Lecture 8

Spread Spectrum and OFDM

Time Domain View (Sieve)

Channel

Direct Sequence Spread Spectrum

Spread Spectrum

- Usually the spectrum of a signal is related to the data (symbol) rate
  - The null-to-null bandwidth $\cong 1/T$
  - T is the symbol duration
- Spread-spectrum
  - The spectrum is much wider than $1/T$
  - The spreading is achieved using a "spreading signal" also called a "code signal" or "spreading code"
  - The receiver uses correlation or matched filtering to recover the original data

Types of Spread Spectrum

- Direct-sequence spread spectrum (DSSS)
  - Each information symbol is “chipped” into a pattern of smaller symbols
  - Pattern is called the spread-spectrum “code” or “sequence”
  - Used in IS-95, W-CDMA, cdma2000 and IEEE 802.11

Periodic

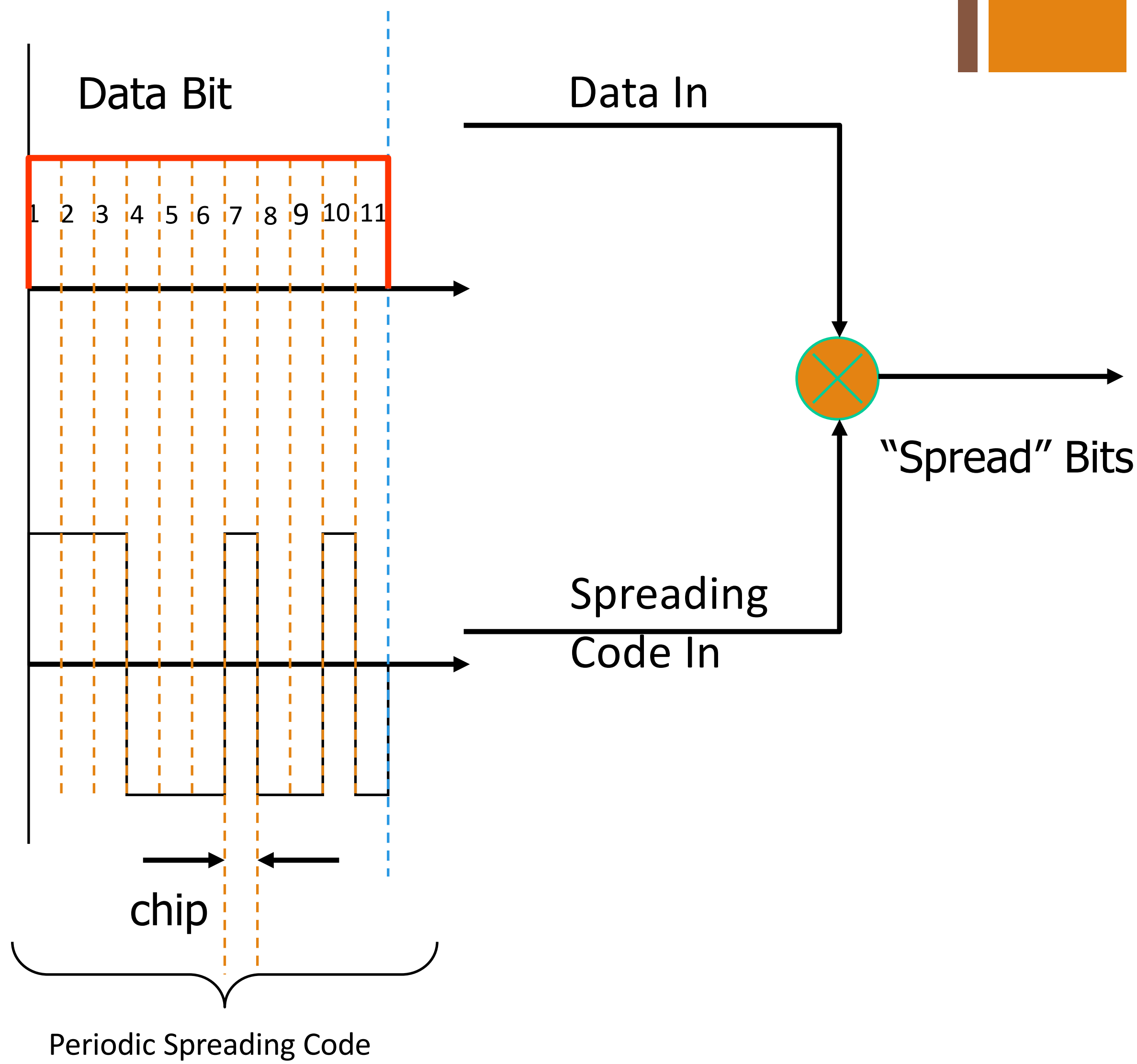
- Frequency hopping spread spectrum (FHSS)
  - Symbols or packets are transmitted on different frequency carriers each time
  - Slow frequency hopping – the same frequency carrier is used over several symbols or a packet (common)
  - Fast frequency hopping – the frequency carrier is changed within a symbol period
  - Used in GSM, IEEE 802.11 (legacy) and Bluetooth

Systems using Spread Spectrum

- DSSS is employed in 2G CDMA systems
  - IS-95, cdma2000
- DSSS is employed in all 3G cellular systems
  - UMTS and HSPA
- DSSS was used in legacy IEEE 802.11 (WiFi)

DSSS Modulation

- The original data stream is "chipped" up into a pattern of pulses of smaller duration
- Good **autocorrelation** properties
- Good **cross-correlation** properties with other patterns
- Each pattern is called a spread spectrum code or spread spectrum sequence



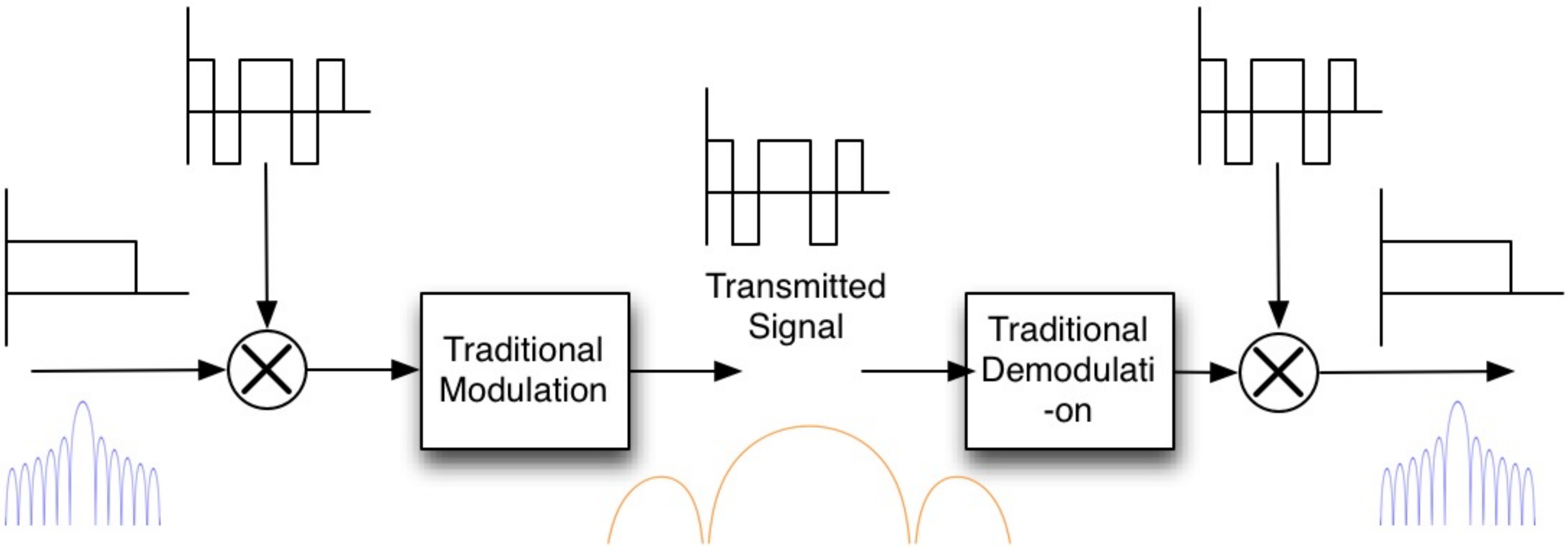
+ DSSS details

- Instead of transmitting a rectangular pulse for a zero or a one, we transmit a sequence of narrower rectangular pulses
- The narrow pulses are called "chips"
  - You often see references to "chips/sec" instead of bits/sec
- The easiest way of creating a DSSS signal is to multiply one period of the spreading sequence with each data symbol
  - Example: IEEE 802.11
    - Barker sequence: [1 1 1 -1 -1 -1 1 -1 -1 1 -1]
    - To transmit a "0", you send [1 1 1 -1 -1 -1 1 -1 -1 1 -1]
    - To transmit a "1" you send [-1 -1 -1 1 1 1 -1 1 1 -1 1]
  - Sometimes parts of the spreading sequence are multiplied with the data symbol

Processing gain

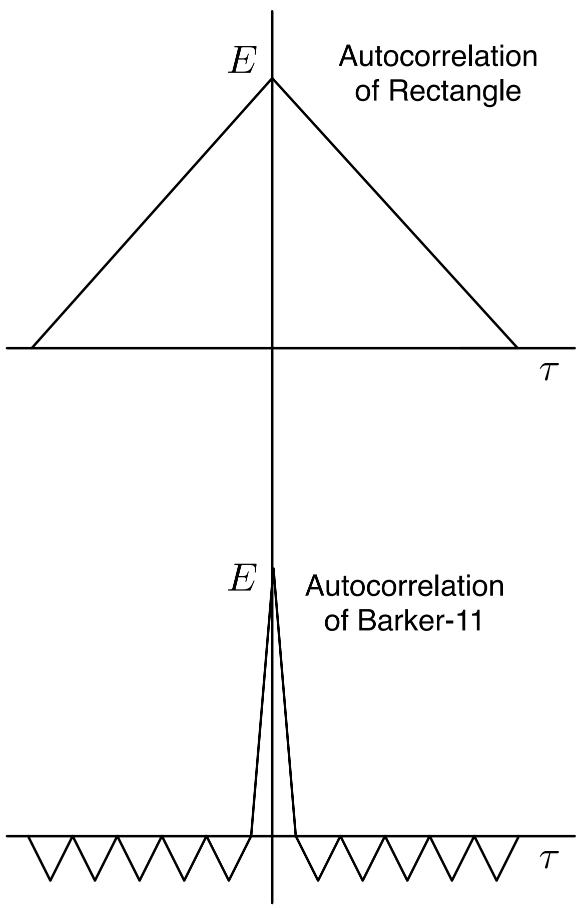
- Definition of processing gain
  - The duration of a chip is usually represented by T_c
  - The duration of the bit is T
  - The ratio $T/T_c = N$ is called the "processing gain" of the DSSS system
- The processing gain is also the ratio between the bandwidth of the spread signal to the bandwidth of the data signal
- In many cases, this is also the ratio of the height of the autocorrelation peak to the maximum sidelobe
  - This ratio depends on the spreading code properties

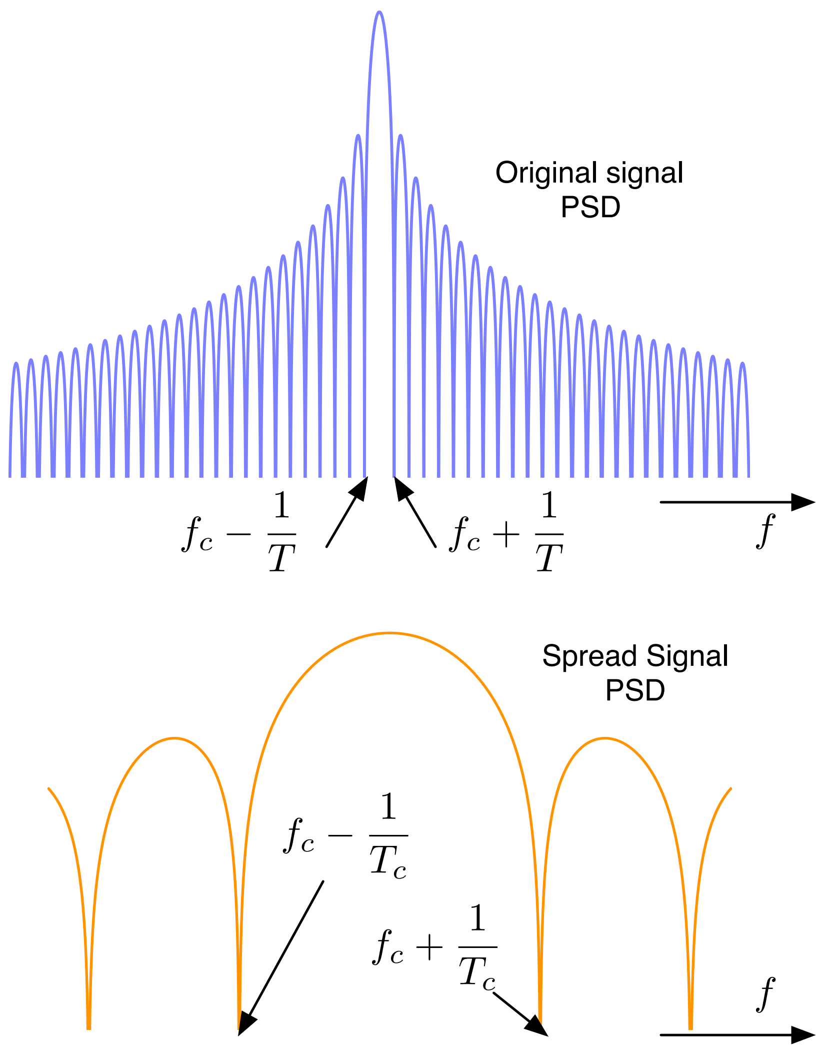
Operation of a DSSS Transceiver



Demodulation involves a process called "correlation"

Spectrum and Autocorrelation

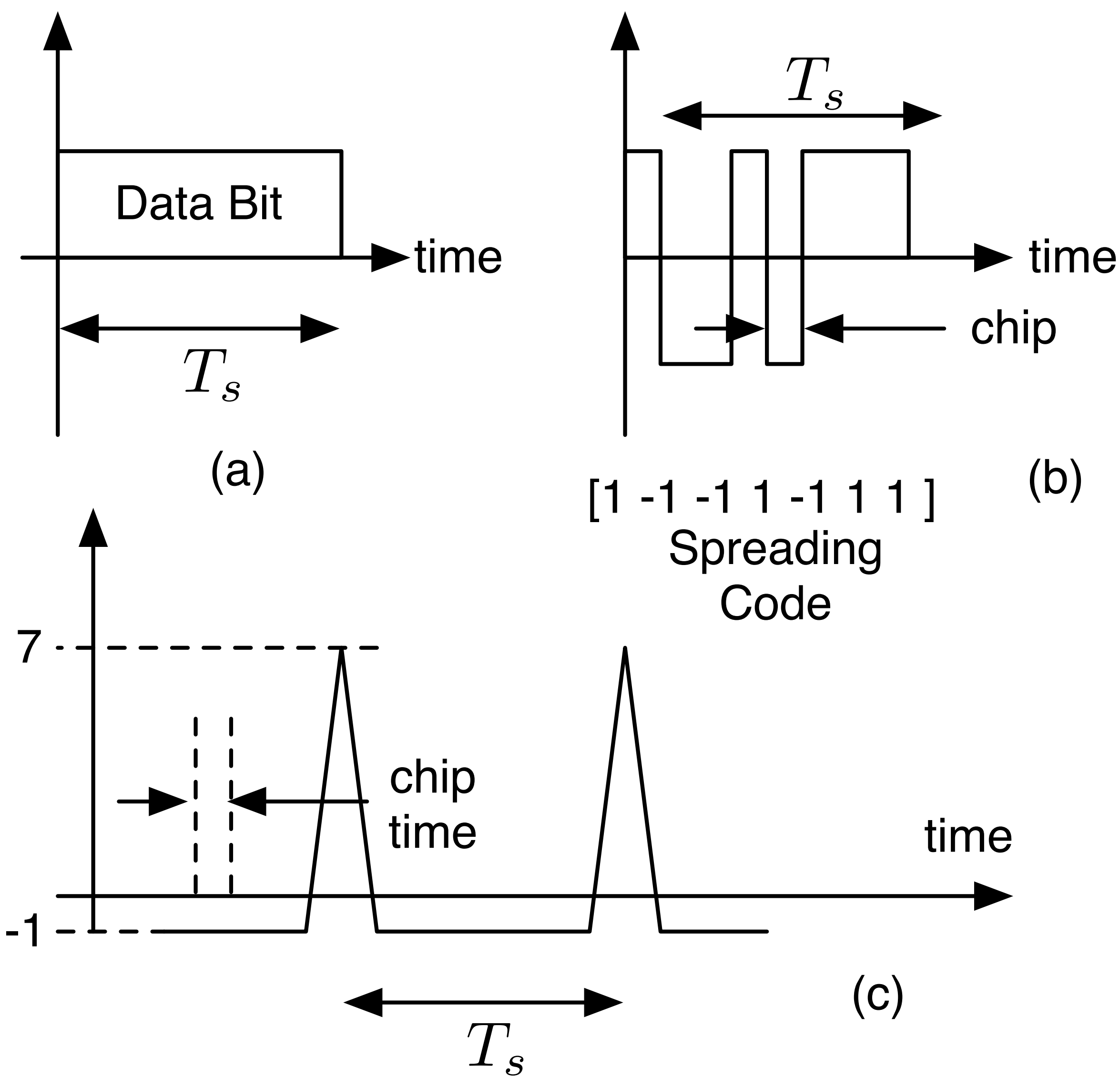




+ Autocorrelation properties of the Barker sequence

- The width of the mainlobe is $2T/11$
  - About one-tenth the width of the autocorrelation of the rectangular pulse
- The height of the mainlobe is 11 times the height of the sidelobes
- The ratio of mainlobe peak to sidelobe is an important measure of how “good” a spreading code is

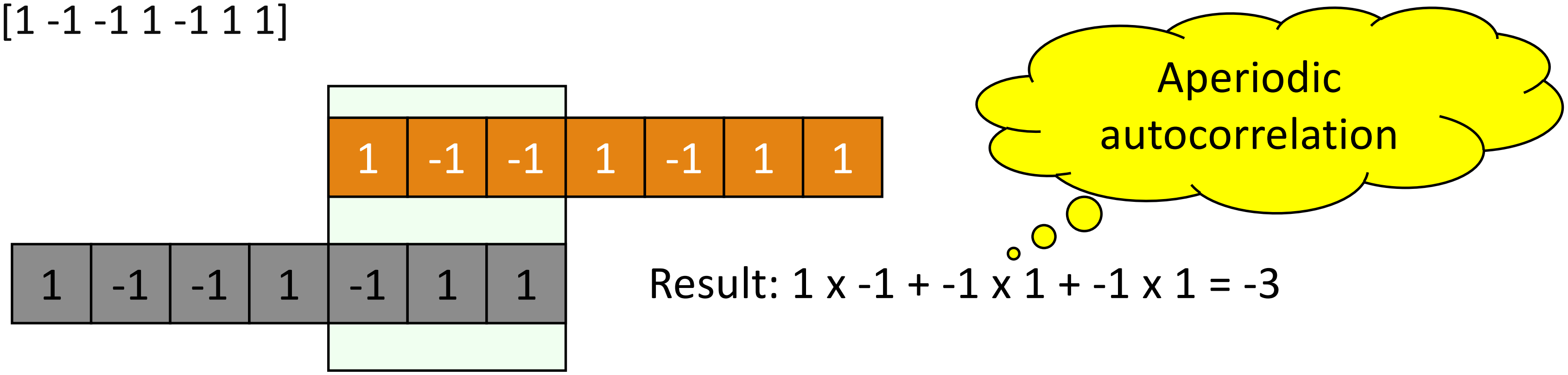
7- Chip M-sequence



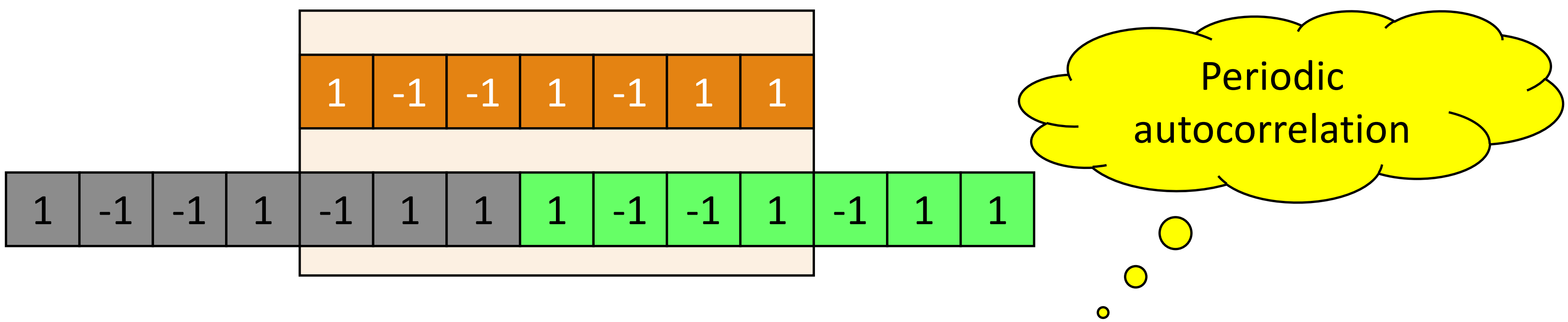
Periodic Autocorrelation

Autocorrelation

- Consider the spreading sequence
  - [1 -1 -1 1 -1 1 1]



Result: 1 x -1 + -1 x 1 + -1 x 1 = -3

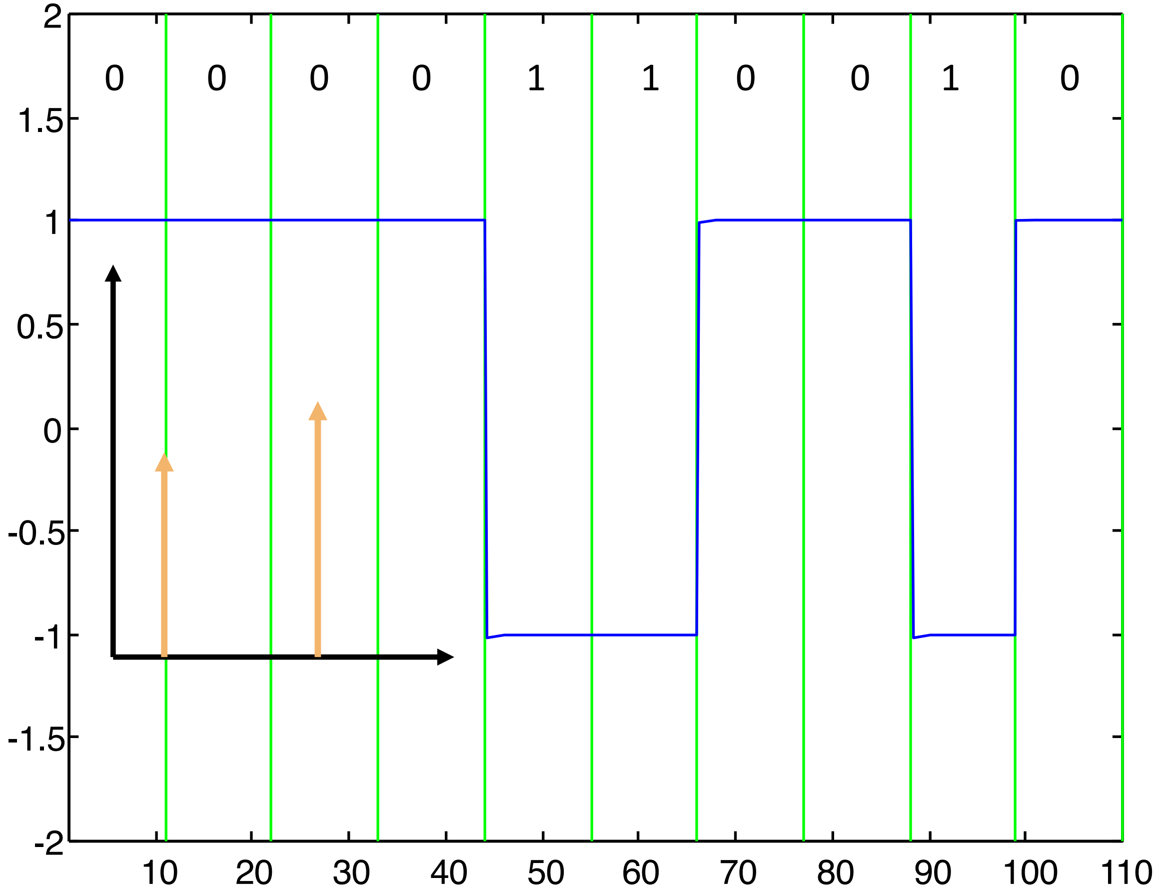


Result: 1 x -1 + -1 x 1 + -1 x 1 + 1 x 1 + -1 x -1 + 1 x -1 + 1 x 1= -1

Example in a two-path channel

- Random data sequence of ten data bits
  - Spreading by 11 chips using a Barker pulse
- Two path channel with inter-path delay of 17 chips > bit duration
- Multipath amplitudes
  - Main path: 1
  - Second path: 1.1
- Just for illustration!
- Reality:
  - Many multipath components
  - Rayleigh fading amplitudes
  - Noise!

Data and Channel

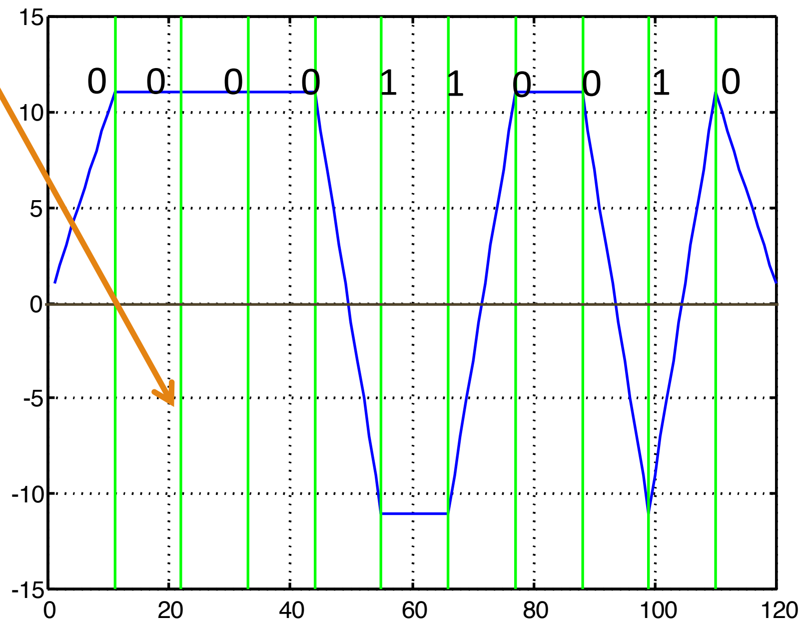


Output without spreading

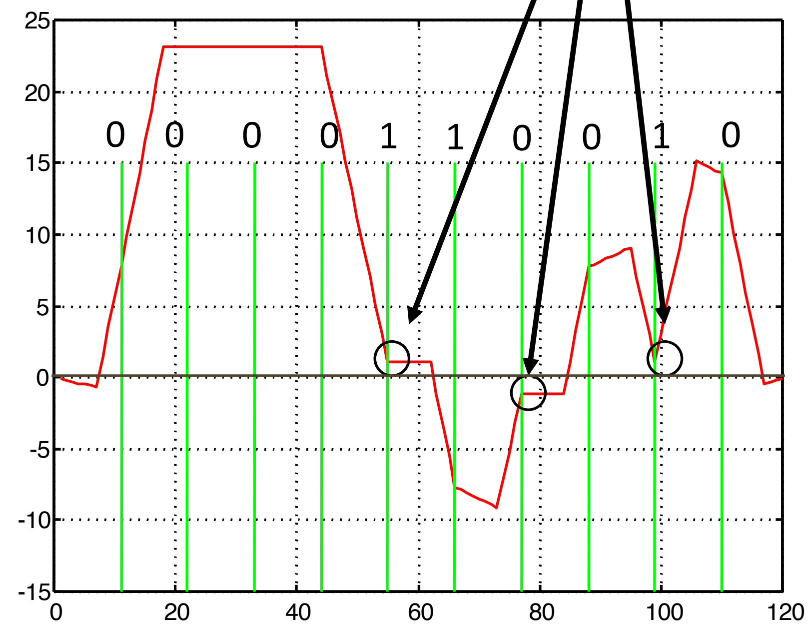
Errors introduced by the channel

Signal after correlation is sampled at green lines

Output of a Matched Filter



Without Multipath

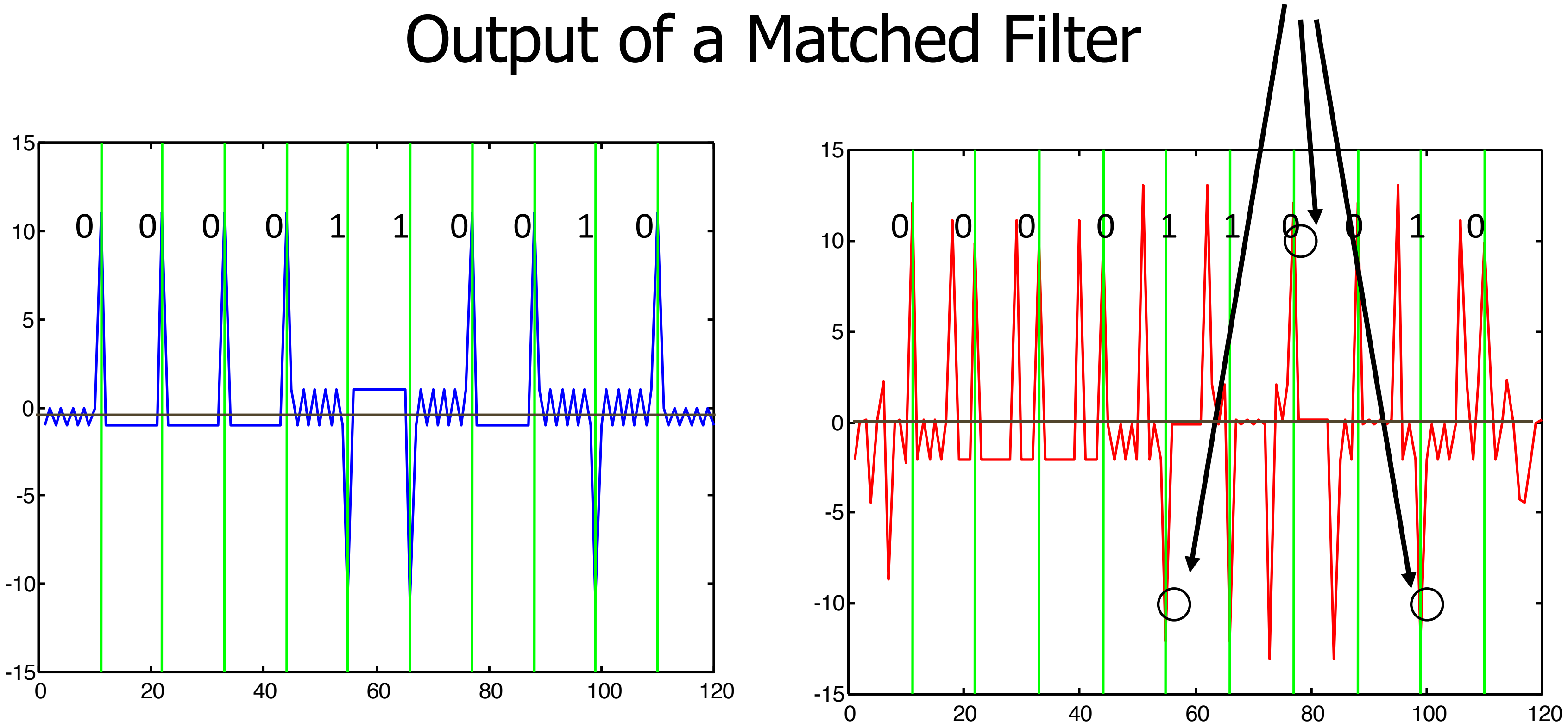


With Multipath

Output with spreading

Errors introduced by the channel are removed

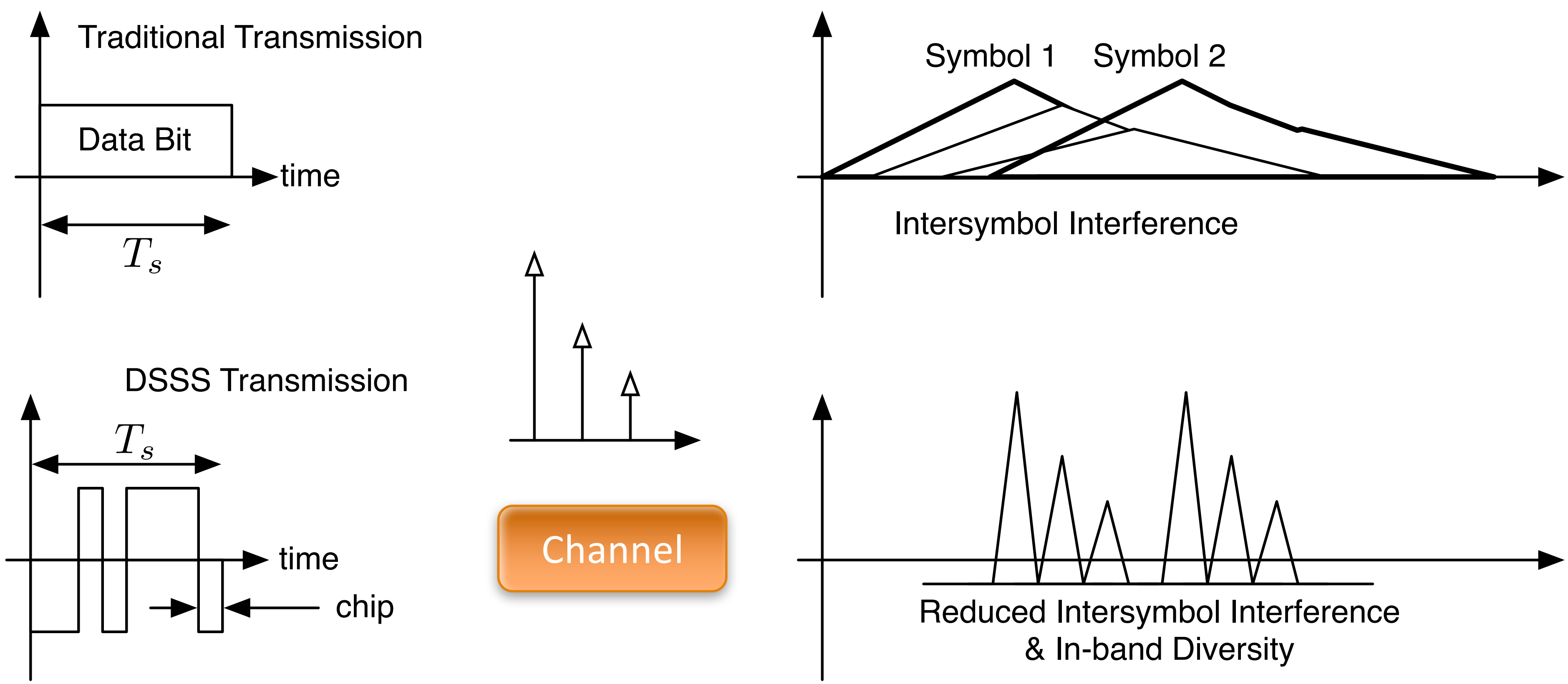
Output of a Matched Filter



Without Multipath

With Multipath

Summary of DSSS and Combatting Multipath

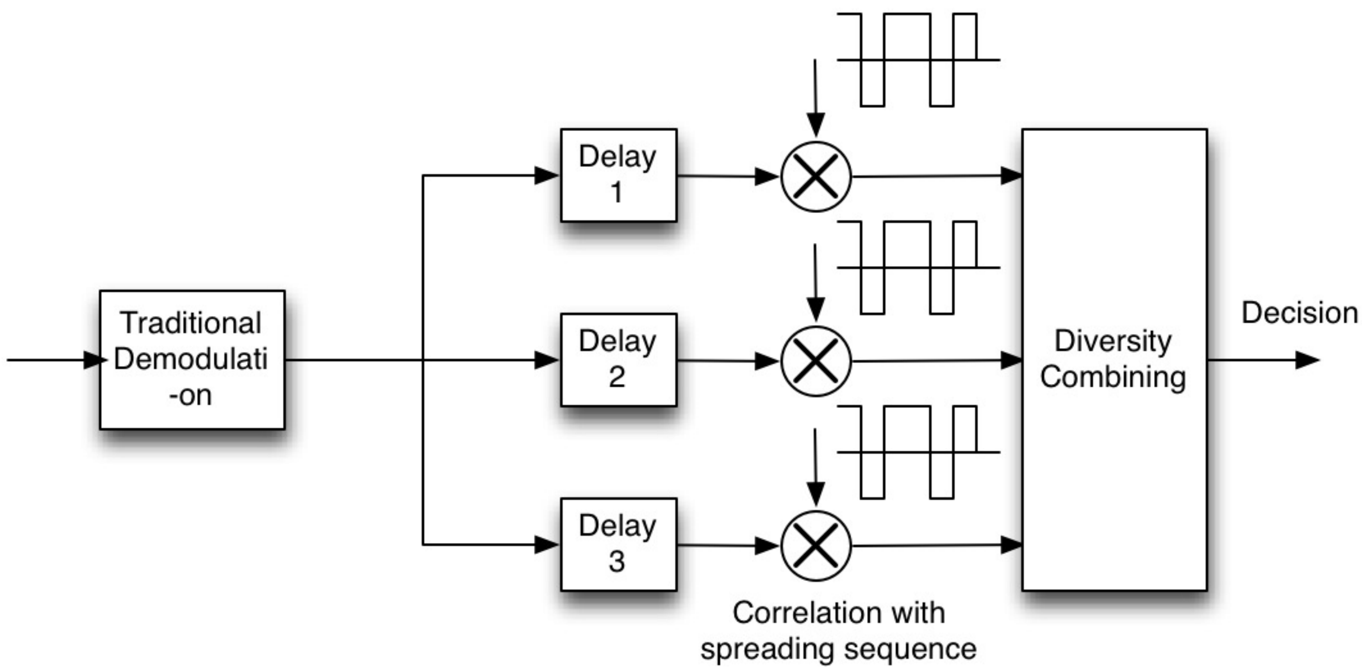


The RAKE receiver

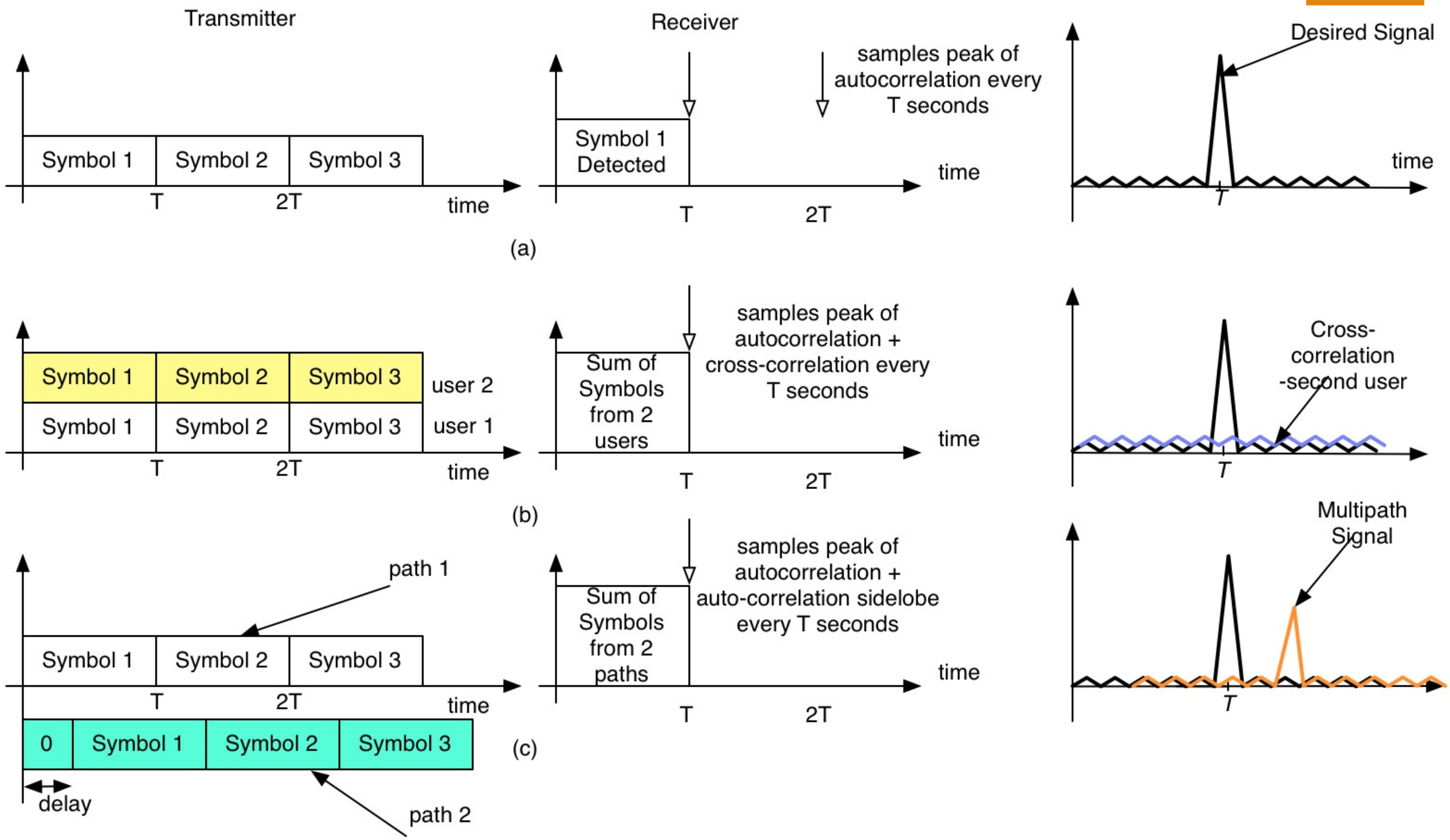
- Observe the peaks in the channel output in the previous slides that are NOT sampled (Peaks that are not at the green vertical line)
  - They contain the "same" information as the sampled peaks – but these peaks are delayed!
- A RAKE receiver consists of a tapped delay-line that samples these peaks
- Each peak usually suffers independent fading
  - This is a form of diversity inherently available in DSSS systems
- In IS-95 systems the RAKE receiver has three "fingers"
  - It can sample three such peaks simultaneously
  - A 4th finger is used to listen to adjacent cells for RSS measurements and to support soft hand-off
    - The mobile station is temporarily connected to more than one base station

Principle of RAKE Receiver

- Steps
  - Multiple versions of a signal arrive *more than one chip interval* apart
  - Receiver attempts to recover signals from multiple paths and combine them
- This method achieves better performance than simply recovering dominant signal and treating remaining signals as noise



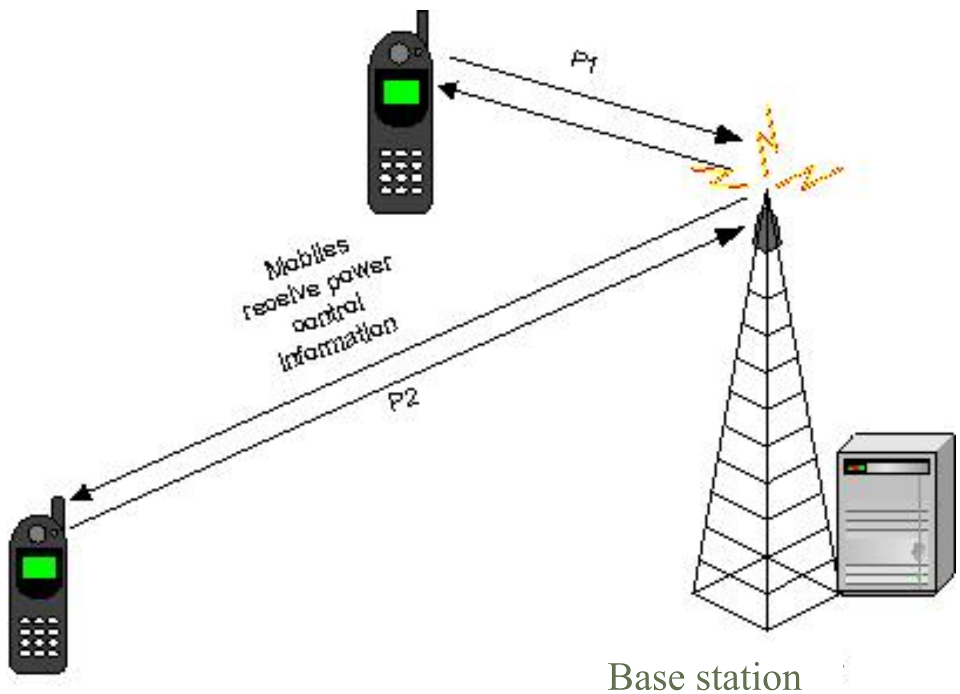
CDMA/DSSS Summary



CDMA Properties: Near-Far Problem

- A CDMA receiver cannot successfully de-spread the desired signal in a high multiple-access-interference environment
- Unless a transmitter close to the receiver transmits at power lower than a transmitter farther away, the far transmitter cannot be heard
- Power control must be used to mitigate the near-far problem
- Mobiles transmit at such power levels to ensure that received power levels are equal at base station

- Power control and channel problems!



CDMA Deployment Issues

- Radio planning in CDMA systems is different from standard TDMA/FDMA systems
  - Reuse is defined differently
  - Capacity calculations are different

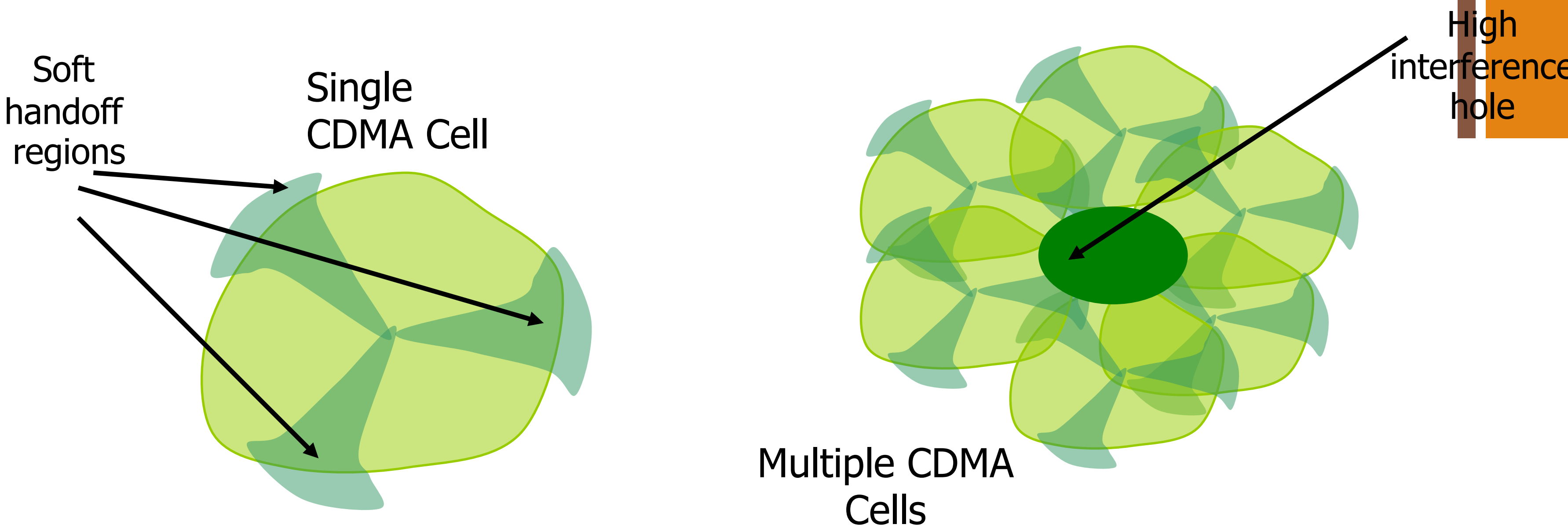
Network planning for CDMA

- There is no concept of co-channel or adjacent channel interference
  - Interference arises from users in the same cell and from neighboring cells
  - Coding and spread spectrum play a very important role in the mitigation of interference
- Instead of defining an S_r based on signal strength, it is more common to use a value of E_b/I_t that provides a given "quality of signal"
  - Usually this is the value that provides a frame error rate of 1% – this provides a good MOS for voice
  - The quantity I_t is the total interference

More on E_b/I_t

- The value of E_b/I_t depends greatly on
  - Propagation conditions
  - Transmit powers of the interfering users
  - Speed of the MS
  - Number of multipath signals that can be used for diversity
- Cell breathing
  - The boundary of a CDMA cell is not fixed and depends on where the E_b/I_t is reached
  - Capacity must be offloaded to other carriers to overcome this effect

Coverage holes in CDMA



- Power control, soft handoff and RSS thresholds play a very important role in the design
  - If too many BSs (or sectors) cover an area, this may create a “coverage hole”
  - Usually, not more than three BSs or sectors should cover an area

Approach

- Somewhat simplified, but works in general for M users in a cell
- Let us consider the reverse link (uplink)
  - There are two components of the interference
    - Own cell interference - I_o
    - Other cell interference – I_{oc}
- Assuming perfect power control, the own cell interference is given by:

$$I_o = (M\text{-}1)\ S\ v_f$$

  - S is the average power received from each of the M mobile stations
  - The reverse link "activity factor" is v_f
- The activity factor is a measure of what fraction of time a transmission occurs

Other Cell Interference

- Interference from other cells fluctuates as a function of the load
- The average value I_{oc} can be expressed as follows

$$I_{oc} = f\, M\, S\, v_f$$

  - Assumption is that all other cells are similar to the current cell
  - The factor f indicates fraction of other cell received power compared to the own-cell received power
  - In some ways, f is a measure of the reuse factor
- The factor f depends on the size of the given cell, the path loss exponent, shadow fading distribution, soft handoff parameters, etc.

Approach (II)

- Total interference is given by:

$$I_{total} = I_o + I_{oc} = [(1+f)M\text{-}1]\ v_f S = [M/\eta - 1]\ v_f S$$

  - Here the term η refers to the "reuse efficiency"
  - Suppose there is imperfect power control, we can represent this by a factor η_c

$$I_{total} = [M/\eta - 1]\ v_f (S/\eta_c)$$

- In general, the required SIR must be smaller than the observed SIR

$$(E_b/I_t)_{\mathrm{req}} < (\mathrm{SIR})_{\mathrm{system}}$$

  - Ignore thermal noise

- The desired signal has a power S multiplied by the "processing gain" G_p

Approach (III)

- Proceeding further, we get:

$$\frac{E_b}{I_t} = \frac{S\,G_p}{[M/\eta - 1]\,v_f\,(S/\eta_c)} = \frac{S\,G_p}{[(1+f)M-1]\,v_f\,S/\eta_c}$$

$$M = \frac{1}{1+f} + \frac{G_p\,\eta_c}{(E_b/I_t)\,v_f\,(1+f)}$$

- Solving for M we get:

$$M_{max} = 1 + \frac{G_p\,\eta_c}{(E_b/I_t)\,v_f\,(1+f)}$$

- M_{max} is called the “pole point” or asymptotic cell capacity

Cell Loading and Pole Point in IS-95

- Cell loading
  - A measure of the total interference in the system compared to thermal noise
  - Represented by the quantity $\rho = M/M_{max}$
  - You can show that it is also approximately equal to the ratio of the total interference to the thermal noise
- Sample calculation
  - Let $(E_b/I_t)_{\text{reqd}}$ = 6 dB = 4, R = 9.6 kbps, R_c = 1.2288 Mcps, η_c = 0.8, v_f = 0.5, f = 0.67
  - Then, the pole point or M_{max} will be:
  - $M_{max} = 1 + (1.2288 \times 10^6/9.6 \times 10^3)(0.8/(4 \times 0.5 \times [1+0.67]) = 1 + 30.65 = 32$
  - If a 3 sector antenna is used, typically, the gain in capacity is by a factor of 2.55 so that the pole point is: $31.65\times 2.55 = 81$

Comparison with AMPS/TDMA

- In AMPS, each service provider has 12.5 MHz BW
  - With a 3 sector antenna, we can have a frequency reuse of 7
  - There are 30 kHz channels per voice call
  - Number of channels/cell =

$$(12.5 \times 10^6 / 30 \times 10^3) \times (1/7) = 57$$

- In the case of IS-136, with a 3 sector antenna, we can have a frequency reuse of 4
  - Each 30 kHz channel can carry 3 voice calls
  - Number of channels/cell =

$$(12.5 \times 10^6 / 30 \times 10^3) \times (1/4) \times 3 = 312.5$$

- What was the pole point of IS-95?
  - 81 per carrier per cell sector
  - With 8 cdma carriers in a 12.5 MHz bandwidth, we can have up to 648 channels per cell sector
  - With 10 cdma carriers in a 12.5 MHz bandwidth, we can have up to 810 channels per cell sector

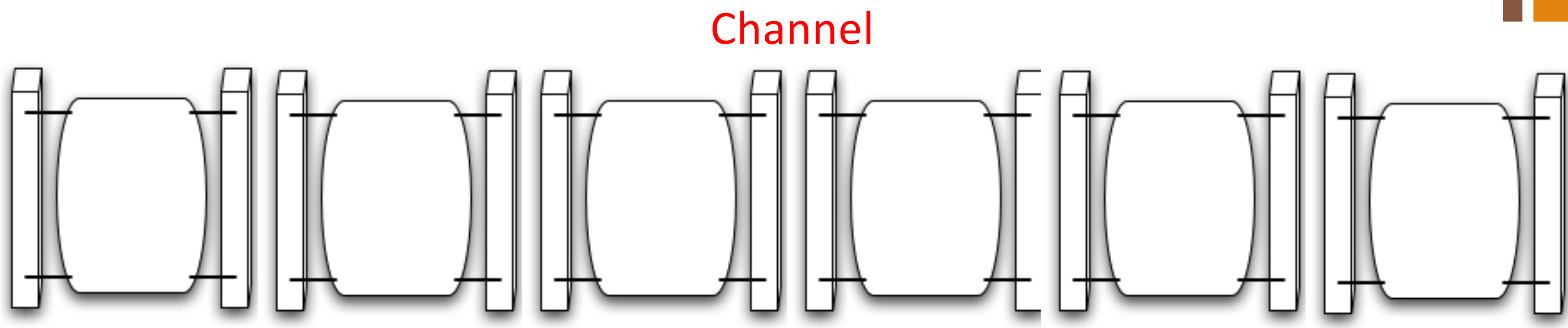
Remarks

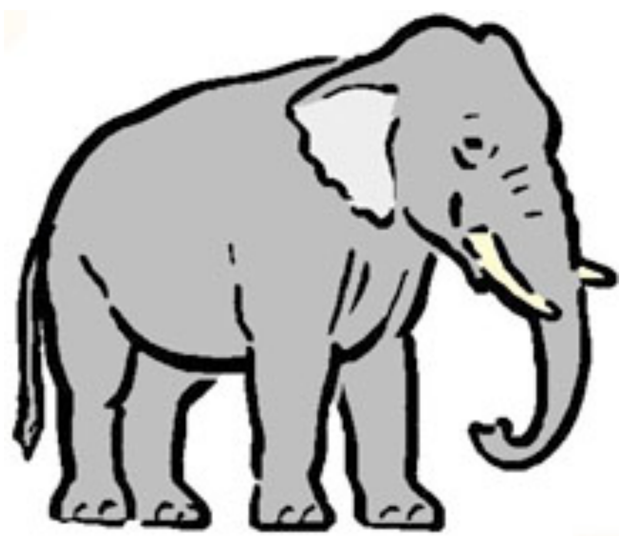
- Ranges of values
  - Power control inefficiency η_c varies between 0.7 and 0.85
  - Voice activity factor v_f varies between 0.4 and 0.6
  - The other cell interference f varies between 0.56 and 1.28 for a path loss exponent of 4 and a standard deviation of shadow fading of 6 to 10 dB

Other issues

- Forward Link
  - We have to be worried about the pilot, sync, paging and traffic channels in IS-95 and many more in cdma2000 and UMTS
  - The strength of the pilot channel effectively determines the size of the cell
  - Interference is from clusters of high power transmitters rather than many distributed low power transmitters
  - Design should try to make the forward and reverse link capacities as close to one another as possible
    - This will reduce the amount of unnecessary interference and enable smooth handoffs between cells
- PN Sequence Reuse
  - How closely should the same pilot offsets be used? (later when we do IS-95)
- How does the link budget affect the capacity?
- How does soft handoff affect the capacity?

Frequency Domain View (Gate)





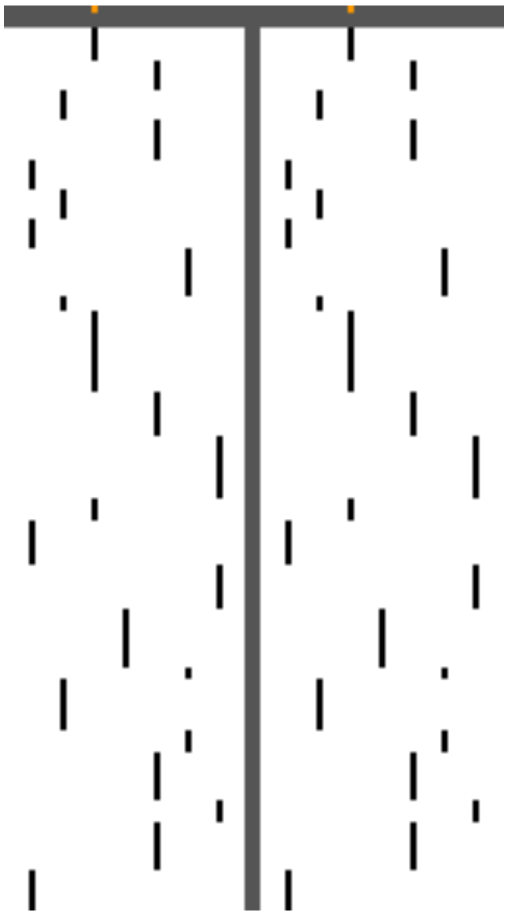
OR

Orthogonal Frequency Division Multiplexing

Diversity (continued) – Frequency Hopping

- Traditional
  - Transmitter/receiver pair communicate on a fixed frequency channel.
- Frequency Hopping Idea
  - Noise, fading and interference change with frequency band in time
    - Move from band to band
  - Time spent on a single frequency is termed the “dwell time”
- Originally developed for military communications
  - Spend a short amount of time in one frequency band
  - Prevent interception or jamming

Frequency Hopping Spread Spectrum



Developed during WWII by actress Hedy Lammar and classical composer George Antheil

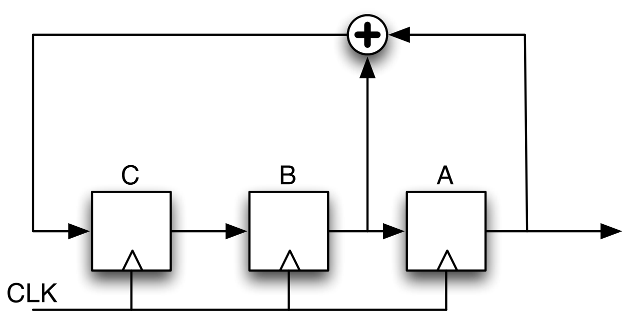
Patent given to government

Frequency Hopping Spread Spectrum

- Two types of systems
  - Slow Hopping
    - Dwell time long enough to transmit several bits in a row (timeslot)
  - Fast Hopping
    - Dwell time on the order of a bit or fraction of a bit (primarily for military systems)

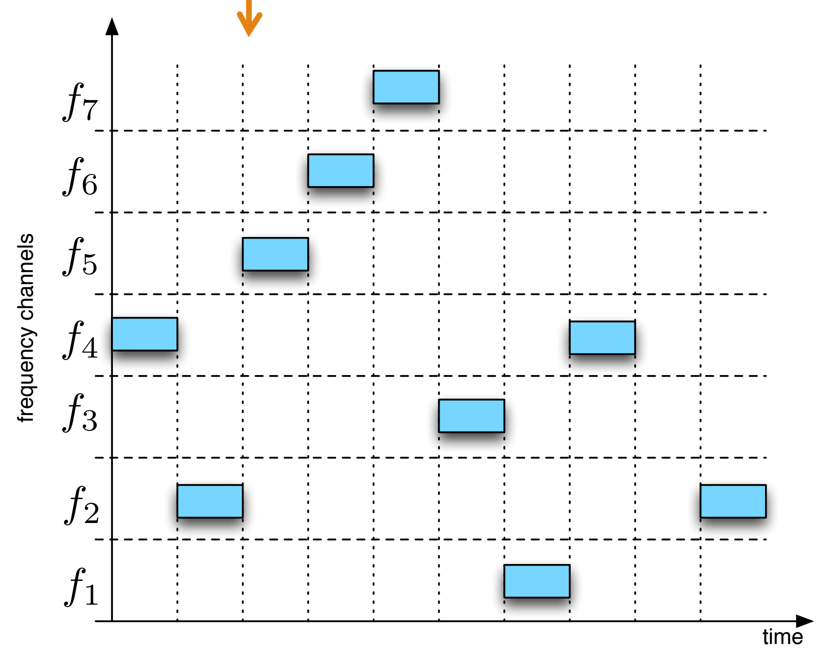
- Transmitter and receiver must know hopping pattern or algorithm that determines the pattern before communications.
  - *Cyclic pattern* – best for low number of frequencies and combating small-scale fading :
    - Example with four frequencies: f4, f2, f1, f3, f4, f2, f1, f3, ….
  - Random pattern – best for large number of frequencies, combating co-channel interference, and interference averaging
    - Example with six frequencies: f1, f3, f2, f1, f6, f5, f4, f2, f6, …
    - Use random number generator with same seed at both ends

Frequency Hopping concept

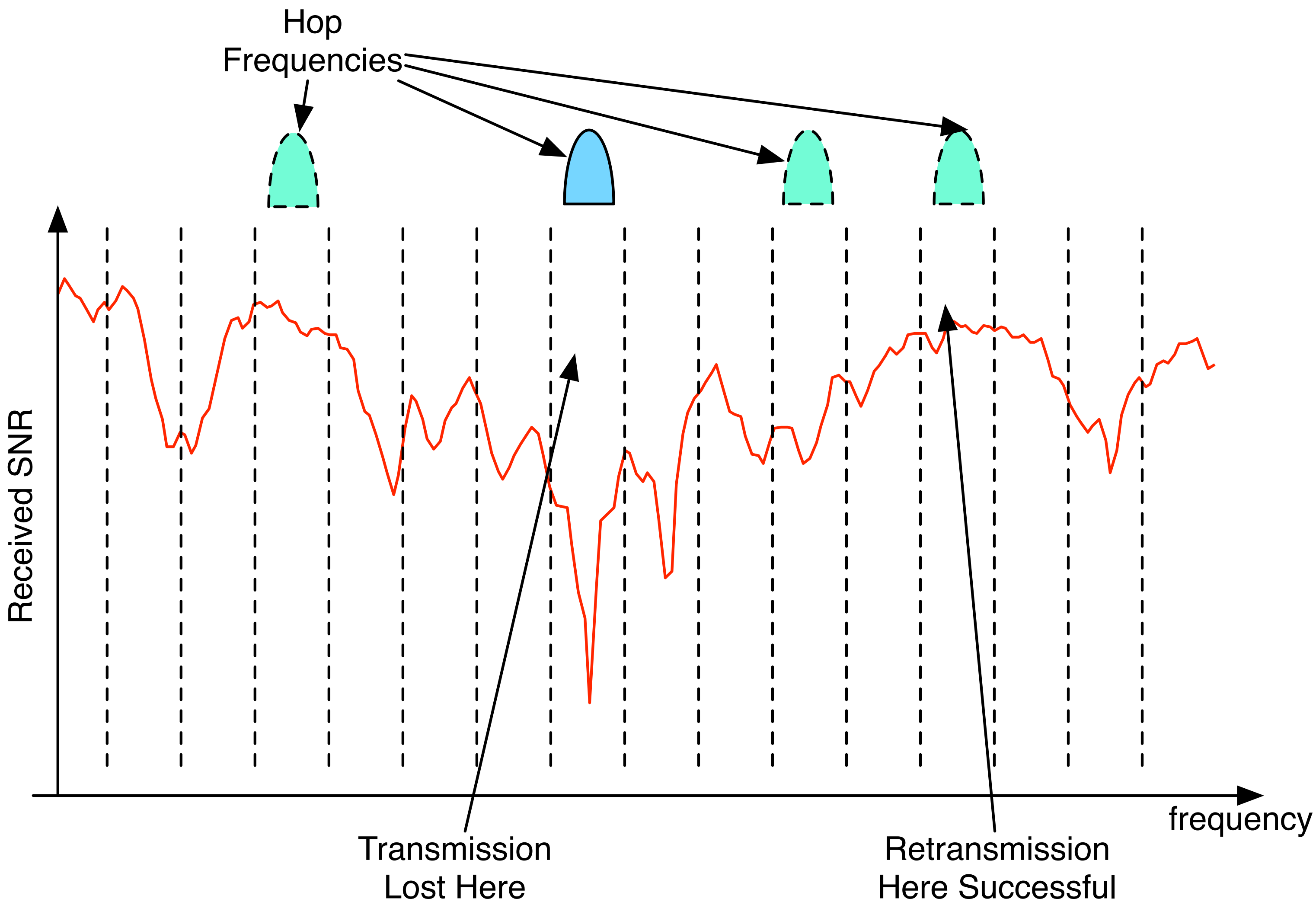


One Period of Sequence = 1 0 0 1 0 1 1

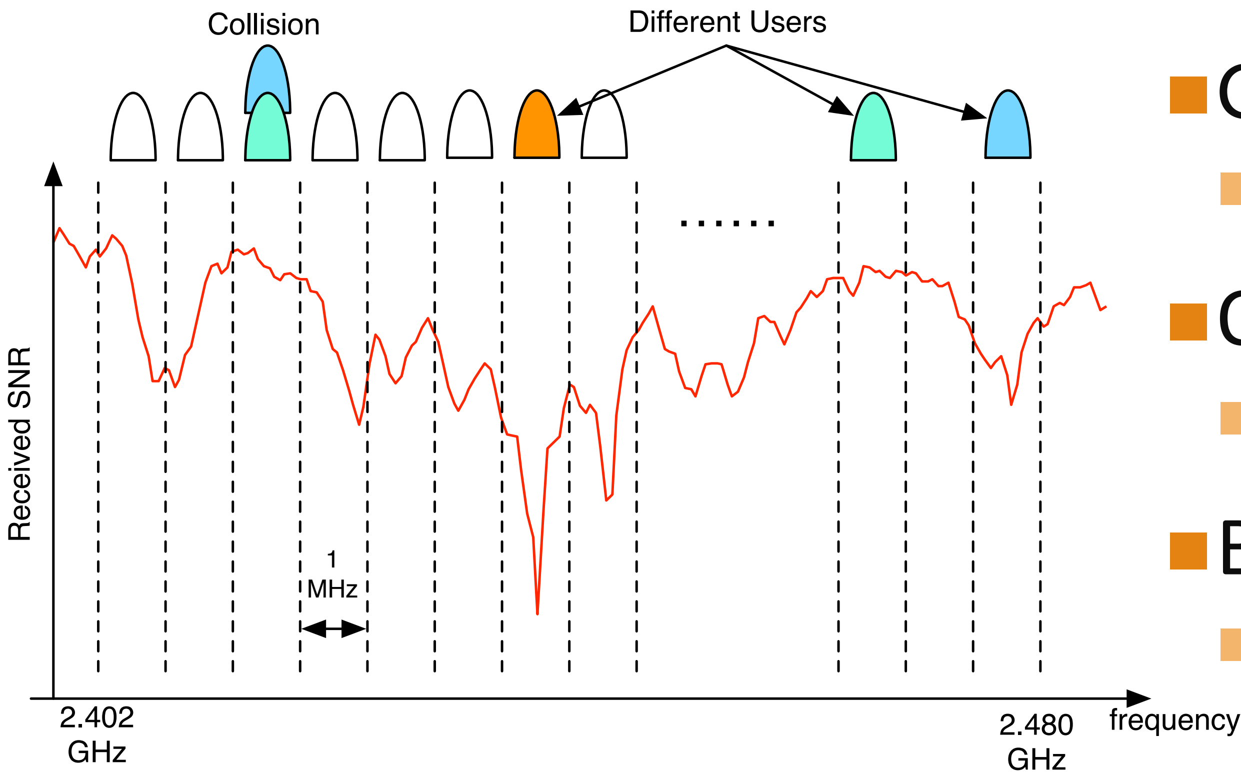
CLK	C	B	A	f_c
t_0	1	0	0	f_4
t_1	0	1	0	f_2
t_2	1	0	1	f_5
t_3	1	1	0	f_6
t_4	1	1	1	f_7
t_5	0	1	1	f_3
t_6	0	0	1	f_1
t_7	1	0	0	f_4



Combatting Time Dispersion

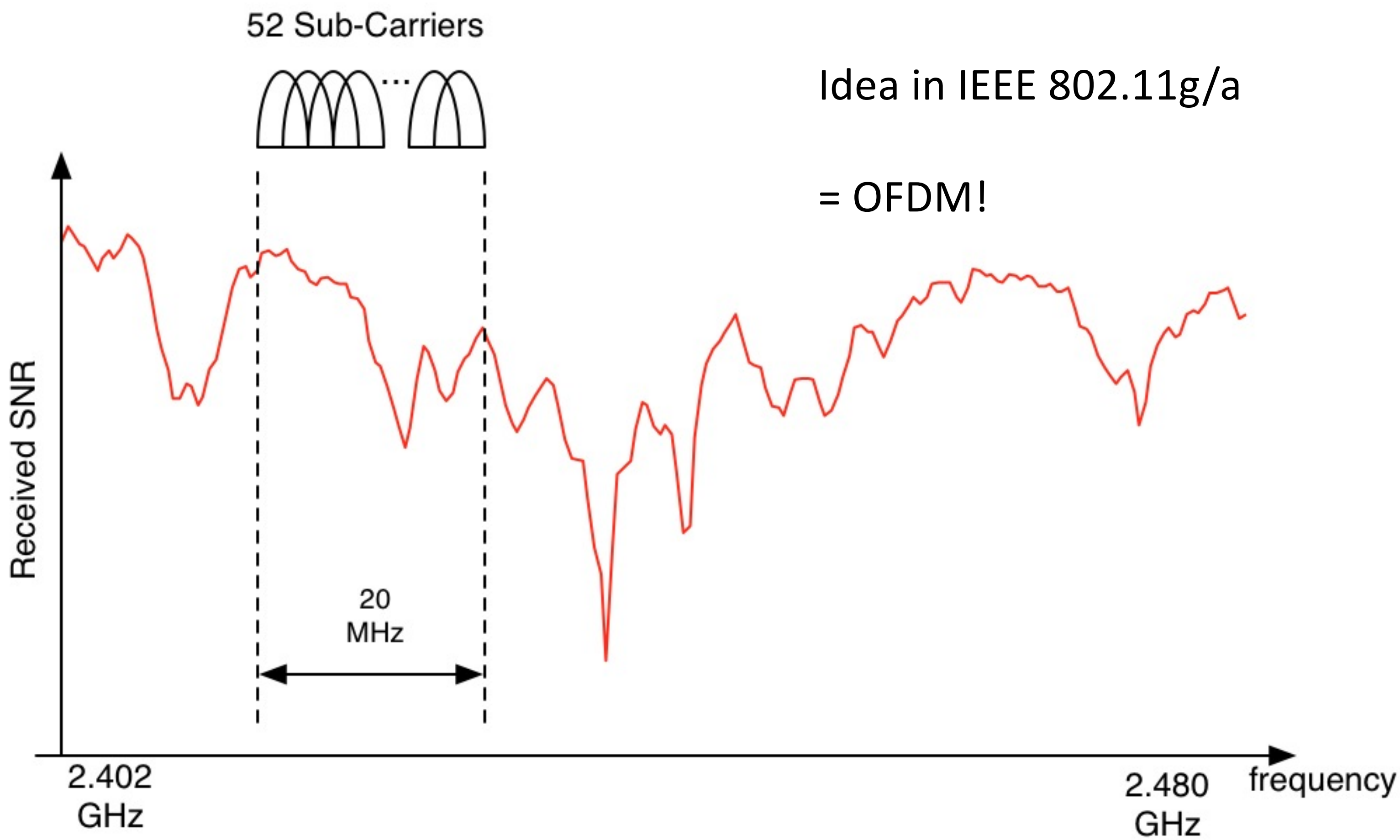


Example Systems



- GSM (2G Cellular)
  - Very slow hopping
- Original IEEE 802.11
  - Slow hopping
- Bluetooth
  - Also slow hopping over 79 frequencies each 1 MHz wide
  - Per packet hopping

How do you utilize the entire bandwidth?



Idea in IEEE 802.11g/a

= OFDM!

Orthogonal Frequency Division Multiplexing

- Idea in frequency domain:
  - Coherence bandwidth limits the maximum data rate of the channel
  - Send data in several parallel sub-channels each at a lower data rate and different carrier frequency
- Idea in time domain:
  - By using several sub-channels and reducing the data rate on each channel, the symbol duration in each channel is increased
  - If the symbol duration in each channel is larger than the multipath delay spread, we have few errors
- OFDM enables
  - Spacing carriers (sub-channels) as closely as possible
  - Implementing the system completely in digital eliminating analog VCOs

What is OFDM?

- Modulation/Multiplexing technique
- Usual transmission
  - Transmits single high-rate data stream over a single carrier
- With OFDM
  - Multiple parallel low-rate data streams
  - Low-rate data streams transmitted on orthogonal subcarriers
  - Allows spectral overlap of sub-channels

OFDM Remarks

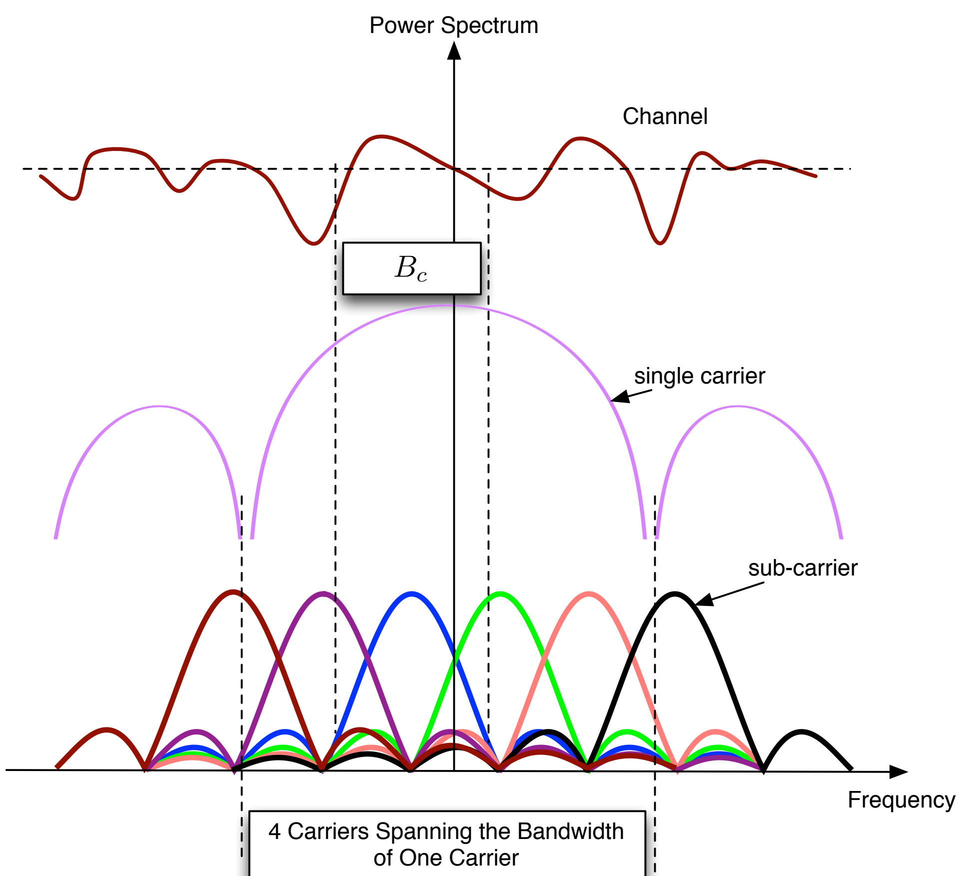
- It is NOT a new technology but has found new importance because of applications
  - DSL modems where the channel is not uniform
  - Digital audio and video broadcast
  - Wireless LAN applications
    - IEEE 802.11a and HIPERLAN-2
- Fast implementation using FFT's is now possible
- Can be adaptive (used in 802.11a)
- Problems
  - Synchronization between carriers
  - Peak-to-average power (PAP) ratios
    - Requires linear amplifiers

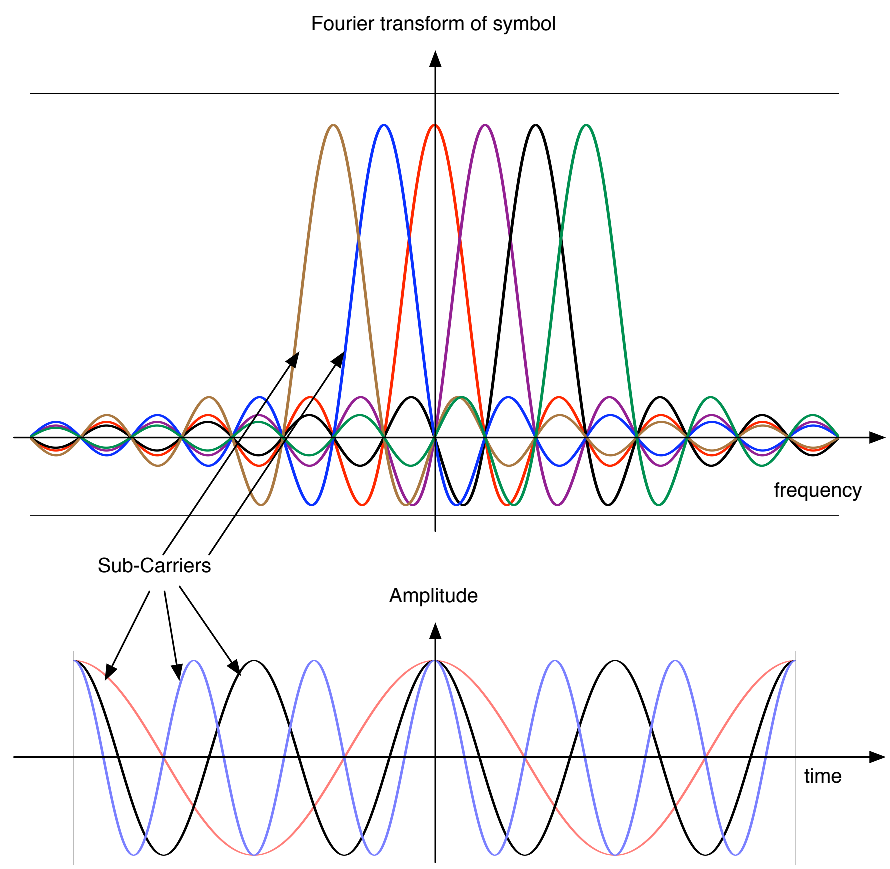
OFDM Advantages

- Bandwidth efficiency
- Reduction of ISI
  - Needs simpler equalizers
- Robust to narrowband interference and frequency selective fading
- Possibility of improving channel capacity using adaptive bit loading over multiple channels

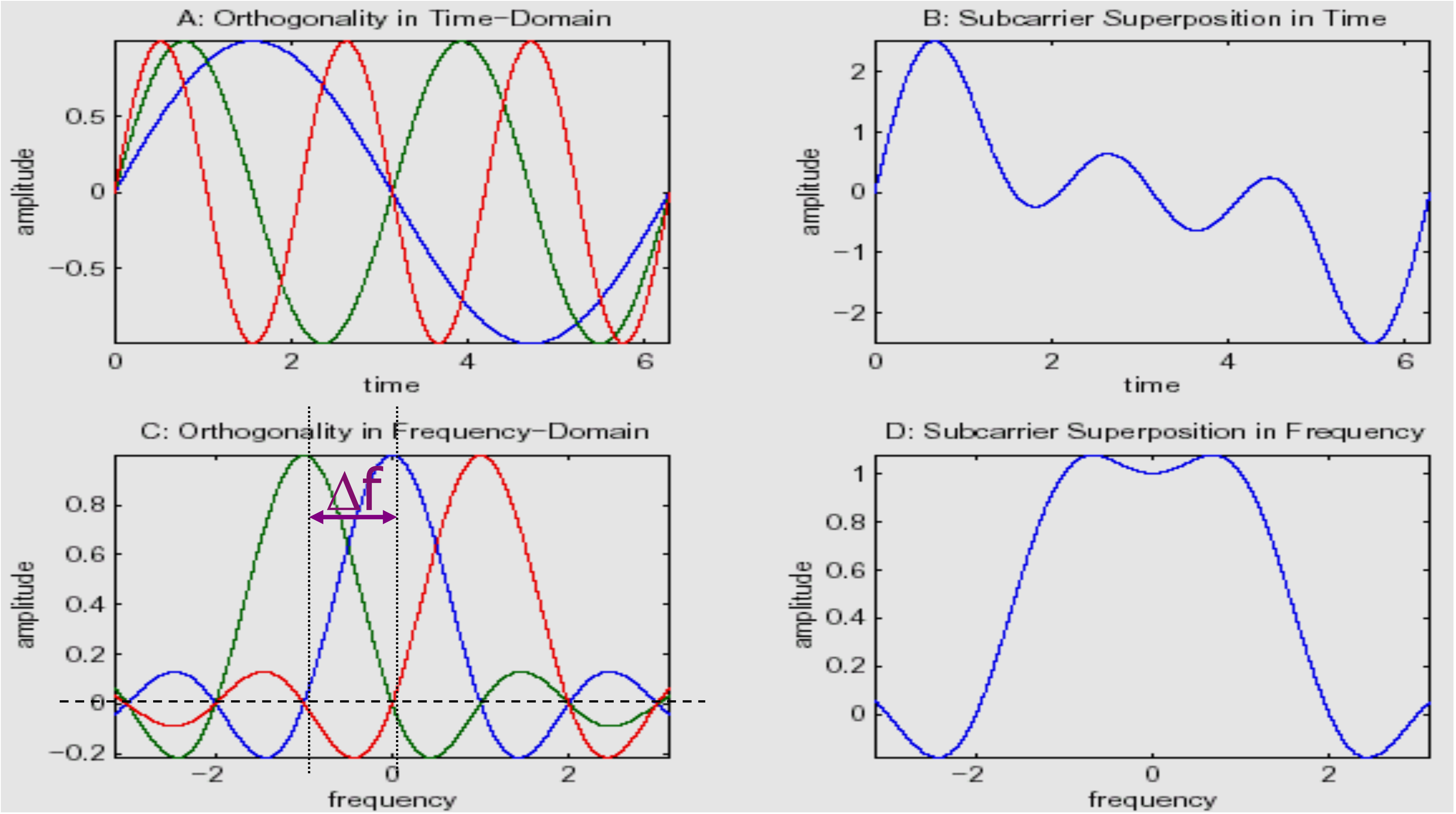
OFDM in frequency and time domains

- Note orthogonality in both domains
- What is one “OFDM symbol”?





OFDM Signal/Symbol



OFDM Symbol

- One OFDM "symbol" lasts for say T_s seconds
  - The symbol **consists of the sum** of the individual symbols from the many sub-carriers
  - Example: Consider QPSK on each carrier
- In general
  - For N subchannels, the N samples of the i-th transmitted OFDM symbol can be written as

$$x_i(k) = \frac{1}{\sqrt{N}} \sum_{n=0}^{N-1} a_i(n) e^{j\frac{2\pi nk}{N}} \quad \text{for } 0 \leq k \leq N-1$$

Complex Number

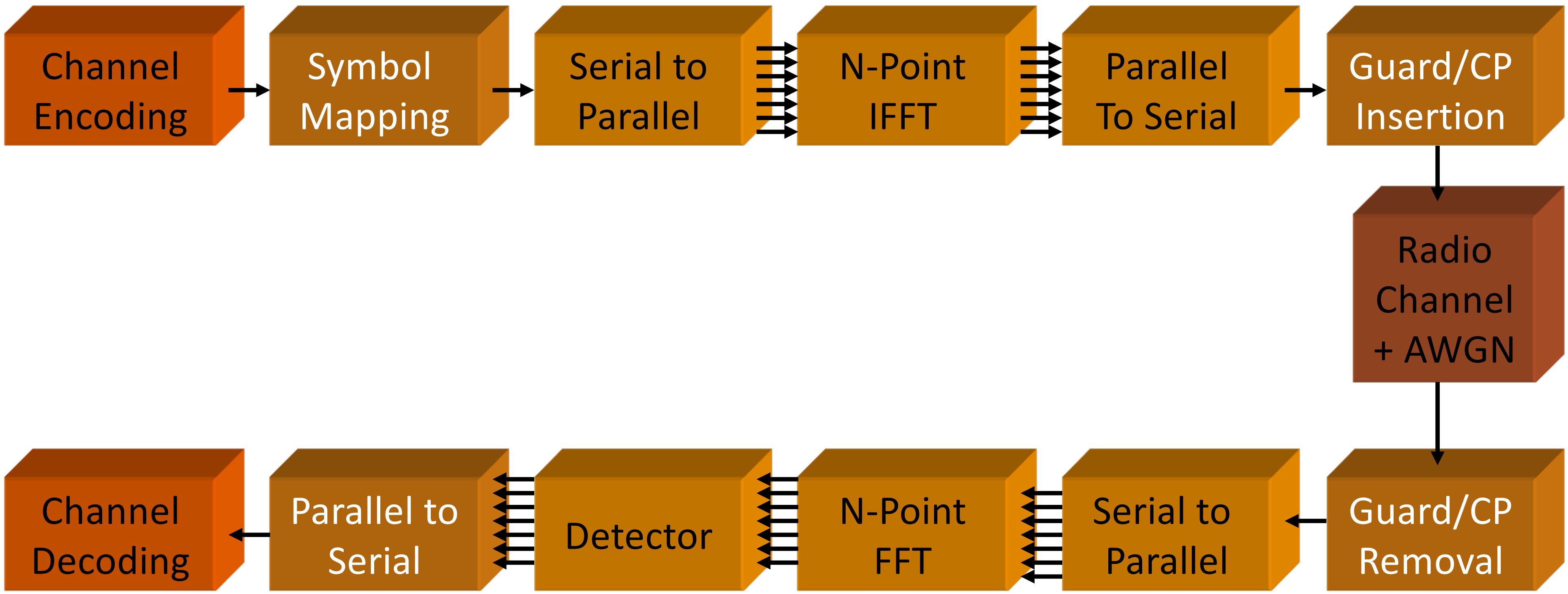
IFFT

Guard Time and Cyclic Prefix

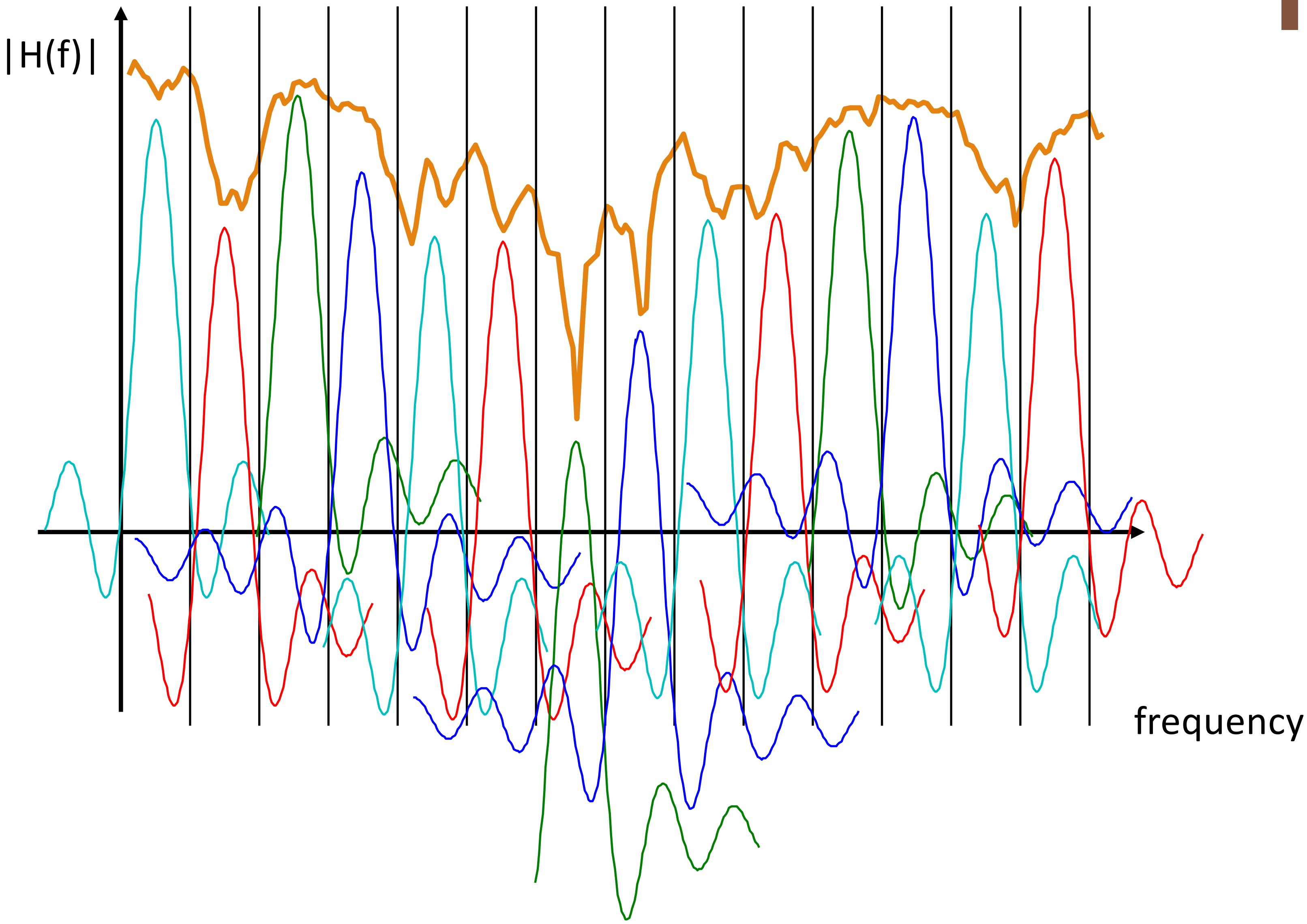
- Guard time eliminates ISI if larger than expected delay spread occurs
- If the guard time has no signal, intercarrier interference (ICI) may occur
  - ICI is like a cross talk between subcarriers
- A cyclic prefix eliminates ICI
  - Ensures that delayed replicas of OFDM symbols always have integer number of cycles within the FFT interval
  - Maintains orthogonality between subcarriers
  - Cyclic prefix is removed at the receiver

OFDM Transmission – basic system

- *N* consecutive complex symbols are converted into a group of N parallel data streams, which then are modulated over orthogonal subcarriers

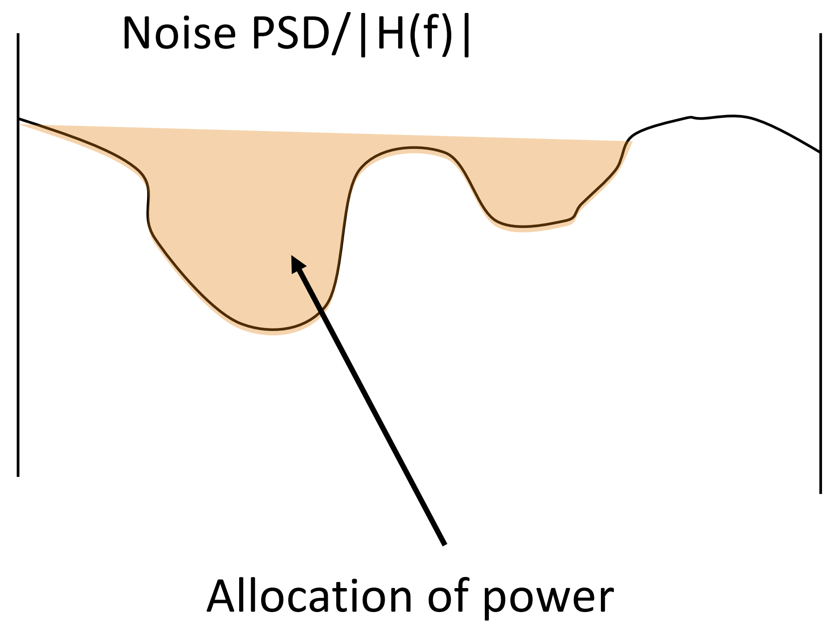


Adaptive OFDM



Channel Partitioning for Multicarrier Modulation

- As the channel is frequency selective, it makes sense to split the channel into several smaller parts
  - Each smaller chunk is now an AWGN channel
  - Each AWGN channel provides a *different* SNR
- Question: How do we allocate transmit powers/modulation schemes to each chunk? What is the most optimal?



Water-filling algorithm

Allocate more energy where the SNR is better!

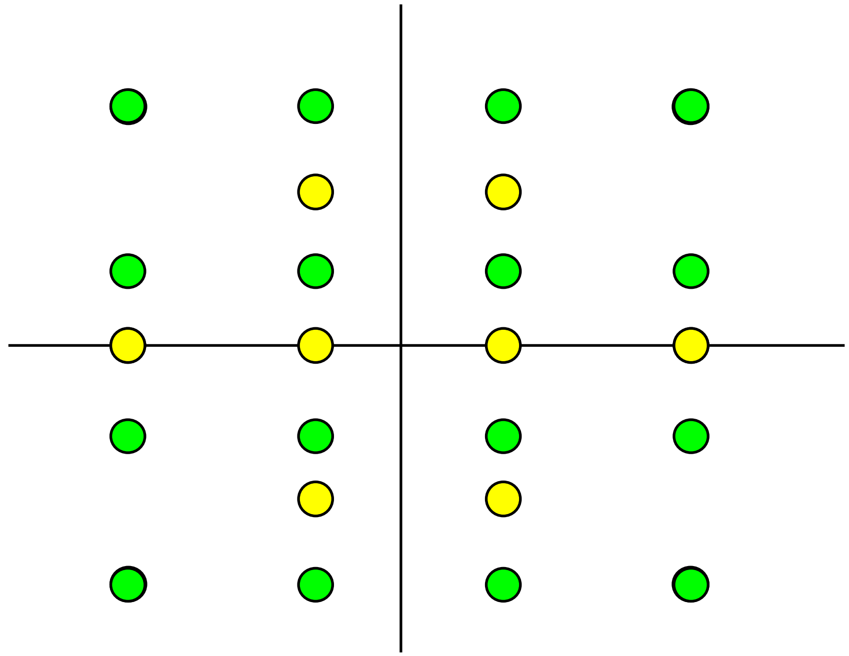
Adaptive OFDM

- Improve channel capacity further
  - Change modulation scheme
  - Allocating bits/power per subcarrier according to the quality of each subchannel

AOFDM Components

- Adaptive Loading/Allocation Algorithm
- Set of Modulation Schemes
- Channel Quality Estimator*

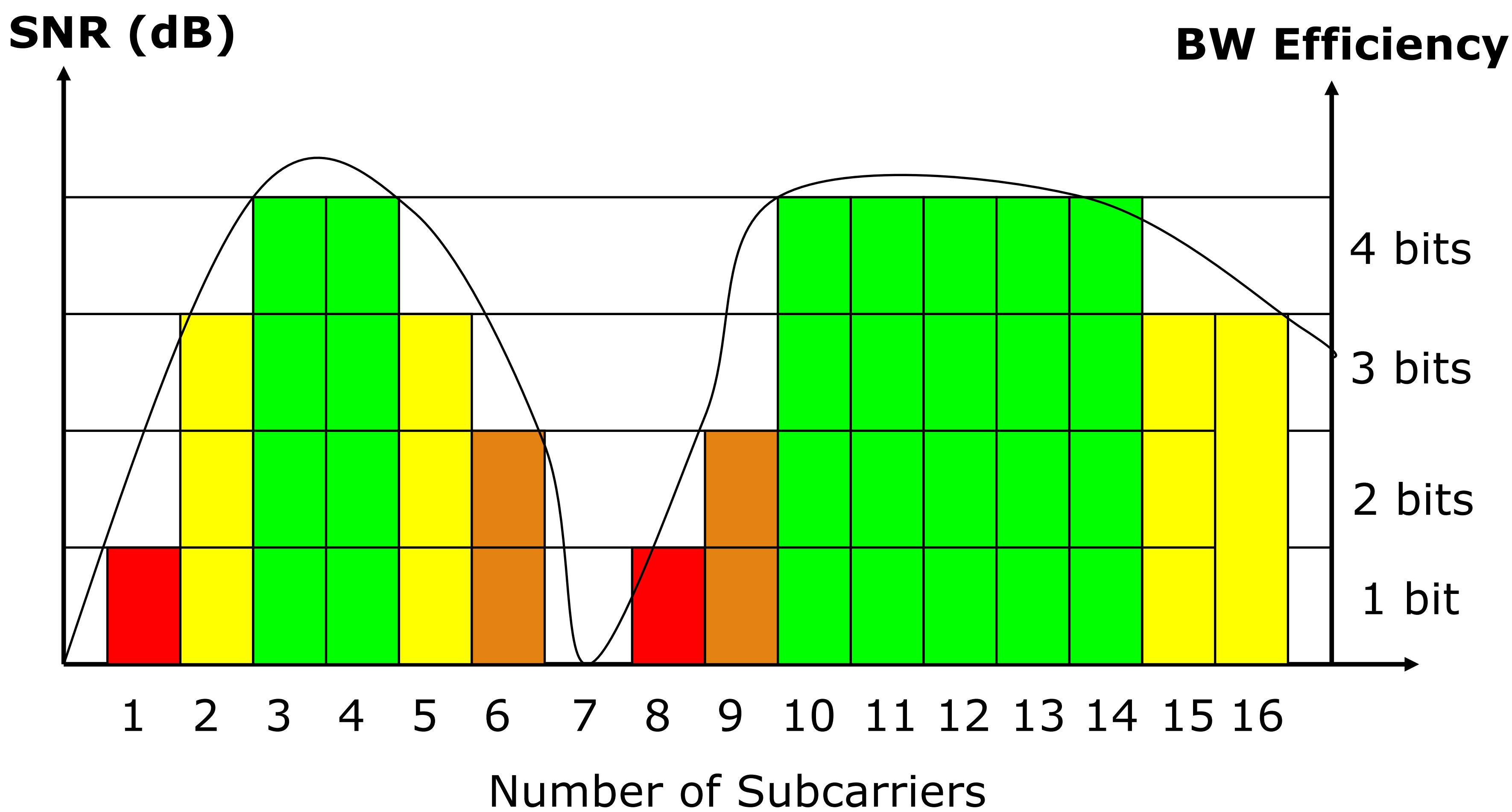
Adaptive Modulation



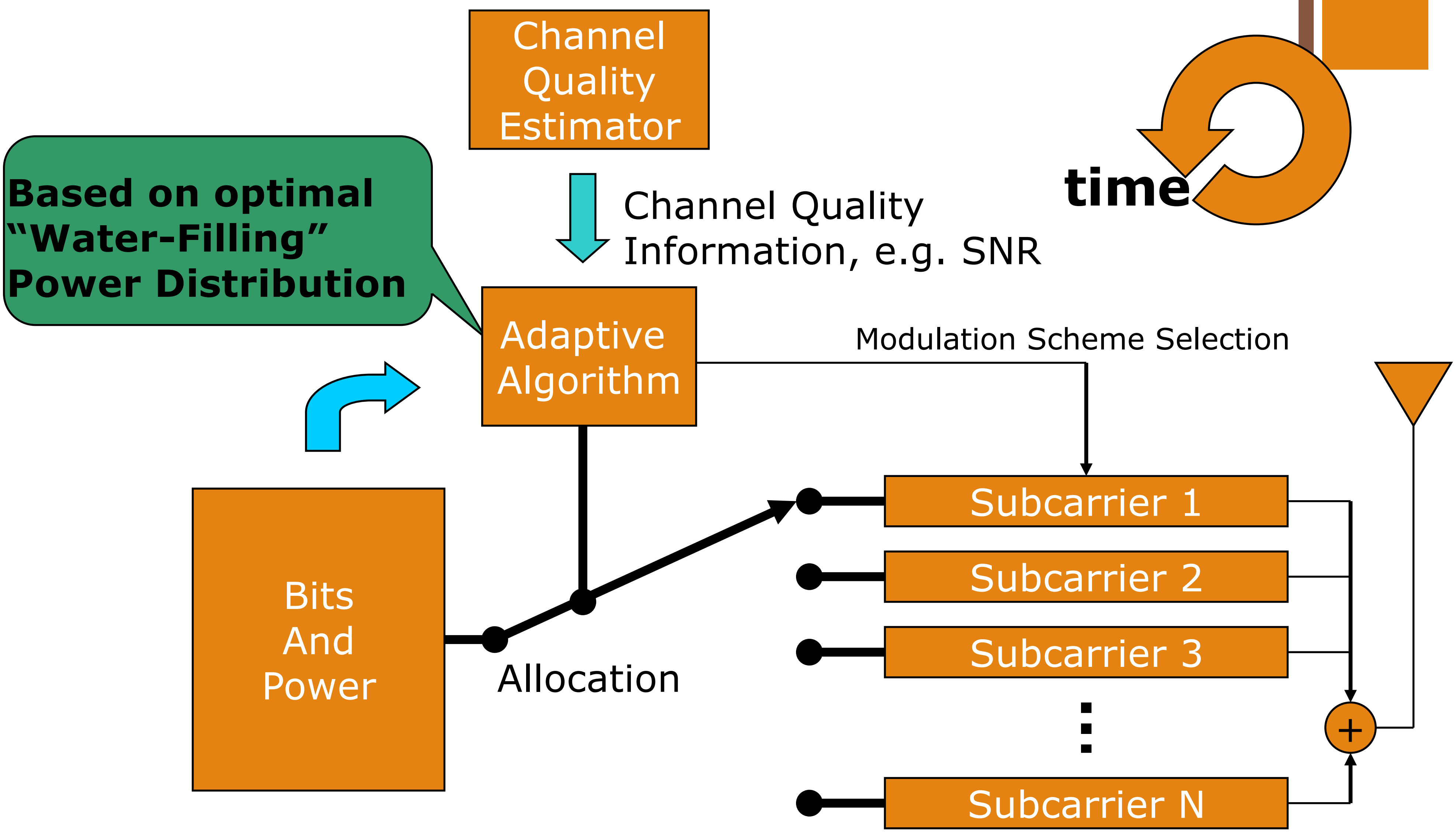
Set of Modulation Schemes

- No transmission (0 bits)
- BPSK (1 bit/symbol)
- QPSK (2 bits/symbol)
- 8-QAM (3 bits/symbol)
- 16-QAM (4 bits/symbol)

Adaptive Modulation on Parallel Channels



Operation of Adaptive Algorithms



OFDM Based Wireless LANs – IEEE 802.11a

- Operates in the U-NII Band
  - 5.15–5.25, 5.25–5.35, and 5.725–5.825 GHz
- Provides multiple transmission modes/rates depending on channel conditions.
  - 6, 9, 12, 18, 24, 36, 48, and 54 Mbps
- 4 digital modulations: BPSK, QPSK, 16-QAM, 64 QAM
- Radio spectrum is divided into 8 separate segments/channels, 20 MHz each
- 52 carriers (subchannels) per channel
  - Each subcarrier has bandwidth of ~300 kHz
  - 48 for data modulation, and 4 for pilot signal

Recent Trends

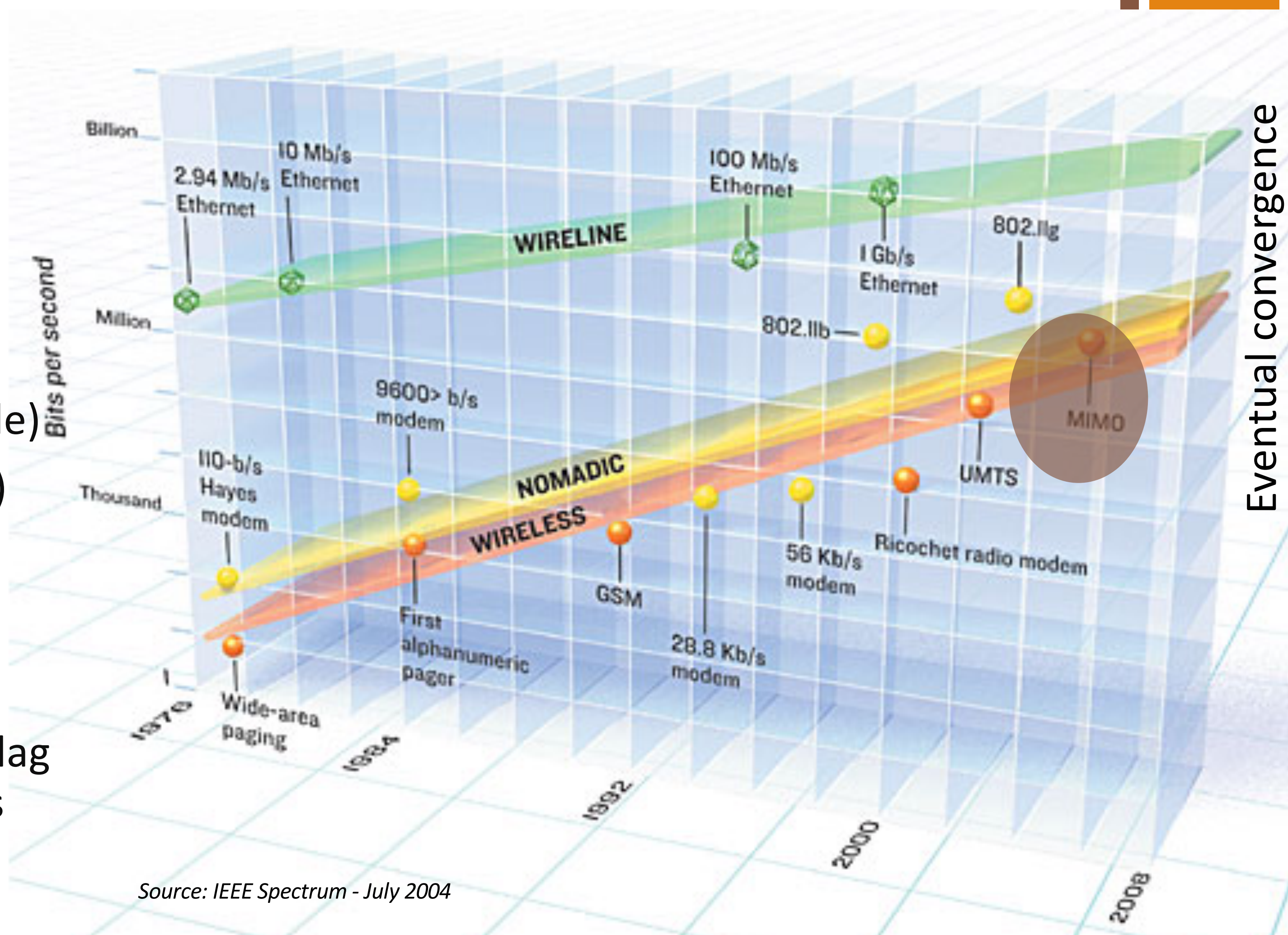
- MIMO with OFDM
  - IEEE 802.11n, 802.11ac
  - Data rates greater than 100 Mbps
- OFDM for wide area data services
  - LTE and WiMax
- Other PHY technologies
  - UWB with OFDM
  - MC-CDMA

Revisiting "Data Rates" in Wireless

- Home A/V networks are expected to need 1-10 Gbps
  - Assuming a spectral efficiency of 1 bps/Hz, we need at least 1 GHz of spectrum
    - Have ignored the effects of multipath fading
  - Brute force approach
    - May not meet the technology, regulatory and cost requirements
- Can we increase the bps/Hz in wireless systems?

Edholm’s Law

- Phil Edholm
  - Nortel’s CTO
- Three Telecom Categories
  - Wireline
  - Nomadic (Portable)
  - Wireless (Mobile)
- Data rates increase exponentially
  - There is a predictable time lag between wireless and wireline systems



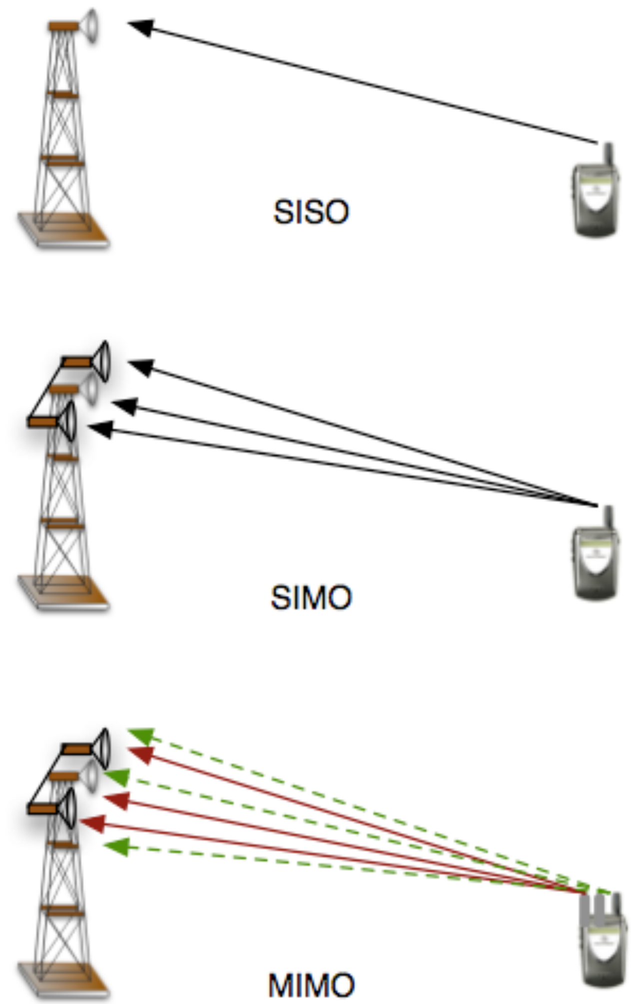
Source: IEEE Spectrum - July 2004

How can we increase data rates?

- Traditional ways
  - Reduce the symbol duration
    - Needs larger bandwidth
    - Leads to a wideband channel and frequency selectivity - irreducible error rates
  - Increase the number of bits/symbol
    - Error rates increase with M for the same E_b/N_0
- MIMO systems
  - There is no need to increase the bandwidth or power
    - But what are the limitations?
  - Use multiple transmit (Tx) and receive (Rx) antennas
  - Increases spectral efficiency to several tens of bps/Hz

What is MIMO?

- So far we have considered Single Input Single Output or SISO systems
  - Both transmitter and receiver have one antenna each
  - Simplest form of transceiver architecture
- Single input multiple-output (SIMO) systems
  - Receiver has multiple antennas
- Multiple input multiple output (MIMO) systems
  - Both transmitter and receiver have multiple antennas
  - Strictly: Each antenna has its own RF chain (modulator, encoder and so on)



Performance enhancements due to MIMO

- Diversity gain
  - Ability to receive multiple copies of the signal with independent fading
- Spatial multiplexing gain
  - Send different information bits over different antennas and recover the information
- Interference reduction
  - Reduce the region of interference thereby increasing capacity