Topic 3: Modulation and Demodulation Techniques for Wireless Communications

Content:

1) Purpose of Digital MODulation and DEModulation (MODEM) in Wireless Communications

2) Example Modulation Formats used in Wireless Systems
   - Bandwidth Efficient Class: BPSK, DPSK, M-aryPSK
   - Power Efficient Class: GMSK

3) Demodulation Techniques
   - Coherent Receivers: Coherent BPSK, Coherent GMSK
   - Noncoherent Receivers: DPSK

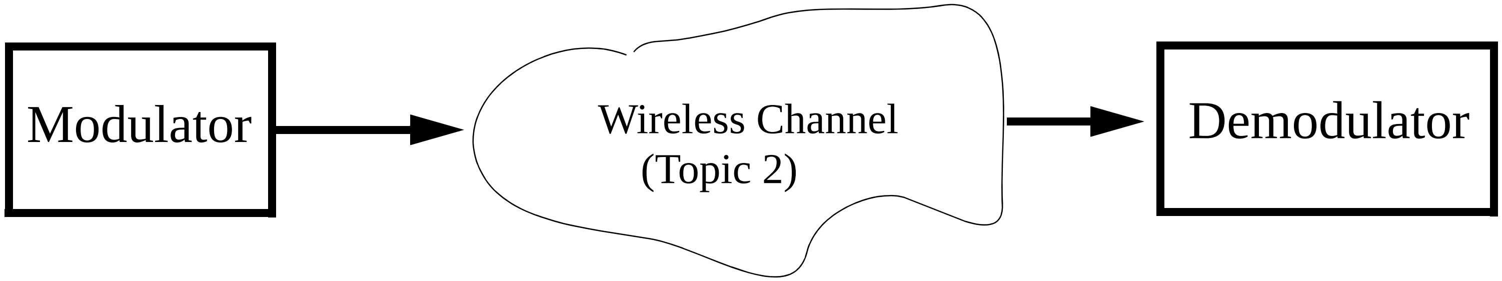
4) MODEM Performance over Wireless Channels

Topic 3 Learning Outcomes

At the end of this Topic, you will be able to:

- Define the factors that determine the selection of digital modulation and demodulation schemes for wireless communications systems
- Analyze the bit error rate performance of digital modulation and demodulation formats when used over the Rayleigh fading channel

Definition of Modulation and Demodulation



- Digital MODulation: Process of varying the parameter(s) of a carrier waveform by the information signal in order to produce a modulated signal that is compatible with the characteristics of the wireless channel
- DEModulation: Process by which an information signal is extracted from the received signal (inverse of modulation)

Purpose of MODEM in Wireless Communications

- Enhance transmission quality over the wireless channel
- Conserve transmission bandwidth
- Minimize transmission power

Factors Influencing the Choice of a Digital Modulation Scheme in Wireless Communication

1. Power Efficiency: provides high quality (e.g., low bit error rate (BER)) at low signal power level

2. Bandwidth Efficiency: requires minimum bandwidth to transmit large amount of data

3. Easy and cost-effective implementation

4. Performs well in multipath and Rayleigh fading conditions

<u>Note:</u> The two most important factors are: Power Efficiency and Bandwidth Efficiency

Power Efficiency

- Power Efficiency (PE):
  - Ability of a modulation technique to preserve the quality (e.g., bit error rate) of the signal with minimal transmission power
  - Metric: E_b/N_o = ratio of the signal energy per bit to noise power spectral density

    E_b = Energy per bit in Joules/bit

    N_o = Noise power spectral density in Watts/Hz
  - High PE implies <u>low</u> transmission power (i.e., low E_b) to achieve a given quality objective

Bandwidth Efficiency

- Bandwidth Efficiency (BE):
  - Ability of a modulation technique to transmit more data using a given bandwidth
  - Metric: $\eta = R/B =$ ratio of the data rate in bits per second to given bandwidth in Hertz
  - System capacity C of a digital mobile communication system is directly related to the bandwidth efficiency of the modulation technique
  - Fundamental upper bound on achievable bandwidth efficiency is given by the Shannon's theorem:

$$\eta_{max} = \frac{C}{B} = \log_2[1 + SNR] \qquad \textit{(AWGN channel!)}$$

  - High BE implies low bandwidth required to transmit a given amount of data

Tradeoff between Bandwidth Efficiency and Power Efficiency

- Assuming a bit duration of T_b and signal bandwidth of B Hz, the ratio of signal power to noise power, *SNR*, is given by:

$$SNR = \frac{E_b / T_b}{N_o B} = \frac{E_b}{N_o}\frac{R}{B} = Power\ Efficiency\ *\ Bandwidth\ Efficiency$$

where the data rate R is equal to $1/T_b$.

<u>Conclusions:</u>

- There exists a tradeoff between power efficiency, E_b/N_o and bandwidth efficiency, *R/B.*
    - If the SNR is fixed, increasing *Power Efficiency* results in a decrease in *Bandwidth Efficiency*, and vice-versa
    - Implication: A modulation technique is either highly bandwidth efficient <u>or</u> highly power efficient

- The SNR is directly proportional to E_b/N_o (constant of proportionality is the BW efficiency, *R/B*). Hence, E_b/N_o is sometimes & loosely referred to as the signal-to-noise ratio in the literature.

M-ary Phase Shift Keying Modulation

- Definition of Phase Shift Keying: Phase of the carrier is varied in accordance with the data bit
- General Analytic Expression for M-ary PSK signal, $s_i(t)$ = modulated signal i

$$s_i(t) = \sqrt{\frac{2E}{T_s}} cos[2\pi f_c t + \varphi_i(t)], \quad 0 \le t \le T_s, \; i = 1, 2, ..., M$$

where

$\varphi_i(t)$: phase terms, with M discrete values, typically given by $\varphi_i(t) = \frac{2\pi i}{M}, \; i = 1, 2, ..., M$

E : symbol energy

T_s: symbol duration

Notes:

1. M = Number of signals in the modulated signal set
2. M is always a power of 2, i.e., $M = 2^k$, where k = number of bits per symbol = 1, 2, 3, ...

Binary Phase Shift Keying (BPSK) Modulation

- Simplest *M*-ary PSK Modulation: *M* = 2 (i.e., Binary PSK or BPSK)
- M = 2 means *k* = 1 bit/symbol (In BPSK: “bit” and “symbol” are synonymous)
- M = 2 also means the modulated signal set comprises 2 signals: $s_1(t)$ and $s_2(t)$

- $s_1(t) = \sqrt{\dfrac{2E}{T_s}}cos(2\pi f_c t + \pi) = -\sqrt{\dfrac{2E}{T_s}}cos(2\pi f_c t)$ [Modulated signal phase = π]

- $s_2(t) = \sqrt{\dfrac{2E}{T_s}}cos(2\pi f_c t)$ [Modulated signal phase = 0]

- Information (data bit) to Modulated signal Phase mapping Rule for BPSK:

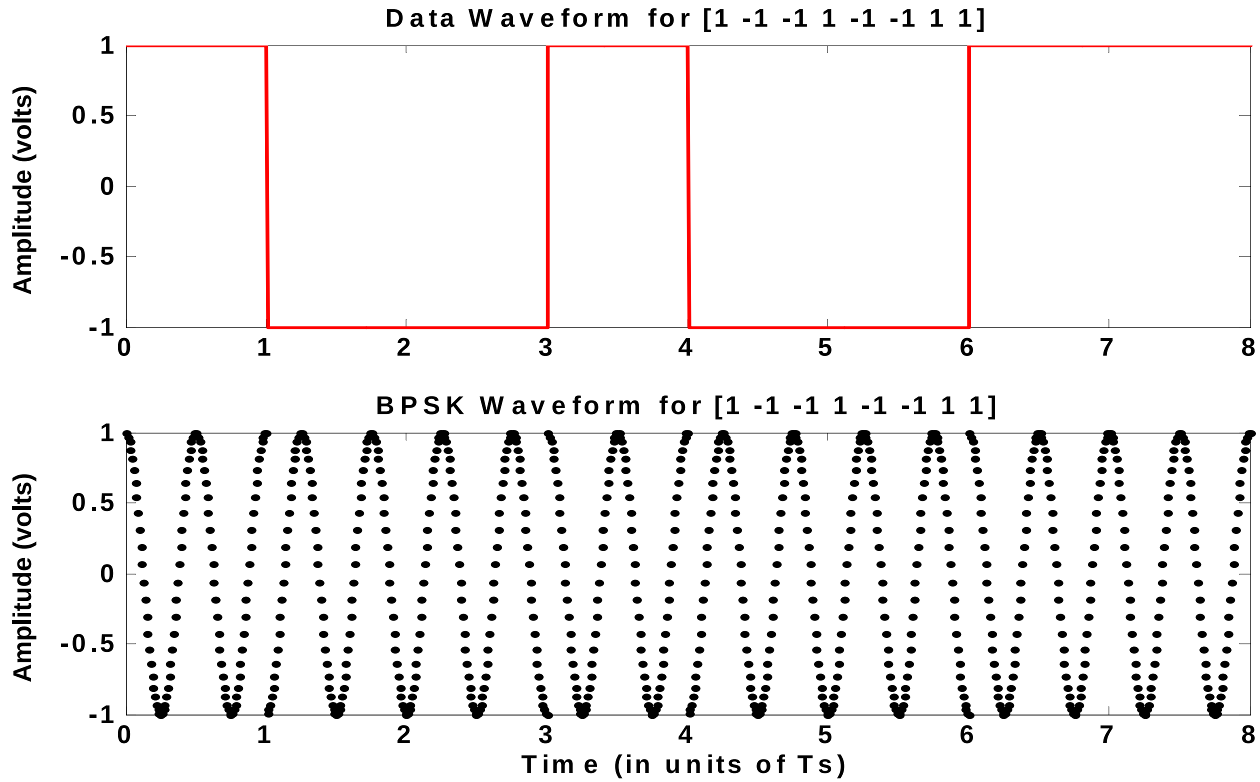
  i) data bit “1” <--> 0^o

  ii) data bit “-1” <--> π or 180^o

- In general, the BPSK modulated waveform is: $s_{BPSK,\,i}(t) = b_i \times \sqrt{\dfrac{2E}{T_s}}cos(2\pi f_c t)$

  where the i^{th} data bit $b_i \in \{1, -1\}$, i = 1, 2, 3, ... of a given data sequence

Example: BPSK Waveforms for Data Sequence [1 -1 -1 1 -1 -1 1 1]



- There are abrupt changes (i.e., phase difference of +/-π between successive symbols) in the data waveform when the polarity of the symbols changes (at T_s, $3T_s$, $4T_s$, and $6T_s$)
- These abrupt changes in the data waveform lead to sidelobes in the spectrum of the BPSK
- Filtering of the sidelobes is required to avoid transmission problems

Practical Application of BPSK in Wireless

- BPSK is very simple, hence used in
  - IEEE802.11 WLAN Standard (1 Mb/sec data rate version)
  - IEEE802.15.4 WPAN Standard (868 - 915 MHz)
  - RFID Standards such as ISO 14443

- BPSK is the most robust of all the PSK modulation formats
  - region of deciding the transmitted symbol is very wide

- BPSK Practical Issues:
  - Unsuitable for high data rate applications (because BPSK modulates at 1 bit per symbol)
  - Presence of sidelobes, due to $+/-\pi$ phase difference between successive symbols
  - BPSK receiver requires a reference signal to estimate the exact phase of the received signal, this increases the receiver complexity and cost

Differential Phase Shift Keying (DPSK) Modulation Format

- DPSK Modulation:
  - information is carried by the "difference" between two successive modulated phases (hence the term "differential")
  - "absolute" phase of current data bit is used to change the "modulated" phase of the previous symbol.

<u>*Differential Formula:*</u>

Modulated Signal phase for the current symbol = modulated signal phase for the previous symbol Θ "absolute" phase corresponding to the current data bit (assuming BPSK)

<u>Notes:</u>

1) The "Θ" denotes modulo-2 subtraction. (Recall: modulo-2 subtraction = modulo-2 addition)

2) To start the process, it is assumed that the phase of the modulated signal has an initial value of zero

- Use of "difference" in phase by DPSK eliminates the need for a reference signal at the receiver, thereby simplifying the receiver design compared to BPSK receiver. The trade-off is worse performance compared to BPSK

Example: Calculating Modulated Phase of a DPSK Signal

Given data bit sequence to be transmitted: [1 -1 -1 1 -1 -1 1 1], determine the modulated phase corresponding to each data bit, assuming DPSK modulation format

Time Index, *i*	**Data bit, b_i**	**"Absolute" Phase corresponding to data bit assuming BPSK (radians)**	**Modulated signal phase assuming DPSK (radians)**
0	-	-	0 (initial value)
1	1	0	0
2	-1	π	π
3	-1	π	0
4	1	0	0
5	-1	π	π
6	-1	π	0
7	1	0	0
8	1	0	0

Notes:

1) The 3rd column uses the data bit to phase mapping rule for BPSK (from Page 10)
2) The 4th column uses the Differential Formula for DPSK (from Page 13)

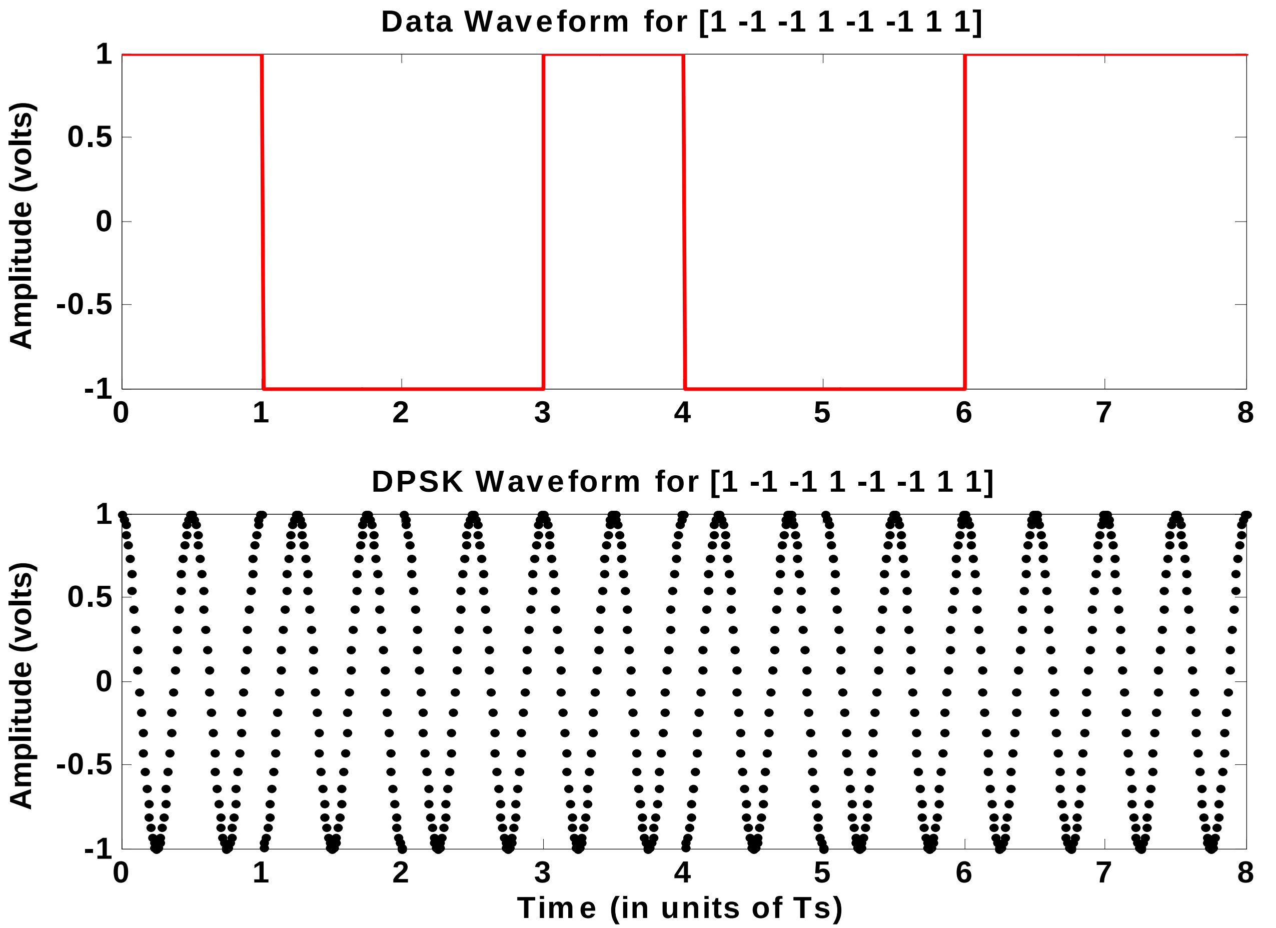
DPSK: Modulated Phase to Transmitted Signal Mapping Rule

- The modulated signal phase is mapped to DPSK signals $s_1(t)$ and $s_2(t)$ as follows:

  - if modulated signal phase = π, $s_1(t) = \sqrt{\frac{2E}{T_s}} cos(2\pi f_c t + \pi) = -\sqrt{\frac{2E}{T_s}} cos(2\pi f_c t)$ is transmitted

  - if modulated signal phase = 0, $s_2(t) = \sqrt{\frac{2E}{T_s}} cos(2\pi f_c t)$ is transmitted

Example: DPSK Waveforms for Data Sequence [1 -1 -1 1 -1 -1 1 1]



Practical Application of DPSK in Wireless

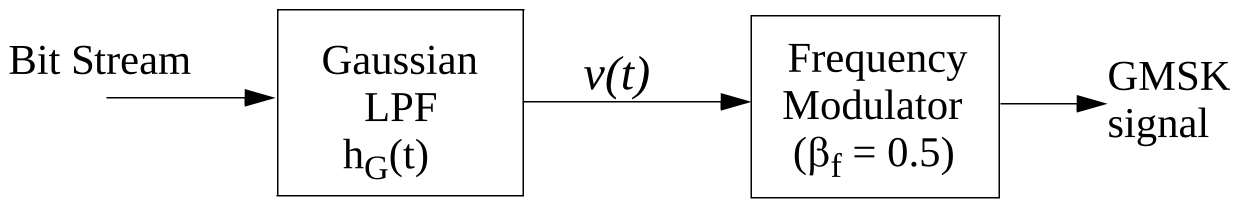
- DPSK receiver is very simple and cheap, because there is no need to recover the absolute phase of the received signal

  Example wireless sytems using DPSK include:

  - IS-54 Standard (old 2G North American Digital Cellular Standard)
  - IEEE802.11b WLAN Standard (1 Mb/sec data rate)
  - IEEE802.11a WLAN Standard (6 & 9 Mbps rates)

- DPSK Practical Issues:
  - Unsuitable for high data rate applications (because DPSK modulates at 1 bit per symbol)
  - Sidelobes due to +/-π phase difference between successive symbols
  - DPSK receiver performance is worse compared to BPSK receiver because DPSK does not estimate the exact phase of the received signal. However, the gains from simpler receiver design far outweigh the loss in performance

Gaussian Minimum Shift Keying (GMSK) Modulation



- pass a binary bit stream $b_i \in \{1, -1\}$ through a Gaussian filter with impulse response

$$h_G(t) = \frac{1}{\sqrt{2\pi}(\sigma T_b)} exp\left(-\frac{t^2}{2(\sigma T_b)^2}\right) \qquad \text{where } \sigma = (\sqrt{ln2})/(2\pi B T_b)$$

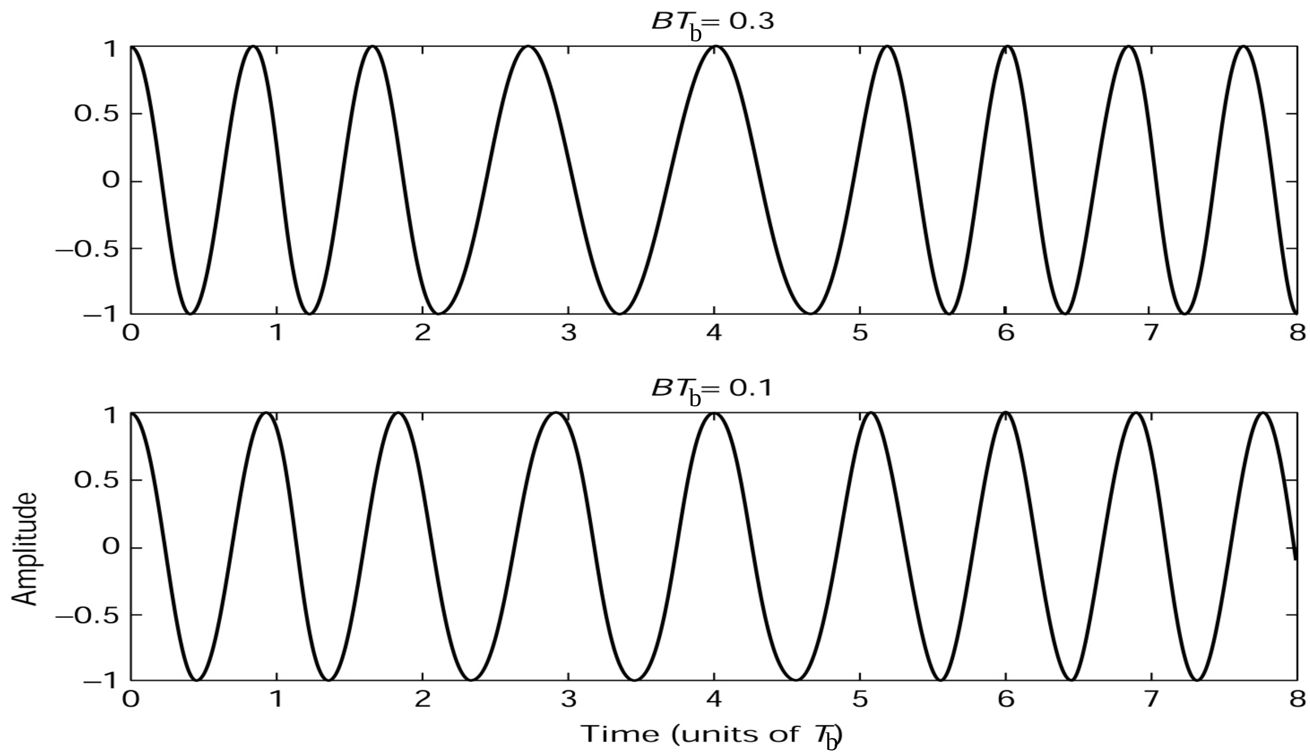
- Output signal of the filter, *v(t)*, is processed by the FM modulator with modulation index β_f = 0.5 (i.e., min. difference between higher & lower freq.) to produce the GMSK signal

- GMSK signal is given by:

$$s_{GMSK}(t) = \sqrt{\frac{2E}{T_b}} cos\left[2\pi f_c t + \pi \sum_{n=-\infty}^{\infty} q_g(t - nT_b)\right] \qquad \text{(CONSTANT ENVELOPE)}$$

where $q_g(t)$ is the phase response of GMSK $\left(q_g(t) = \int_0^t v(u)du,\ 0 \le t \le T_b\right)$

GMSK Waveforms



(*b*)

- At small bandwidth delay product (e.g., BT_b = 0.1), the effect of modulation becomes unnoticeable. However, as BT_b increases (e.g., BT_b = 0.3), the effect of frequency modulation becomes observable.

Practical Application of GMSK in Wireless

- GMSK is most attractive for its power efficiency and good spectral efficiency. Has been adopted in:
  - 2G Global System for Mobile Communications (GSM) Standard
  - US Cellular Digital Packet Data (CDPD) Standard
  - Digital European Cordless Telecommunications (DECT) Standard

- GMSK Practical Issue:
  - Intersymbol interference, resulting in irreducible error rate.

  However, the irreducible error rate is controllable by proper choice of Gaussian filter parameter, BT_b (i.e., σ). For example, the irreducible error rate is not severe if $BT_b > 0.5$, the trade-off is low bandwidth efficiency.