Revision of Lecture Three

1. Doppler spread which causes frequency dispersion
    - Physical dimension **Doppler frequency**, effects of which are characterised by Doppler power spectrum with parameters Doppler spread/coherence time

2. Multipath which causes time dispersion
    - Physical dimension **excess delay**, effects of which are characterised by power delay profile with parameters root mean square delay spread/coherence bandwidth

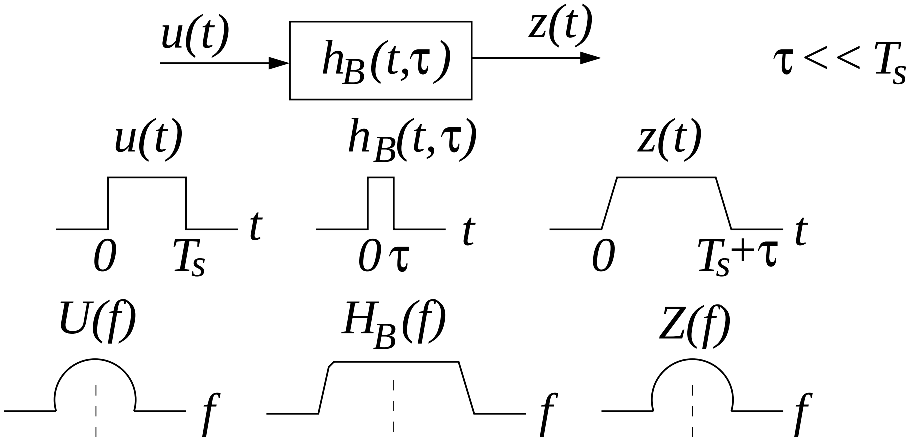
3. Angle spread which causes space selective fading
    - Physical dimension **angle**, effects of which are characterised by angle power spectrum with parameters root mean square angle spread/coherence distance

- This lecture we use first two important physical dimensions to further classify channels, in particular, channel impulse response

- However, the third dimension, spatial or angular dimension, is playing even increasing important role too

Narrow-Band Channels

- **Narrow-band** channels: also called **flat fading**, occurs when $B_S \ll B_C$ or $T_S \gg \sigma_\tau$



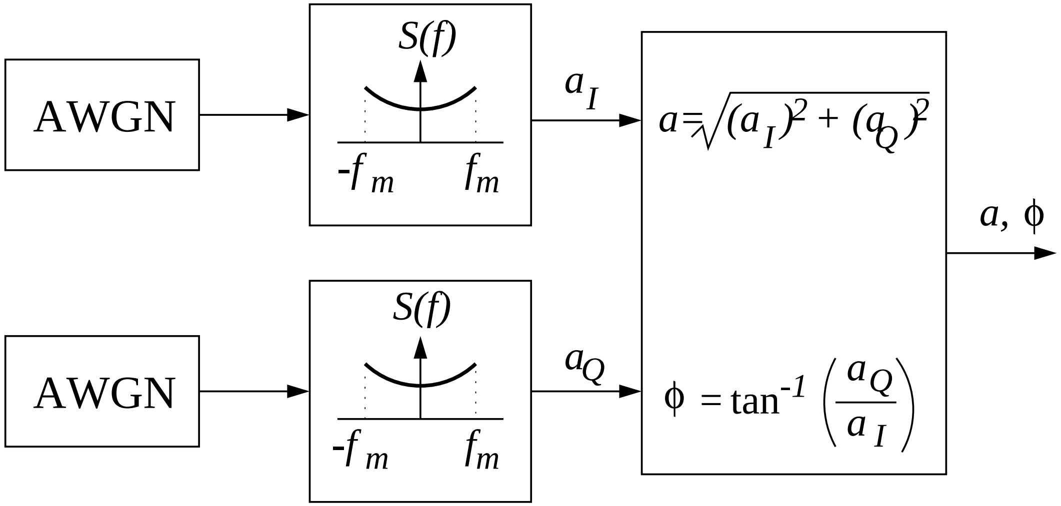
- Transmitted signal bandwidth B_S is **much smaller** than channel coherence bandwidth B_C, or symbol period T_S **much larger** than rms delay spread σ_τ
  - All the transmitted frequency components encounter nearly identical propagation delay, and received signal sampled at symbol rate is given by

$$r(k) = (a_I + j a_Q) \cdot s(k)$$

where $s(k)$ is transmitted symbol at sample k, and $r(k)$ received signal sample

Narrow-Band Channels (continue)

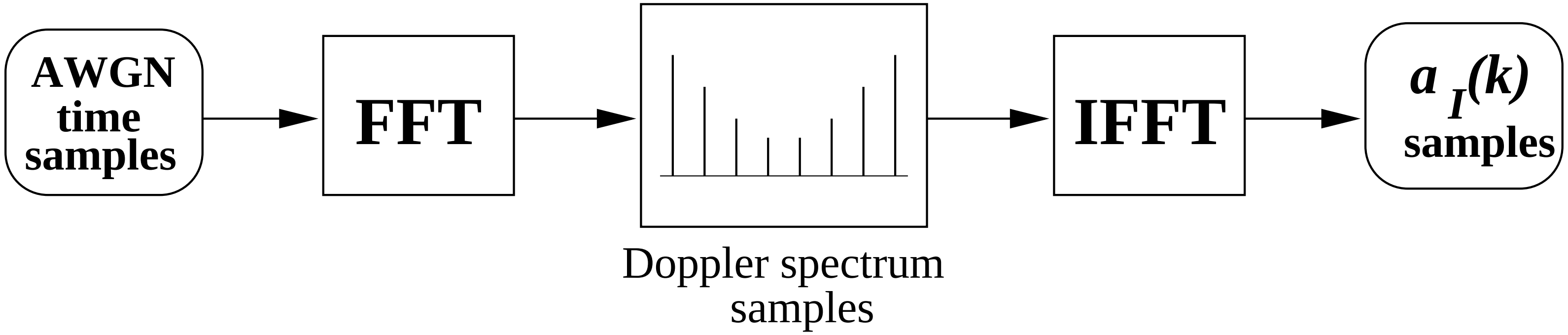
- There is **no intersymbol interference** for a narrow band channel, but the channel can be time varying, that is, a_I and a_Q are time varying (fading)
- **Time varying nature** of a_I and a_Q is characterised by **Doppler spectrum** $S(f)$, and $a = \sqrt{a_I^2 + a_Q^2}$ is Rayleigh distributed (fading)
- Baseband **Rayleigh fading channel** simulator:
  - An white Gaussian process with unit variance convoluted with a filter having specified Doppler spectrum yields real part a_I of channel tap
  - Similarly, imaginary part a_Q is generated, and $a = \sqrt{a_I^2 + a_Q^2}$ is the required Rayleigh process



- This is sometime called correlated fading channel, as a_I is correlated, and a_Q is also correlated
- Worst case uncorrelated fading channel: a_I and a_Q are two white Gaussian processes
  - $a = \sqrt{a_I^2 + a_Q^2}$ is Rayleigh distributed
  - $S(f)$ is a flat PSD with maximum Doppler frequency $f_m = \infty$

Generating Flat Rayleigh Channel

- Method of generating Rayleigh channel can be time-domain based, but **frequency-domain** based is more convenient
  - Given carrier frequency f_c and mobile speed v specifies Doppler frequency f_m
  - Symbol rate or symbol period T_s determines how you should sample AWGN process, and T_s and f_m specify required normalised Doppler frequency $\bar{f}_m$

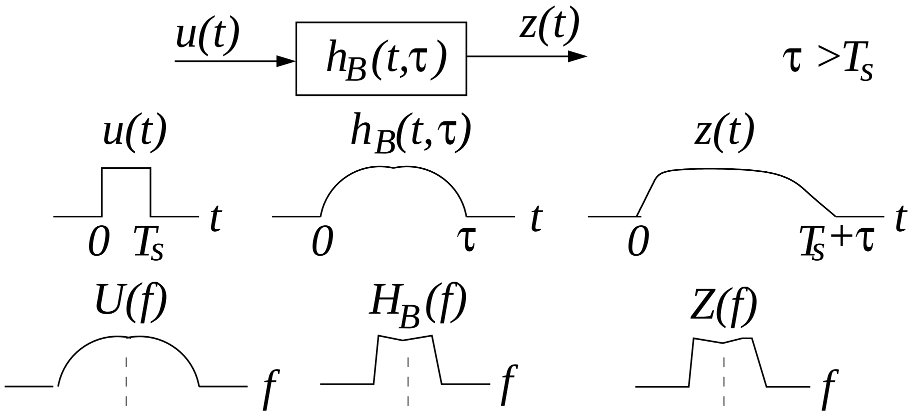


- Block of AWGN time samples is FFT → frequency samples are convoluted with Doppler spectrum samples → Doppler spectrum shaped frequency samples are IFFT to yield block of real-part channel tap time samples $\{a_I(k)\}$

- Similarly, $\{a_Q(k)\}$ are generated, and $a(k) = \sqrt{a_I^2(k) + a_Q^2(k)}$ is the required Rayleigh process time sample

Wideband Channels

- **Wideband channels**: also called **frequency selective**, occurs when $B_S > B_C$ or $T_S < \sigma_\tau$



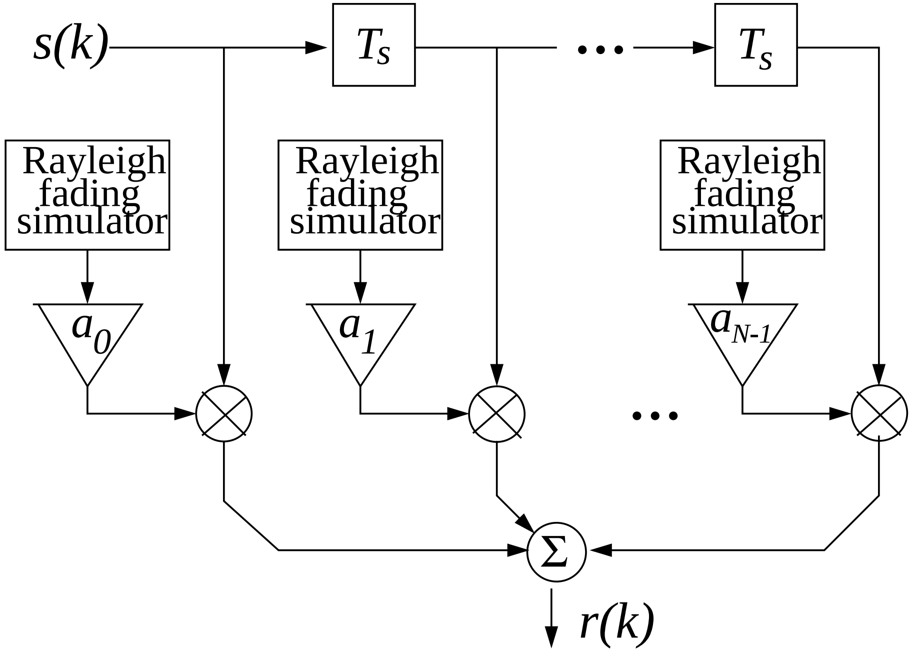
- Signal bandwidth B_S is **larger** than channel coherence bandwidth B_C, or symbol period T_S is **smaller** than rms delay spread $\sigma_\tau \Rightarrow$
  - Channel has different gains and delays for different frequency components
  - Symbol-rate received signal sample is given by

$$r(k) = \sum_{i=0}^{N-1} (a_{I,i} + j a_{Q,i}) \cdot s(k-i)$$

where $s(k)$ is transmitted symbol at sample k and $r(k)$ received signal sample

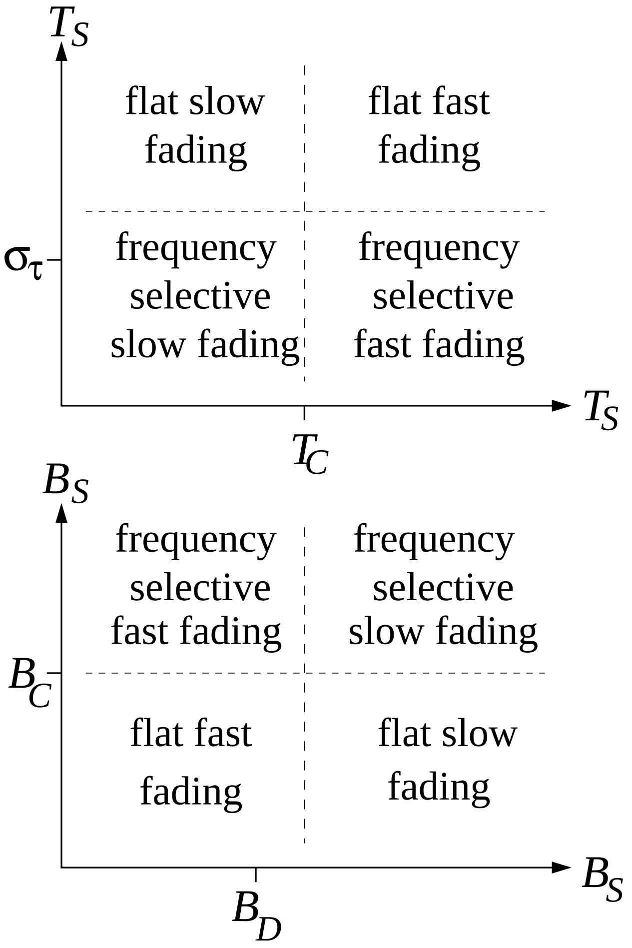
Wideband Channels (continue)

- A frequency selective channel introduces **ISI**, and an equaliser is required at receiver
- Each $a_{I,i} + j a_{Q,i}$ represents a Rayleigh fading multipath component, with $a_i = \sqrt{a_{I,i}^2 + a_{Q,i}^2}$ Rayleigh distributed
- How fast time varying the channel is depends on Doppler spread
- Baseband channel simulator:



Channel Classification Summary

- **Time-varying rate** depends on T_S/T_C or B_S/B_D
  - Slow fading: $T_S \ll T_C$ or $B_S \gg B_D$
  - Fast fading: $T_S > T_C$ or $B_S < B_D$
- **Frequency selective** depends on T_S/σ_τ or B_S/B_C
  - Flat: $T_S \gg \sigma_\tau$ or $B_S \ll B_C$
  - Frequency selective: $T_S < \sigma_\tau$ or $B_S > B_C$
- Sources of (time) fading and frequency selective: Doppler spread and multipath
- Spatial dimension can also be exploited
  - With rms angle spread σ_θ or coherence distance D_c, channels can be classified into various three-D regions



T_S: symbol period

T_C: coherence time

σ_τ: rms delay spread

B_S: signal bandwidth

B_D: Doppler spread

B_C: coherence bandwidth

A note on multipath: two-edges "sword"

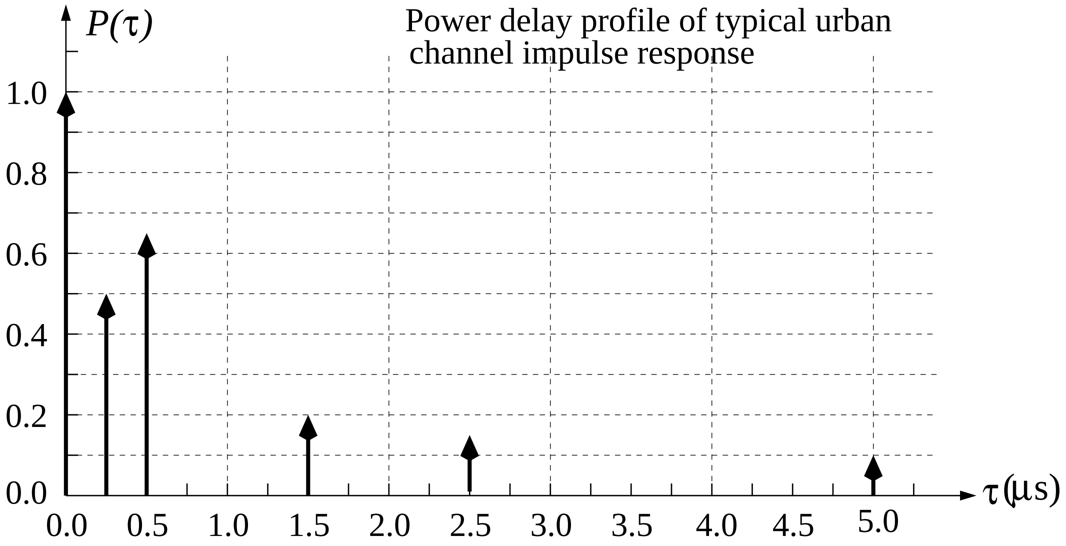
- Bad effect: time dispersion causing intersymbol interference
- Good effect: yielding time diversity

Comments on Wireless Channels

- We have finished **mobile radio channels**. To understand mobile communication technologies, you need an understand of **mobile communication media**
- Two main sources of hostility in mobile media are **Doppler spread** and **multipath**. Many techniques developed are counter measures for **fading and frequency selective**
  - Consider a simple example. Channel coding is very good in detecting and correcting isolated bit errors
  - When a channel is in a deep fade, bursts of bit errors will occur, and this causes problem for channel decoding
  - A simple interleaver will do the trick: it mixes up bit sequence for transmission. At receiver, de-interleaver will break up bursts of bit errors into isolated ones.
- There are many examples. When a new mobile communication technology is coming to use, usually you can always make a connection with mobile radio media
  - Space-time processing or MIMO technology is powerful, as it exploits a whole new spatial (angular) dimension
  - Capable of offering effective countering measures for fading and frequency selective mobile media
  - Effectively improve system performance and system capacity
- Mobile communications have gone through 1G, 2G, 3G, and currently 4G, and we are looking into B4G or 5G
  - Informative to review history of mobile communications from mobile radio media viewpoint

Fading Channel Example

The power delay profile of a typical urban mobile radio channel is given below:



1. Estimate the 50% coherence bandwidth of the channel.

2. Will this channel be suitable for AMPS (which has a baseband signal bandwidth $B_S = 30$ kHz) and GSM (which has a baseband signal bandwidth $B_S = 200$ kHz) service without the use of an equaliser?

In a GSM system with the carrier frequency $f_c = 1.8$ GHz, a mobile moves at a speed of $v = 120$ km/hr.

3. Estimate the Doppler spread of the corresponding channel.

4. Is this channel classified as being slow or fast fading?

Note: AMPS – Advanced mobile phone system (1G); GSM – Global system for mobile communications (2G)

Solution: **1**. RMS delay spread σ_τ and coherence bandwidth B_C

$$\sum P(\tau_i) = 1 + 0.5 + 0.65 + 0.2 + 0.15 + 0.1 = 2.6$$

$$\sum P(\tau_i)\tau_i = 1\times 0 + 0.5\times 0.25 + 0.65\times 0.5 + 0.2\times 1.5 + 0.15\times 2.5 + 0.1\times 5 = 1.625\ (\mu\mathrm{s})$$

$$\sum P(\tau_i)\tau_i^2 = 1\times 0^2 + 0.5\times 0.25^2 + 0.65\times 0.5^2 + 0.2\times 1.5^2 + 0.15\times 2.5^2 + 0.1\times 5^2 = 4.08125\ (\mu\mathrm{s})^2$$

$$\bar{\tau} = \frac{\sum P(\tau_i)\tau_i}{\sum P(\tau_i)} = 0.625\ (\mu\mathrm{s}), \quad \bar{\tau^2} = \frac{\sum P(\tau_i)\tau_i^2}{\sum P(\tau_i)} = 1.5697115\ (\mu\mathrm{s})^2$$

$$\sigma_\tau = \sqrt{\bar{\tau^2} - (\bar{\tau})^2} = 1.086\ (\mu\mathrm{s}), \quad B_C \approx \frac{1}{5\sigma_\tau} = 184\ (\mathrm{kHz})$$

2. For AMPS, as $B_S = 30\ \mathrm{kHz} \ll B_C$, the channel is flat, and an equaliser is not required. For GSM, as $B_S = 200\ \mathrm{kHz} > B_C$, the channel is frequency selective, and an equaliser would be required.

3. For single carrier frequency $f_c = 1.8$ GHz, $v = 120$ km/hr and $c = 3 \times 10^8$ m/s, the maximum Doppler frequency deviation is

$$f_m = \frac{v f_c}{c} = \frac{1.2 \times 10^5 \times 1.8 \times 10^9}{3600 \times 3 \times 10^8} = 200\ (\mathrm{Hz})$$

Since the signal bandwidth is very small in comparison to the the carrier frequency, the Doppler spread

$$B_D \approx f_m = 200\ (\mathrm{Hz})$$

4. Since $B_S = 200\ \mathrm{kHz} \gg B_D$, the channel is slow fading.

History of Mobile Communications

1G Birth of mobile (cellular) phone, limited coverage and service, basic technology was FDMA

- Rate is very low, and channel is frequency non-selective – no need for equaliser

2G Mobile communications really took off with 2G (GSM), and basic technology was TDMA

- Rate is higher than 1G, and channel is frequency selective – worst case symbol-rate CIR has 6 taps, and equaliser is hence defined in the standard
- To better combating fading (time-varying), periodic training is introduced: transmission organised in time frame with 200 data symbols, and middle of frame containing 20 training symbols

3G Mobile communications in expansion, coverage and service were dramatically enhanced with much higher rate, many new technologies came to play, e.g. CDMA

- CDMA technology is attractive, as it offers an effective means of combating fading and exploiting multipath
- CDMA is also vital for expanding communications resources, as we pretty much run out of frequency/time resources, and we have "new" resource – channelisation spreading codes

4G Golden age of mobile communication has arrived, mobile Internet, smart phones, digital world, and social media, all those things your generation is growing up with

1. Coverage and service are dramatically enhanced, and rate is going sky high, unthinkable for my generation – lucky your generation
2. Birth of many new technologies, such as MIMO, and in particular, OFDMA and multi-carrier technology

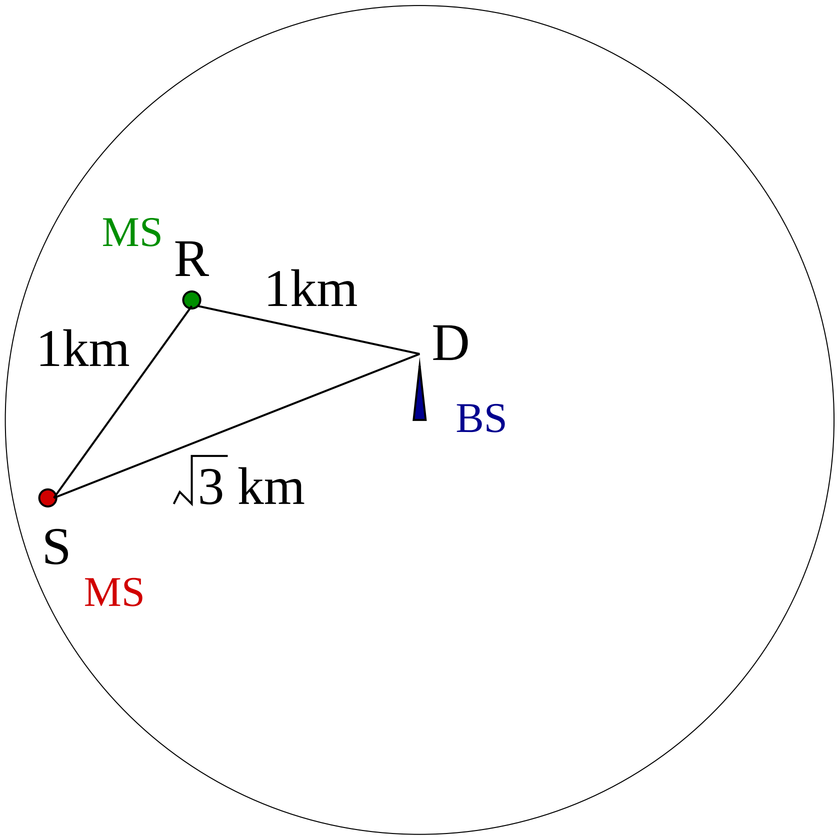
- Prof Lajos Hanzo's personal story:
  - Lajos's PhD was about orthogonal frequency division multiplexing (OFDM), and you could say he was an inventor of OFDM technology
  - But at that time (well before you were born), no one seemed to be interested on it – could not see its use? – so he never got credit for it
- OFDM and multi-carrier technology whose time has come:
  - With 4G, channel ISI can span tens to hundred symbol-rate channel taps – nightmare for usual time-domain equaliser
  - OFDM and multi-carrier technology offers low-complex effective means of dealing such hostile mobile wireless media

5G? Even before 4G has been fully deployed, we already busy thinking beyond 4G

So what 5G will look like ? Surely rate, coverage and service will be improved significantly again, and many new technologies will be born

- "**Space**" time is arriving: MIMO, particularly large-scale or massive MIMO, with tens and hundreds of antennas, will boost coverage, service and rate to another level
- **Device-to-device** communication underlaying cellular network:
  1. You all use your smart mobile phone doing WiFi offloading: when you come to near a fixed WiFi network, you switch your mobile phone to do communications through WiFi
  2. 5G will enable D2D communications: a device can communicate directly with a nearby device, to exploit good local channel condition and to save communication energy cost
- "**Green**" communications: we all want to save the world, so collaborative or relaying communication whose time will come soon

Why Relaying or Collaboration



- Recall simple channel model relating receive signal power P_{Rx} to transmit signal power P_{Tx}

$$P_{Rx} = P_{Tx} \cdot h \cdot d^{-\alpha}$$

  - d: distance, h: small-fading channel gain, α: pathloss exponent
  - $P_{Rx} \geq P_{Th}$ is required to correctly recover transmitted information

- Consider this example: assume h is the same for all links and $\alpha = 2$
  - Direct communication requires transmit power

$$P_{Tx}^{S\rightarrow D} = 3 \cdot h^{-1} \cdot P_{Th}$$

- Relay communication requires total of transmit power

$$P_{Tx}^{S\rightarrow R} + P_{Tx}^{R\rightarrow D} = h^{-1} \cdot P_{Th} + h^{-1} \cdot P_{Th} = 2 \cdot h^{-1} \cdot P_{Th}$$

  - Potential saving in transmit signal power: only need $\frac{2}{3}$ of the direct transmission power

Summary

To understand mobile communication technologies, one needs a deep understand of **mobile communication media**

- **Time-varying rate** depends on T_S/T_C or B_S/B_D
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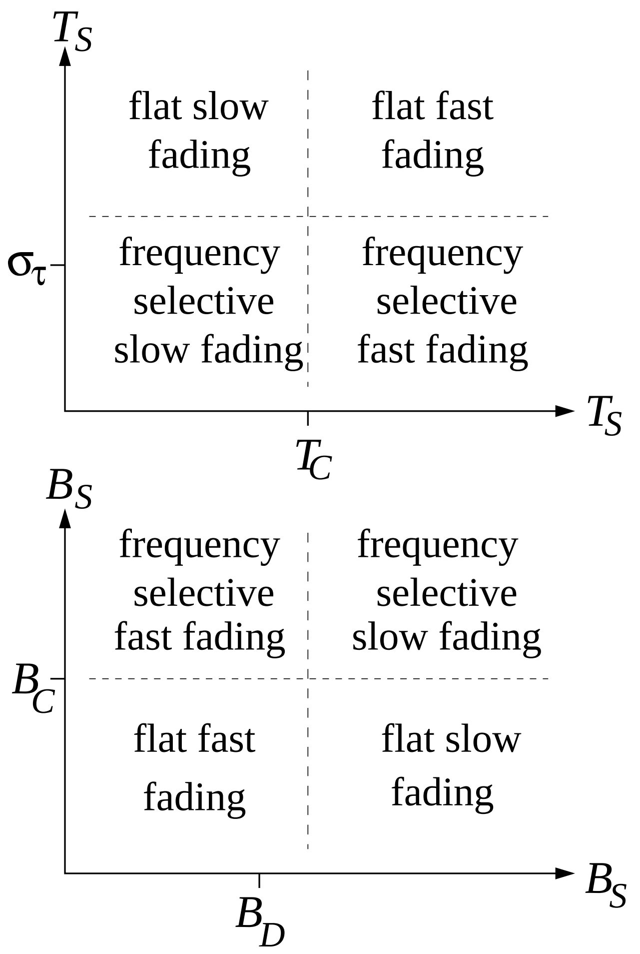

T_S: symbol period

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σ_τ: rms delay spread

B_S: signal bandwidth

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Critically important to truly understand this classification of mobile channels