Basic Principles of Wireless Networks (II)

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Based on slides prepared by Nima Seifi at Chalmers, based on slides from P. Viswanath/Tse, A. Goldsmith, Shiv Kalyanaraman, Tae Hyun Kim, David Gesbert & textbooks by Tse/Viswanath, A. Goldsmith, J. Andrews et al.

Outline

- Wireless channel
- Physical layer
- Mitigating the wireless channel impairments
  - Equalization
  - Spread spectrum
  - Multicarrier modulation and OFDM
  - Antenna solutions
- Multi-antenna techniques

Mitigating the Wireless Channel Impairments

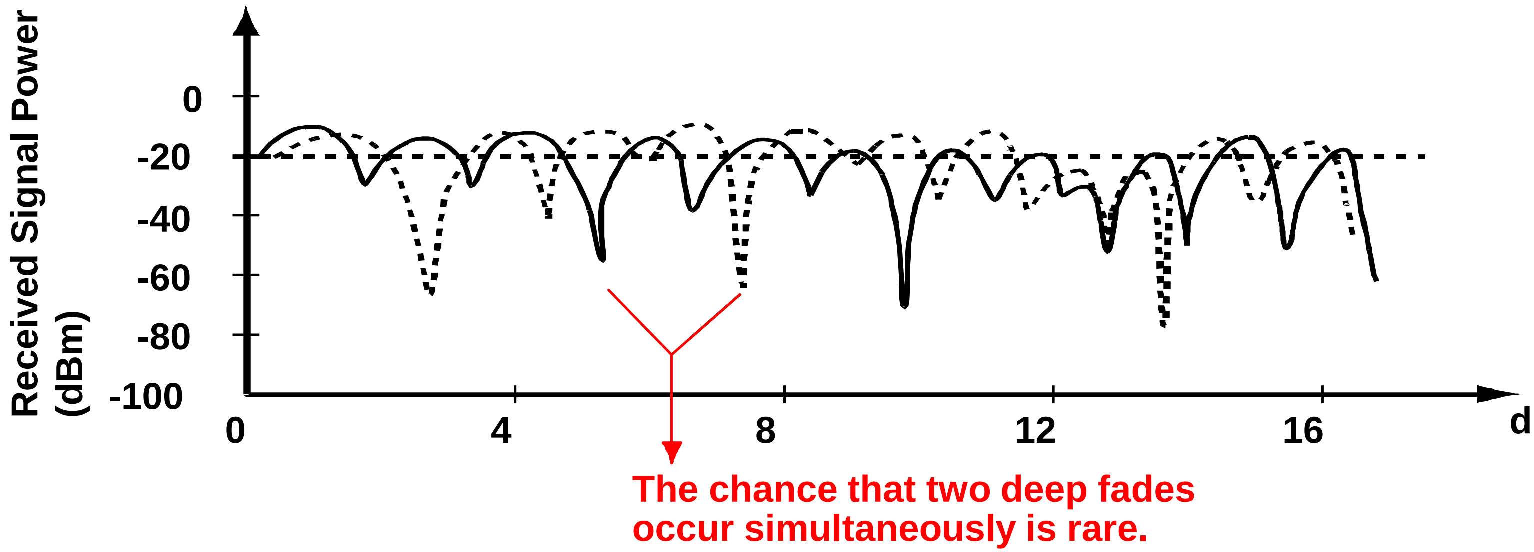
How to Overcome Limitations Imposed by the Wireless Channel?

- Flat Fading Countermeasures
  - Diversity
  - Coding and Interleaving
  - Adaptive Techniques

- Delay Spread Countermeasures
  - Equalization
  - Multicarrier Modulation
  - Spread Spectrum
  - Antenna Solution

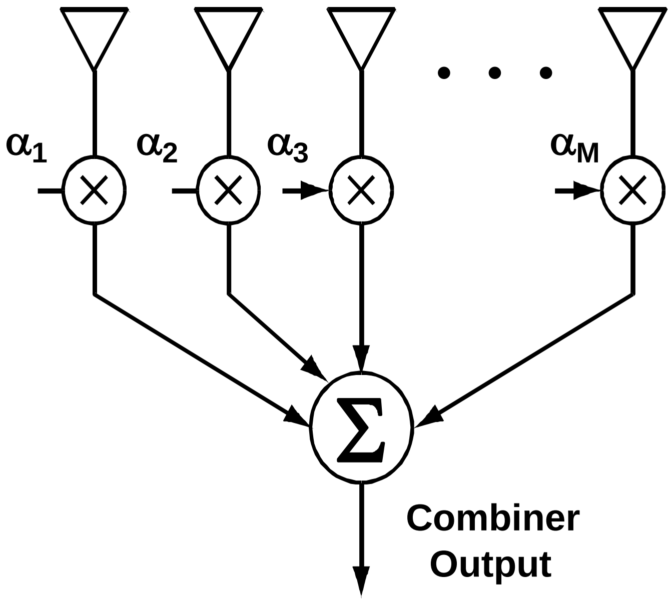
Diversity

- Independent signal paths have a low probability of experiencing deep fades simultaneously.



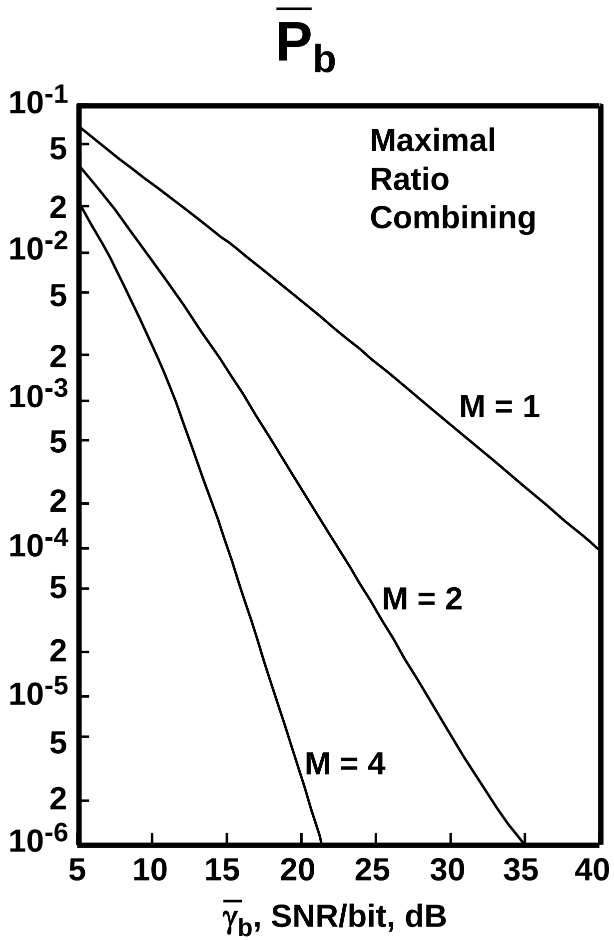
- The basic concept is to send the same information over independently fading radio
- Independent fading paths can be achieved by separating the signal in time, frequency, space, polarization, etc.

Diversity Combining Techniques



- **Selection Combining:**
  - picks the branch with the highest SNR
- **Equal-Gain Combining:**
  - all branches are coherently combined with equal weights
- **Maximal-Ratio Combining:**
  - all branches are coherently combined with weights which depend on the branch SNR.

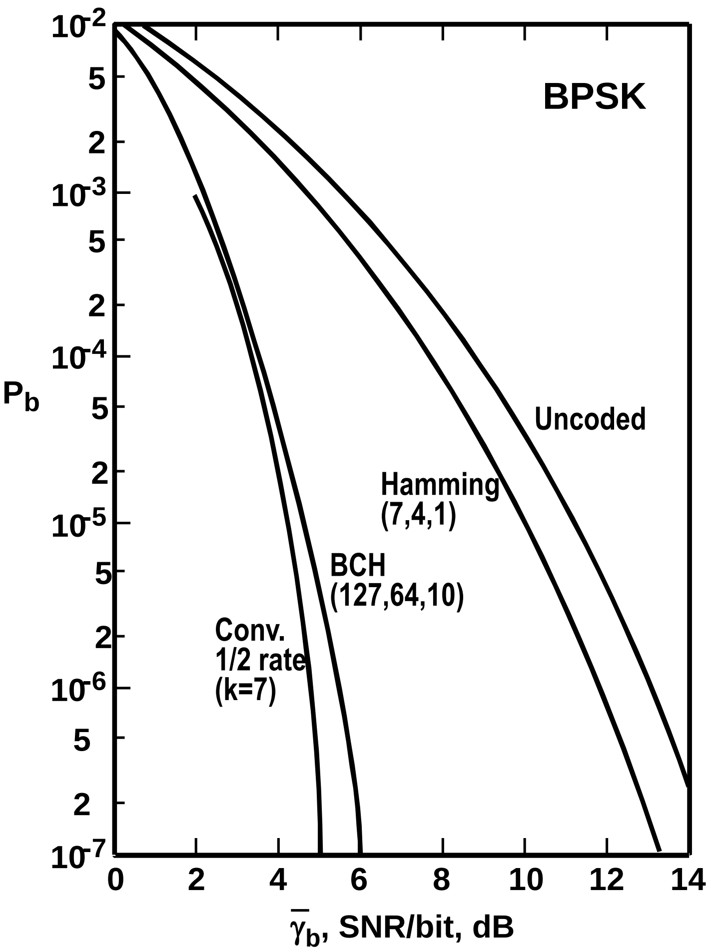
Diversity Performance



- There is dramatic improvement even with two-branch selection combining.
- The output SNR with Maximal-Ratio Combining improves linearly with the number of diversity branches, M $\Longrightarrow$ the complexity becomes prohibitive.

Channel Coding (Forward Error Correction, FEC)

Bit error probability–AWGN channel

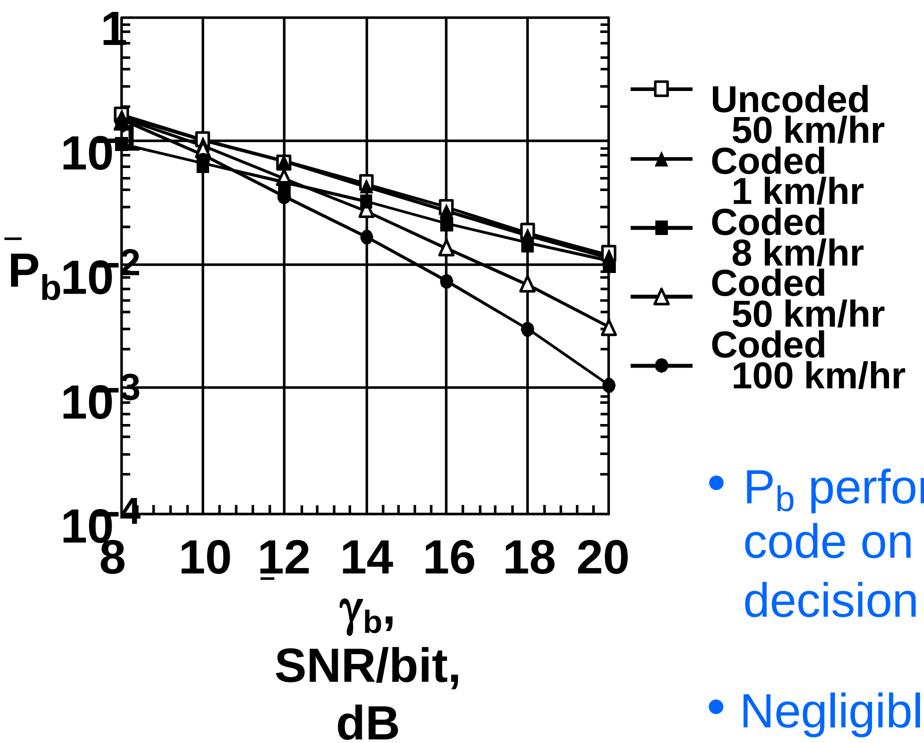


For $P_b = 10^{-6}$

Uncoded	10.5 dB
Hamming	10.0 dB
BCH	6.5 dB
Conv.	5.0 dB

- Channel coding reduces P_b by introducing redundancy in the transmitted bit stream.
- This improvement comes at the expense of increased signal bandwidth or a lower data rate.
- Fading causes burst errors. If the fading is slow enough relative to the symbol rate, coding will not be effective.

Coding Performance over Fading

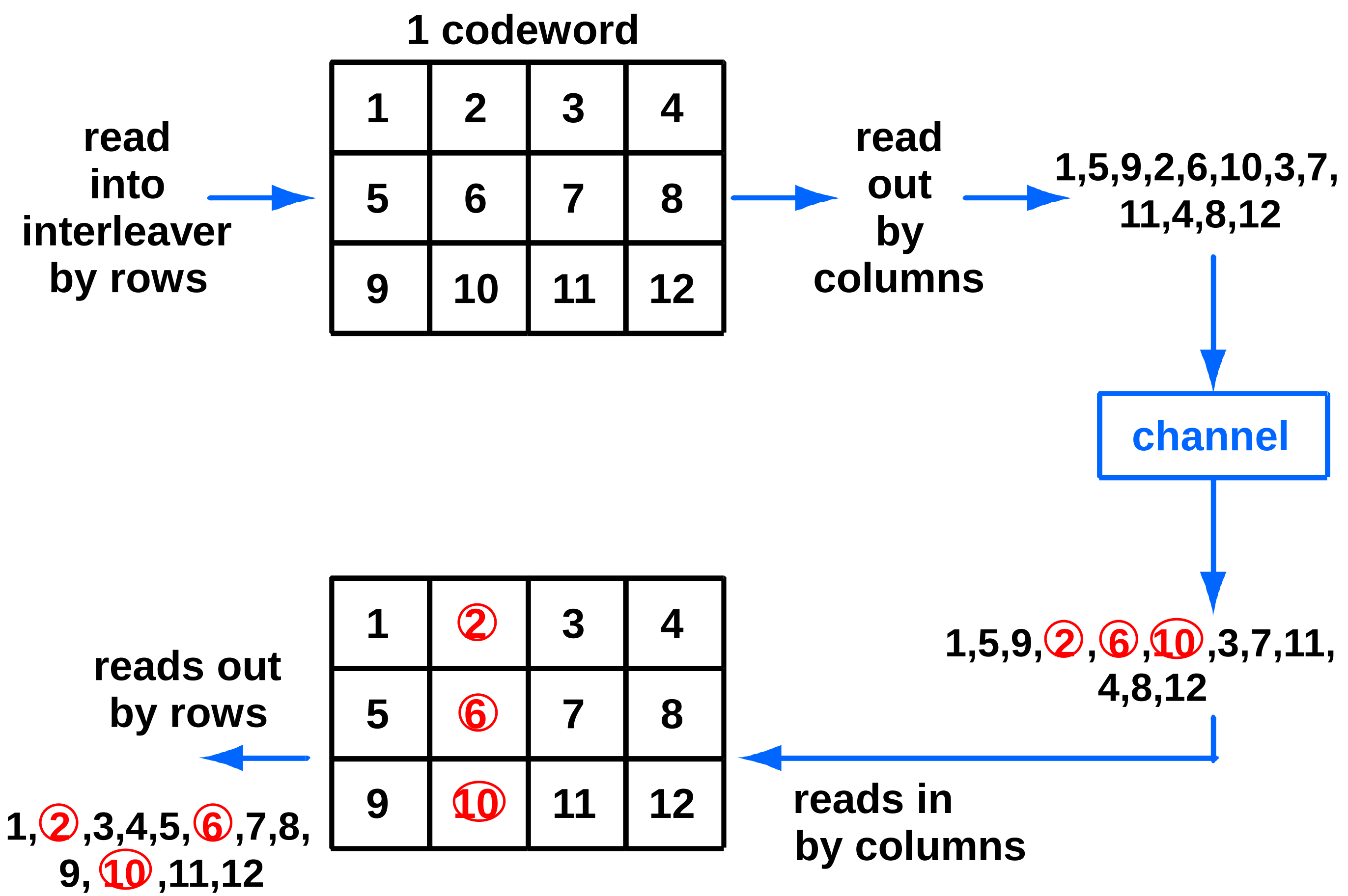


- P_b performance for the IS-136 rate-1/2 convolutional code on a simulated mobile radio channel (hard-decision decoding).
- Negligible coding gain if fading is slow compared to bit rate $\Rightarrow$ interleaving

[V. Iyengar and J. Michaelides, "Performance Evaluations of RLPs (Radio Link Protocols) for TDMA Data Services," *ITIA Contribution TR45.3.2.5/93.03.30.10,* Chicago, March 30, 1993]

Coding and Interleaving

- **The basic principle is to spread the burst errors over many code words.**

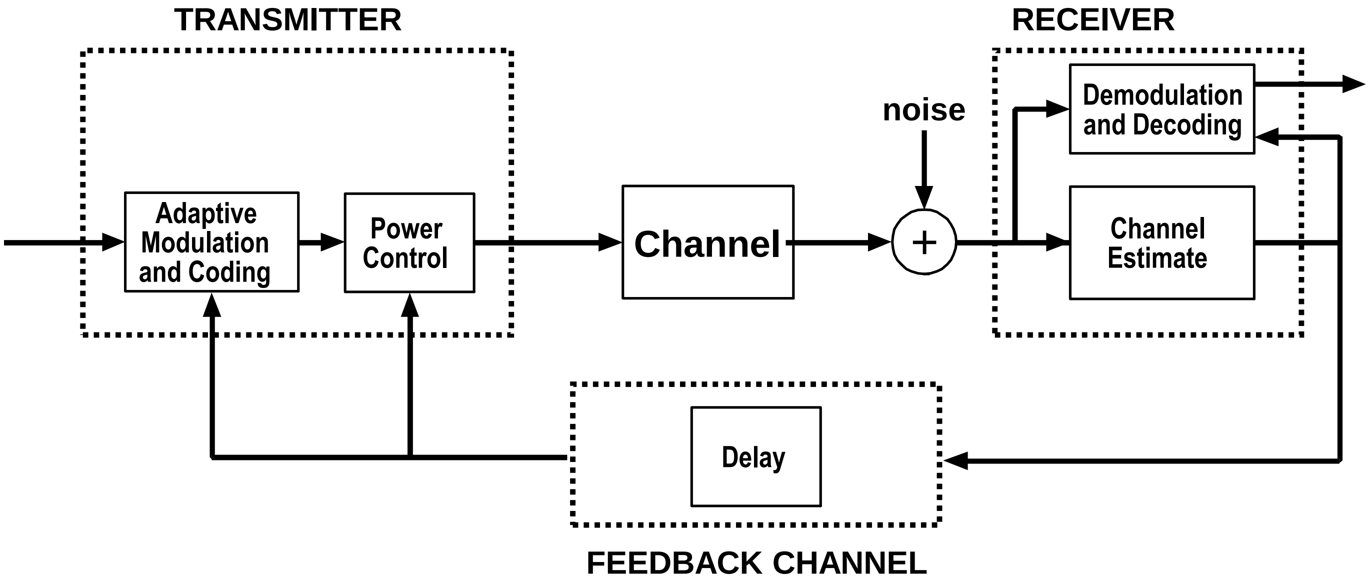


Adaptive Techniques

- **Adaptive Modulation**

- **Automatic Repeat Request**

Adaptive Modulation



- Power and/or data rate adapted at transmitter to channel conditions
- Potential for large increase in spectral efficiency
- Can be combined with adaptive compression

⇒

– requires reliable feedback channel and accurate channel estimation

– increases transmitter and receiver complexity

Automatic Repeat Request (ARQ)

- Method of "self-adapting" the data rate to the channel conditions
- Used in combination with error-detecting code
- Types: Stop-and-Wait, Go-Back-N, Selective-Repeat

$\Downarrow$

- power and spectrally inefficient
- impacts higher layer protocols
- necessary for meeting stringent P_b requirements or data
- can be combined with channel coding – Hybrid ARQ (HARQ)

Delay Spread Countermeasures

- Signal Processing
  - at the receiver, to alleviate the problems caused by delay spread (equalization)
  - at the transmitter, to make the signal less sensitive to delay spread (multicarrier, spread spectrum)

- Antenna Solutions
  - change how to inject the radio waves into the environment to reduce, or eliminate, the delay spread (distributed antenna system, small cells, directive antennas)

Equalization

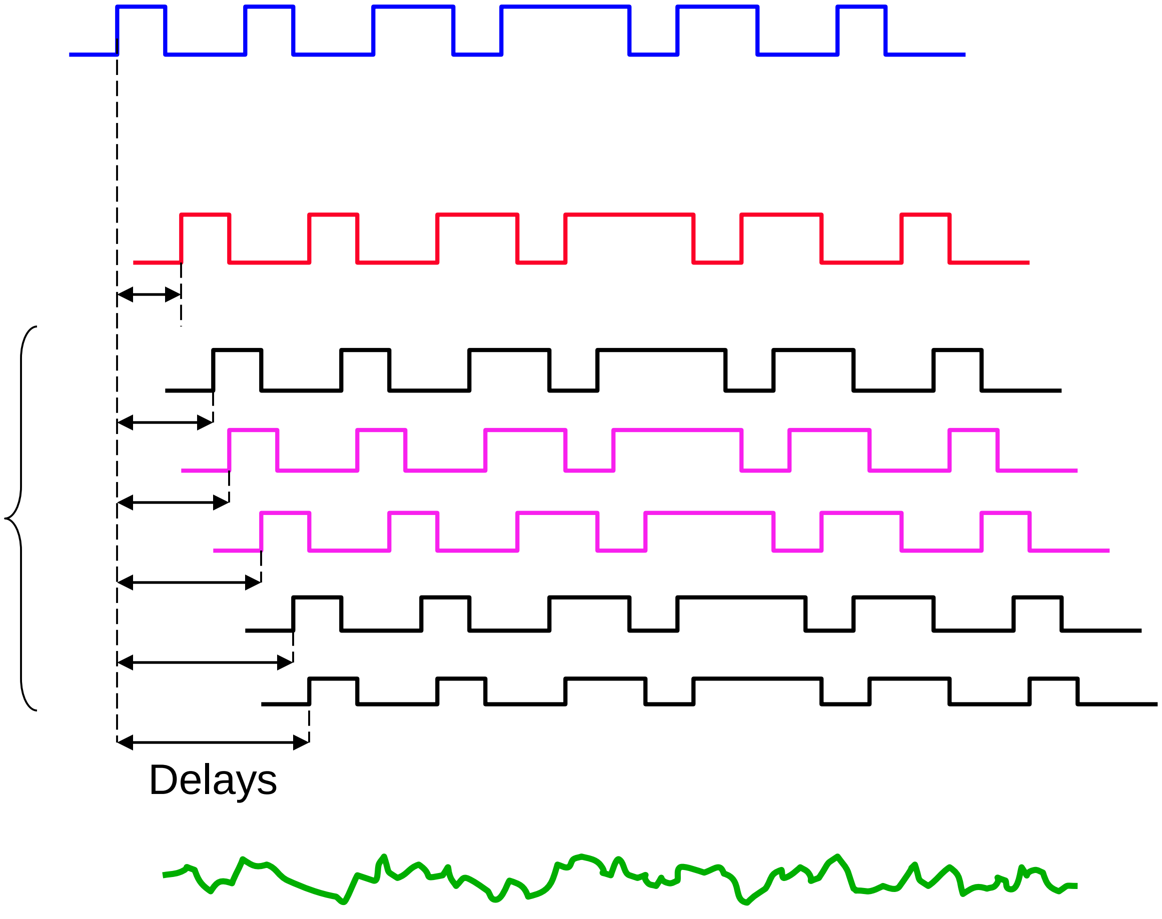
Recap: Inter-symbol Interference (ISI) due to Multi-path Fading

Transmitted signal:

Received Signals:

Line-of-sight:

Reflected:



The **symbols add up** on the channel

→ **Distortion!**

Equalization at no Doppler: Channel is an LTI Filter

- ISI due to filtering effect of the communications channel (e.g. wireless channels)
- Channels behave like band-limited filters

$$H_c(f) = \underbrace{\left|H_c(f)\right|} e^{j\underbrace{\theta_c(f)}}$$

Non-constant amplitude

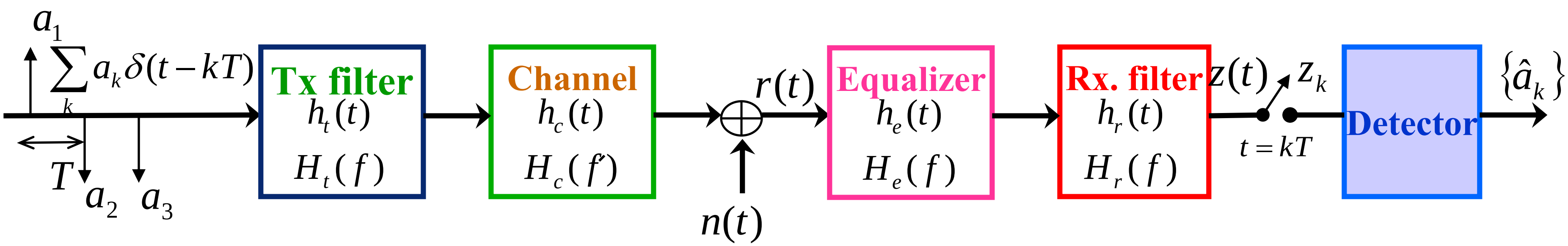
Amplitude distortion

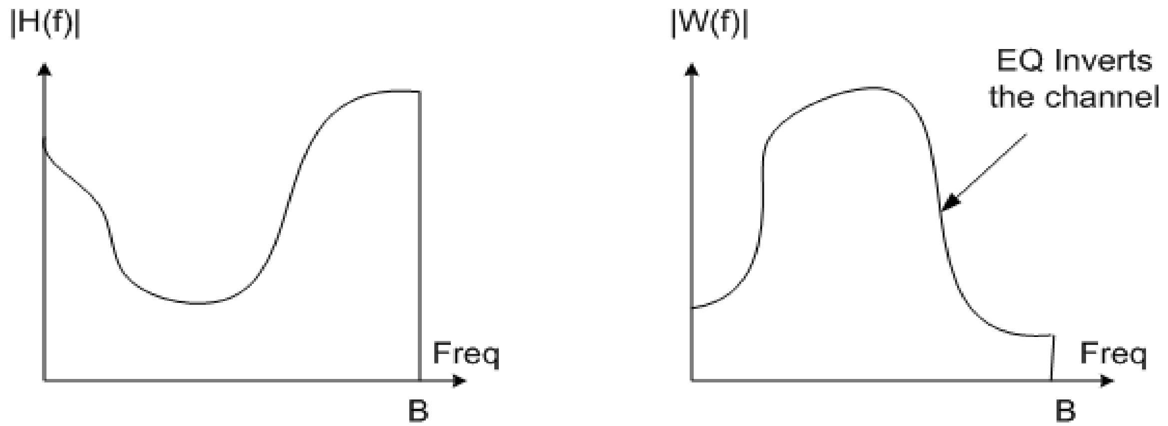
Non-linear phase

Phase distortion

Equalization Principle

- Equalizer: enhance weak freq., dampen strong freq. to flatten the spectrum
- With Doppler: Since the channel $H_c(f)$ changes with time, we need *adaptive* equalization, i.e. re-estimate channel & equalize

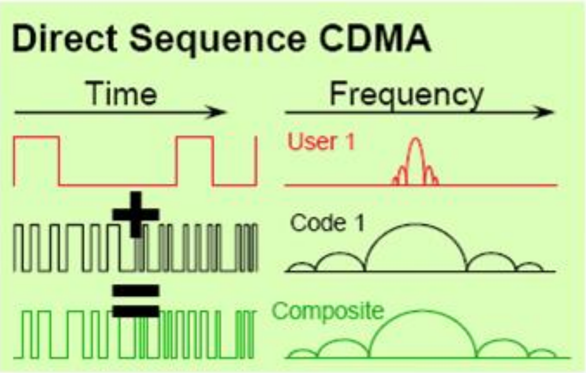


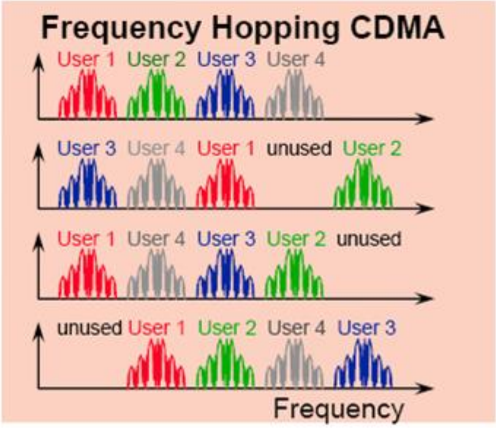


Spread Spectrum

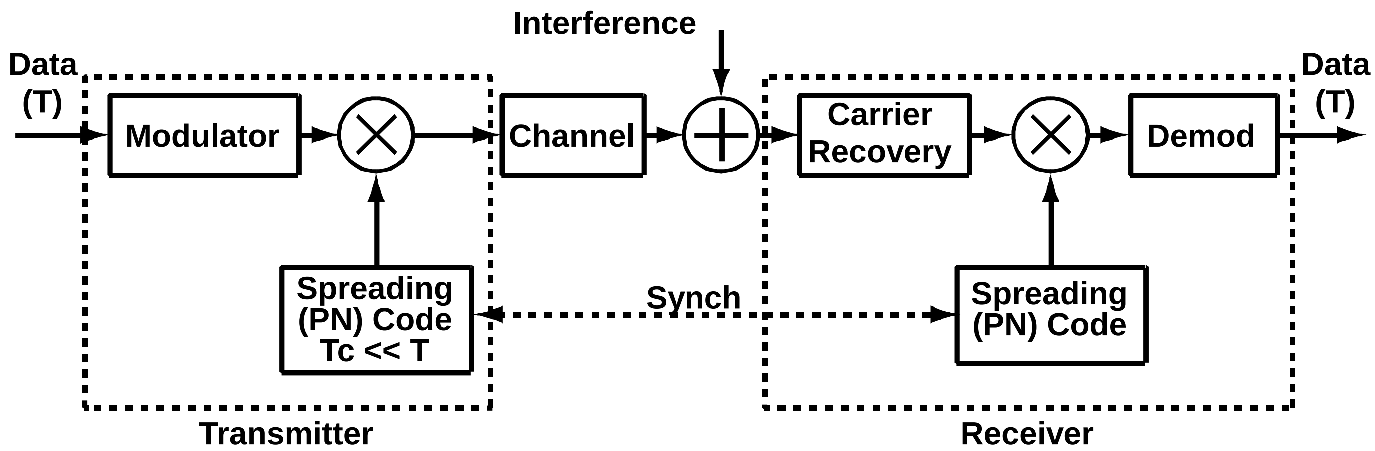
Spread Spectrum

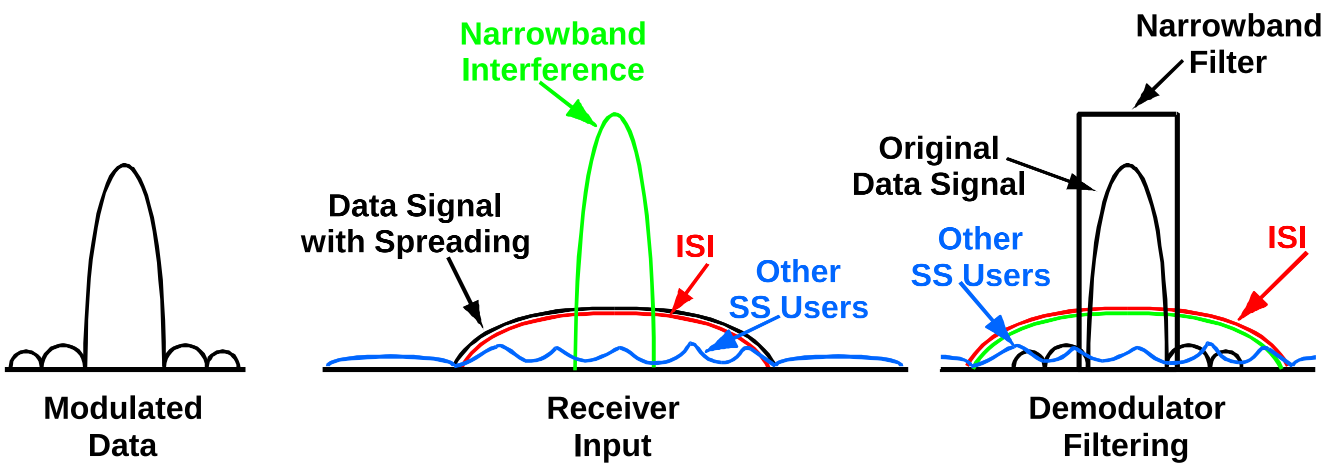
- Spread spectrum (SS) increases the transmit signal bandwidth to reduce the effects of flat fading, ISI and interference.
- There are two SS methods: direct sequence and frequency hopping
  - Direct sequence multiplies the data sequence by a faster chip sequence
  - Frequency hopping varies the carrier frequency by the same chip sequence



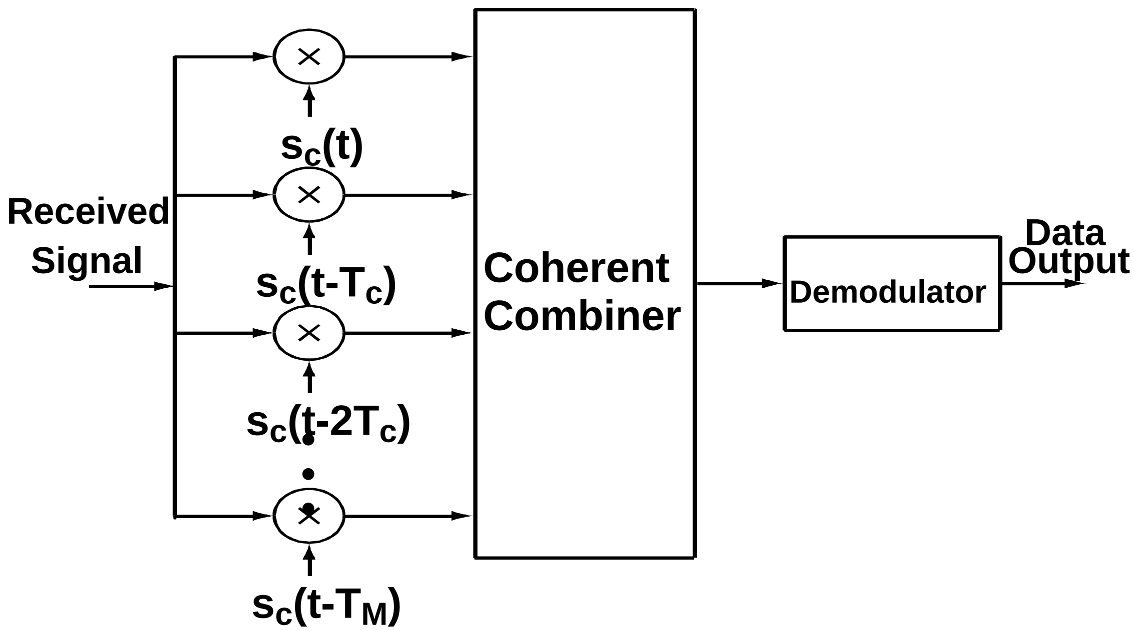


Direct Sequence Spread Spectrum





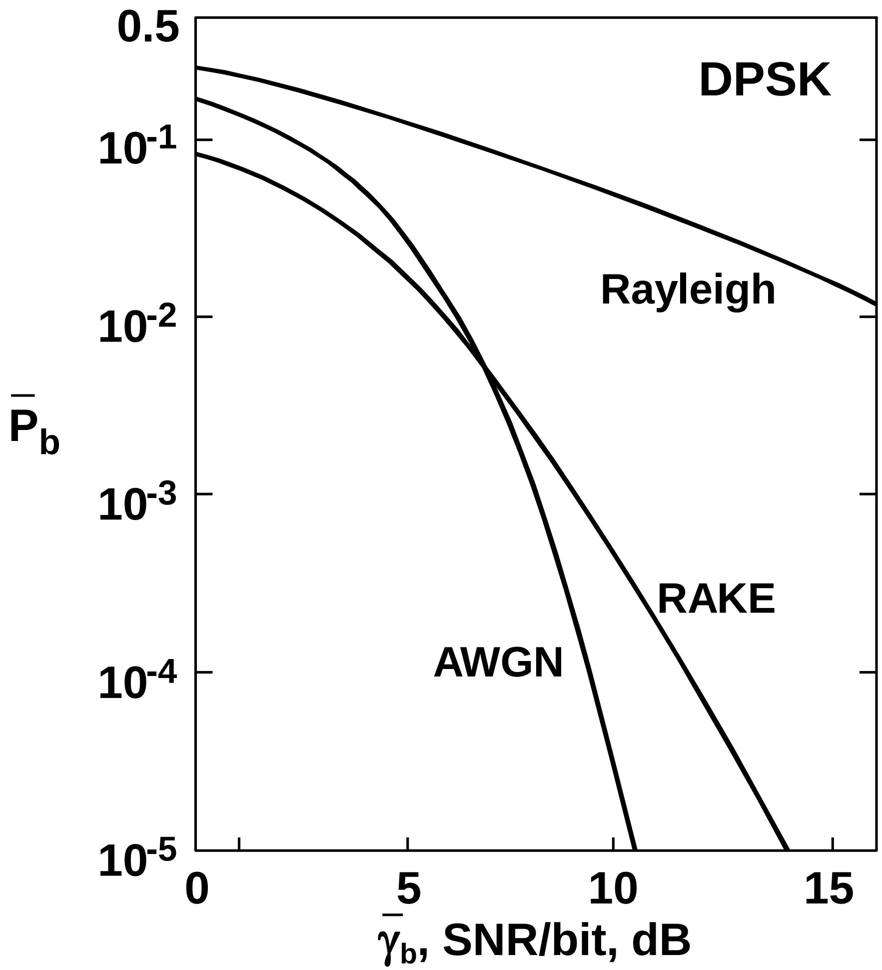
Rake Receiver



- When the chip time is much less than the rms delay spread, each branch has independent fading → equivalent to diversity combining.
- When the chip time is greater than the rms delay spread, the paths cannot be resolved ⇒ no diversity gain.

Performance of Rake Receiver

Fading Channel

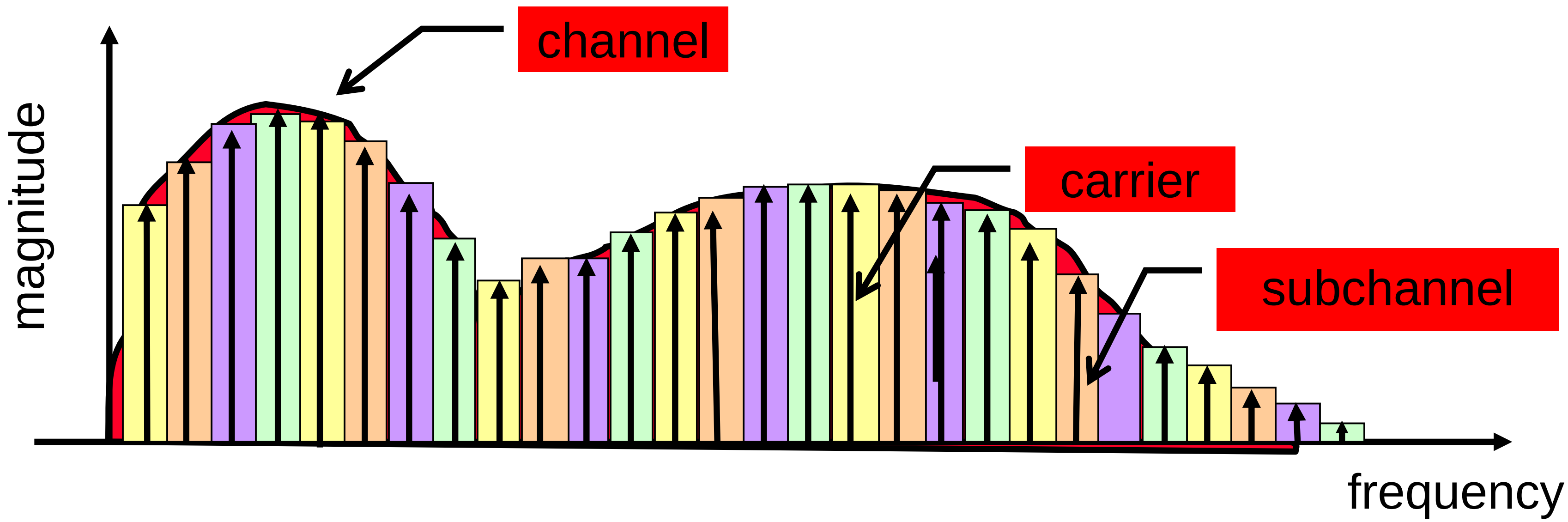


Multicarrier Modulation and OFDM

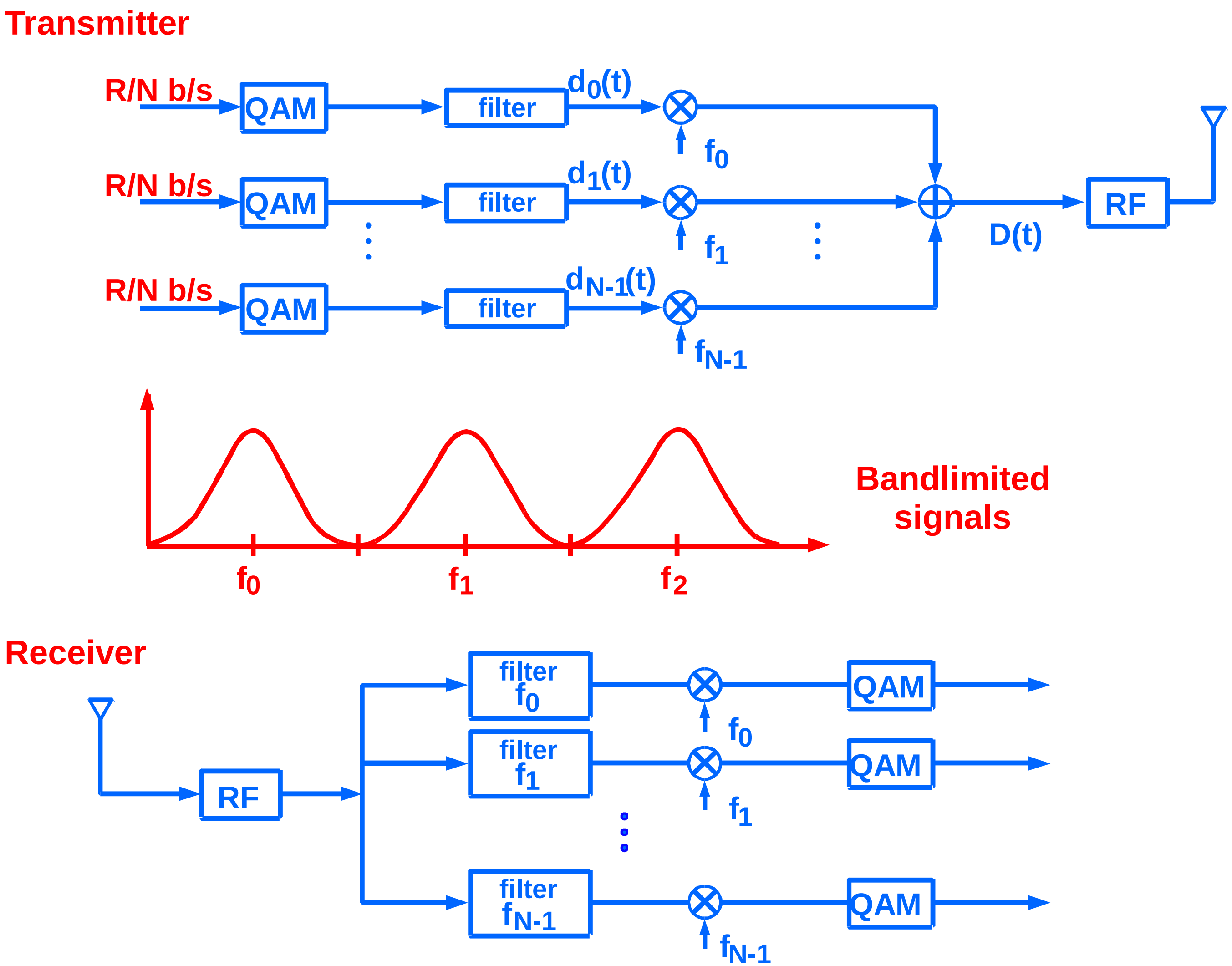
Multicarrier Modulation

- Key Idea: Since we avoid ISI if Ts > τ (delay spread), just send a large number of *narrowband* carriers

- M subcarriers each with rate R/N, also have Ts' = Ts*N. Total data rate is unchanged.



Multicarrier Modulation Cont'd

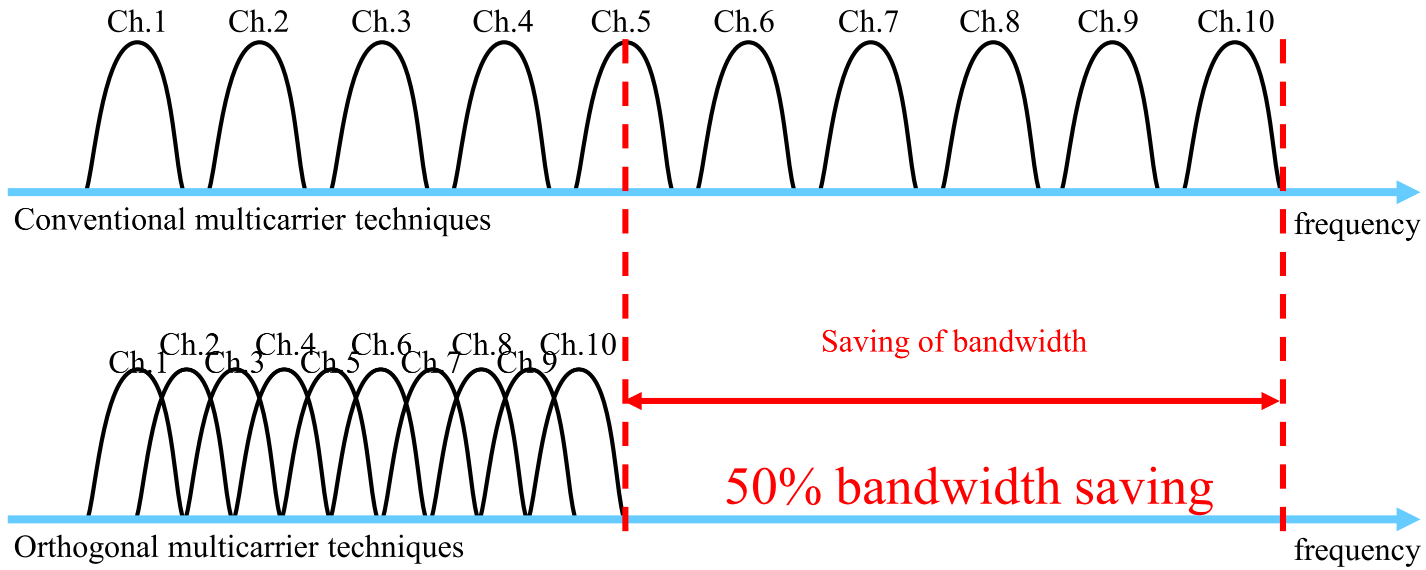


Issues w/ Multicarrier Modulation

- 1. **Large bandwidth penalty** since the subcarriers can't have perfectly rectangular pulse shapes and still be time-limited.
- 2. Very **high quality (expensive) low pass filters** will be required to maintain the orthogonality of the subcarriers at the receiver.
- 3. This scheme requires ***N* independent RF units and demodulation paths**.
- Orthogonal Frequency Division Multiplexing (OFDM) overcomes these shortcomings!

Orthogonal Frequency Division Multiplexing (OFDM)

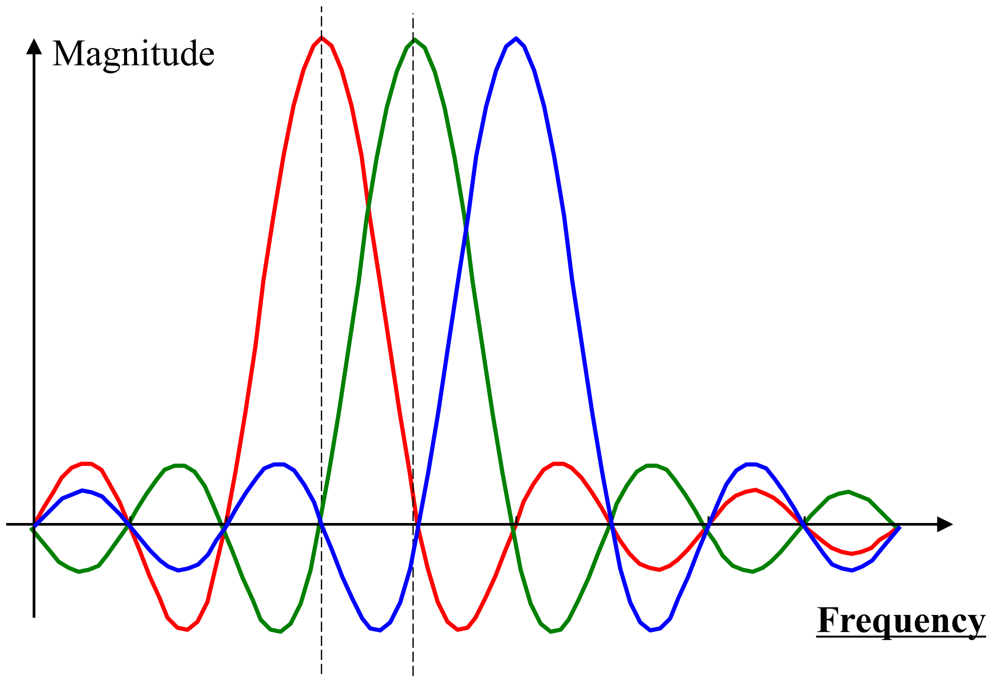
- OFDM uses a computational technique known as the Discrete Fourier Transform (DFT)
  - … which lends itself to a highly efficient implementation commonly known as the Fast Fourier Transform (FFT).
  - The FFT (and its inverse, the IFFT) are able to create a multitude of orthogonal subcarriers ***using just a single radio***.



Spectrum of the Modulated Data Symbols

- Rectangular Window of duration T_0
- Has a sinc-spectrum with zeros at $1/T_0$

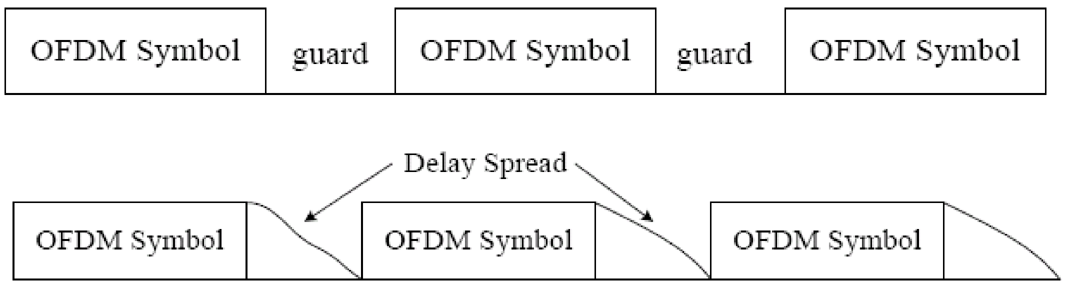
- Other carriers are put in these zeros
- → sub-carriers are orthogonal



OFDM Symbols

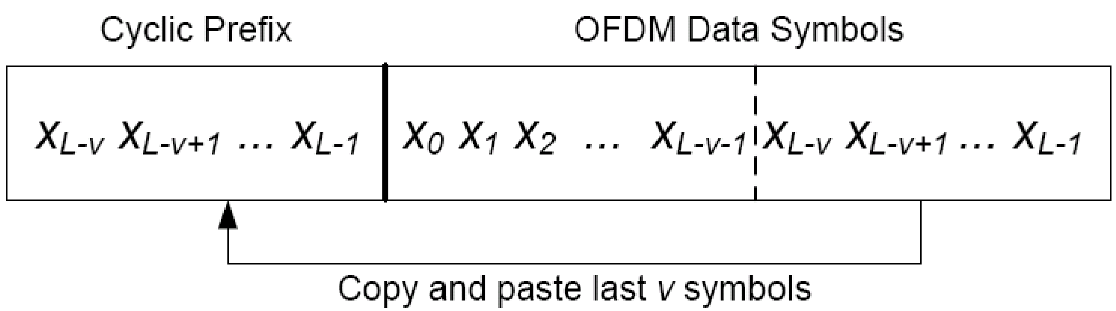
- Group ***L data symbols*** into a block known as an ***OFDM symbol***.
  - An OFDM symbol lasts for a duration of T seconds, where T = LTs.
  - Guard period > delay spread
  - OFDM transmissions allow ISI *within* an OFDM symbol, but by including a sufficiently large guard band, it is possible to guarantee that there is no interference *between* subsequent OFDM symbols.

- The next task is to attempt to remove the ISI *within* each OFDM symbol



Cyclic Prefix: Eliminate *intra*-symbol interference!

- In order for the IFFT/FFT to create an ISI-free channel, the channel must *appear to provide a circular convolution*
- If a cyclic prefix is added to the transmitted signal, then this creates a signal that appears to be $x[n]_L$, and so $y[n] = x[n] * h[n]$.



Cyclic Prefix Cont'd

$$\mathrm{x}_{cp} = [\underbrace{x_{L-v}\ x_{L-v+1}\ \ldots\ x_{L-1}}_{\text{Cyclic Prefix}}\ \underbrace{x_0\ x_1\ \ldots\ x_{L-1}}_{\text{Original data}}].$$

$\mathrm{y}_{cp} = \mathrm{h} * \mathrm{x}_{cp}$, h is a length $v+1$ vector

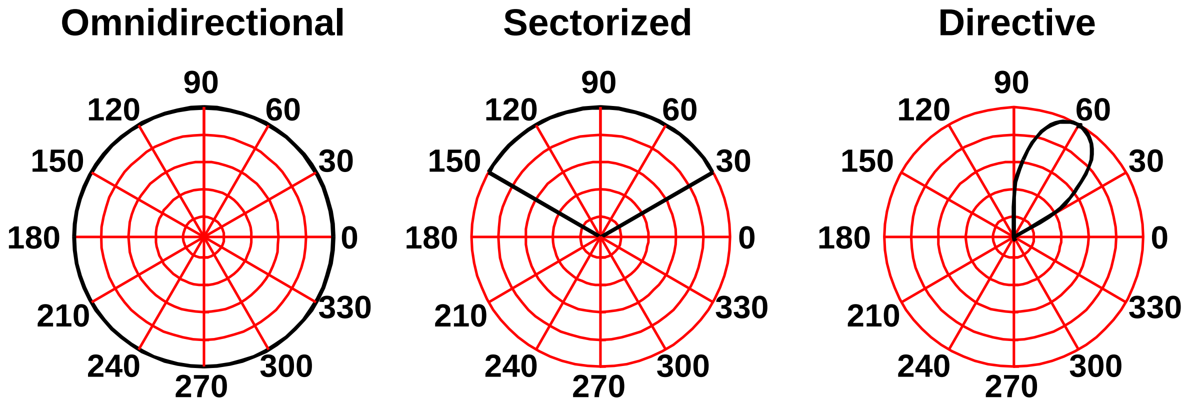
output y_{cp} has $(L+v)+(v+1)-1 = L+2v$ samples.

- The first v samples of $\mathbf{y}_{cp}$ interference from preceding OFDM symbol => discarded.
- The last v samples disperse into the subsequent OFDM symbol => discarded.
- This leaves exactly L samples for the desired output y, which is precisely what is required to recover the L data symbols embedded in x.

Antenna Solutions

Goal: Reduce (or eliminate) delay spread

- Distributed Antenna System
- Very Small Cells $\Rightarrow$ antenna in every room/ street corner
- Sectorization
- Directive Antennas/Beam Steering



Summary of Countermeasures for Wireless Channel Impairments

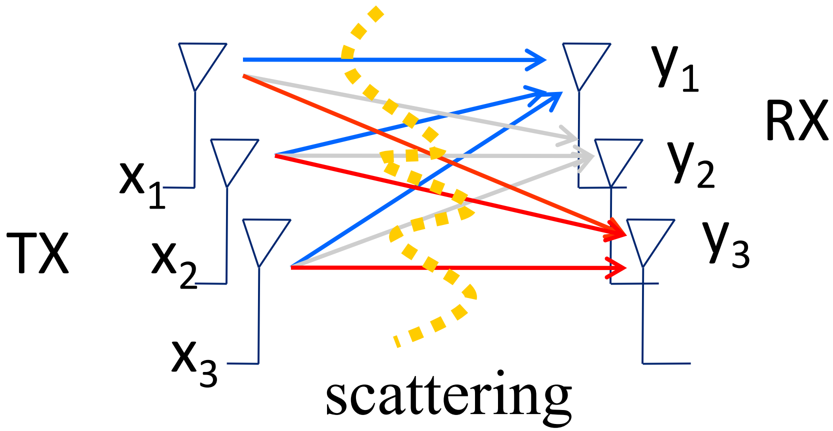
- Diversity
- Coding and Interleaving
- Adaptive Techniques
- Equalization
- Spread Spectrum
- Multicarrier
- Antenna Solutions

$\Rightarrow$ These techniques can be combined.

Multi-Antenna Techniques

Multiple-Input Multiple-Output (MIMO)

- Expanding resources in space dimension
  - key idea: different propagation path for each signal from different transmit antennas



$y_1 = h_{11}x_1 + h_{12}x_2 + h_{13}x_3$

$y_2 = h_{21}x_1 + h_{22}x_2 + h_{23}x_3$

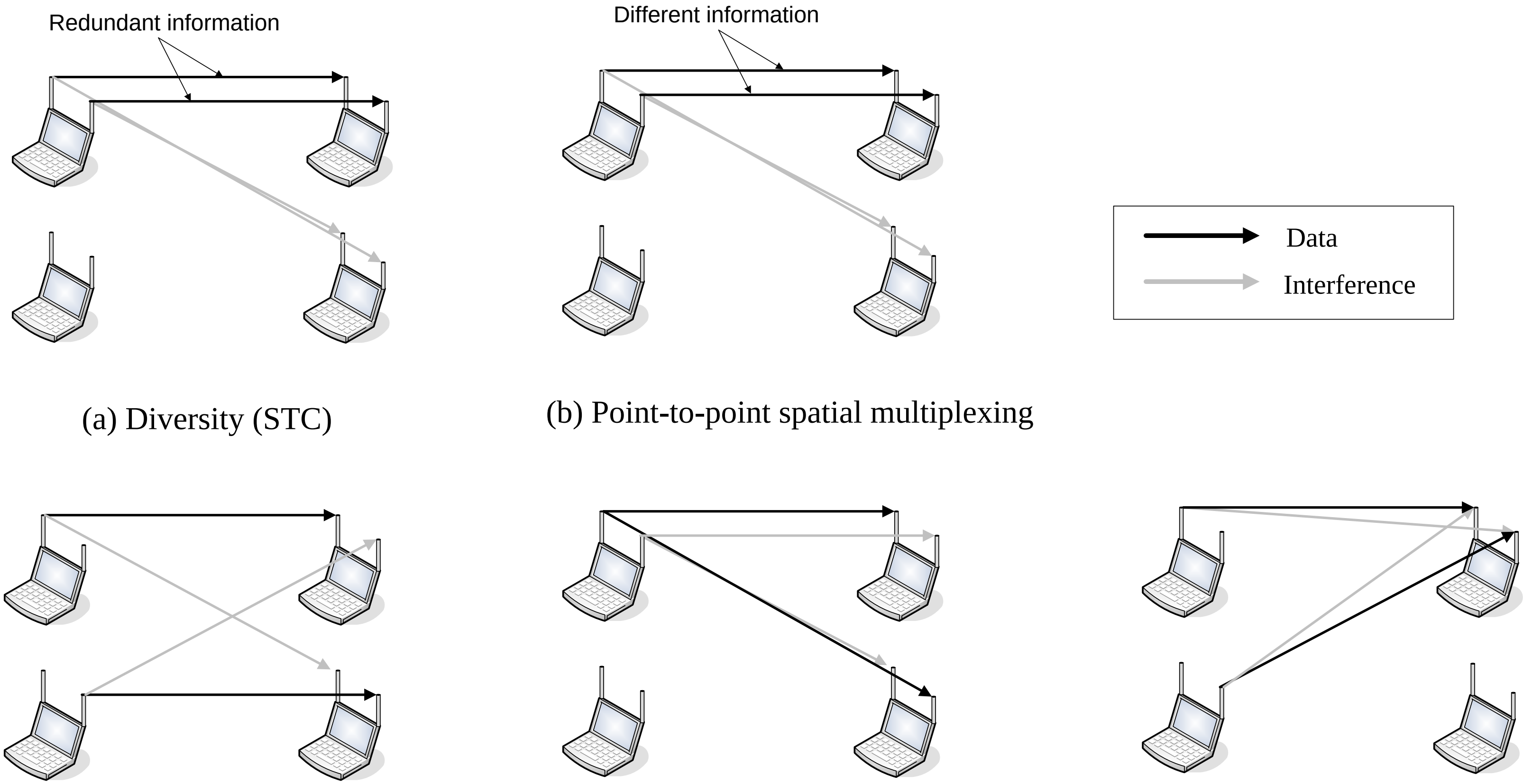
$y_3 = h_{31}x_1 + h_{32}x_2 + h_{33}x_3$

matrix form: $\mathbf{y} = \mathbf{H}\mathbf{x}$

MIMO Leverages

- **Array gain**
  - by combining multiple signals
- **Diversity**
  - Transmitting same information redundantly
  - Usually in a form of space-time (block) coding
- **Spatial multiplexing/Spacial multiple access**
  - Transmitting different info, creating multiple spatial streams to one or several users
- **Interference cancellation**
  - Two methods
    - Decoding and discarding signals not destined to oneself
    - Using spatial streams which are orthogonal to each other
  - Can be seen as one method of spatial multiplexing

What Can We Do with MIMO?



(a) Diversity (STC)

(b) Point-to-point spatial multiplexing

(c) Concurrent transmission by interference cancellation

(d) Multi-user MIMO - MIMO broadcast

(e) Multi-user MIMO – MIMO multiple access

Summary

- Mitigating the wireless channel impairments
  - **Equalization**: Compensate the channel response
  - **Spread spectrum**: Utilize frequency diversity
  - **Multicarrier modulation and OFDM**: Adapt to frequency response
  - **Antenna solutions**: Spatially direct RF signal
- Multi-antenna techniques
  - Interference rejection
  - Spatial reuse to boost performance