

Radio-Frequency IC Design

Lecture: Digital Communications

ELEC 404

Acknowledgement: B. Razavi's lecture notes



©Sudip Shekhar

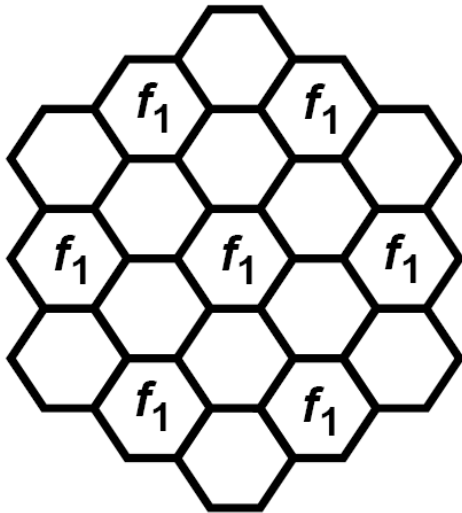
Not to be copied, used, or revised without explicit written permission from the copyright owner.

Some RF Communication Concepts

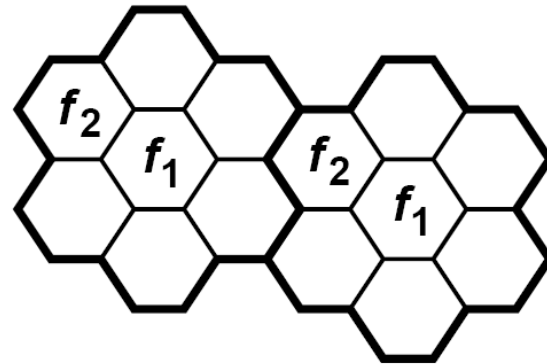
- **Cellular System**
- **Co-Channel Interference (CCI)**
- **Handoff**
- **Multipath and Delay-spread**
- **OFDM**
- **Spectral regrowth**
- **Time-Division Duplexing (TDD) and Frequency-Division Duplexing (FDD)**
- **Multiple Access (TDMA, FDMA, DS-CDMA)**
- **Diversity, including Spatial Diversity**
- **Beamforming**
- **Spatial Multiplexing**
- **RF Standard Specifications**

Mobile RF Com. : Cellular System

- Immediate neighbors (UEs) cannot utilize same frequency
- UEs in each cell served by a base station (BS) through Uplink and Downlink channels.
- BSs controlled by a “mobile telephone switching office” (MTSO)



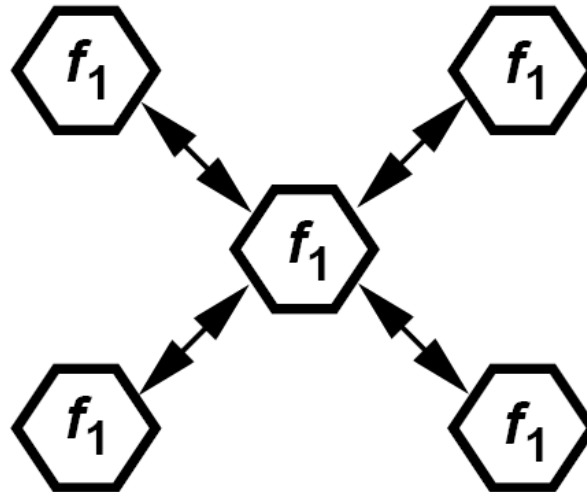
Simple Cellular System



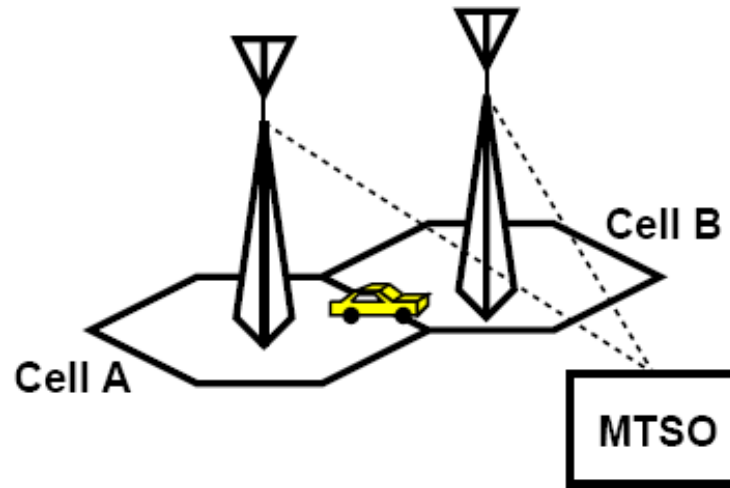
More efficient 7-cell reuse pattern

Co-Channel Interference

- CCI → Interference between two cells using the same frequency
- Depends on the ratio of the distance between two co-channel cells to the cell radius
- Independent of the transmitted power
- Given by the frequency reuse plan
- Ratio ≈ 4.6 for the 7-cell pattern → Signal/CCI ratio of 18dB

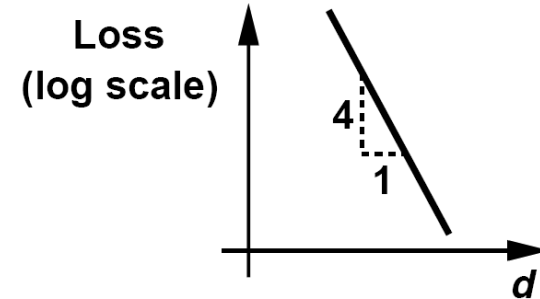
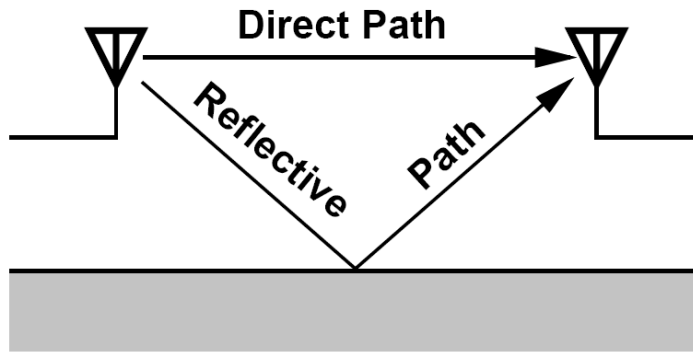


Hand-off

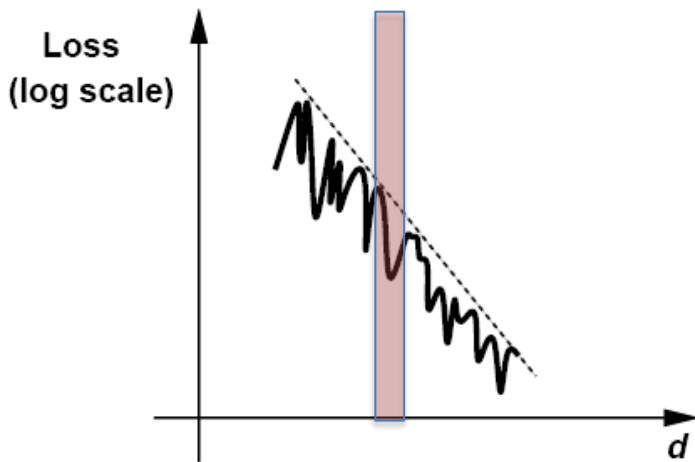


- When a UE roams from cell A to cell B, the channel must also change since adjacent cells do not use the same group of frequencies.
- Once the level received by BS in cell A drops below a threshold, MTSO does the handoff to BS in cell B hoping that the latter is close enough → probability of dropped calls.
- 2G cellular systems allow the UE to measure the RX signal level from different BSs, thus performing hand-off when the path to the second BS has sufficiently low loss.

Path Loss and Multipath Fading

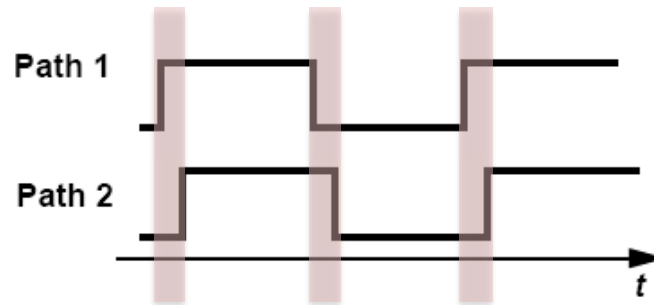
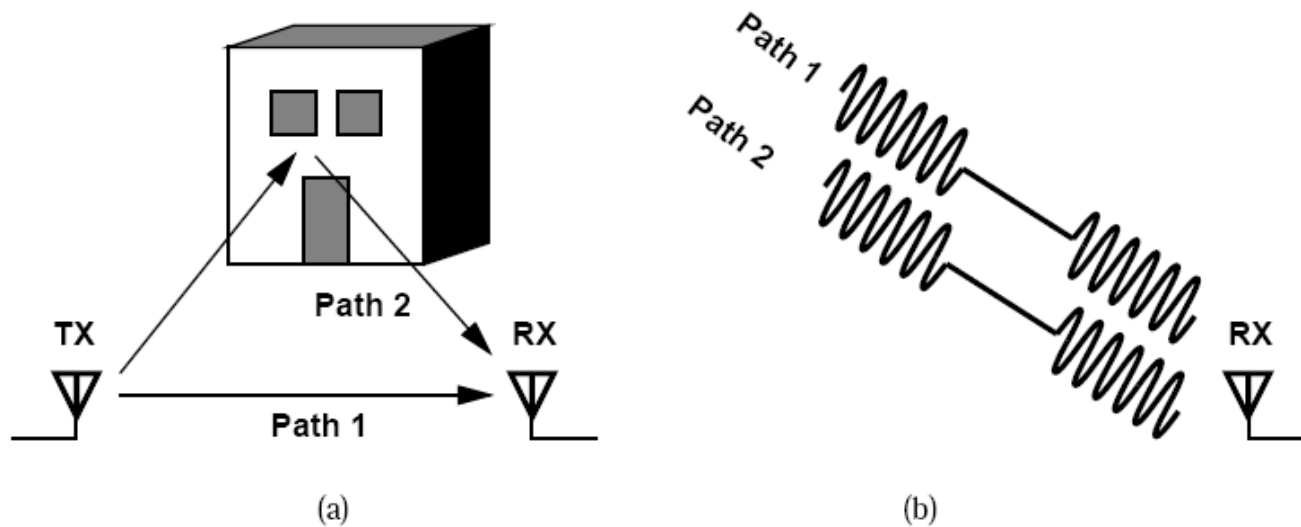


- Direct path: signals experience a power loss $\propto d^2$
- Reflective path: loss increases $\propto d^4$



- Multipath fading: two signals possibly arriving at the RX with opposite phases and roughly equal amplitudes \rightarrow net RX signal may be very small.
- **Enormous variations in the signal level as the RX moves by a fraction of the wavelength.**
- Fading and/or ISI
- TX output power and RX DR must accommodate overall path loss ($\propto d^2$ to d^4) *and* multipath fading

Multipath Propagation & Delay Spread

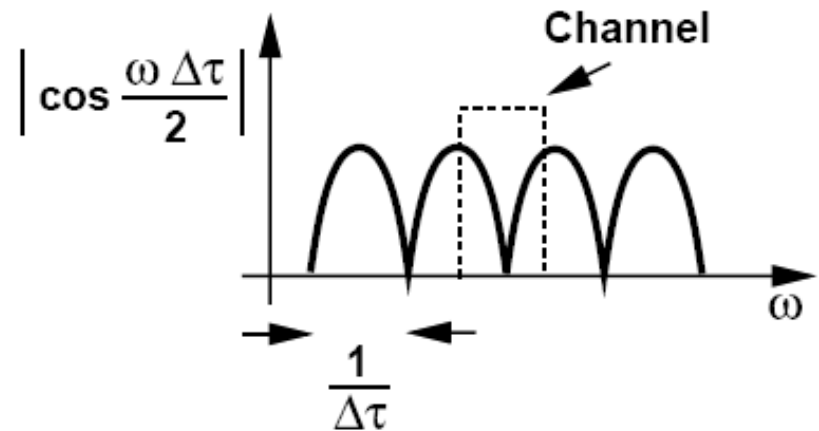
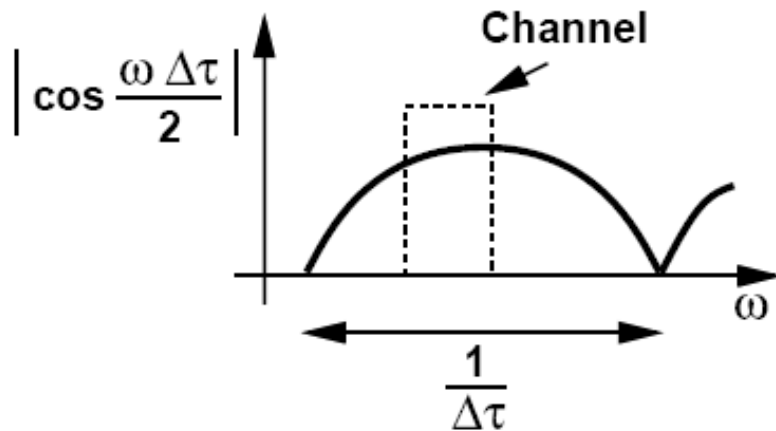


- Phase shift in reflected wave(s) depends on path length and reflecting material
→ waves arrive @ RX with vastly different delays, or a large *delay spread*.
- Multipath Propagation may lead to considerable Inter-Symbol Interference (ISI)
- Higher bit rate → larger delay spread → worse ISI

Delay Spread

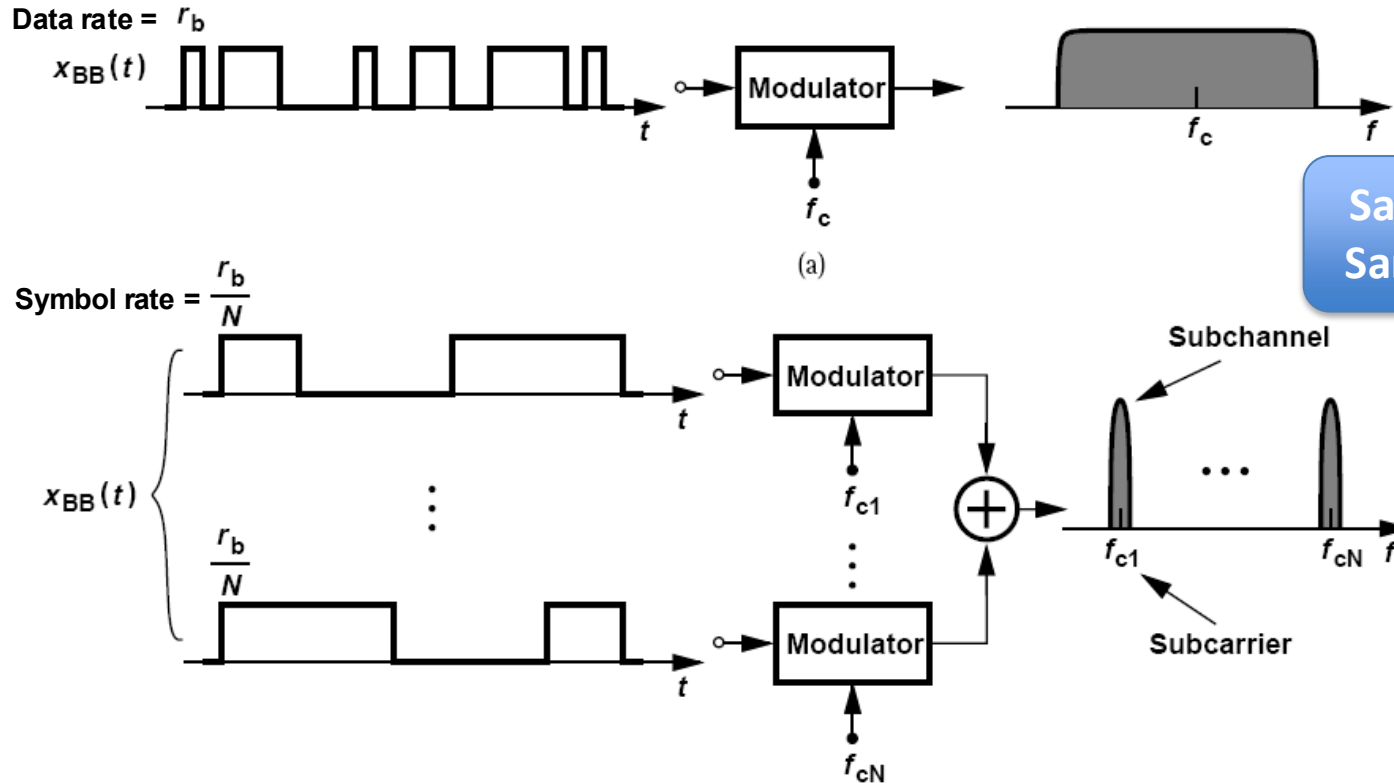
- Larger delay spread \rightarrow worse ISI
- Two signals in a multipath environment can experience roughly equal attenuations but different delays.

$$x(t) = A \cos \omega(t - \tau_1) + A \cos \omega(t - \tau_2) = 2A \cos[(2\omega t - \omega\tau_1 - \omega\tau_2)/2] \cos[\omega(\tau_1 - \tau_2)/2]$$



- Small delay spread yield a relatively flat fade whereas large delay spreads introduce considerable variation in the spectrum

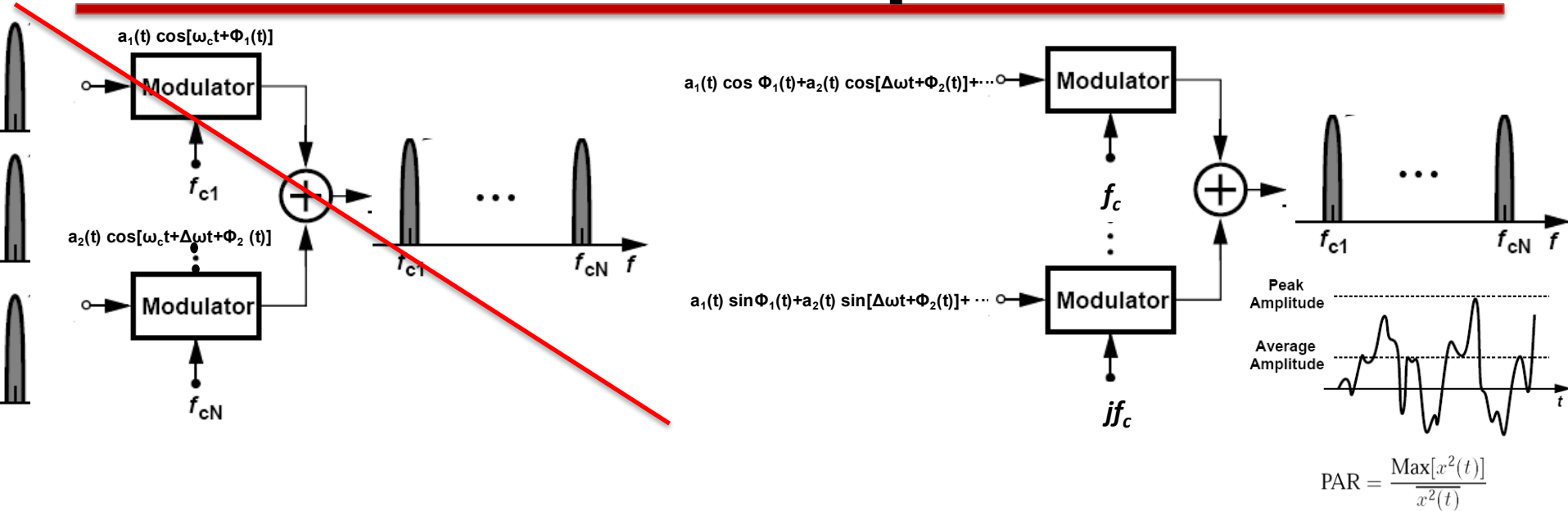
OFDM Mitigating Multipath



- OFDM: Orthogonal Frequency Division Multiplexing
- DeMux BB data by N , then transmit these N orthogonal subchannels on N different subcarrier frequencies.
- Each subcarrier contains a low-rate data stream \rightarrow can tolerate a larger delay spread

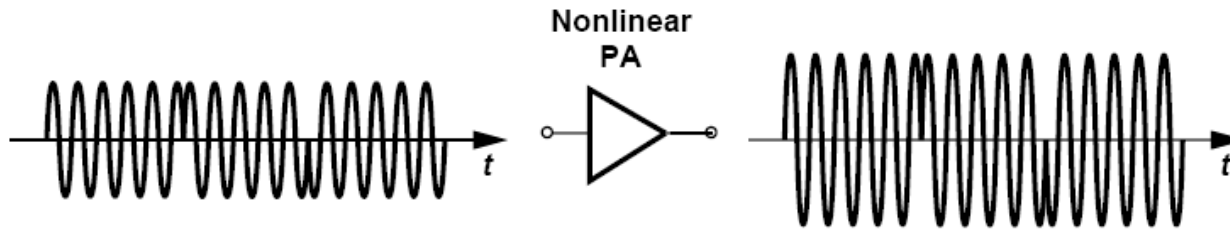
S. B. Weinstein, "The history of orthogonal frequency-division multiplexing," IEEE Comm. Mag., Nov. 2009.

OFDM Practical Implementation



- Avoid tens of carrier frequencies and modulators (oscillators, mixers)
- Perform subchannel modulations in the digital BB and subsequently convert to analog form with a quadrature modulator and an LO of f_c .
- OFDM exhibits large envelope variations even if the modulated waveform in each subchannel does not because summation of subchannels can be constructive/destructive with large/small amplitude.
- Severe linearity requirements on PA \rightarrow large PAR (peak-to-average ratio).
- Deadly combo for PAR – BB pulse shaping, AM (eg. QAM), OFDM

Spectral Regrowth $y(t) = \alpha_3 x^3(t) + \dots$



$$x(t) = A(t) \cos[\omega_c t + \phi(t)]$$

$$A(t) = A_c$$

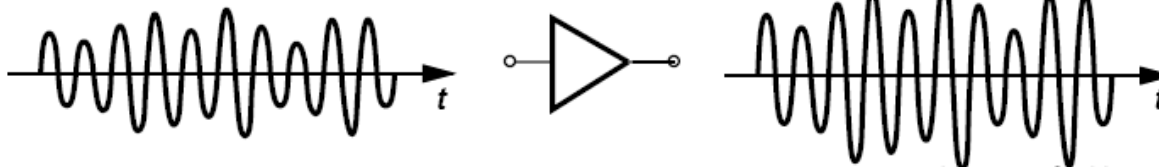


$$y(t) = \alpha_3 A_c^3 \cos^3[\omega_c t + \phi(t)] + \dots$$

$$= \frac{\alpha_3 A_c^3}{4} \cos[3\omega_c t + 3\phi(t)] + \frac{3\alpha_3 A_c^3}{4} \cos[\omega_c t + \phi(t)]$$



Nonlinear PA

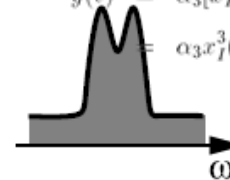


$$x(t) = x_I(t) \cos \omega_c t - x_Q(t) \sin \omega_c t$$



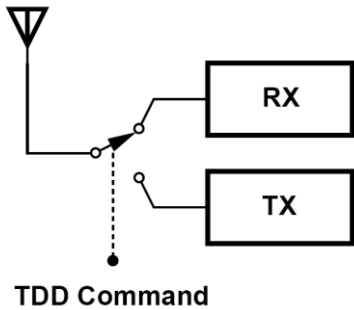
$$y(t) = \alpha_3 [x_I(t) \cos \omega_c t - x_Q(t) \sin \omega_c t]^3 + \dots$$

$$= \alpha_3 x_I^3(t) \frac{\cos 3\omega_c t + 3 \cos \omega_c t}{4} - \alpha_3 x_Q^3(t) \frac{-\cos 3\omega_c t + 3 \sin \omega_c t}{4}$$

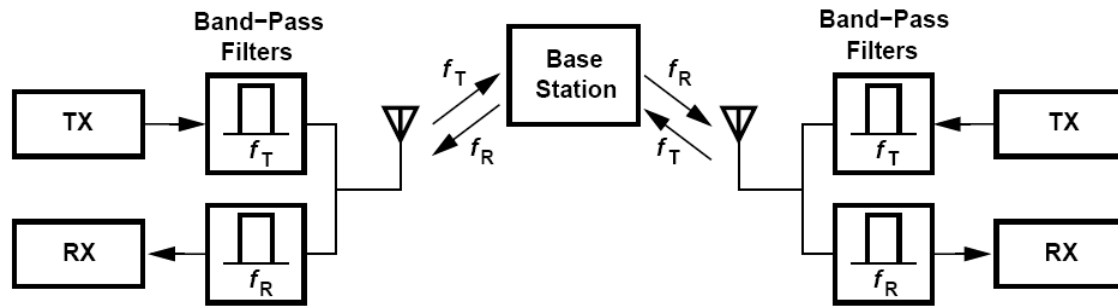


- **Constant Envelope: Shape of Spectrum unchanged**
- **Variable Envelope: Spectrum grows**

Time & Frequency Division Duplexing



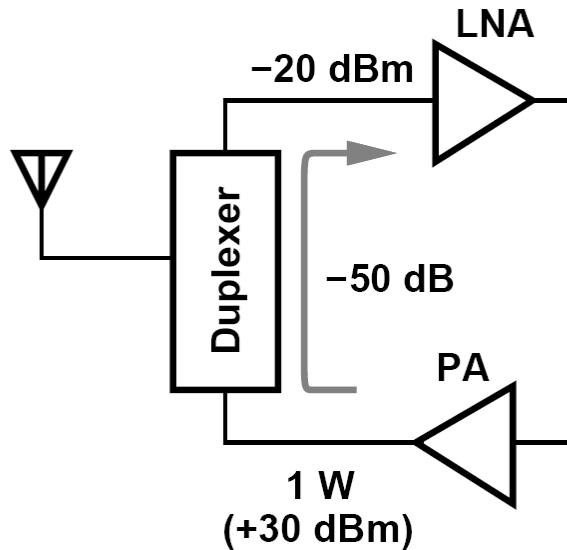
- TDD: same frequency band utilized for both TX and RX paths but the system transmits for half of the time and receives for the other half.
- Switch fast enough to be transparent to the user.



- FDD: employ two different frequency bands for the TX and RX paths → UE-TX/UE-RX isolation
- BPFs at f_T and f_R together are called Duplexer

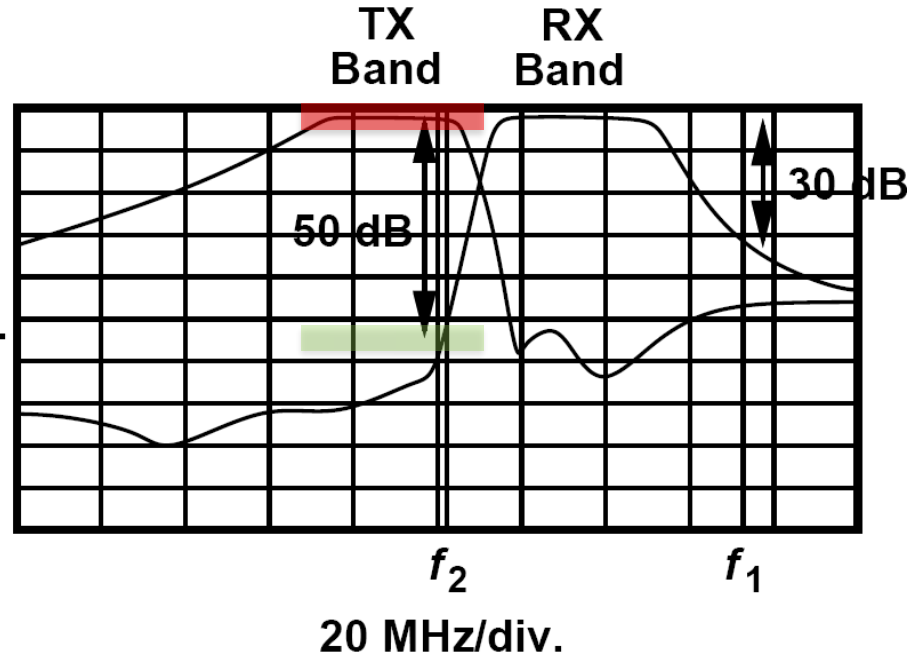
TDD	FDD
Two paths (RX, TX) do not interfere because TX is turned off during RX reception.	Components of the TX signal that leak into the RX band are attenuated by typically only about 50dB.
Allows direct (peer-to-peer) communication between two transceivers	Owing to the trade-off between the loss/Q of filters, the loss of the duplexer is typically quite higher than that of a TDD switch.
1dB loss in TX path of switch → 80% of signal power reaches antenna	3dB loss in RX path of duplexer → 3dB NF degradation 3dB loss in TX path of switch → 50% of signal power reaches antenna
Strong signals generated by all of the nearby mobile transmitters fall in the receive band, thus desensitizing the receiver.	Spectral leakage to adjacent channels in the TX output

TX-RX Feedthrough



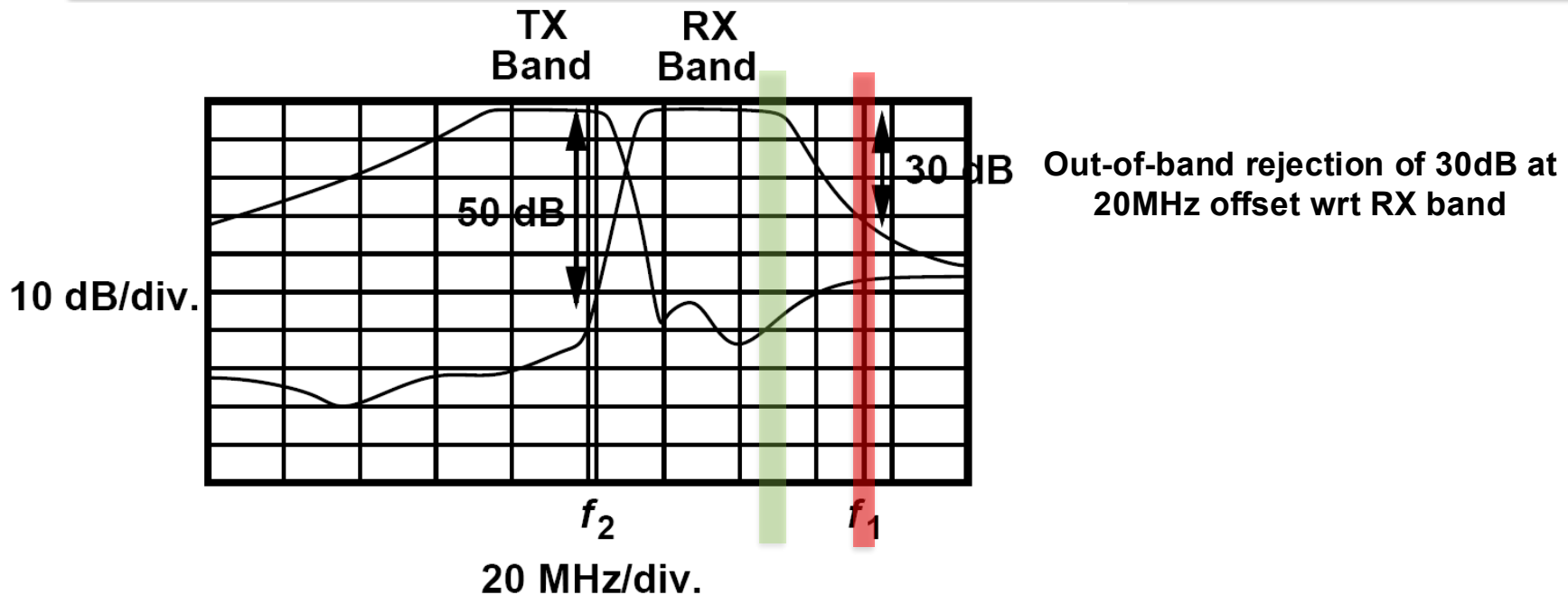
10 dB/div.

TX output near f_2 attenuated by only 50dB as it leaks to the RX.



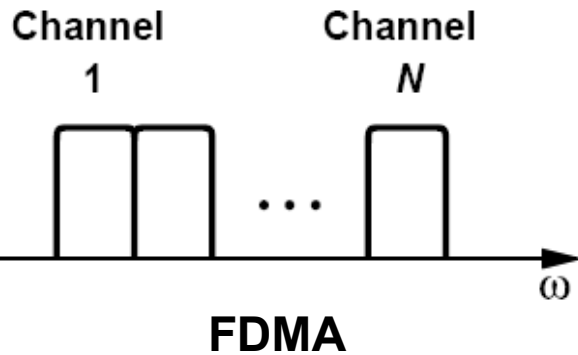
- In full-duplex DS-CDMA, the TX and the RX operate concurrently.
- With a 1-W TX power, the leakage sensed by LNA can reach -20dBm, dictating a substantially higher RX compression point.

Duplexer Characteristics



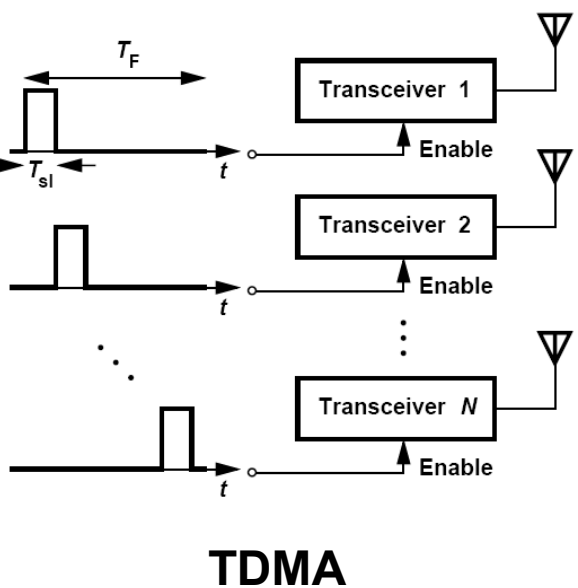
- Front-end BSF suffers from a trade-off between selectivity/in-band loss because the edges of the BPF response can be sharpened only by increasing the order of the filter.
- Front-end loss directly raises the NF of the entire RX \rightarrow design to have small loss (0.5-1dB) and some frequency selectivity
- Front-end loss in the TX band degrades efficiency \rightarrow With 2dB loss and 1W PA, 370mW is wasted within the duplexer \rightarrow more than the entire RX power budget!
- Interferer at f_1 (20MHz away from the RX band) is attenuated by only 30dB \rightarrow Difficult RX design and PLL design

Multiple Access: FDMA & TDMA



- Available frequency band partitioned into many channels, each of which is assigned to one user for the call-duration
- FDMA + FDD: Each user gets two channels (TX, RX)
- Simple implementation but Insufficient capacity:

$$\# \text{ simultaneous users} = \frac{\text{Total available Band}}{\text{Channel Width}} = 25\text{MHz}/200\text{kHz in GSM}$$



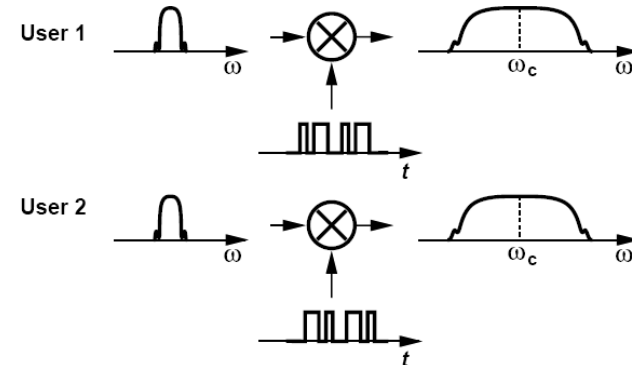
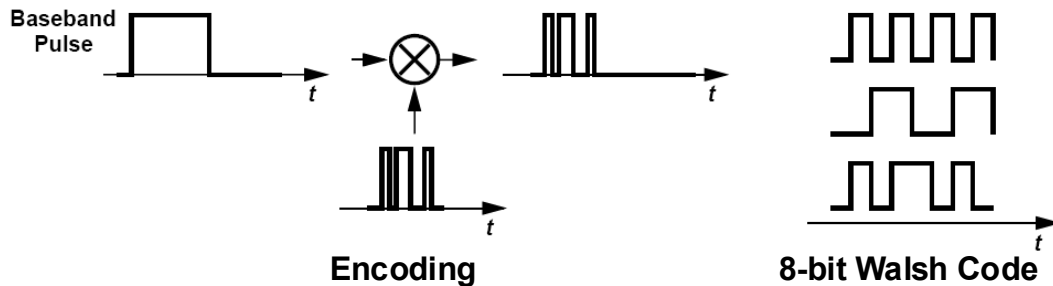
- Same band available to each user but at different time-slots (T_{sl}) in a frame (T_F).
- Data compressed + stored for $T_F - T_{sl}$; burst-transmitted in T_{sl}
- More complex due to A/D conversion, digital modulation, time slot and frame synchronization, etc.
- Digitized speech can be compressed in time by a large factor, smaller required BW, higher # users.
- PA can be turned off during $T_F - T_{sl}$
- TDMA + FDD: Bursts can be timed so the receive and transmit paths are never enabled simultaneously

- Most TDMA systems actually use a combination of TDMA and FDMA [each of FDMA channel is time-shared among many users]

Multiple Access: DS-CDMA

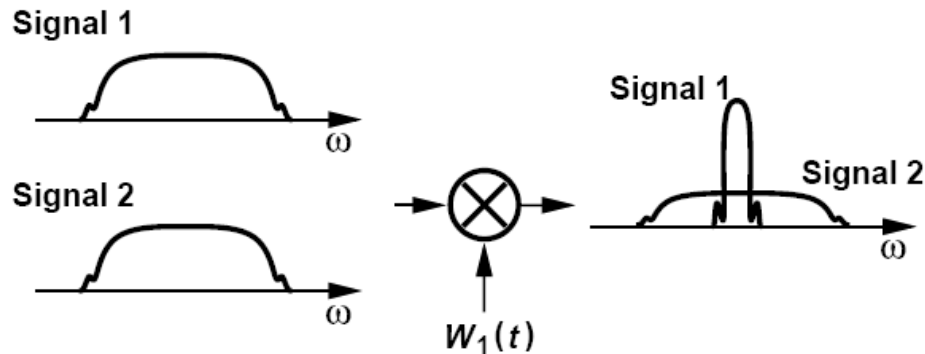
	Simultaneous	Orthogonal	Capacity
TDMA	Frequency	Time	↑↑
FDMA	Time	Frequency	↑
CDMA	Both Frequency & Time	Message Code	↑↑↑

- Direct-Sequence (DS) Code-Division Multiple Access – an example of Spread-Spectrum communication
- Upon initiation, each TX-RX pair is assigned a code and each bit of the BB data is translated to that code before modulation at TX.

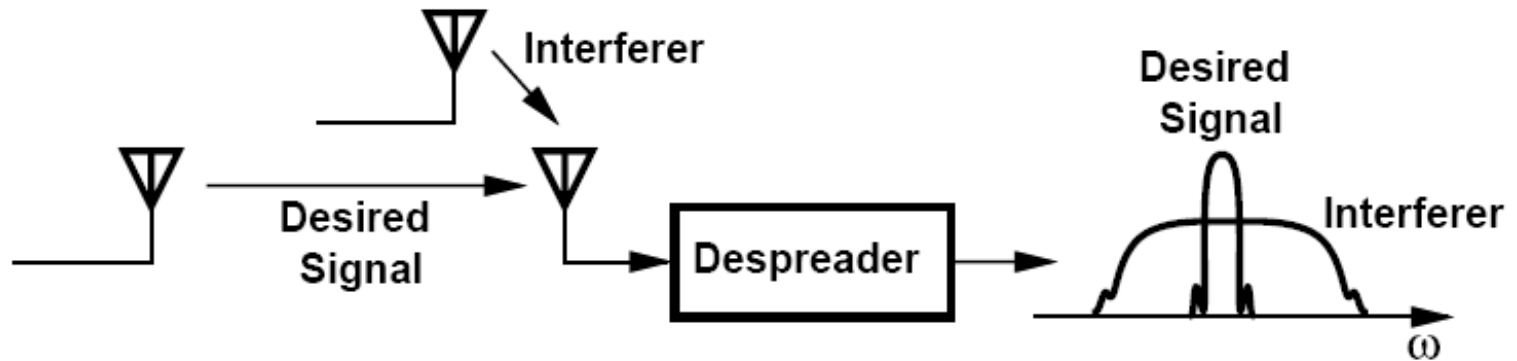


- At RX, the demodulated signal is decoded with the same code.
- $Y(t) = [x_{BB1}(t).W_1(t) + x_{BB2}(t).W_2(t)].W_1(t) = x_{BB1}(t).W_1(t)$ if W_1 and W_2 are orthogonal
- Encoding increases the BW of the data spectrum by the # of pulses in the code. However, widened spectra of many users call fall in the same frequency band, so actual capacity ↑

DS-CDMA: Spectrum and Power



- Desired signal is “despread” back to original BW; Unwanted signal remains spread as noise
- Increasing the # of users only linearly raises the noise floor. In FDMA and TDMA, the maximum # of users is fixed once the channel width or time slots are defined, respectively.

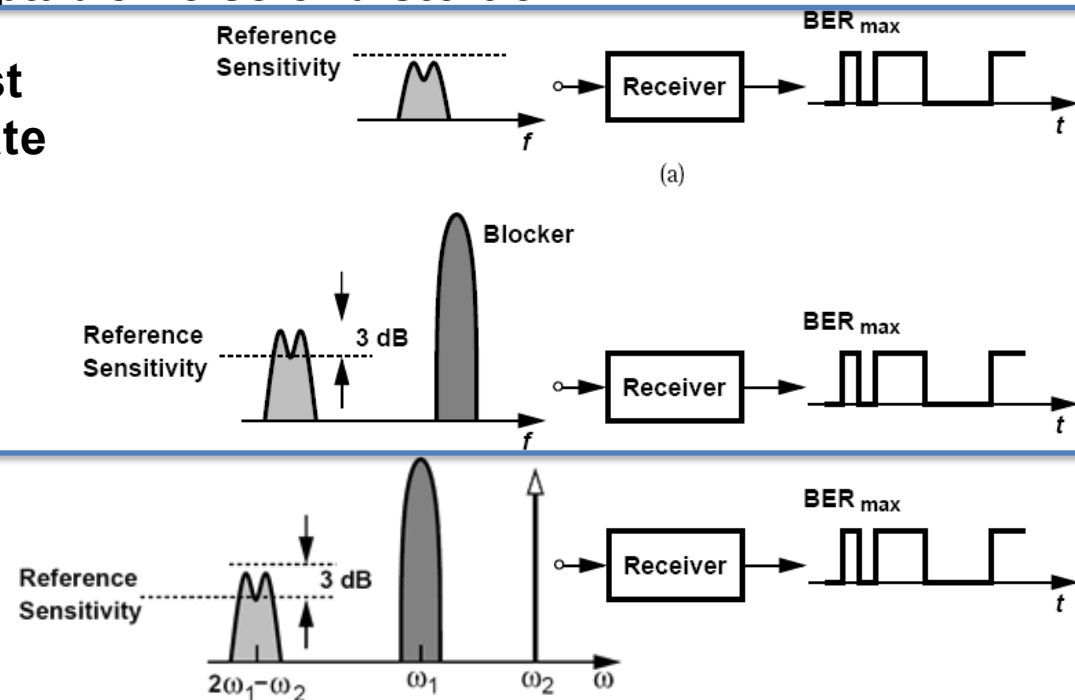


- Near/Far Effect: one high-power TX can virtually halt communications among others by significantly increasing the noise floor → Requires Power Control between BS and UE

Wireless Standards: Common Specs

- Frequency Bands and Channelization
- Data Rates
- Antenna Duplexing Method: FDD (most cellular) and TDD
- Type of Modulation
- TX output power, TX EVM and Spectral Mask
- RX Sensitivity: usually in terms of maximum BER
- RX Input Level Range: with acceptable noise or distortion

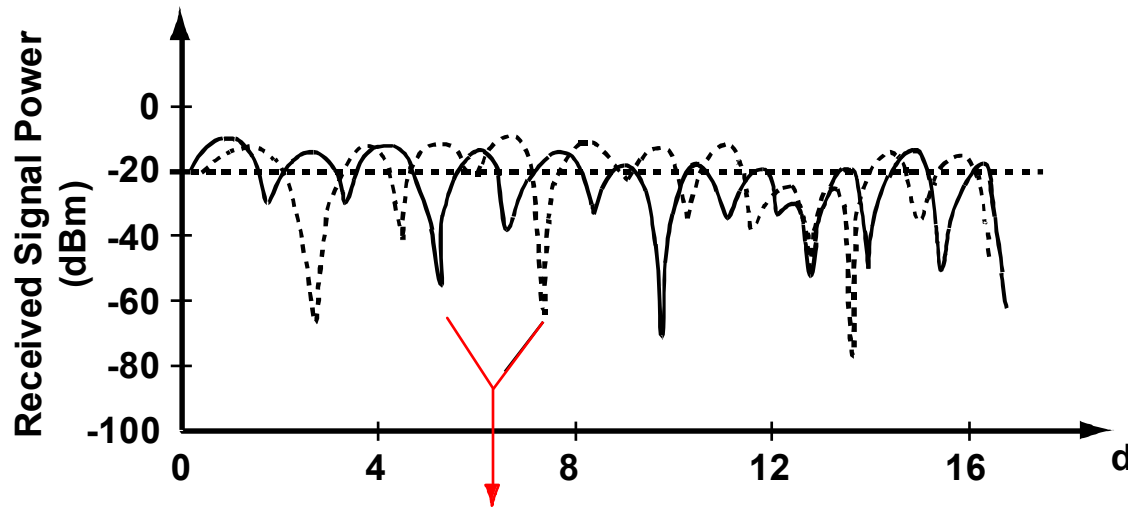
- RX Tolerance to Blockers: largest interferer that the RX must tolerate while receiving a small desired signal.



- Many standards also stipulate an IM test.

Diversity

Employ redundancy to the transmission or reception of the signal to mitigate fading



The chance that two deep fades occur simultaneously (frequency, time, space, polarization) is rare

- **Frequency Diversity** refers to the case where multiple carrier frequencies are used → fading is unlikely to happen simultaneously at two frequencies sufficiently far apart.
- **Time Diversity**: the data is transmitted or received more than once to overcome short-term fading
- **Spatial Diversity or Antenna Diversity** employs *two or more antennas* spaced apart by a significant fraction of the wavelength so as to achieve a higher probability of receiving a nonfaded signal

Multiple-Antenna Systems

Utilize multiple antennas at the TX and/or RX

- Multiple-input multiple-output (MIMO) system
- Single-input multiple-output (SIMO) system
- Multiple-input single-output (MISO) system

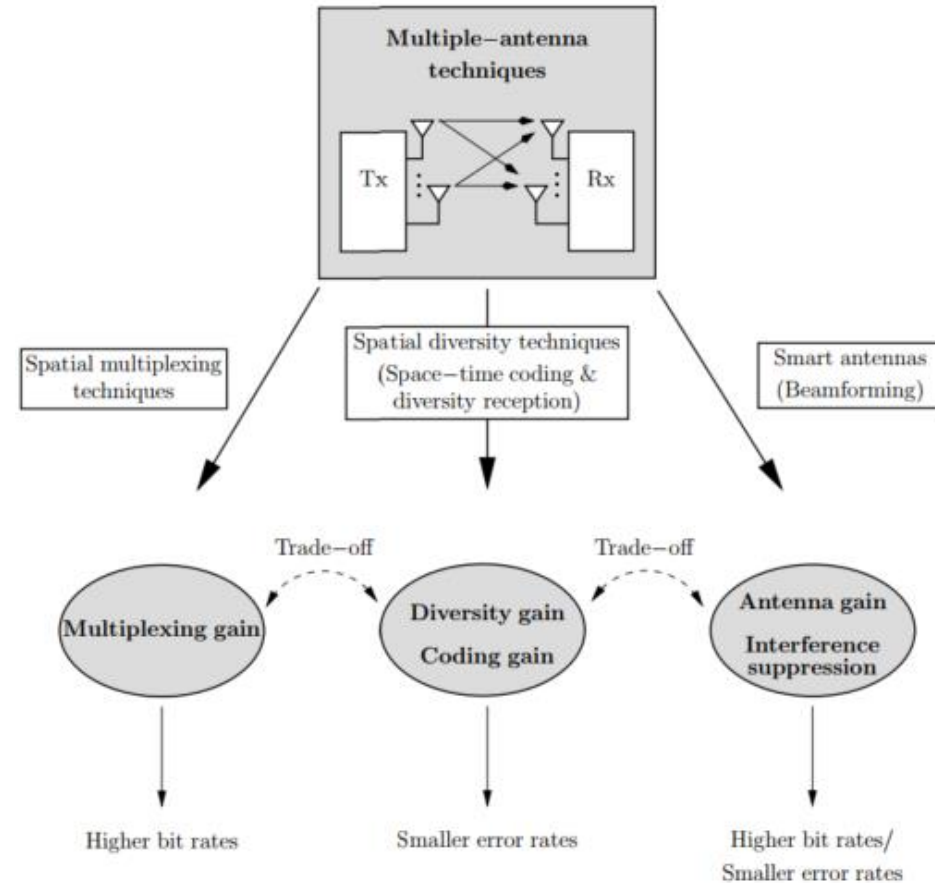
⇒ Exploit spatial domain along with time/ freq. domain

⇒ Better trade-off between spectral efficiency and power efficiency

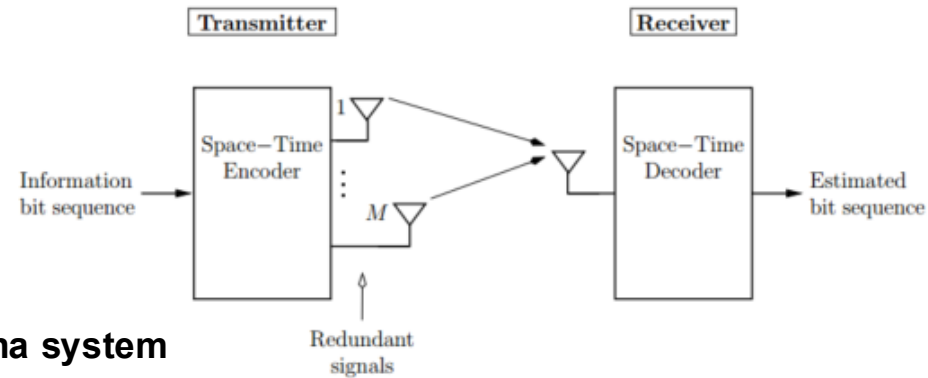
Benefits of multiple antennas:

- Increased data rates with spatial multiplexing
- Decreased error rates with spatial diversity
- Improved SNRs/ SINRs with beamforming

Note: Some use “MIMO” specifically to imply spatial multiplexing.



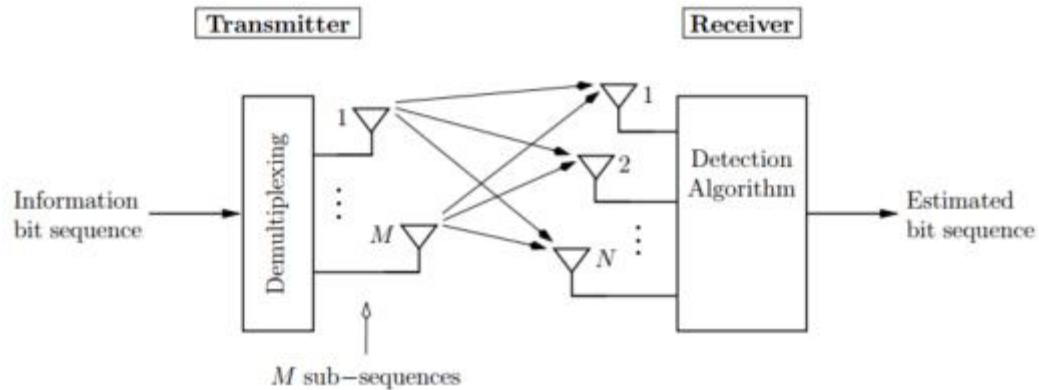
Spatial Diversity



Goal: Decreased error rates compared to single-antenna system

- **Send/ receive multiple redundant versions of the same data sequence and perform appropriate combining (in baseband domain)**
 - ⇒ If the redundant signals undergo statistically independent fading, it is unlikely that all signals simultaneously experience a deep fade
 - ⇒ Spatial diversity gain (typically, small antenna spacings sufficient)
- **Receive diversity: SIMO system with N RX antennas and linear combining of the received signals**
- **Transmit diversity: MISO system with M TX antennas**
 - **Appropriate pre-processing of transmitted redundant signals to enable coherent combining at RX (space-time encoder/ decoder)**
 - **Optionally, $N > 1$ RX antennas for enhanced performance**
 - **Typically, channel knowledge required solely at the RX**
 - **Well-known techniques are Alamouti's scheme for $M = 2$ transmit antennas [Alamouti'98], space-time trellis codes [Tarokh et al.'98], and orthogonal space-time block codes [Tarokh et al.'99]**

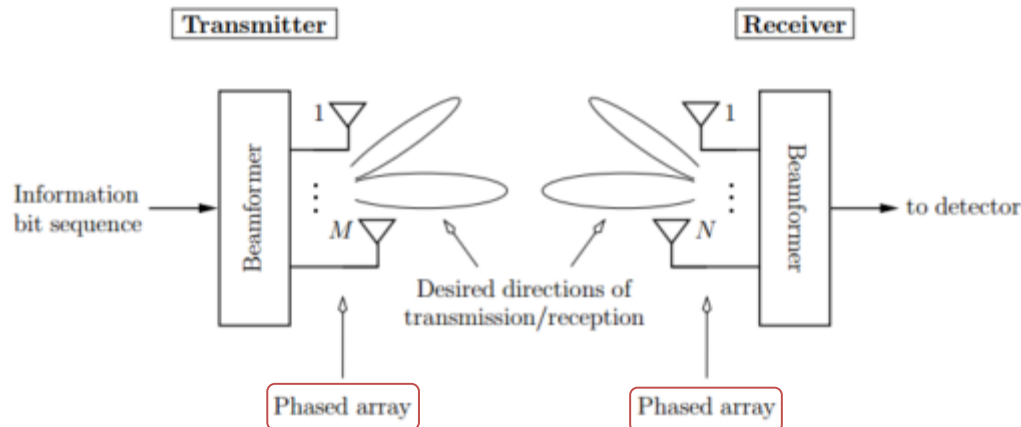
Spatial Multiplexing



Goal: Increased data rates compared to single-antenna system

- Capacity of MIMO systems grows linearly with $\min\{M, N\}$
- At TX, the data sequence is split into M sub-sequences that are transmitted simultaneously using the same frequency band
 - ⇒ Data rate increased by factor M (multiplexing gain)
- At RX, the sub-sequences are separated by means of interference cancellation algorithm, e.g., linear zero-forcing (ZF)/ minimum-mean-squared-error (MMSE) detector, maximum-likelihood (ML) detector, successive interference cancellation (SIC) detector, ...
- Typically, channel knowledge required solely at RX.
- For a good error performance, typically $N \geq M$ required

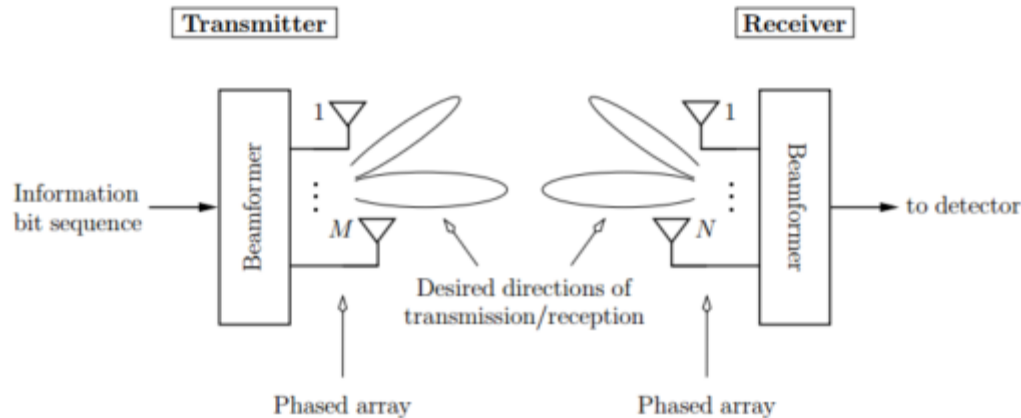
Beamforming – I



Goal: Improved SNRs or SINRs in multiuser scenarios

- **Beamforming can be interpreted as linear filtering in the spatial domain**
- **Consider antenna array with N elements and directional antenna pattern receiving RF signal from a certain direction**
- **Due to antenna array geometry, impinging RF signal reaches antenna elements at different times (underlying baseband signal does not change)**
 - ⇒ **Adjust phases of RF signals to achieve constructive superposition**
 - ⇒ **Corresponds to steering of antenna pattern towards desired direction (*beamsteering*)**
 - ⇒ **Additional weighting of RF signals can shape antenna pattern ($N - 1$ degrees of freedom for placing maxima or nulls)**
- **Principle can also be utilized at the TX (reciprocity)**

Beamforming – II



- **Improved SNRs: Focus antenna patterns on desired angles of reception/ transmission, e.g., towards line-of-sight (LoS) or significant scatterers \Rightarrow Antenna gain**
- **Improved SINRs: Steer nulls towards co-channel users \Rightarrow Interference suppression**
- **Beamforming/smart antenna techniques thus enable space-division multiple access (SDMA), as an alternative to TDMA/FDMA**
- **SNR/ SINR gains can be utilized to decrease error rates or to increase data rates (by switching to a higher-order modulation scheme)**
- **In practical systems directions of significant scatterers must be estimated (e.g., MUSIC or ESPRIT algorithm); SINR can also be optimized without knowing the directions of all co-channel users (Capon beamformer)**
- **Beamforming can also be performed at BB, if channel is known at TX and RX (eigen-beamforming)**