Wireless Sensor Networks

Lecture 4: Basics of Physical-layer Communication (II)

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Course structure

- WSN
  - WSN concepts
    - Concepts & applications of WSN
    - Node architecture & operating systems
  - Communcation protocols
    - Physical layer
    - MAC layer & link layer
    - Network layer
  - Node and network management
    - Time synchronization
    - Localization & positioning
    - Topology control
    - Security

Outline

- Wave propagation and noise (II)
- Spread-spectrum communication
- Synchronization
- Physical layer designs in WSNs

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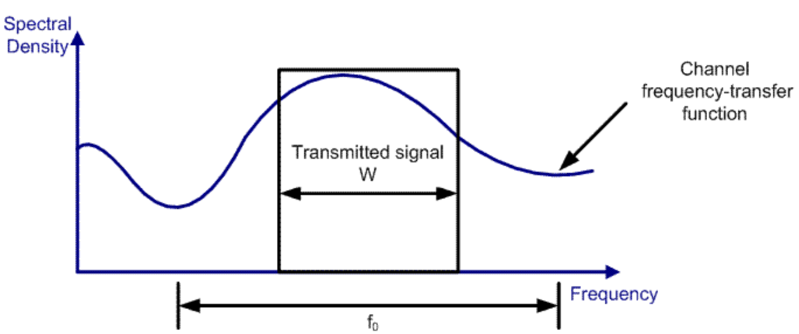
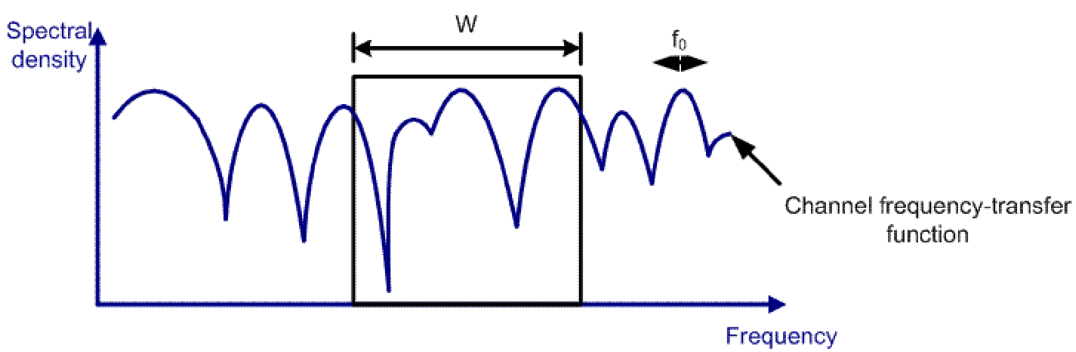
Wave propagation and noise

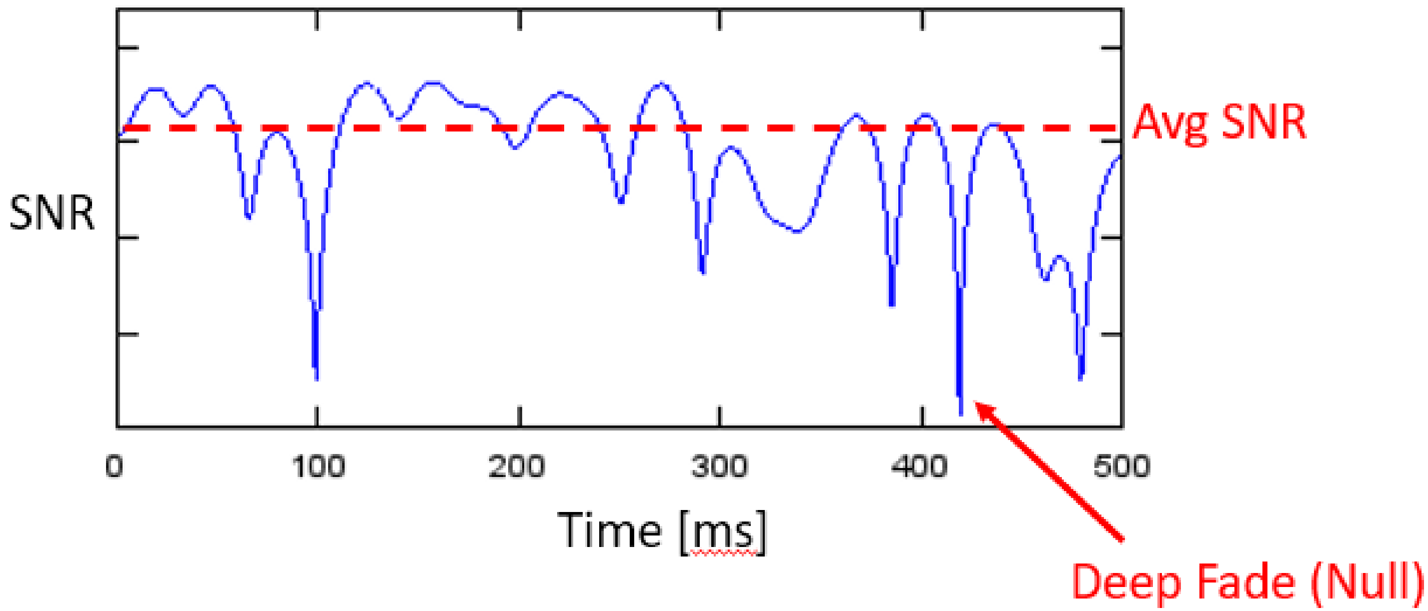
- Due to reflection, scattering, …,
  - *Fading*: received signal's attenuation varies with time, geographical position, and radio frequency.
  - *Flat fading channel*: different frequencies experience **same** fading
  - ***Frequency-selective channel:*** different frequencies experience **different** fading





Wave propagation and noise

- Due to reflection, scattering, …,
  - *Fast fading:* received signal strength changes fast with time
  - *Slow fading:* received signal strength changes slow with time
  - *Deep fading*: signal strength < a minimum detectable strength; symbol errors
  - *Bursty errors*: symbol errors as clusters; errorfree periods



Wave propagation and noise

- Due to reflection, scattering, …,
  - ***Path loss***: distance-dependent power loss of received signal
    - Received power at distance *d*

$$P_{\mathrm{rcvd}}(d) = P_{\mathrm{rcvd}}(d_0) \cdot \left(\frac{d_0}{d}\right)^{\gamma}$$

path-loss exponent, varies 2~5

    - Path loss $\frac{P_{\mathrm{tx}}}{P_{\mathrm{rcvd}}(d)}$ in logarithmic form (in dB)

$$\mathrm{PL}(d)[\mathrm{dB}] = \mathrm{PL}(d_0)[\mathrm{dB}] + 10\gamma \log_{10}\left(\frac{d}{d_0}\right)$$

    - Presence of obstacles

$$\mathrm{PL}(d)[\mathrm{dB}] = \mathrm{PL}(d_0)[\mathrm{dB}] + 10\gamma \log_{10}\left(\frac{d}{d_0}\right) + X_{\sigma}[\mathrm{dB}]$$

Wave propagation and noise

- single transmitter assumed
  - Only disturbance: self-interference of a signal with multi-path "copies" of itself
- In reality, two further disturbances
  - *(Thermal) Noise* : due to thermal motions of electrons, depends on temperature, additive to the sum of transmitted signals
    - Typical model: a Gaussian with constant PSD, Additive White Gaussian Noise (AWGN)
  - ***Interference:*** from third parties
    - Co-channel interference: another sender uses the same spectrum
    - Adjacent-channel interference: another sender uses some other part of the radio spectrum, but receiver filters are not good enough to fully suppress it

Wave propagation and noise

- Effect: Received signal is distorted by channel, corrupted by noise and interference
  - What is the result on the received bits?
- Extracting symbols out of a distorted/corrupted wave form is fraught with errors
  - Depends essentially on strength of the received signal compared to the corruption
  - Captured by ***signal to noise and interference ratio (SINR)*** given in decibel:

$$\mathrm{SINR} = 10 \log_{10} \left(\frac{P_{\mathrm{rcvd}}}{N_0 + \sum_{i=1}^{k} I_i} \right)$$

$$\frac{E_b}{N_0} = \mathrm{SNR} \cdot \frac{1}{R} = \frac{P_{\mathrm{rcvd}}}{N_0} \cdot \frac{1}{R}$$

Wave propagation and noise

- SINR allows to compute bit error rate (BER) for a given modulation
  - Also depends on data rate (# bits/symbol) of modulation

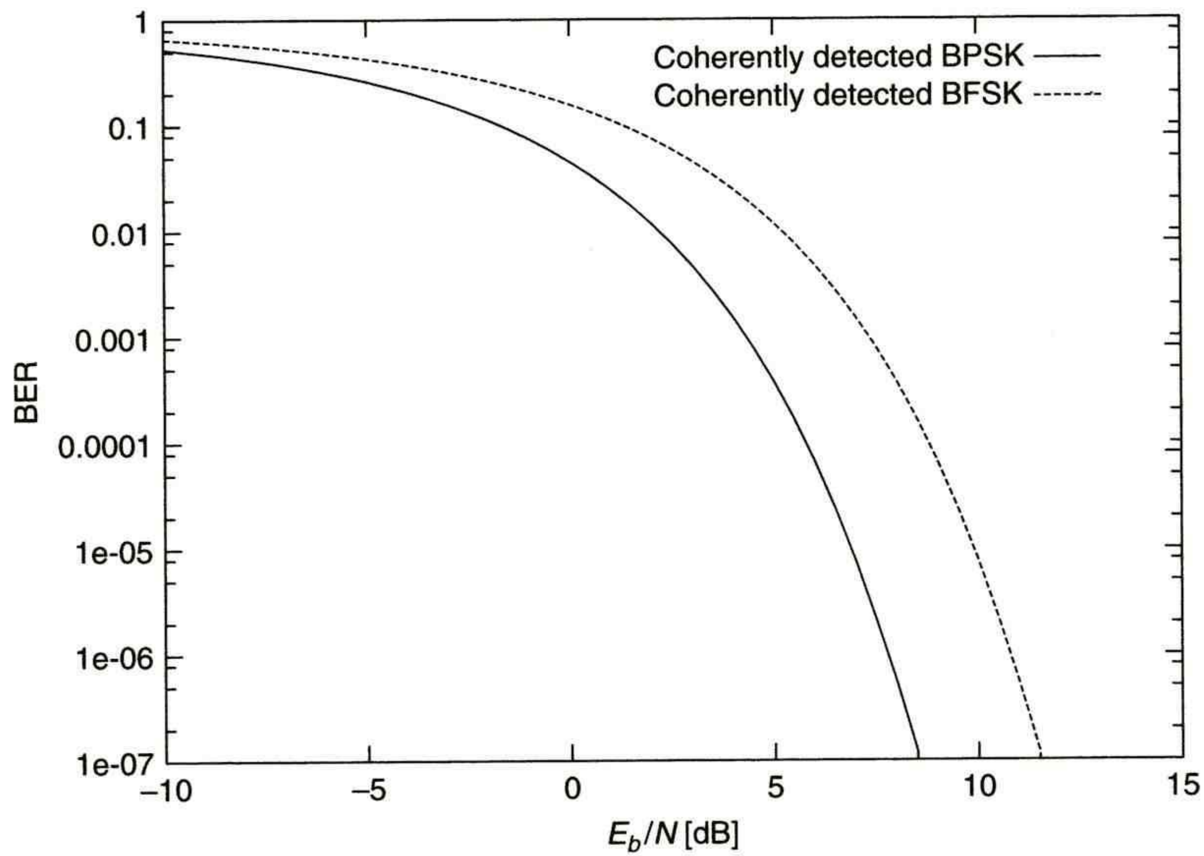


Figure 4.7 Bit error rate for coherently detected binary PSK and FSK

Question 1

Question1: The path-loss is a monotonic increasing function of the distance?

Wave propagation and noise

- How to stochastically capture the behavior of a wireless channel
  - Channel models
- Signal model
  - AWGN model

$$r(t) = s(t) + n(t),$$

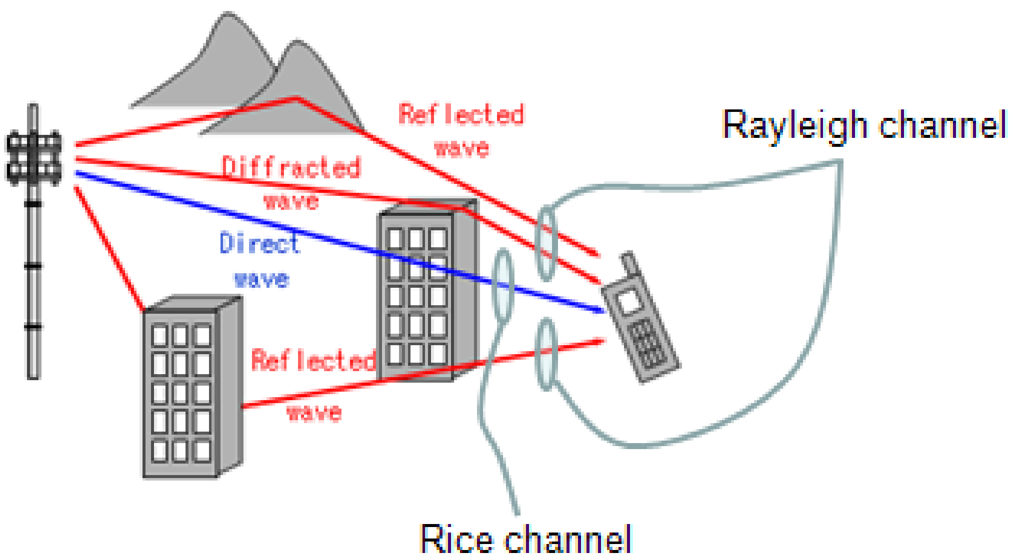
  - Rayleigh/Rice fading model

$$r(t) = R \cdot e^{i\theta} \cdot s(t) + n(t)$$

Wave propagation and noise

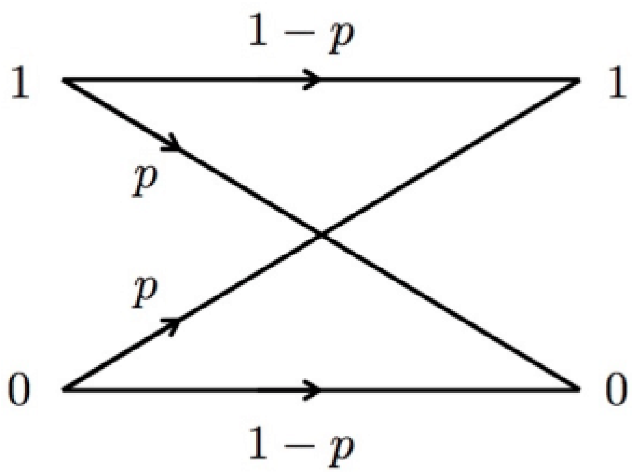
- ***Rayleigh fading :*** Situation with no line-of-sight path, but many indirect paths, attenuation amplitude R follows a ***Rayleigh*** distribution
- ***Rice fading :*** One dominant line-of-sight plus many indirect paths, attenuation amplitude R follows a ***Rice*** distribution

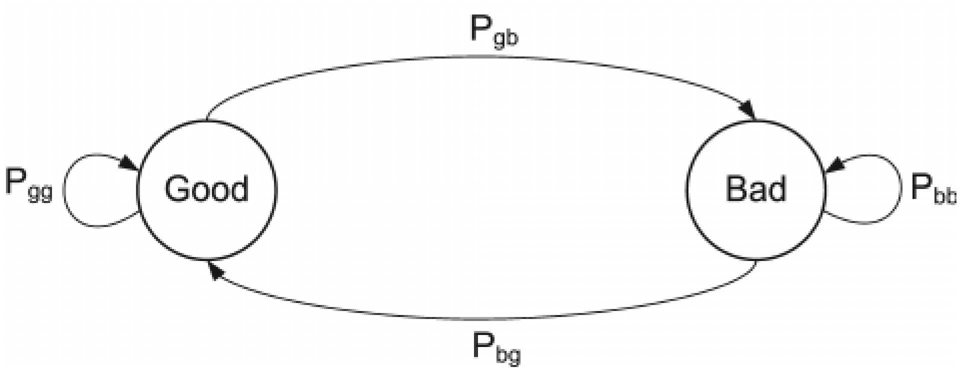
$$r(t) = R \cdot e^{i\theta} \cdot s(t) + n(t)$$



Wave propagation and noise

- Digital model–Directly model the resulting bit error behavior
  - ***Binary symmetric channel (BSC):*** Each bit is erroneous with constant probability, independent of the other bits
  - ***Markov models***: Capture fading models' property that channel is in different states – states with different BERs
    - Example: Gilbert-Elliot model with "bad" and "good" channel states and high/low bit error rates





Wave propagation and noise

- Improve wireless channel quality
  - **Transmission parameters optimization**: modulation & transmit power
  - **Diversity mechanism**: use statistically independent replicas of a same signal (time/frequency/spatial diversity); Combine different signals by selection combining or maximum ratio combining
  - **Equalization**: use training sequence to combat InterSymbol Interference
  - **Forward error correction(FEC)**: channel coding
  - **ARQ**: feedback from receiver

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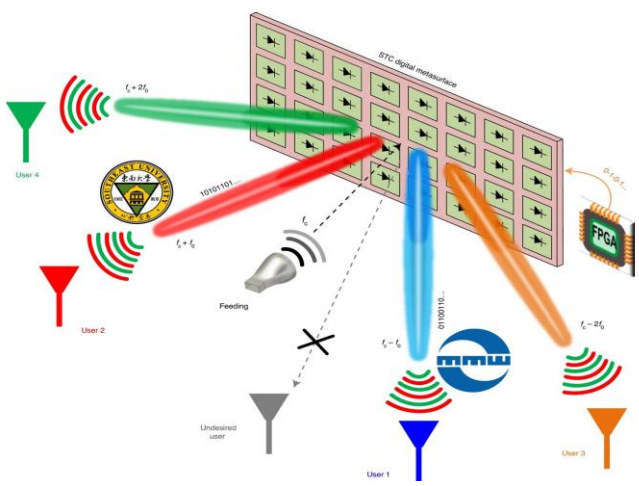
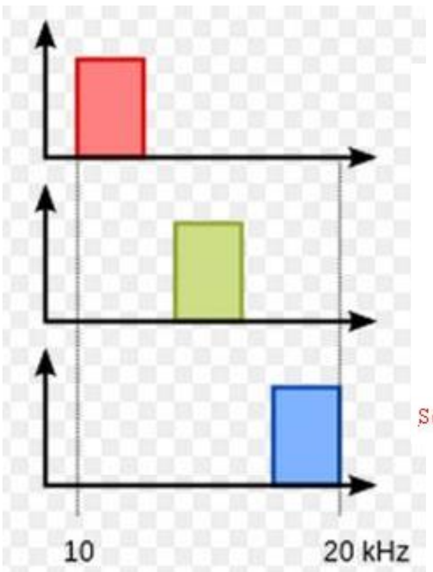
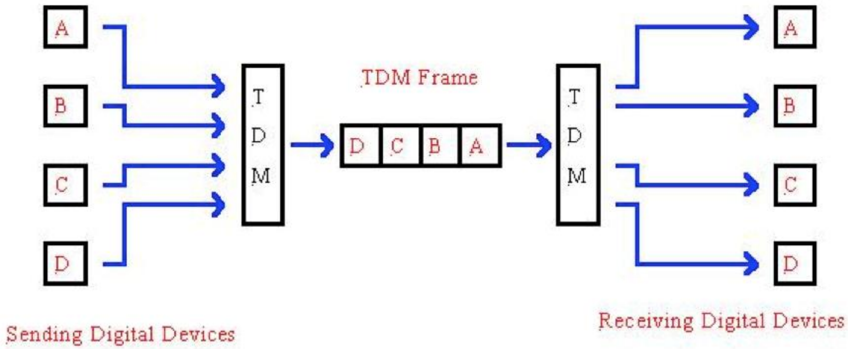
Sharing the Medium

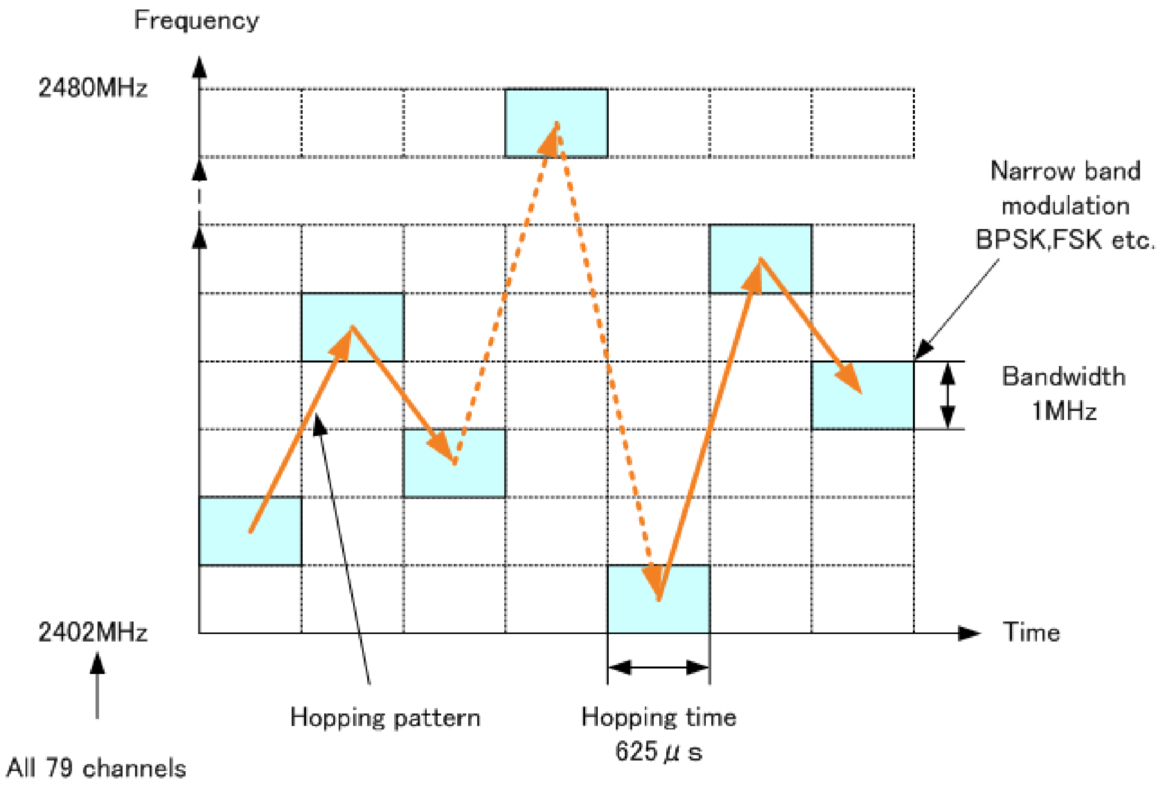
- Multiplexing: multiple signals are communicated over a shared medium
- Different shared medium
  - Space-Multiplexing: directional beam
  - Frequency-Multiplexing: assign different frequencies to the senders
  - Time-Multiplexing: assign time slots for each sender



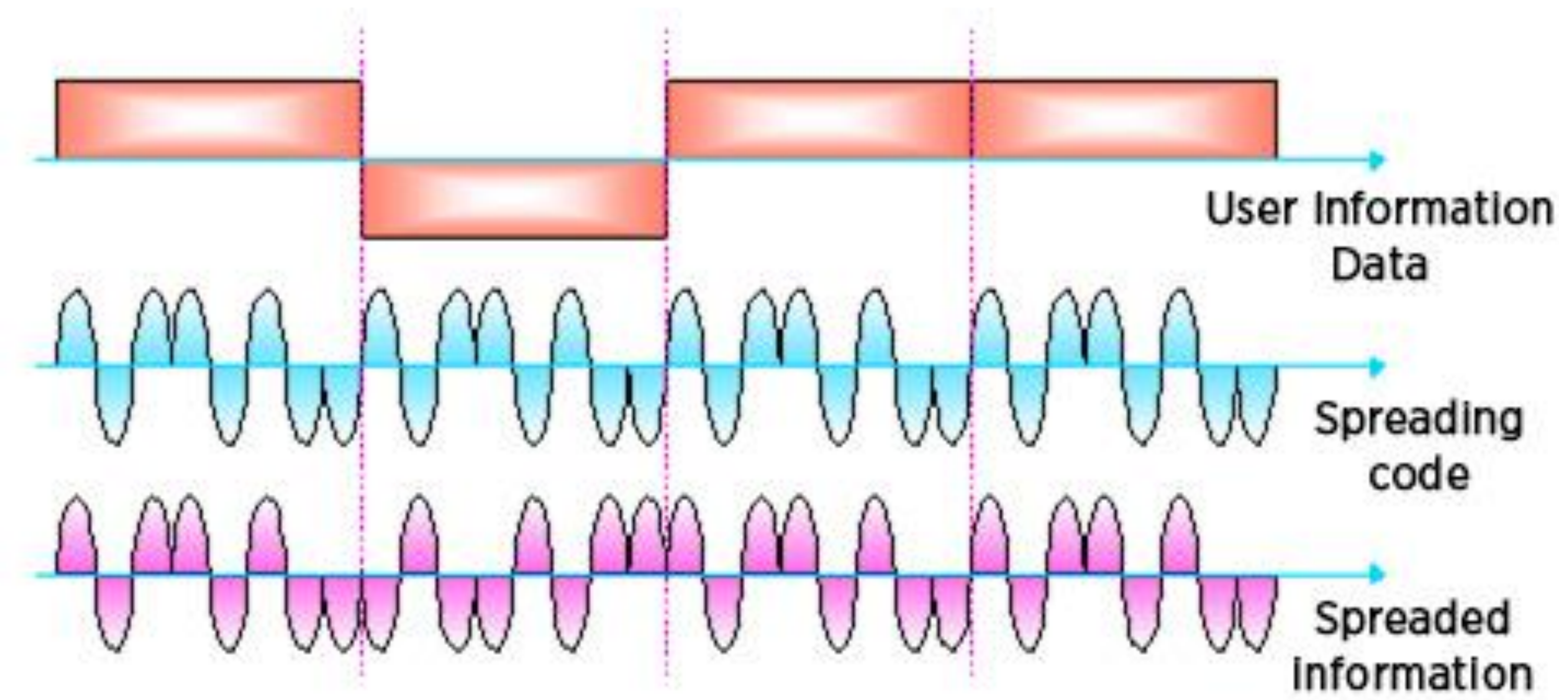




- Spread-spectrum communication
  - Frequency Hopping Spread Spectrum (FHSS)



- Spread-spectrum communication
  - Direct Sequence Spread Spectrum (DSSS)



Example of DSSS

- A Chip is a sequence of bits (given by {-1, +1}) encoding a smaller set of symbols
- E.g. Transform signal: 0 = (+1,+1,-1), 1=(-1,-1,+1)

  0 1 0 1

  +1 +1 -1, -1 -1 +1, +1 +1 -1, -1 -1 +1
- Decode by taking the inner product for bits c_i of the received signals si and the chips $c_0 = - c_1$:

$$\sum_{i=1}^{m} c_{0,i} s_i \qquad \sum_{i=1}^{m} c_{1,i} s_i$$

- Now if an overlay arrives then the signal can be deconstructed by applying dedicated filters
- DSSS is used by GPS, WLAN, UMTS, ZigBee, Wireless USB based on an
  - Barker Code (11Bit): +1 +1 +1 −1 −1 −1 +1 −1 −1 +1 −1
  - For all v<m

$$\left| \sum_{i=1}^{m} a_j a_{j+v} \right| \leq 1$$

- Spread-spectrum communication
  - Code Division Multiple Access (CDMA)

- Use chip sequence such that each sender has a different chip C with
    - $C_i \in \{-1,+1\}^m$
    - $-C_i = (-C_{i,1}, -C_{i,2}, \ldots, -C_{i,m})$
- For all $i \neq j$ the normalized inner product is 0:

$$C_i \bullet C_j = \frac{1}{m} C_i \cdot (C_j)^T = \frac{1}{m} \sum_{k=1}^{m} C_{i,k} C_{j,k} = 0 \; .$$

- If synchronized the receiver sees linear combination of A and B
- By multiplying with proper chip he can decode the message.
- Multiple users can occupy the same resource (time/frequency/space)

Example of CDMA

- Code $C_A = (+1,+1,+1,+1)$
- Code $C_B = (+1,+1,-1,-1)$
- Code $C_C = (+1,-1,+1,-1)$

- A sends Bit 0, B sends Bit 1, C sends nothing:
  - $V = C_1 + (-C_2) = (0,0,2,2)$
- Decoded according to A: $V \bullet C_1 = (0,0,2,2) \bullet (+1,+1,+1,+1) = 4/4 = 1$
  - equals Bit 0
- Decoded according to B: $V \bullet C_2 = (0,0,2,2) \bullet (+1,+1,-1,-1) = -4/4 = -1$
  - equals Bit 1
- Decoded according to B: $V \bullet C_3 = (0,0,2,2) \bullet (+1,-1,+1,-1) = 0$
  - means: no signal.

Question 2

Question2: which belongs to the spread-spectrum communication?

A.Code division multiple access

B.Frequency division multiple access

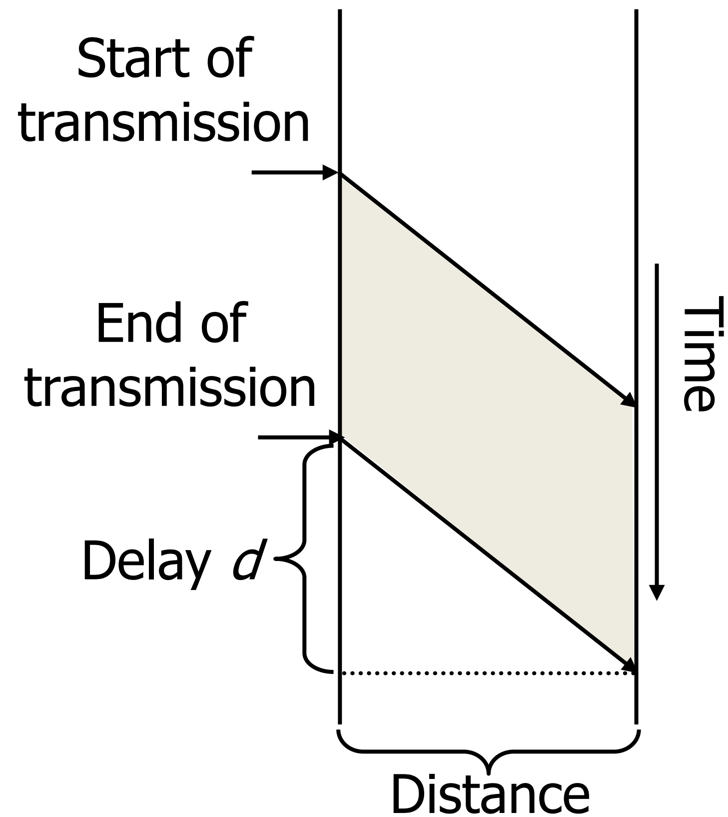
C.Time division multiple access

D.Space division multiple access

Signals propagate in medium

- Signals traveling in a medium takes time to reach destination – *delay d*
  - Depends on distance and propagation speed in transmission medium
- To represent one or several bits, a signal extending in time is needed – *duration of transmission*
  - Determined by rate ***r*** and data size

Message Sequence Charts (MSC)



Synchronization

- The receiver must know certain properties of an incoming waveform to detect a frame
  - Frequency/Phase
  - Start and end of bits/symbols
  - Start and end of frames(packets)

- Why the synchronization is needed
  - The generation of sinusoidal carriers and of local clocks involves **oscillators** of a certain **frequency**
  - Production inaccuracies
  - Temperature differences
  - Aging effects

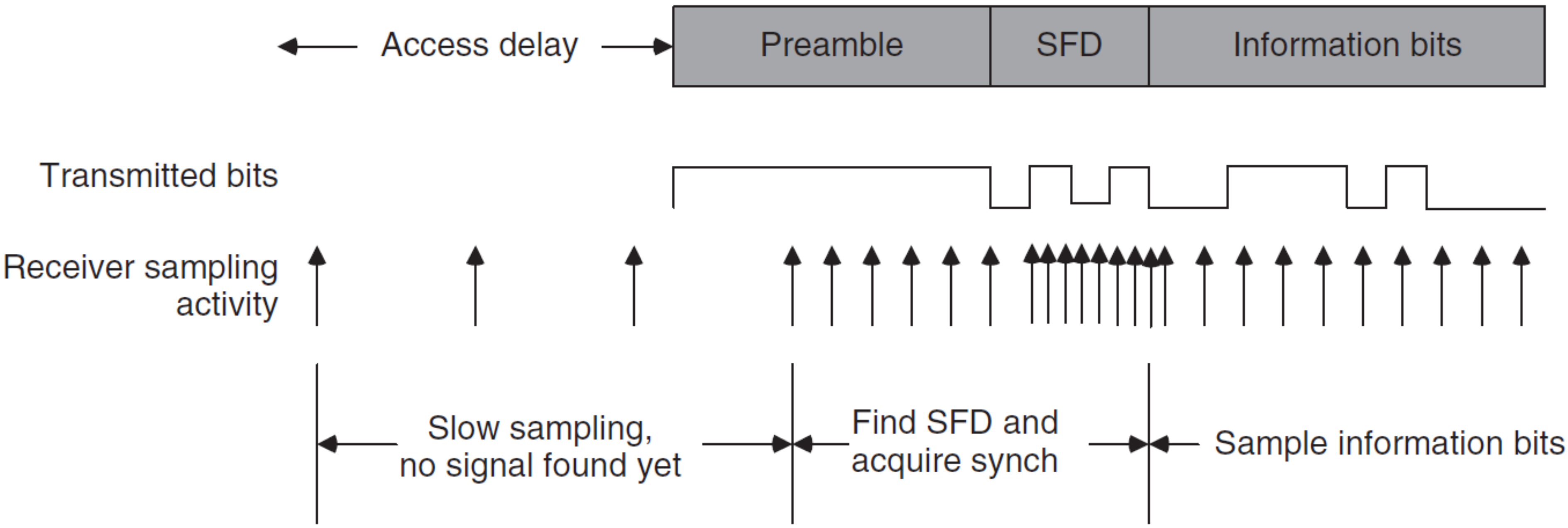
Synchronization

- Carrier synchronization
  - The receivers learn the frequency and the phase of the signal
    - E.g., let the transmitter send packets with known spectral shape to calibrate frequency

- Bit/symbol synchronization
  - The receiver must determine both the symbol duration as well as the start and end of symbols
    - sufficient “stimuli” is required indicating symbol bounds (no consecutive zeros/ones)
    - **scrambling** shifts the data stream via a linear-feedback shift register

Synchronization

- Frame synchronization
  - The receivers detect the start and end of a frame
  - Start Frame Delimiter (SFD) marks the start of frames (part of the physical layer header)



Physical layer designs in WSNs

- Characteristics affecting PHY design in WSN
  - Low power consumption
  - Small transmit power and small transmission range
  - low duty cycle (switched off in most of the time)
  - Low data rates (tens to hundreds kilobits/s)
  - Low implementation complexity and costs
  - Low degree of mobility
  - A small form factor for the overall node

Physical layer designs in WSNs

- Transceiver design in WSN
  - Small radiated energy (0dBm, 1mW)
  - Sleep mode instead of just idling
  - Proper operational mode scheduling (traffic patterns)
  - Computation is cheaper than communication

Physical layer designs in WSNs

- Choice of modulation in WSN
  - *m*-ary modulation (high data rate but low symbol rate)
  - Larger *m* means more complex circuitry
  - Larger *m* means higher bandwidth efficiency but increased radiated power
  - Proper *m* is obtained to balance these tradeoffs
  - Computation is cheaper than communication
- Dynamic modulation scaling
  - Adapt modulation scheme to the current situation (e.g., BER target, packet sizes, symbol rate)

Physical layer designs in WSNs

- Antenna considerations in WSN
  - Limited size & number of antennas (antenna < carrier's wavelength, bad antenna efficiency)
  - Close antennas (no receive diversity)
  - Close to the ground (higher path-loss coefficients)
  - Inside the node's casing (limited quality)
  - Facing the ground (different strength in different directions)

Wave propagation and noise

- WSN specific channel models
  - Typical WSN properties
    - Small transmission range
    - Implies small delay spread (nanoseconds, compared to micro/milliseconds for symbol duration)

    ! Frequency-non-selective fading, low to negligible inter-symbol interference
    - Coherence bandwidth often > 50 MHz
  - Some example measurements
    - γ path loss exponent
    - Shadowing variance σ^2
    - Reference path loss at 1 m

Location	Average of γ	Average of σ^2[dB]	Range of PL(1m)[dB]
Engineering Building	1.9	5.7	[−50.5, −39.0]
Apartment Hallway	2.0	8.0	[−38.2, −35.0]
Parking Structure	3.0	7.9	[−36.0, −32.7]
One-sided Corridor	1.9	8.0	[−44.2, −33.5]
One-sided patio	3.2	3.7	[−39.0, −34.2]
Concrete canyon	2.7	10.2	[−48.7, −44.0]
Plant fence	4.9	9.4	[−38.2, −34.5]
Small boulders	3.5	12.8	[−41.5, −37.2]
Sandy flat beach	4.2	4.0	[−40.8, −37.5]
Dense bamboo	5.0	11.6	[−38.2, −35.2]
Dry tall underbrush	3.6	8.4	[−36.4, −33.2]

Assignment

Assignment: Please describe the digital communication process.