CISC 7332X T6
Digital Modulation

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Outline

- Digital modulation
  - Baseband transmission
    - Line codes
    - Design considerations
  - Passband transmission
    - Digital modulations
- Multiplexing
  - FDMA, TDMA, and CDMA
- Switching
  - Circuit switching and packet switching

Digital Modulation

- Wire and wireless channels carry analog signals
  - Examples of analog signals
    - continuous electrical current varying voltage
    - continuous light emissions with varying intensity
    - continuous sound with varying intensity
- Digital modulation
  - The process that converts between fundamental unit of digital data (e.g., bits) and signals
    - How do we represent bits in analog signal?
    - How do we extract bits from analog signals?

Schemes of Digital Modulations

- Baseband transmission
- Passband transmission

Baseband and Passband Signals

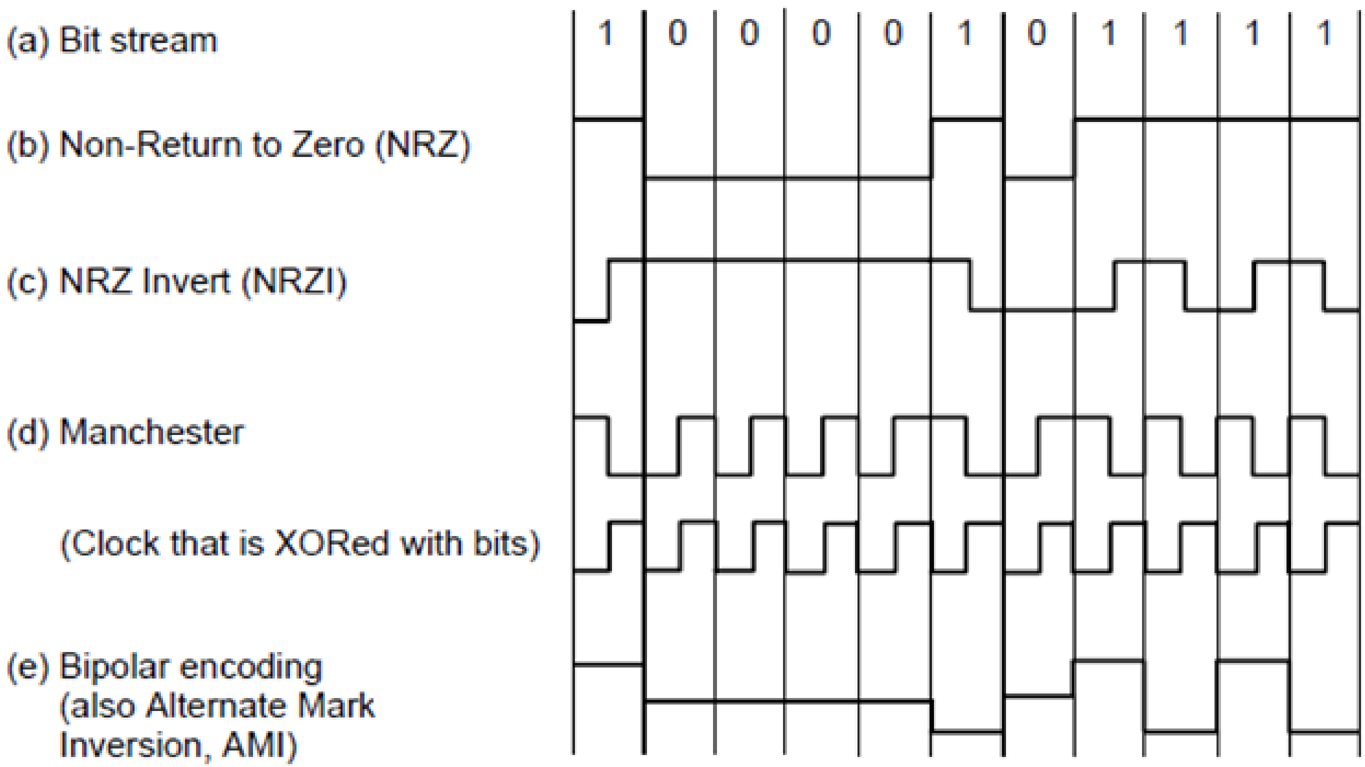
- Review
  - Bandwidth (an overloaded term), based on context,
    - The width of frequency range transmitted without being strongly attenuated
    - A physical property of the transmission medium
  - Max data rate of noiseless and noisy channels
- Signals that run from 0 up to a maximum frequency are called baseband signals
  - 0 ~ B Hz, where B is the bandwidth
- Signals that are shifted to occupy a higher range of frequencies are called passband signals
  - S ~ S + B Hz, where S the frequencies shifted

Baseband Transmission

- A few schemes (also called encoding in the context of baseband transmission, or line codes)
  - Non-Return-to-Zero (NRZ)
  - NRZ Invert (NRZI)
  - Manchester, 4B/5B
  - Bipolar encoding/Alternate Mark Inversion (AMI)
- Issues to consider
  - Bandwidth efficiency
  - Clock recovery
  - Balanced signals
  - Baseline wander

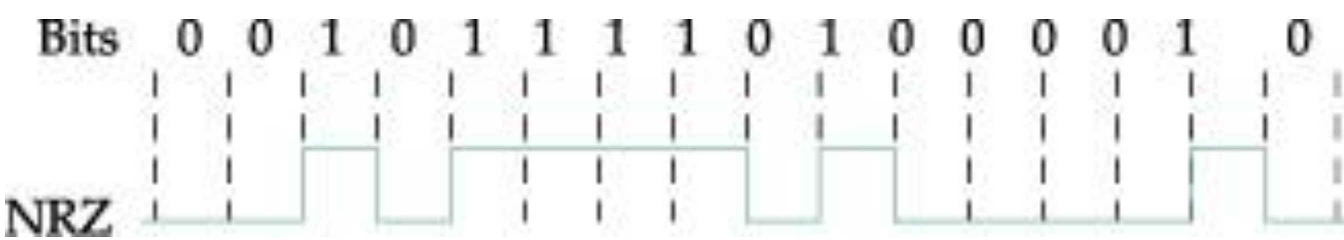
Line Codes/Encoding Schemes

- An overview with an example



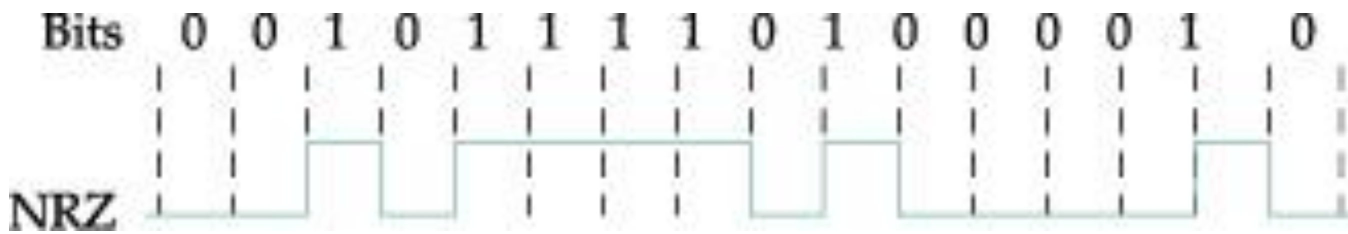
Non-Return-to-Zero (NRZ)

- Low = 0, e.g., negative voltage
- High = 1, e.g., positive voltage
- Difficult to recover clock
  - When long strings of 1s or 0s
- Bandwidth efficiency
  - B/2 bandwidth for B bps data rate for the example below (why?)
  - More than 2 levels? e.g., 4 levels for 00, 01, 10, 11
  - Symbol, symbol rate (baud rate), bit rate



Bandwidth Efficiency/Spectral Efficiency

- Consider the example



- We observe
    - V = 2
  - If we want max. bit rate to be R bps, what is the required bandwidth B Hz?
    - R = 2 B log2 V, and B = R/2, i.e., R/B = 2 bps/Hz
  - What if V = 4?

More Examples on the Web

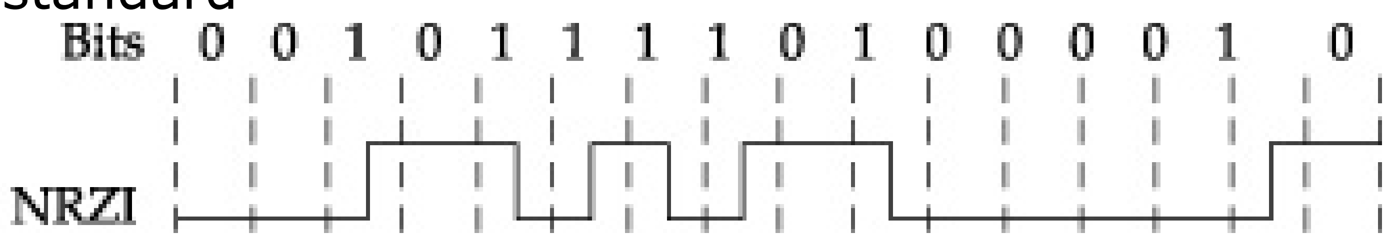
- http://www.techplayon.com/spectral-efficiency-5g-nr-and-4g-lte/
- and
- *https://www.scribd.com/document/403729934/LTE-to-5G-Cellular-and-Broadband-Innovation-Rysavy-for-upload-pdf* (slide 21)

Clock Recovery

- The receiver needs to know when one symbol ends and the next begins to tell bits apart
- Clock is imperfect, a long running of 0 and 1's makes it difficult
- Transmitting clock
  - A dedicated line for clock → wasteful, difficult, and sometimes impossible
  - Recovering clocks
    - Synchronize clocks when detecting transition of signal levels
    - XORing clock and NRZ signal (Manchester encoding)
    - Increasing transitions (NRZI)

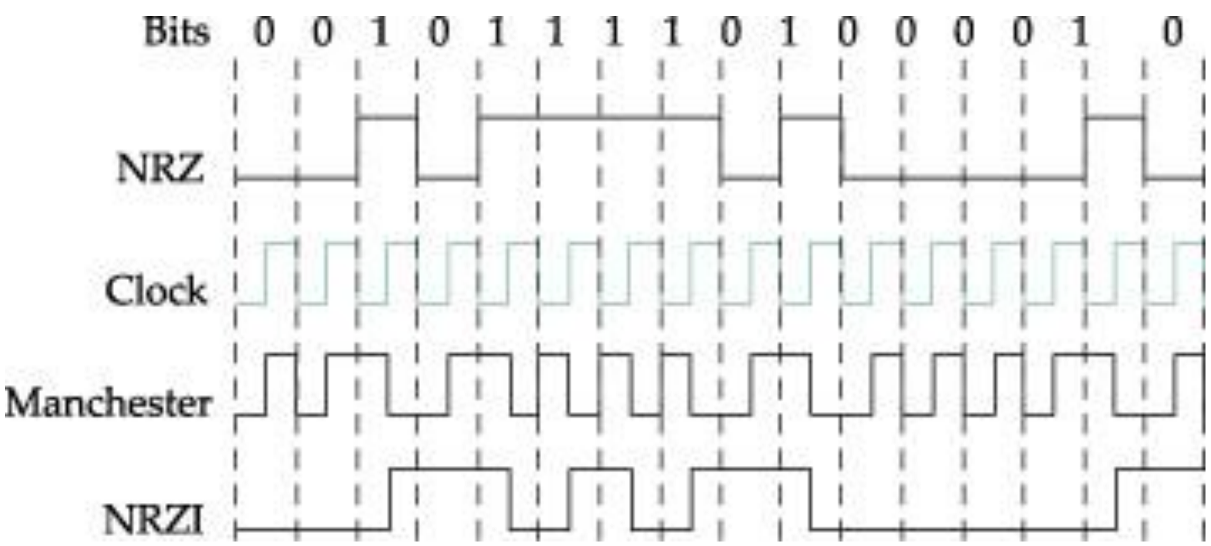
Non-Return-to-Zero Invert (NRZI)

- Signal transition = 1
- No transition = 0
- Solve the *clock recovery* problem caused by consecutive 1's
- The problem caused by consecutive 0's remains
  - Prohibits sender from transmitting two many 0's in a row, e.g., no more than 15 consecutive 0's on T1 line
- Application: the popular USB (Universal Serial Bus) standard



Manchester

- NRZ signal ⊕ Clock signal
    - low-to-high transition = 0; high-to-low transition = 1
- Application: classic Ethernet
- Solve the problems caused by both consecutive 1's and 0's
- New problem:
    - Clock's frequency is required twice as high, bandwidth efficiency?



4B/5B

- Addressing clock recovery and bandwidth efficiency
  - Map consecutive 0’s or 1’s to slightly longer patterns that do not have too many consecutive 0’s and 1’s
- 4B/5B uses a fixed 4-bits-to-5-bits translation table
  - 4B/5B’s (5-4)/4 = 25% overhead, much less than Manchester’s (2-1)/1 = 100% overhead
  - Transmit resulting codes using NRZI

4B/5B Translation

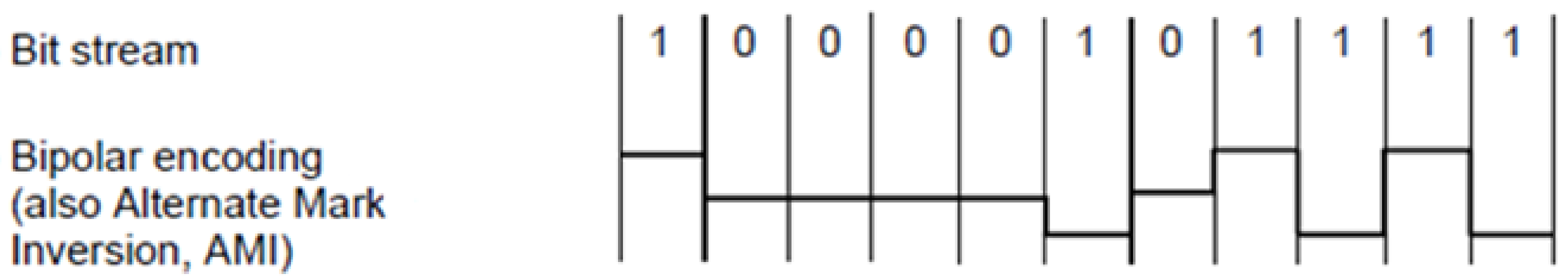
4-Bit Data Symbol	5-Bit Code
0000	11110
0001	01001
0010	10100
0011	10101
0100	01010
0101	01011
0110	01110
0111	01111

4-Bit Data Symbol	5-Bit Code
1000	10010
1001	10011
1010	10110
1011	10111
1100	11010
1101	11011
1110	11100
1111	11101

Balanced Signals

- Signals that have as much positive voltage even over short period of time
- Balanced signals are desired
  - Balanced signals have no Direct-Current (DC) component
    - Some physical media, such as, coaxial cable strongly attenuate a DC component
    - Some methods of connecting the receiver to the channel pass only the Alternate-Current (AC) portion of the signal, e.g., capacitive coupling
    - Helps clock recovery since balanced signals must be a mix of positive and negative voltages
    - Eases receiver calibration because the average of the signal can be measured and used as a decision threshold to decode symbols
- Example line codes
  - Bipolar encoding, e.g., Alternate Mark Inversion (AMI) in traditional telephone network
  - 8B/10B line code

Alternate Mark Inversion (AMI)



Questions?

- Line codes and issues
- NRZ, NRZI, Manchester, 4B/5B
- Design consideration: bandwidth efficiency, clock recovery, balanced signals

In-Class Exercise 1

- Encode bit sequence 01101 using NRZ, NRZI, Manchester encoding
- Draw signals, clocks, and bit boundaries

In-Class Exercise 2

- Encode bit sequence 01101100 using NRZ; however, with 2 bits / symbol.
- Draw the signal, clock, symbol boundaries.
- What is the ratio of Max. Data Rate / Required Bandwidth?

Passband Transmission

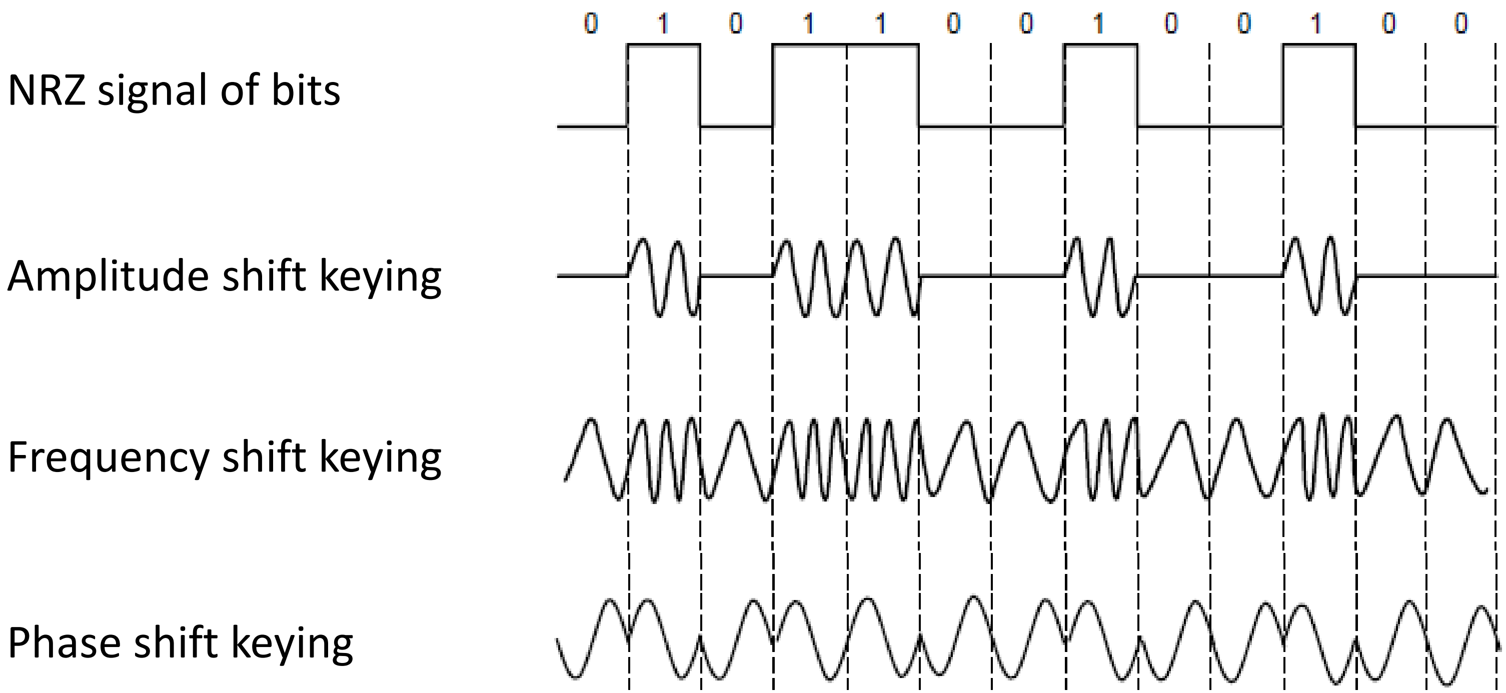
- Baseband transmission
  - Signal: 0 ~ B Hz. Not always available; low frequency → large size of antenna (antenna size and wave length are comparable, e.g., https://en.wikipedia.org/wiki/Project_Sanguine); need to control attenuation …
- Passband transmission
  - Signal: S ~ S+B Hz
  - Digital modulation: regulating a carrier signal that sits in the passband with a baseband signal, i.e., modulating the amplitude, frequency, and/or phase of a carrier signal sends bits in a (non-zero) frequency range

Passband Transmission: Modulation

- Amplitude Shift Keying (ASK)
- Frequency Shift Keying (FSK)
- Phase Shift Keying (PSK)
- Simplest form: Binary Phase Shift Keying (BFSK)

Modulation: Overview by Example

- Modulate NRZ with ASK, FSK, and PSK

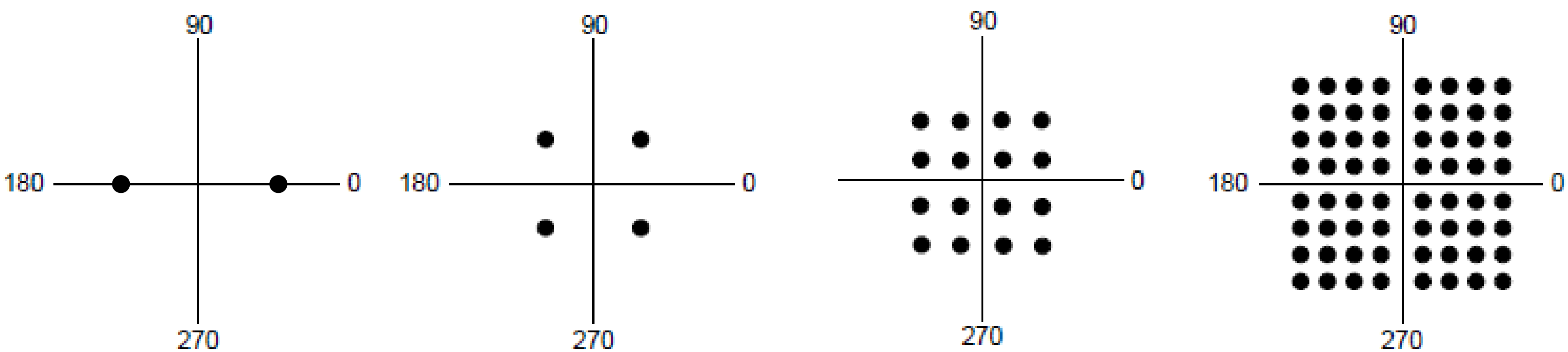


Modulating Amplitude/Phase

- Binary Phase Shift Keying (BPSK)
  - 2 symbols, each 1 bit (e.g., 0 or 180 degrees)
- Quadrature Phase Shift Keying (QPSK)
  - 4 symbols, each 2 bits (e.g., 45, 135, 225, 315 degrees)
- Quadrature Amplitude Modulation (QAM)
  - Examples: QAM-16, QAM-64

Constellation Diagram

- A shorthand to capture the amplitude and phase modulations of symbols



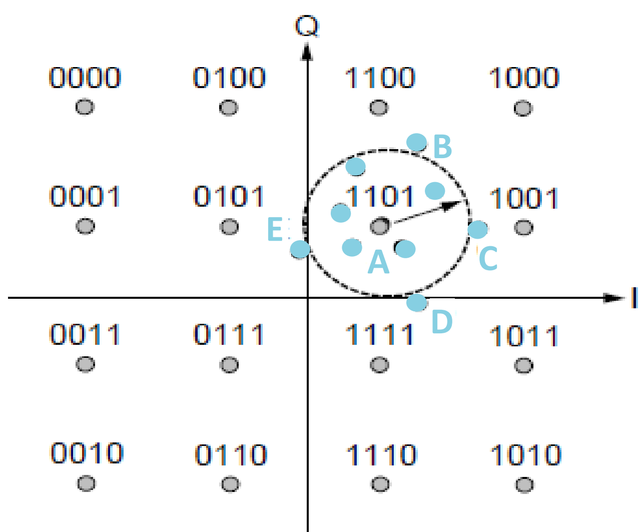
BPSK	QPSK	QAM-16	QAM-64
2 symbols	4 symbols	16 symbols	64 symbols
1 bit/symbol	2 bits/symbol	4 bits/symbol	6 bits/symbol

BPSK/QPSK varies only phase

QAM varies amplitude and phase

Constellation and Symbol-Bit Mapping

- Design consideration: small burst of noise at the receiver not lead to many bit errors
  - Not to assign consecutive bit values to adjacent symbols
  - Gray-coding assigns bits to symbols so that small symbol errors cause few bit errors



When 1101 is sent:

Point	Decodes as	Bit errors
A	1101	0
B	1100	1
C	1001	1
D	1111	1
E	0101	1

Questions?

- Baseband vs. passband transmission
- Modulation
  - ASK, FSK, PSK
  - QAM
  - Symbol
  - Symbol rate and bit rate

In-Class Exercise 3

- Motivating example in practice
  - See https://documentation.meraki.com/MR/WiFi_Basics_and_Best_Practices/802.11_fundamentals%3A_Modulation
- Consider BPSK, QPSK, QAM-16, and QAM-64. Assume the *max. data rate* can be obtained when QAM-64 is use at a given S/N denoted as $SNR_{64.}$ What would be the required S/N (in relation to SNR_{64}) for BPSK, QPSK, and QAM-16 if the same *max. symbol rate* must be maintained?