ELEC6214 Advanced Wireless Communications Networks and Systems

Professor Sheng Chen: Building 53, Room 4005

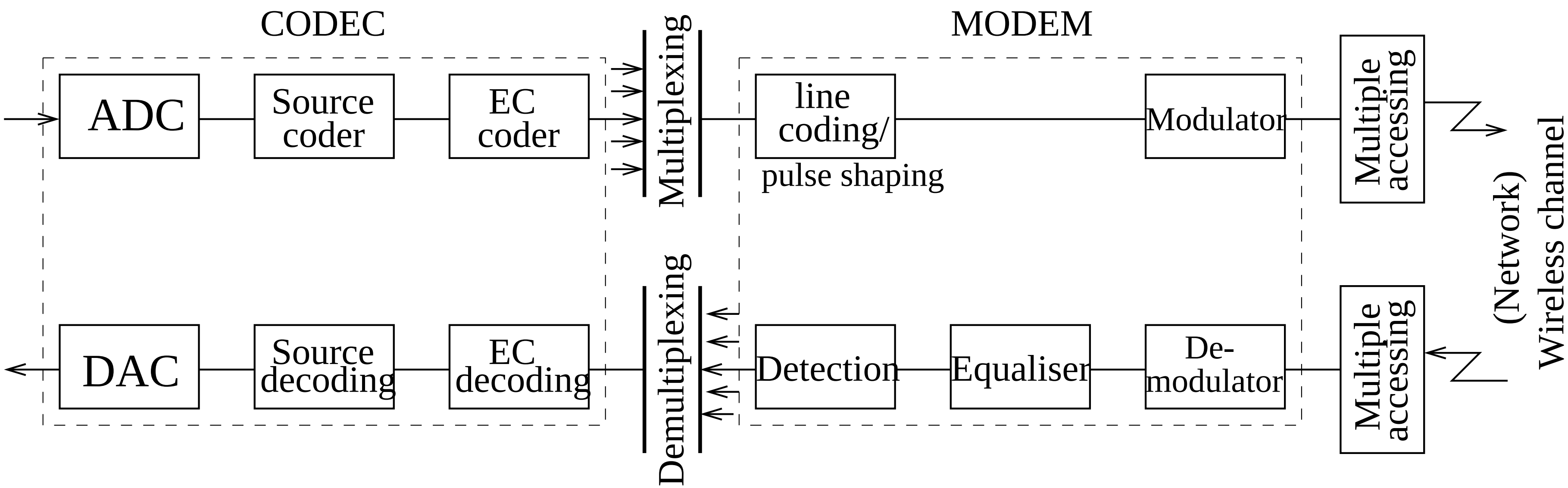
E-mail: sqc@ecs.soton.ac.uk

Get lecture slides from https://secure.ecs.soton.ac.uk/notes/elec6214/

Or download them from: http://www.ecs.soton.ac.uk/∼sqc/ELEC6214/

Fundamental **theory** and **practice** of **mobile networks** as well as **future** state-of-the art technology

Transceiver Overview



Transmitter

- **Source coding**: analogue to digital, data compression to remove redundancy
- **Error control coding**: add redundancy for error detection and correction at receiver
- **Multiplexing**: accommodate several simultaneous transmissions, i.e. combine several low-rate signals to a high-rate one
- **Line coding/pulse shaping**: how bits are transmitted and how to limit transmit signal bandwidth
- **Modulator**: modulate baseband signal by carrier frequency for radio transmission

Transceiver Overview (continue)

Medium

- **Multiple access**: multiple transceiver pairs (users) to share common transmission medium
  This is about how different users are *physically* separated, separation can be in frequency, and/or time, and/or other means
- **Transmission channel**: which can distort signal and corrupt signal with noise
  Note that distortion includes intersymbol interference (ISI) and/or multiple access interference (MAI)

Receiver

- **Demodulator**: carrier recovery and remove carrier, i.e. passband signal $\longrightarrow$ baseband one
- **Equaliser**: compensate channel distortion (ISI) and/or multiuser detection for combating MAI
- **Detection**: make decisions on received symbols/bits, which can be hard or soft one depending on what sort of channel decoding scheme used
- **Error control decoding**: detect and correct errors in bits, which can be hard, or soft, or iterative (turbo), and it can even be iterative with equaliser and multiuser detector
- **Source decoding**: recover original digital data, digital to analogue

Mathematical Revision

- Time function $x(t)$ $\underset{\text{Fourier transform}}{\Longleftrightarrow}$ Frequency spectrum $X(f)$

  $X(f)$ is two-size (artificial negative frequency) and complex-valued (amplitude and phase spectra)

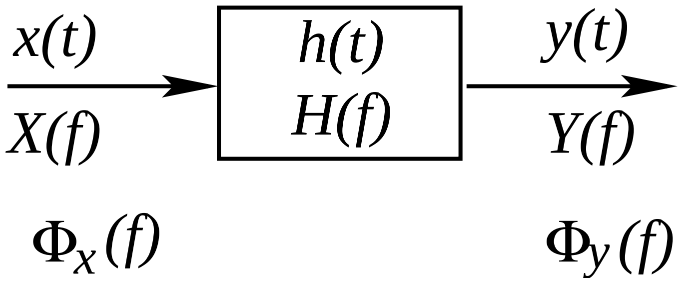
- Baseband sampling theorem: if $x(t)$ is bandlimited to B and sampling rate $\geq 2B$, $x(t)$ can be reconstructed from samples

- Baseband Nyquist criterion for zero ISI: transmission rate f_b, require at least $f_b/2$ baseband bandwidth

- Linear system theory: impulse response $h(t)$ and its transfer function $H(f)$

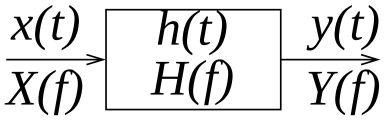
  Power spectrum density of output

$$\Phi_y(f) = |H(f)|^2 \Phi_x(f)$$

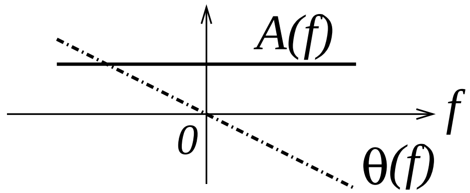


Channel Fundamentals

- Ideal (baseband) channel:



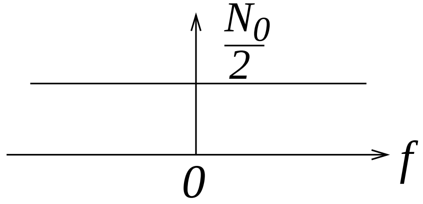
Channel



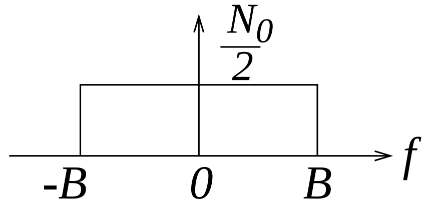
Distortionless

$y(t) = \alpha x(t - t_d) \rightarrow H(f) = \alpha \exp(-j2\pi f\, t_d)$: $|H(f)| = \alpha$ and $\angle H(f) = -2\pi f t_d$

- Channel noise (in baseband):



WN



bandlimited WN

White noise has a constant PSD. Since power is area under PSD, white noise has infinitely large power. But communication system is bandlimited

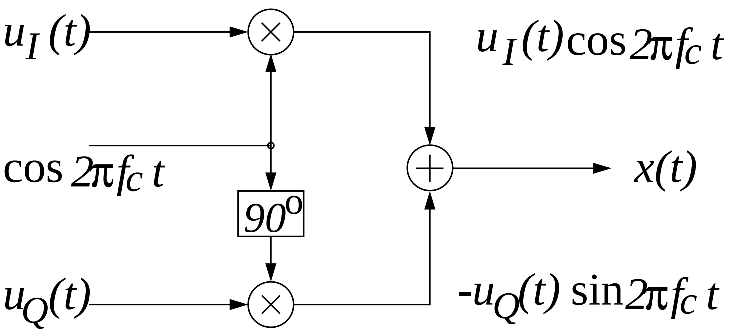
- Channel capacity*: $C = B_p \log_2(1 + \mathrm{SNR})$ (bps), where SNR is channel signal to noise ratio and B_p is passband channel bandwidth (Hz)

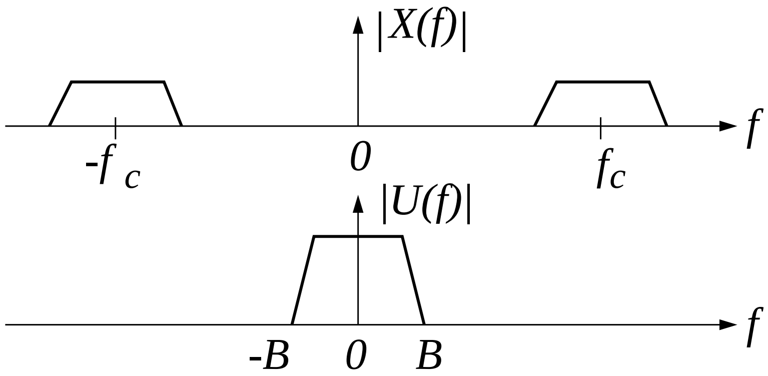
* This is for ideal channel with Gaussian signal. For digital signal or dispersive channel, is channel capacity larger or smaller than ideal case?

Bandpass / Baseband Signals

- Let a **bandpass signal** be: $x(t) = a(t)\cos(2\pi f_c t + \phi(t))$, and its spectrum $X(f)$
- Define a **baseband complex envelope**: $u(t) = a(t)\exp(j\phi(t)) = u_I(t) + ju_Q(t)$, and its spectrum $U(f)$ Assumption: signal $X(f)$ bandwidth $<< f_c$ then $\longrightarrow$
- Relationship: $u(t)\exp(j2\pi f_c t) = (u_I(t) + ju_Q(t))(\cos 2\pi f_c t + j\sin 2\pi f_c t)$

$$x(t) = \mathrm{Re}[u(t)\exp(j2\pi f_c t)] \qquad X(f) = \frac{1}{2}[U(f - f_c) + U^*(-f - f_c)]$$





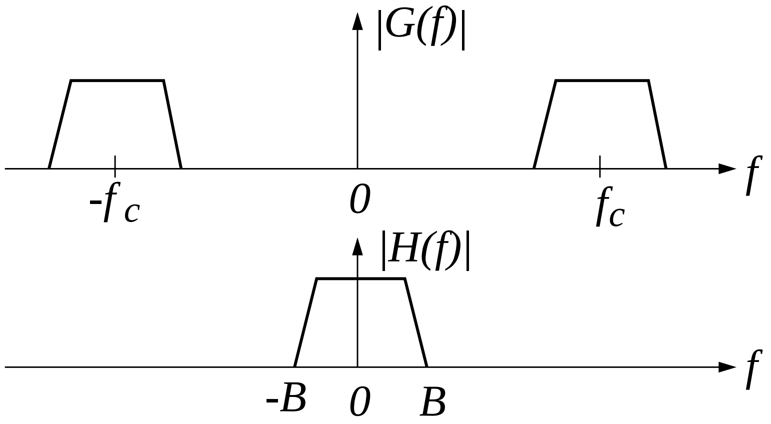
Bandpass / Baseband Systems

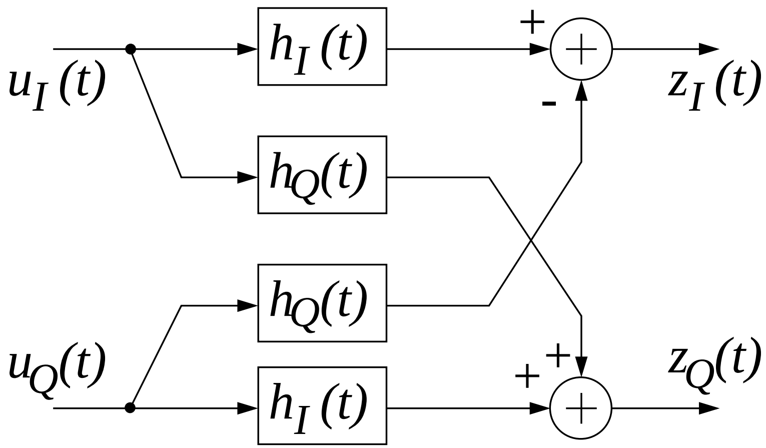
- **Bandpass** signal and system: $x(t), X(f) \rightarrow \lceil g(t), G(f) \rfloor \rightarrow y(t), Y(f)$
- **Baseband** signal and system: $u(t), U(f) \rightarrow \lceil h(t), H(f) \rfloor \rightarrow z(t), Z(f)$
- Relationship between baseband and passband systems is:

$$G(f) = H(f - f_c) + H^*(-f - f_c)$$

- Noting $X(f) = \frac{1}{2}[U(f - f_c) + U^*(-f - f_c)]$, passband output spectrum is:

$$Y(f) = \frac{1}{2}[H(f - f_c)U(f - f_c) + H^*(-f - f_c)U^*(-f - f_c)]$$





Bandpass / Baseband (continue)

- Passband output signal: $y(t) = \text{Re}[z(t)\exp(j2\pi f_c t)]$, where baseband signal $z(t) = z_I(t) + jz_Q(t)$, and with $\star$ denoting convolution

$$z_I(t) = h_I(t) \star u_I(t) - h_Q(t) \star u_Q(t) \quad z_Q(t) = h_I(t) \star u_Q(t) + h_Q(t) \star u_I(t)$$

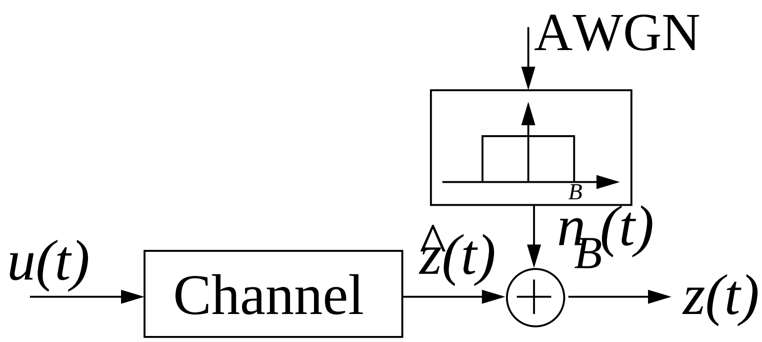
- **Comment 1**: Recall complex-valued representation of inphase and quadrature components $\longrightarrow$ link to baseband complex envelope
- **Comment 2**: Real-world passband CIR $g(t)$ is real-valued $\longrightarrow$ baseband equivalent CIR $h(t)$ is complex-valued

- Baseband equivalent channel model:

  Again real-world noise is real-valued, but equivalent baseband noise is a complex-valued AWGN

$$n(t) = n_I(t) + jn_Q(t)$$

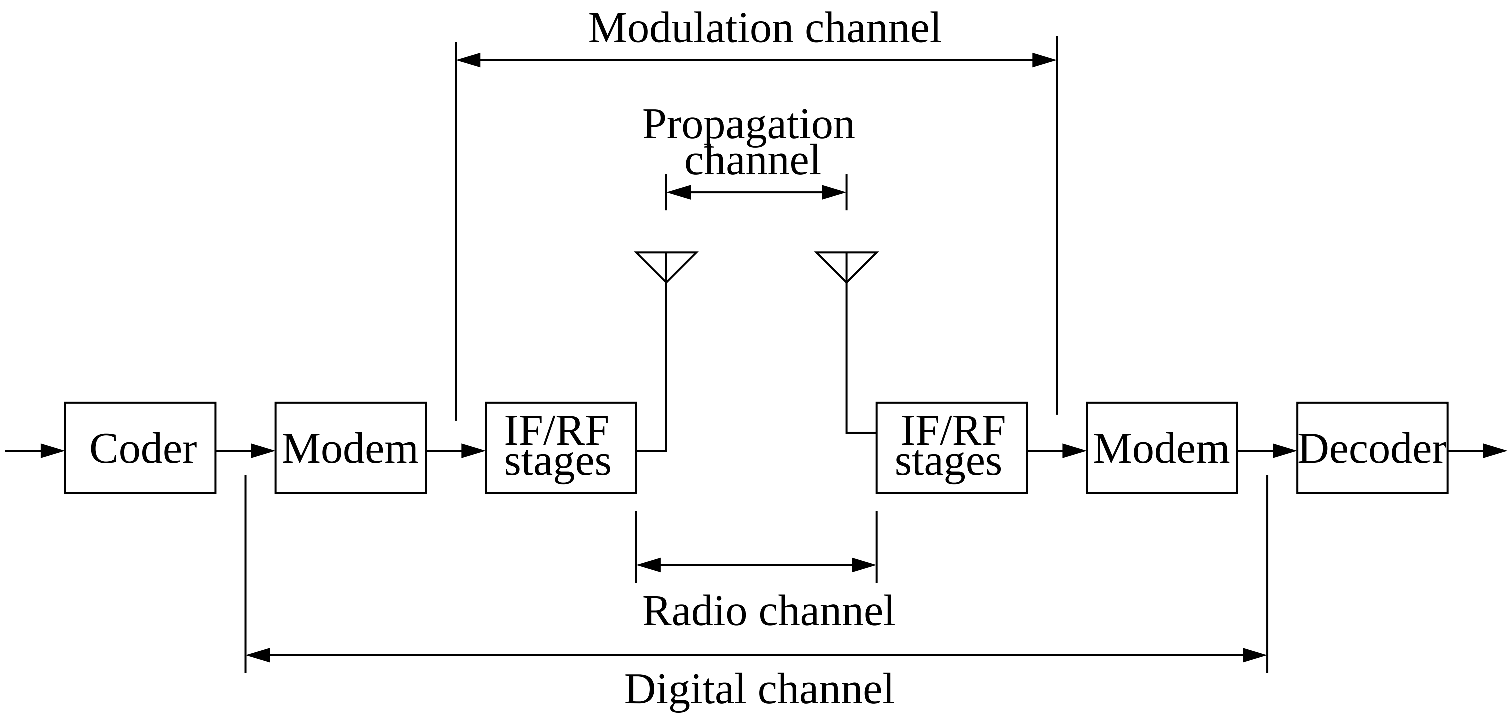
  which is bandlimited by the Rx filter



- **Comment 3**: Analysis and simulation are much easier in equivalent baseband

Mobile Radio Channel Definitions

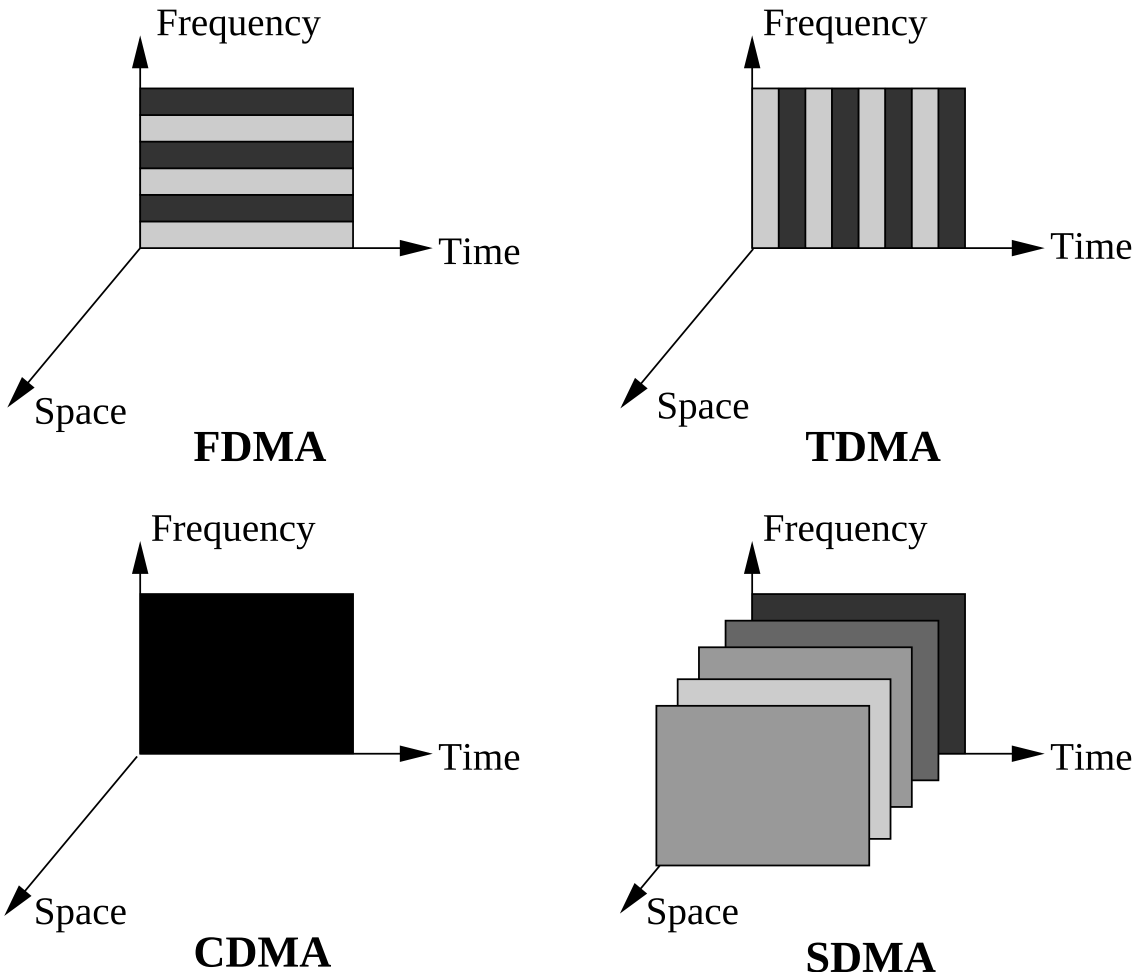
- The term "channel" depends on the context. Sometime it refers to the whole communication system, sometime part of it. Here are some of definitions



- For example, when designing decision circuit and equaliser, it is convenient to consider channel as "digital channel"

Wireless Access Technology

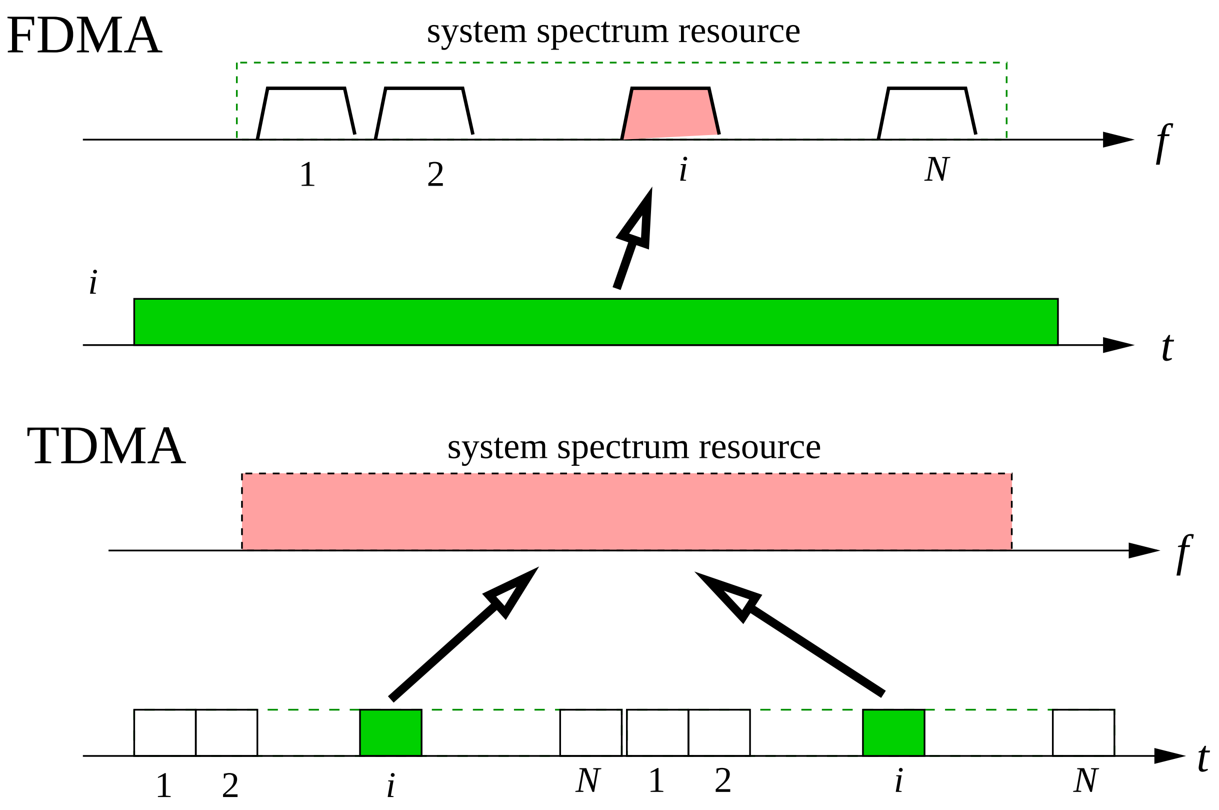
- **Spectrum**: basic resource
- **User separation**: Users must be separated in some way
- **Multiple access**: separation ("channels") can be in
  - frequency domain (different frequency bands)
  - time domain (different time slots)
  - code domain (different spreading codes)
  - spatial domain (different CIRs as seen at multiple Rx antennas)



"**New**" multiple access techniques: interleaver division multiple access, channel code division multiple access

Channel Partition (FDMA and TDMA)

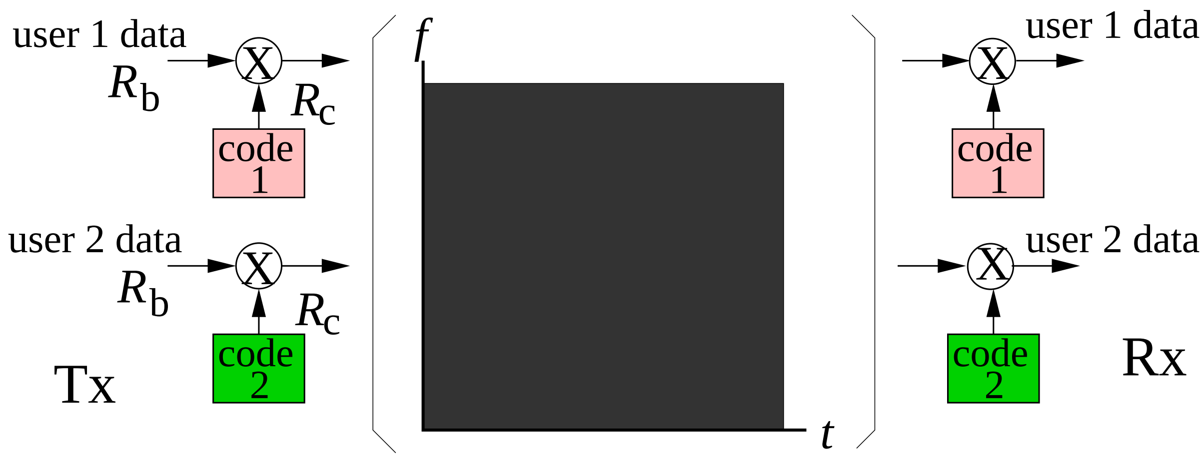
- Frequency division multiple access: system spectral band is divided into frequency slots
  - A user is assigned with a frequency slot (channel), who can transmit continuously in time, but its signal spectrum must be inside its allocated frequency slot



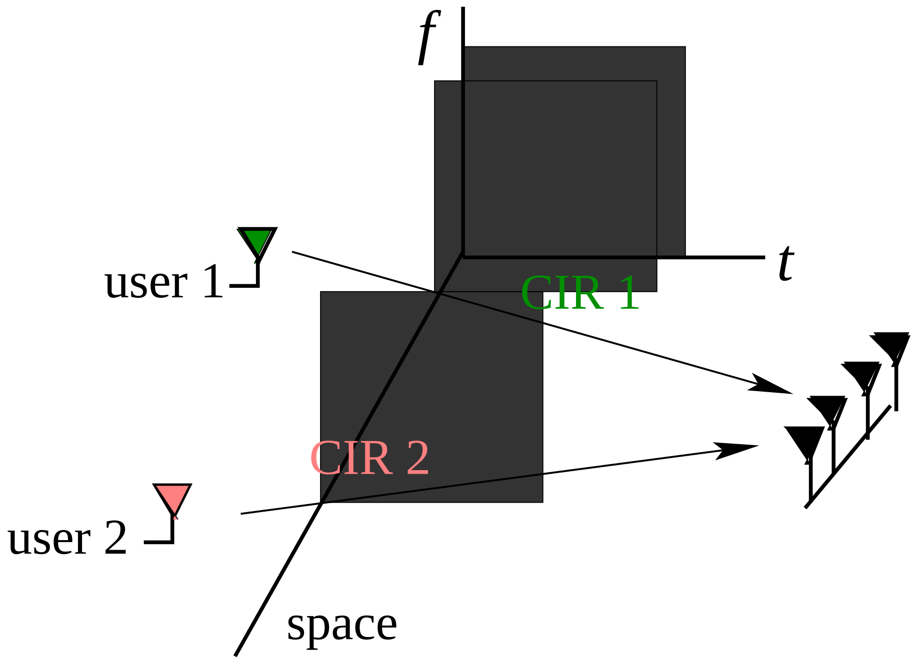
- Time division multiple access: transmission in time frames, and each frame divided into time slots
  - A user is assigned with a time slot (channel), who can only transmit in time bursts, i.e. in its allocated time slots, and its signal spectrum can occupy whole system spectral band

Channel Partition (CDMA and SDMA)

- Code division multiple access: users are separated in "code" domain
  - Code rate $R_c \gg R_b$ data rate
  - Users share same system frequency and time resources
  - CDMA resource: "orthogonal" codes called channelisation spreading codes



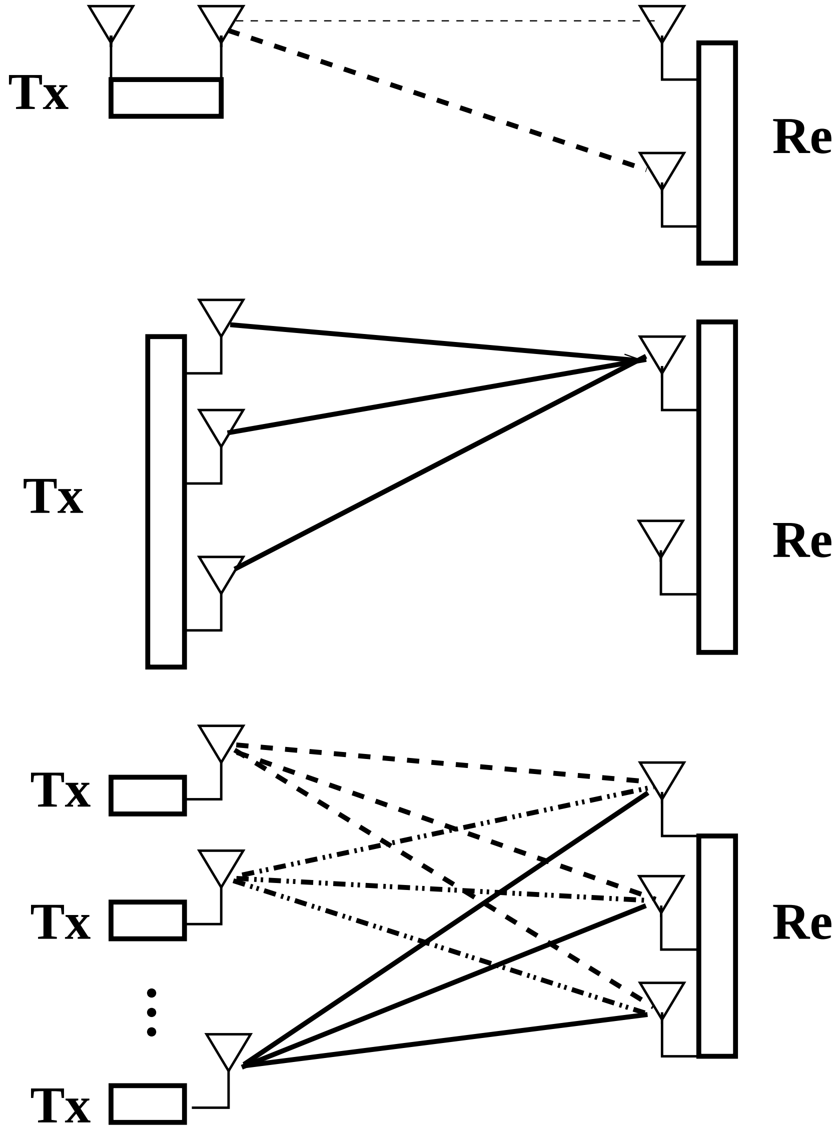
- Space division multiple access: users are separated in "spatial" domain
  - Users share same system frequency, time and code resources
  - SDMA relies on multi-antenna techniques to distinguish users by users' specific CIRs
  - Unlike FDMA, TDMA or CDMA, where "channels" are orthogonal
  - Users' CIRs are not orthogonal, hence SDMA is challenging but enhances spectral efficiency to another level



MIMO Technology

MIMO are used for diversity gain and/or multiplexing gain

- Create **diversity** for combating fading
  - With sufficient antenna spacing (10 wavelengths), each antenna experiences independent fading → When one signal is in its deep fade, others are unlikely the same
- Increase **throughput**
  - Data stream is first S/P, each sub-sequence mapped to an antenna → This creates many "digital pipes" to support higher rate
- Support **multiple users**
  - With multiple receive antennas, each spatially separated user has a unique set of CIRs seen at receiver → This enables SDMA
- Support **beamforming**
  - Focus transmit/receive signal on desired direction to enhance transmit/receive signal power → This improves system performance



Massive MIMO

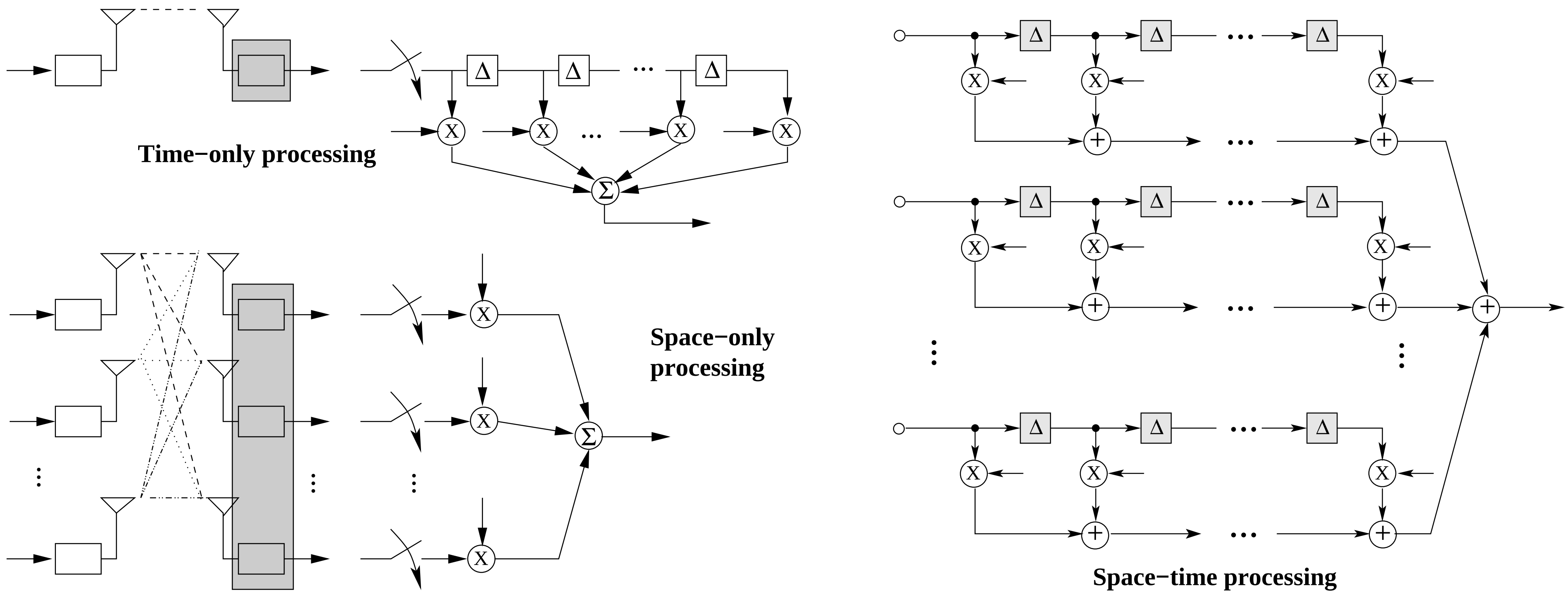
- Fundamentally, MIMO trades off between **diversity gain** and **multiplexing gain**
  - Diversity gain can be utilised to improve system's performance
  - Multiplexing gain can be utilised to increase system's throughput, or alternatively to support multiple users

- **Beamforming** (transmit/receive beamforming) can also be utilised to improve system's performance, or alternatively to support SDMA
  - Digital beamforming: at baseband, each antenna requires one RF chain
  - Analog beamforming: at RF band, whole array just requires one RF chain
  - Hybrid beamforming

- Basically, MIMO combines frequency-domain/time-domain processing with spatial-domain processing

- For **massive** MIMO, such as **millimeter Wave** MIMO, huge number of antennas can be realized in a very small areas: enabling technology for 5G and beyond

Space-Time Processing



- Basic processing is in time domain, i.e. temporal filtering, or equivalently in frequency domain
- With aid of multiple antennas (smart antenna), processing in spatial domain can be exploited, e.g. space-time coding, beamforming, and space-time equalisation
- **Space-time processing** are powerful technology for improving system capacity, coverage and quality of service

Summary

- **System overview**: knowing each part of study fits into this overall picture
- **Revision**: time - Fourier transform - spectrum, sampling theorem, Nyquist criterion for zero ISI, linear system theory
- **Channel fundamentals**: ideal channel, white noise, channel capacity
- **Bandpass/baseband**: signals, systems, relationships, why consider equivalent complex-valued baseband forms
- **Multiple access**: user separation, frequency, time, code and/or spatial "channels"
- **MIMO**: diversity for combating fading, increase throughput, support multi users
- **Space-time processing**: exploits temporal and/or spatial domain processing