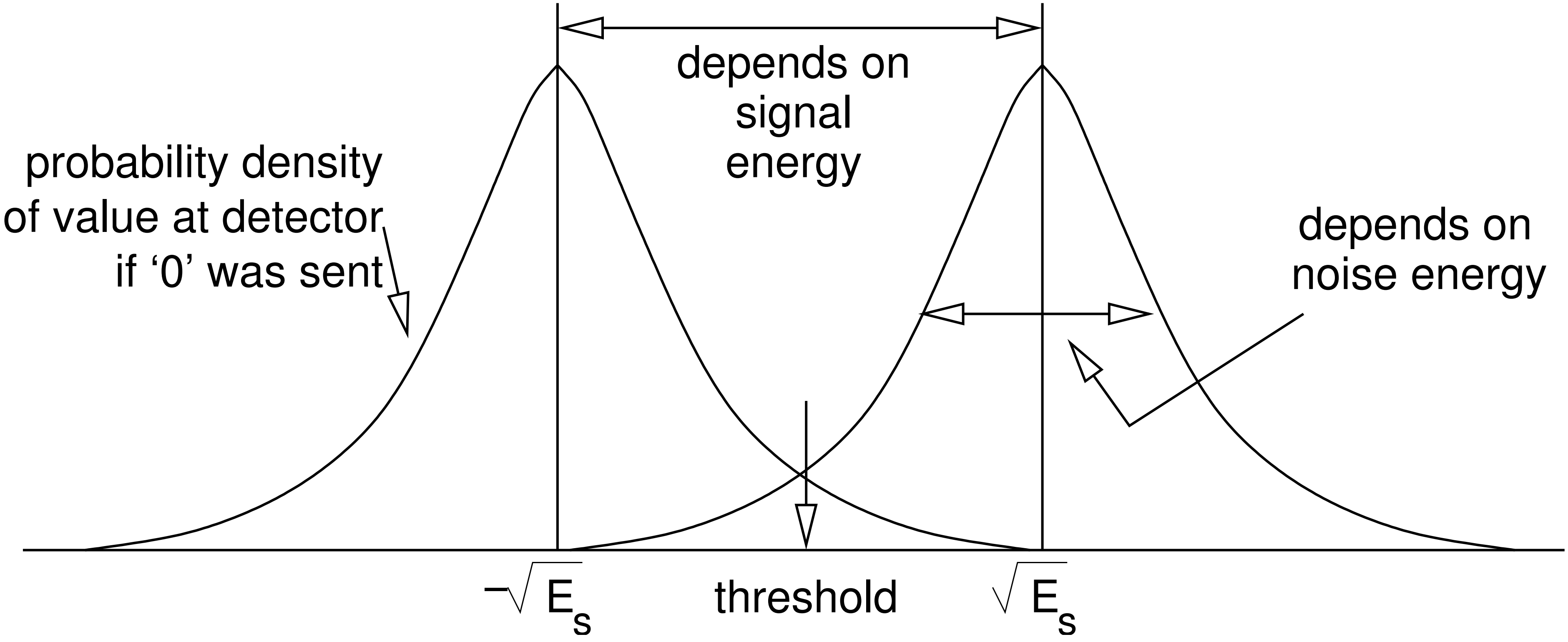
s.t. the energy in the modulated symbols is E_s



- Symbol-by-symbol channel model
  - Relates the source symbol sequence C_k and the predetection statistic Y_k, from which the source symbol has to be inferred

$$Y_k = C_k + Z_k$$

where Z_k is a sequence of i.i.d. zero mean Gaussian random variables with variance $N_0/2$ (i.e., additive white Gaussian noise AGWN)



depends on signal energy

probability density of value at detector if ‘0’ was sent

depends on noise energy

$$P_{bit-error-AWGN} = Q(\sqrt{\frac{2E_s}{N_0}})$$

- In general, given a modulation scheme

$$P_{bit-error} = f(SNR)$$

where SNR is the *signal power to noise power ratio*

- When considering interference

$$P_{bit-error} = f(SINR)$$

where SINR is the *signal power to interference-plus-noise power ratio*

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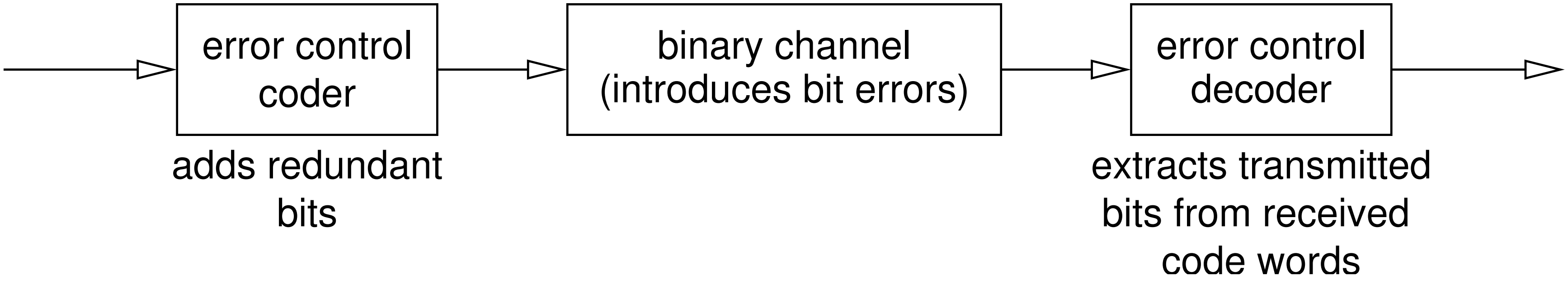
Channel coding

- To reduce bit-error-rate (BER)

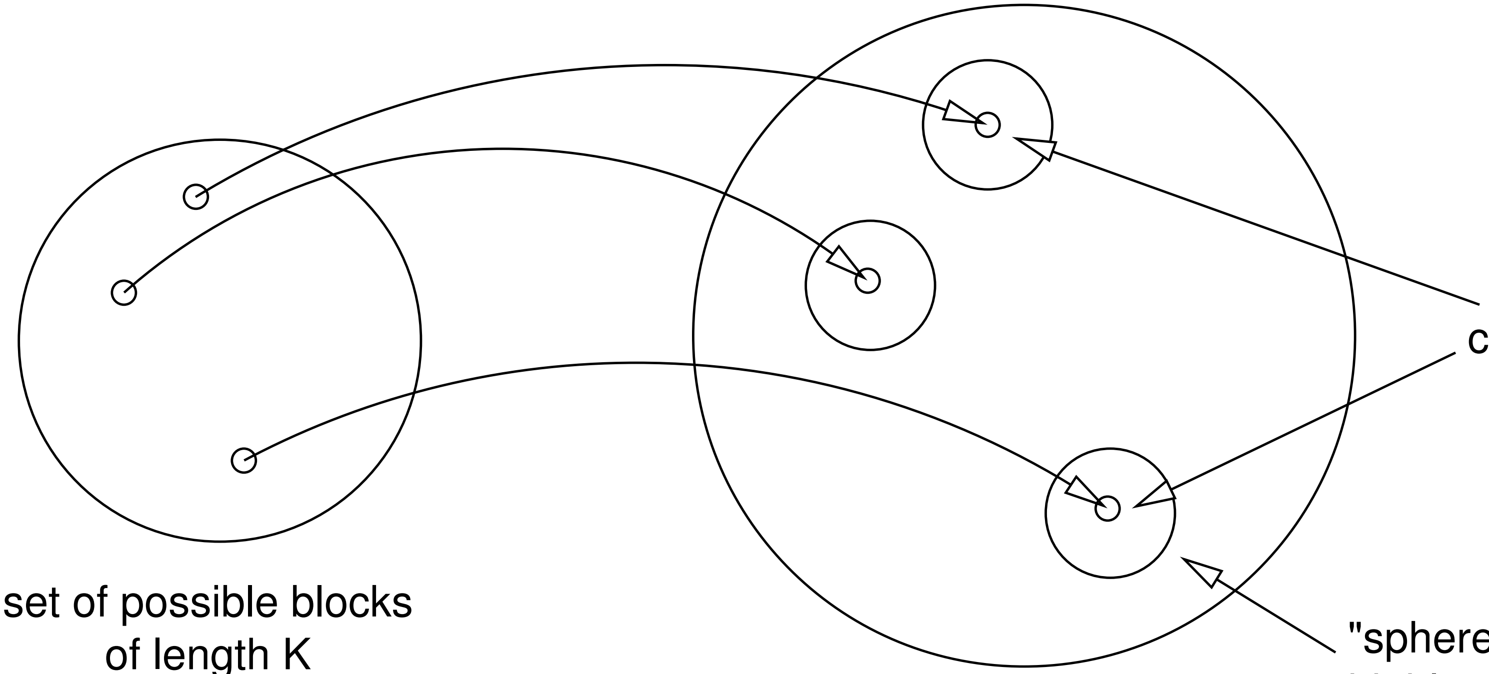

error control coder

binary channel (introduces bit errors)

error control decoder

adds redundant bits

extracts transmitted bits from received code words



set of possible blocks
of length K
(2^K blocks)

set of possible blocks
of length N
(2^N blocks)

code words

"sphere" of
highly probable
errored code words

- Shannon’s noisy channel coding theorem
  - There is a number C, called *channel capacity*, such that if the information rate R<C, then, as the block length increases, an arbitrary small BER can be achieved (of course, at the cost of a large block coding delay);
  - If we attempt to use R>C, then BER cannot be reduced to 0.

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Delay spread and inter-symbol interference (ISI)

- Delay spread T_d
    - For a transmitter receiver pair, the difference between the smallest signal delay and the largest signal delay

- If delay spread is *not very small* compared to symbol time, then the superposition of the signals received over the variously delayed paths at the receiver leads to ISI; thus

$$Y_k = \sum_{j=0}^{J_d - 1} G_k(j) X_{k-j} + I_k + Z_k$$

where J_d denotes the length of channel memory (in # of symbols), $G_k(j)$ models the (attenuation) influence that the j-th past symbol has on channel output at k, I_k models the interference, and Z_k models random background noise

- Interpretation in frequency domain
  - Coherence bandwidth W_c: $W_c = 1/T_d$
  - If W_c is small compared to W, superposition of variously delayed versions of some frequency components in the baseband pulse can cancel out;

    In this case, some of the frequency components in the pulse get selectively attenuated, leading to symbol corruption;

    This is called *frequency selective fading.*

- If $W_c >> W$ (channel bandwidth), all the frequency components fade together, and we have *flat fading;* thus negligible ISI and

$$Y_k = G_k X_k + I_k + Z_k$$

  note: $H_k = |G_k|^2$ is also called *channel gain*

- The assumption of flat fading is reasonable for a narrowband system;

- For wideband systems where W_c may be small compared to system bandwidth W (i.e., T_d is large compared to 1/W), the channel is frequency selective, and we need to use mechanisms such as *channel equalizer* which compensate for various channel delays to make the overall systems appear like a fixed delay channel
  - In mobile networks, channel equalizer needs to be adaptive

Power attenuation process: path loss, shadowing, fading

- Channel power attenuation process H_k

$$H_k = \left(\frac{d_k}{d_0} \right)^{-\eta} S_k R_k^2$$

- Path loss factor: $\left(\frac{d_k}{d_0} \right)^{-\eta}$
  - d_0: (far field) reference distance
  - η: path loss exponent; usually between 2 and 5

- Shadowing: S_k
  - Characterize the spatial variation in signal attenuation for the same distance from transmitter
  - Usually follows a log-normal distribution, such that

$10\log_{10} S = -\xi$ dB is a zero mean Gaussian with variance σ^2. A typical value of σ is 8 dB.

- Multipath fading: R_k^2
  - the superposition of delayed carriers results in constructive and destructive carrier interference, leading to variations in signal strength
    - Exists even if multipath time delays do not lead to ISI
  - it has strong autocorrelation over a duration of *coherence time T_c*
    - T_c is approximately the inverse of the Doppler frequency $f_d = f_c \frac{v}{c}$
    - In indoor office or home environment, the Doppler frequency could be just a few Hz (e.g., 3Hz), leading to coherence time of 100s of milliseconds

- When all the signals arriving at the receiver are scattered signals, R^2 follow a Rayleigh distribution

$$f_{R^2}(x) = \frac{1}{E(R^2)} e^{\left(-x/E(R^2)\right)}$$

- When a fraction K/(K+1) of the signal arrives directly (i.e., line of sight) and the remaining arrives uniformly over all directions, R^2 follows a Ricean distribution

$$f_{R^2}(x) = \frac{K+1}{E(R^2)} e^{\left(-K\frac{(K+1)x}{E(R^2)}\right)} I_0\left(2\sqrt{\frac{K(K+1)x}{E(R^2)}}\right)$$

where

$$I_0(x) = \frac{1}{2\pi}\int_0^{2\pi} e^{-x\cos(\theta)}\mathrm{d}\theta$$

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Channel capacity

- Shannon's Noisy Channel Capacity Theorem (without fading)

$$C = W\log_2\left(1+\frac{P_{rcv}}{N_0 W}\right), \text{ where } N_0 \text{ is the noise power spectral density}$$

- With fading: assuming the receiver can precisely track fading,

$$C_{fading-CSIR} = \int W\log_2\left(1+\frac{hP_{xmt}}{N_0 W}\right) g_H(h)\mathrm{d}h$$

$CSIR$: channel state (or side) information at receiver

note:

$$C_{fading-CSIR} \le W\log_2\left(1+\frac{E(H)P_{xmt}}{N_0 W}\right)$$

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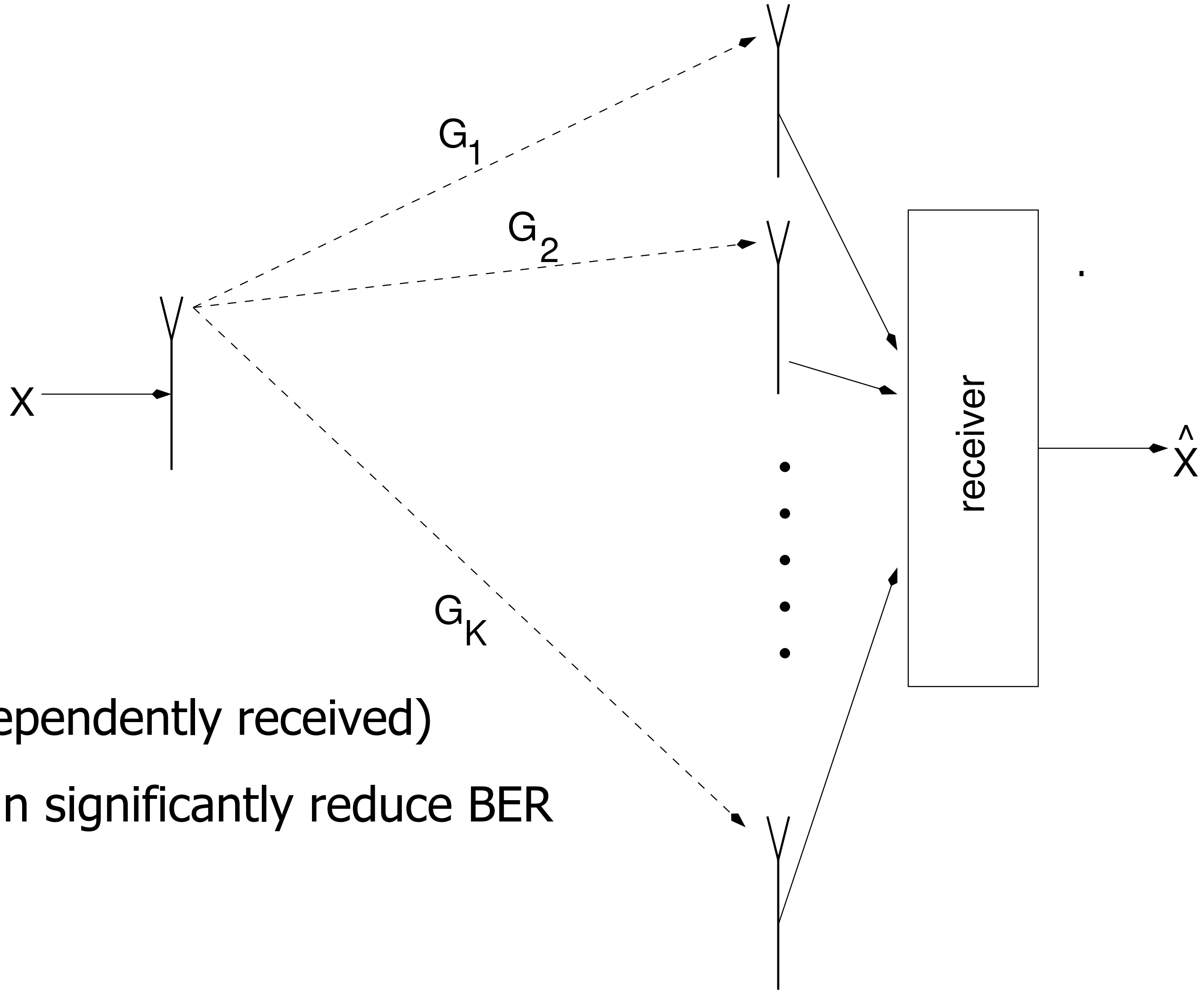
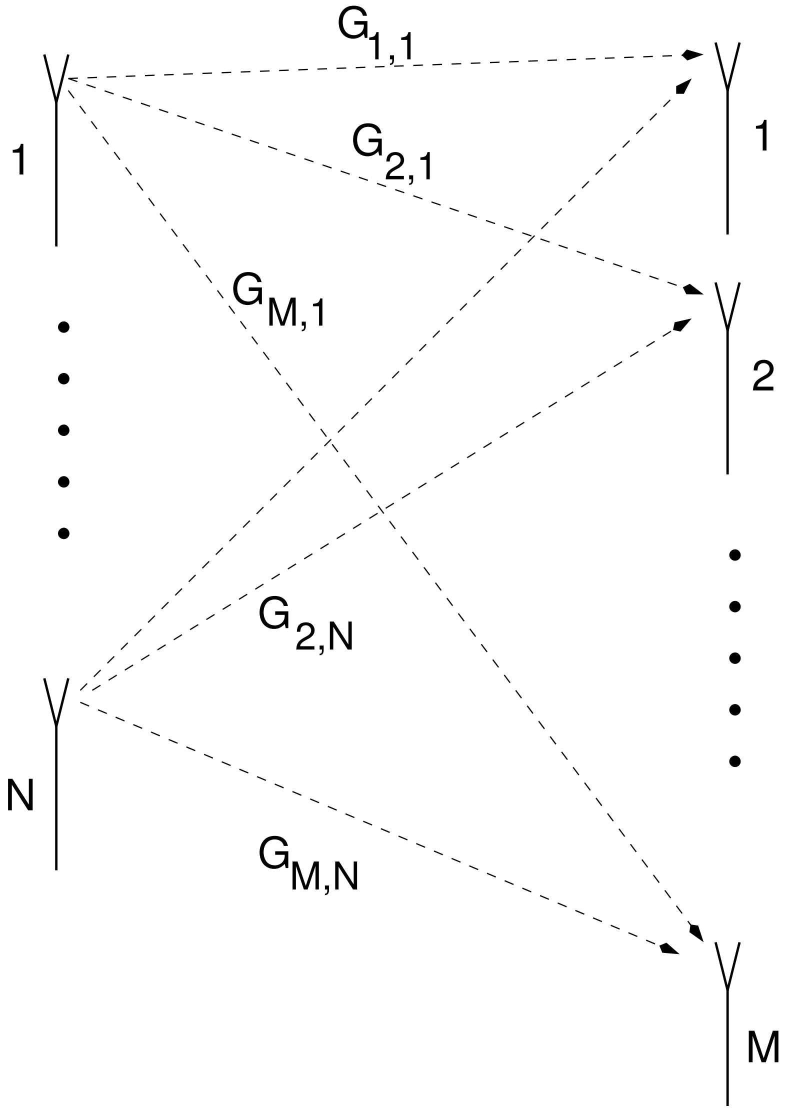
SIMO



- Exploiting the K (independently received) signals at receiver can significantly reduce BER
- Diversity gain: K
  - BER is proportional to ψ^{-K}, where ψ is the receiver SNR
    - In contrast, in SISO, BER approximately decreases only as the reciprocal of ψ (note: approximate the Q(.) function)

MIMO



- Multiplexing gain: # of parallel channels <= min{M, N}
- Diversity gain: <= M*N

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CDMA

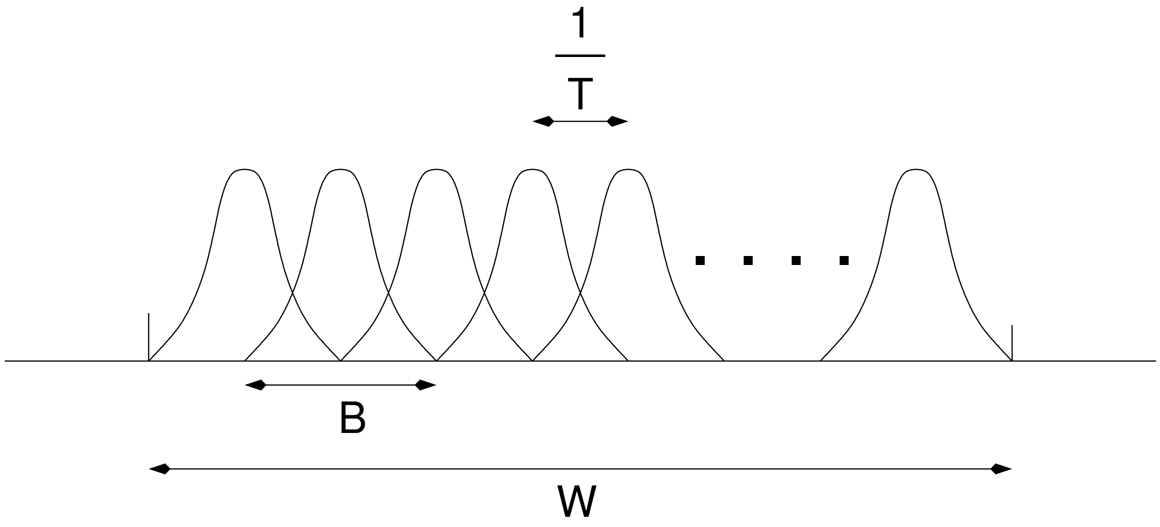
- Direct sequence spread spectrum (DSSS)
  - Each user symbol is multiplied by a *spreading code* of length L *chips*
  - L is called the *spreading factor*
- Spreading code
  - Take values in the set $\{-1, +1\}^L$
  - Each code is approximately orthogonal to all the time shifts of the other codes, and to its own time shifts

- Effective pre-detection SINR

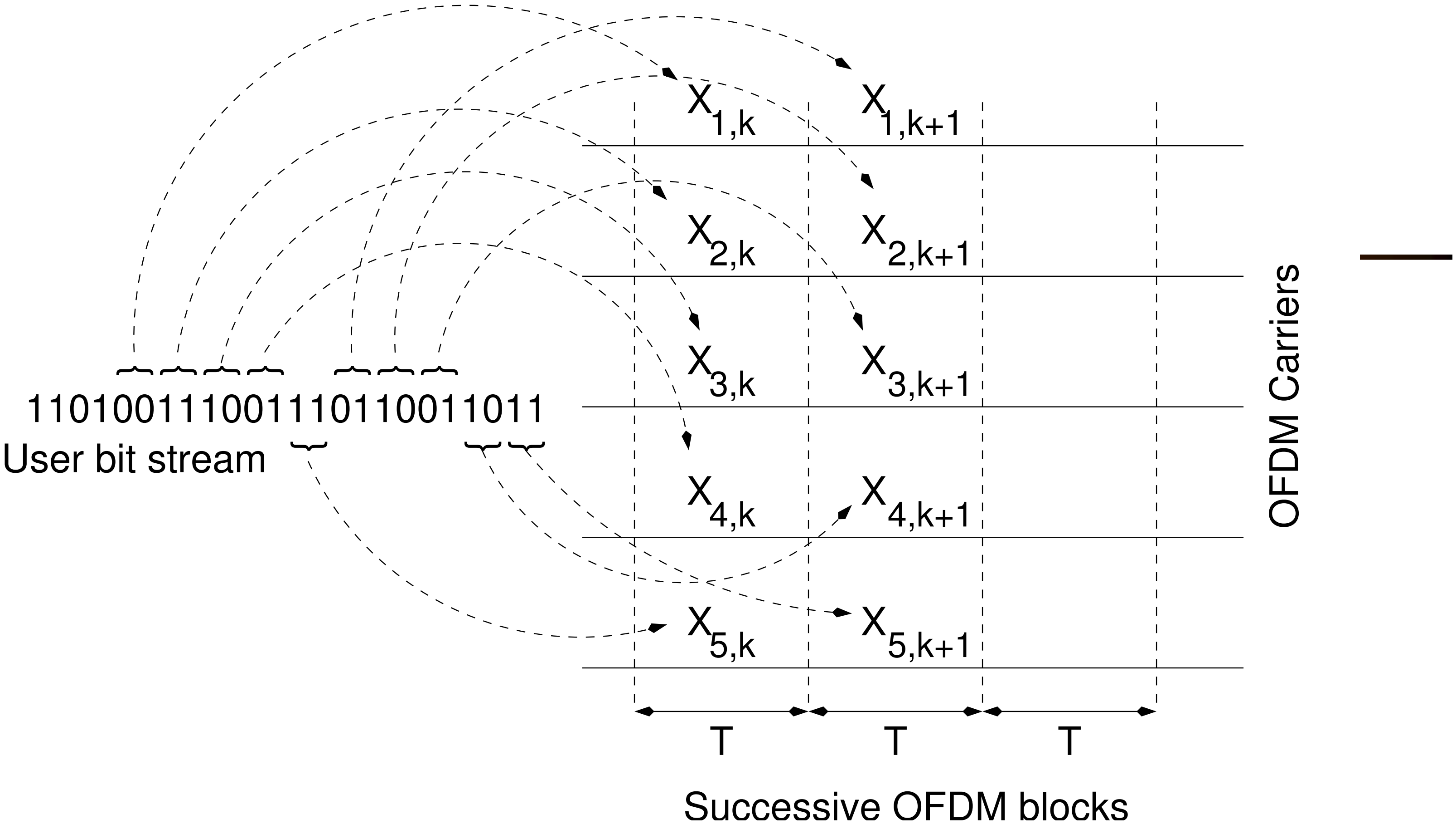
$$\frac{LP_{rcv}}{\sum_{j\in \text{interferers}} P_{j,rcv} + N_0 W}\text{, which is } L \text{ times the received SINR (i.e., } \frac{P_{rcv}}{\sum_{j\in \text{interferers}} P_{j,rcv} + N_0 W}\text{)}$$

- Scheduling in CDMA systems includes
  - allocating spread code and transmission power for each user

OFDMA



- Based on OFDM
  - statistically partitions the available spectrum into several (e.g., 128 or 512) subchannels
  - Each subchannel has bandwidth B s.t. B << $1/T_d$, enabling flat fading
  - If there are n subchannels, the OFDM *block length* is n
    - In the basic scheme, user bit stream is mapped into successive blocks of n channel symbols that are then transmitted in parallel



- Block time T = 1/B; the term orthogonal in OFDM refers to the fact that the center frequencies of the subchannels are separated by the reciprocal of the block time T, which facilitates demodulation at the receiver

- It can be shown that fading is uncorrelated between subcarriers that are spaced by more than the coherence bandwidth, W_c Hz (= $1/T_d$)
  - Similar to how TDM exploits time diversity, OFDM exploits *frequency diversity*: successive symbols of a user’s codeword can occupy independently fading subcarriers.

- Scheduling in OFDMA includes, depending on channel conditions and user rate requirement,
    - Allocating a certain number of subcarriers to each user, and
    - Choosing the modulation schemes, channel coding scheme, and transmission power from time to time
- Resource allocation decisions in OFDMA can vary from frame to frame, depending on channel conditions and traffic demands

Summary

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