Optimisation of wireless transmissions in 5G networks

Remco Litjens

WND-conferentie 'Natuurkunde op Afstand', 11-12-2020

Nice to meet you …

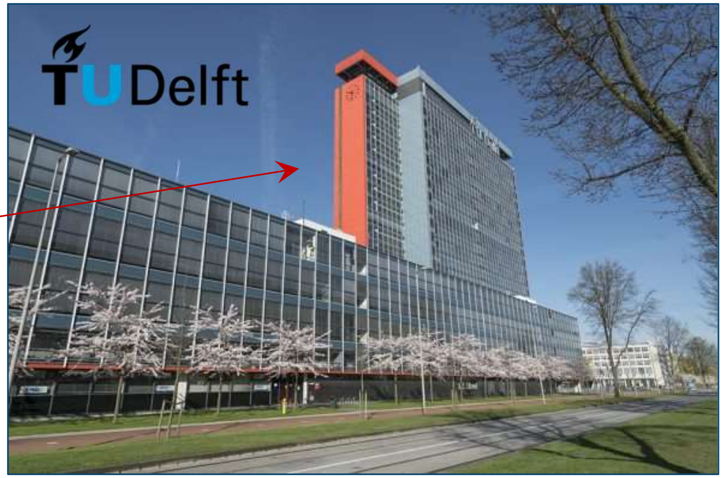
10th floor

- Remco Litjens
- Education
  - Econometrics, Tilburg University, 1989-94
  - EECS, University of California at Berkeley, 1995-96
  - Applied Mathematics, University of Enschede, 1998-2003
- Work
  - KPN, 1997-2001
  - TNO, 2001-now
  - TU Delft, 2014-now

TILBURG UNIVERSITY

University of Twente
The Netherlands

kpn



Outline

- Introduction
- Preliminaries
- Packet scheduling
- Beamforming
- Wrap-up

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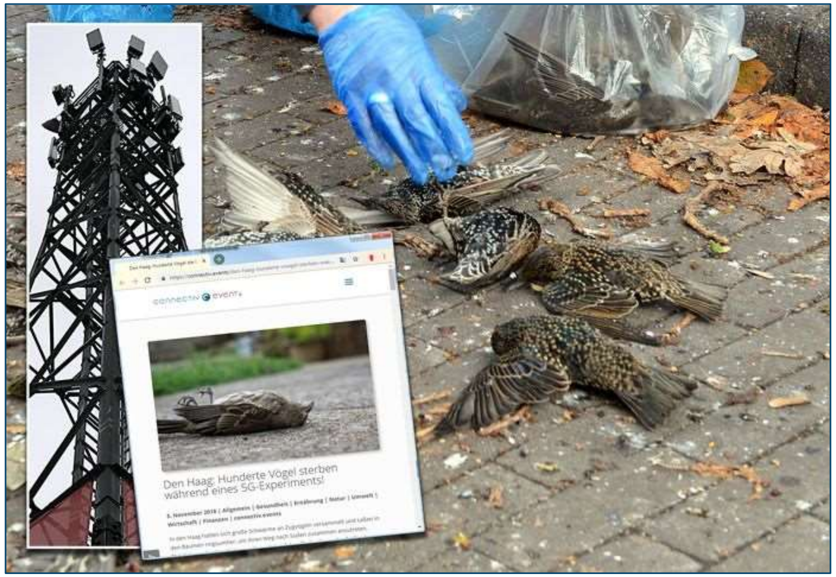
Mobile networks

Is 5G welcome?



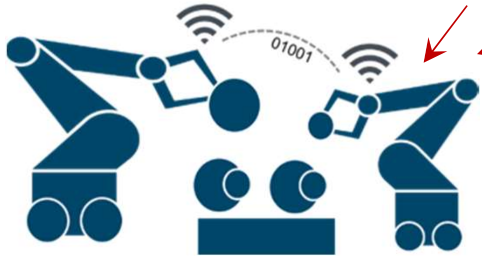
Mobile networks

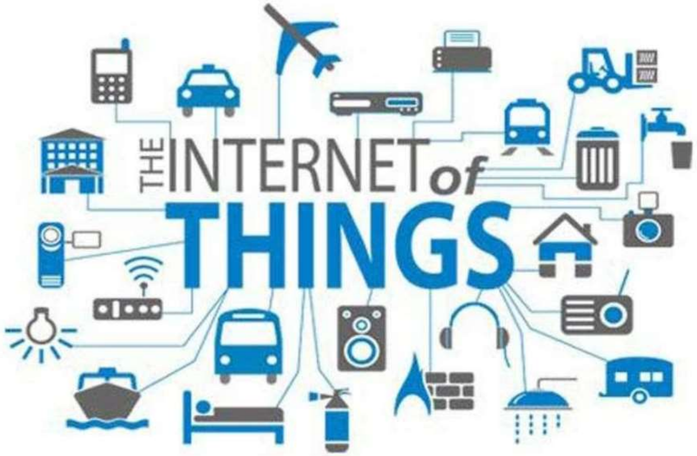
5G is welcome!

Factory of the Future

Internet of Things

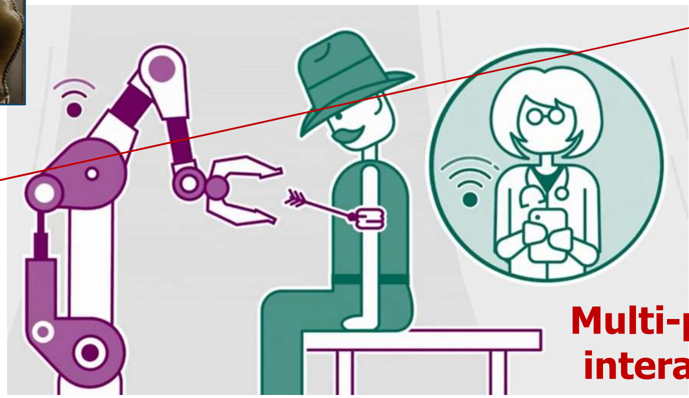
Smart city





Social XR meetings

Internet of Skills

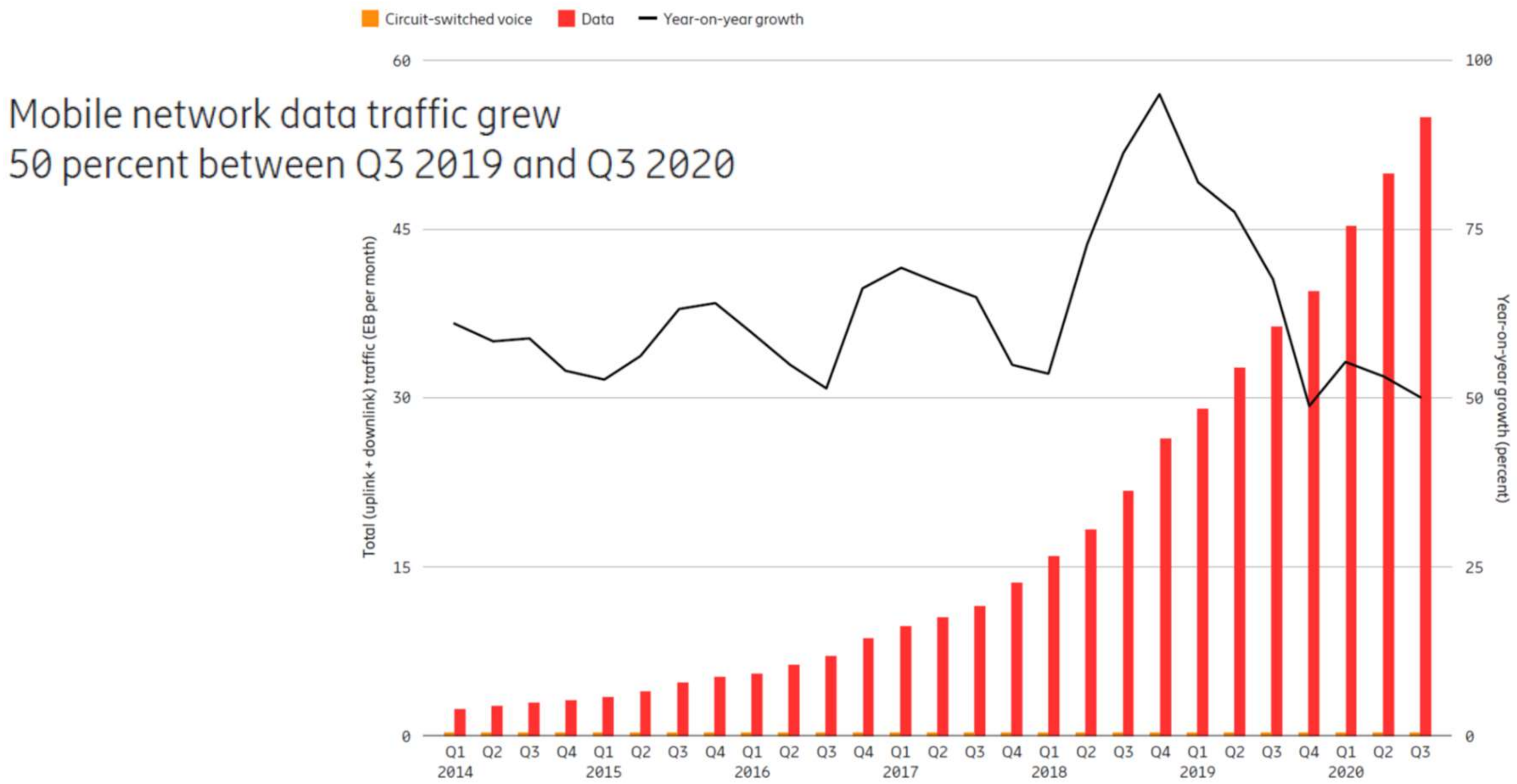


Multi-player interactive gaming

Source: Ericsson, 'Mobility Report' (November '20, http://www.ericsson.com/mobility-report)

About the mobile market

Statistics on usage

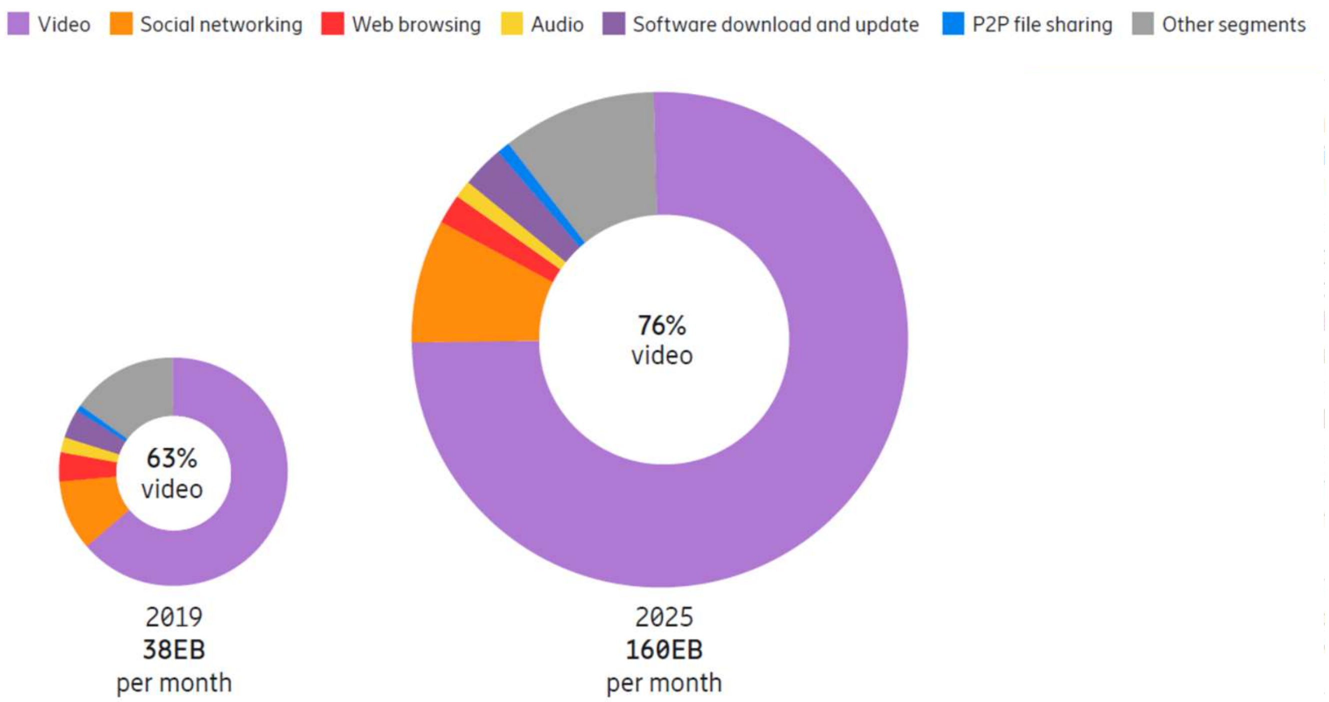


Source: Ericsson, 'Mobility Report' (February '20, http://www.ericsson.com/mobility-report)

About the mobile market

Statistics on usage

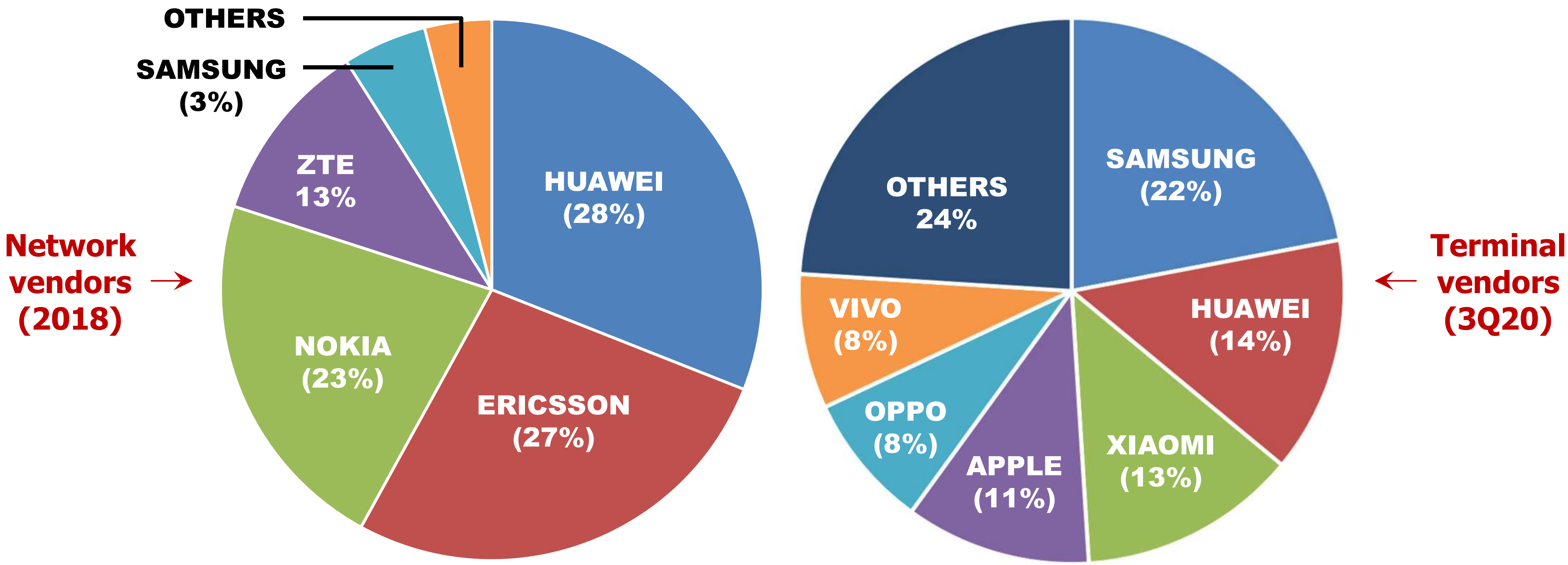
Figure 11: Mobile traffic by application category per month (percent)



Sources: IHS Markit (2019, https://techblog.comsoc.org/2019/04/03/huawei-led-global-4g-lte-infrastructure-market-which-totalled-22-9b-in-2018/)
Counterpoint, 'Global Smartphone Market Share: By Quarter' (11-2020, https://www.counterpointresearch.com/global-smartphone-share/)

About the mobile market

Market shares of network and terminal vendors

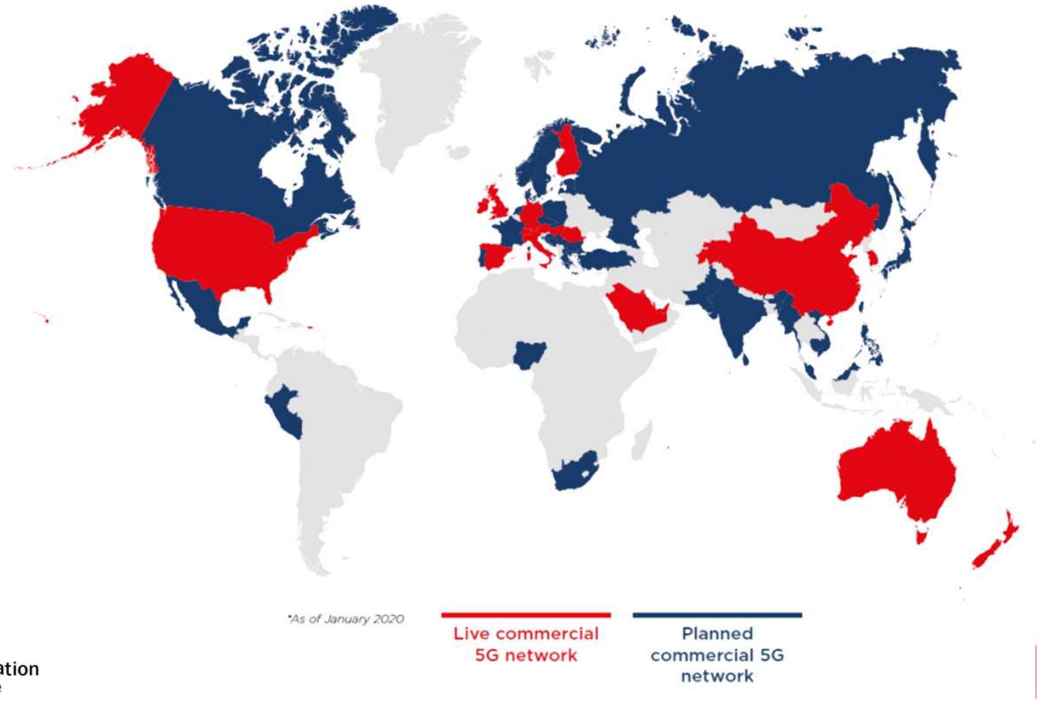


Source: GSM Association, 'The Mobile Economy' (2020, https://www.gsma.com/r/mobileeconomy/)

About the mobile market

Statistics on 5G technology deployment

- 5G commercially available from 46 operators in 24 markets; 79 operators across a further 39 markets plan to launch 5G services

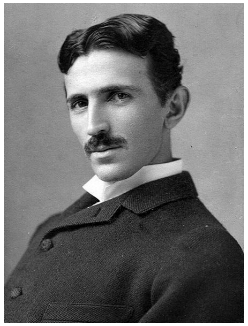


A bit of history

1800s

- 1864 The Scottish physicist James Clerk Maxwell (1831–1879) postulated the possibility of generating electro-magnetic waves that would propagate at the speed of light.

- 1886 The German physicist Heinrich Rudolph Hertz (1857-1894) demonstrates the wave character of electromagnetic transmission. *'It's of no use whatsoever[...] this is just an experiment that proves Maestro Maxwell was right – we just have these mysterious electromagnetic waves that we cannot see with the naked eye. But they are there.'*



- 1893 The Serbian-American inventor Nikola Tesla (1856-1943) was the first to publicly demonstrate wireless transmission and is thus credited with inventing modern radio communications.

A bit of history

1800-1900s

- 1895 The Italian inventor Guglielmo Marconi (1874-1937) demonstrated the electromagnetic transmission and reception of messages.
- 1896 The world's first patent on wireless telegraphy using Hertzian waves was awarded to Marconi (see also 1943).
- 1900 On December 23, 1900 the Canadian inventor Reginald Fessenden (1866-1932) generated the first-ever intelligible speech successfully broadcast by radio waves: the beginning of wireless telephony.
- 1935 The American inventor Edwin Howard Armstrong (1890-1954) develops FM in 1935, the technological basis of 1G.

A bit of history

1900s

- 1943 The world's first patent on wireless telegraphy, previously awarded to Marconi, was overturned by the US Supreme Court in favor of Tesla, after 30 years of legal battles.
- 1956 The first fully automated mobile phone system for vehicles was launched in Sweden. The network was operated by Televerket, with equipment provided by Ericsson and Marconi.

A bit of history

1900s

- 1979 The Japanese telecommunications operator NTT deployed the world’s first public wireless telephony network in Tokyo based on the cellular concept.
- 1981 The cellular era reached Europe when Nordic Mobile Telephone (NMT) systems (1G/FM) became operational in the 450 MHz band in Scandinavia, which later spread in slightly different versions to several countries in Europe.

A bit of history

1900-2000s

- 1982 The Conférence Européenne des administrations des Postes et des Télécommunications (CEPT) installed the Groupe Spécial Mobile, with the task to devise a pan-European mobile telecommunication system, supporting seamless roaming across Europe.
- 1991 The world's first GSM (2G) call was made by the Finnish prime minister Harri Holkeri with a Nokia car phone.
- 2000 The Dutch government auctions UMTS (3G) spectrum for HFL 5.9 billion!!

A bit of history

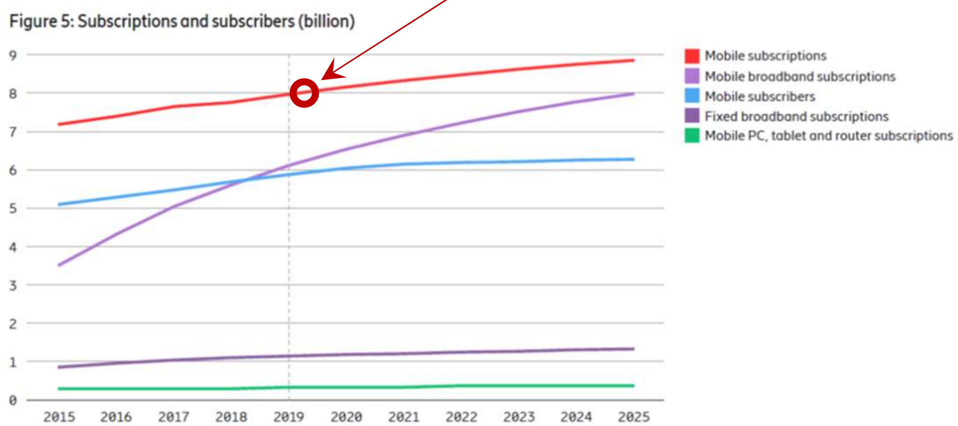
2000s

- 2001 On October 1, 2001, the Japanese network operator NTT DoCoMo commercially launches the world's first 3G network based on wideband CDMA technology.
- 2002 Number of mobile subscribers surpasses number of fixed-line subscribers worldwide.
- 2007 Launch of Apple's iPhone.
- 2009 World's first commercial launch of LTE (Long-Term Evolution; 4G) by TeliaSonera in Sweden and Finland.

A bit of history

2000s

- 2017 3GPP approves 5G logo.
- 2018 The Academy of Finland grants the €250 million 6Genesis project, the world's first research programme focusing on 6G research
- 2019 World's first commercial 5G launch in South Korea.
- 2020 The number of cellular subscriptions exceeds the 8 billion mark



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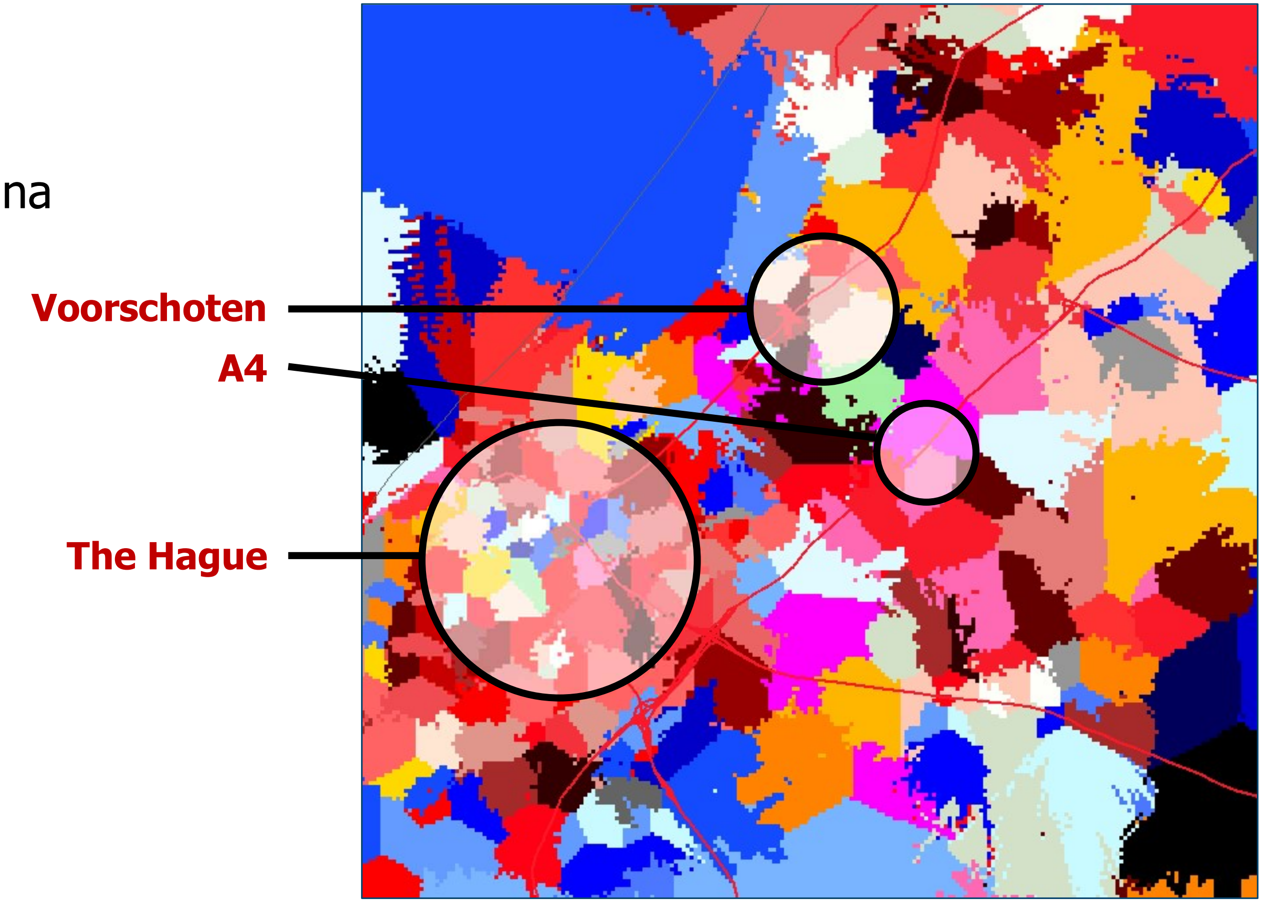
A mobile cellular network

Some terminology

- Each colored area is a *cell*, i.e. the service area of a given antenna
- A typical *site* serves three cells



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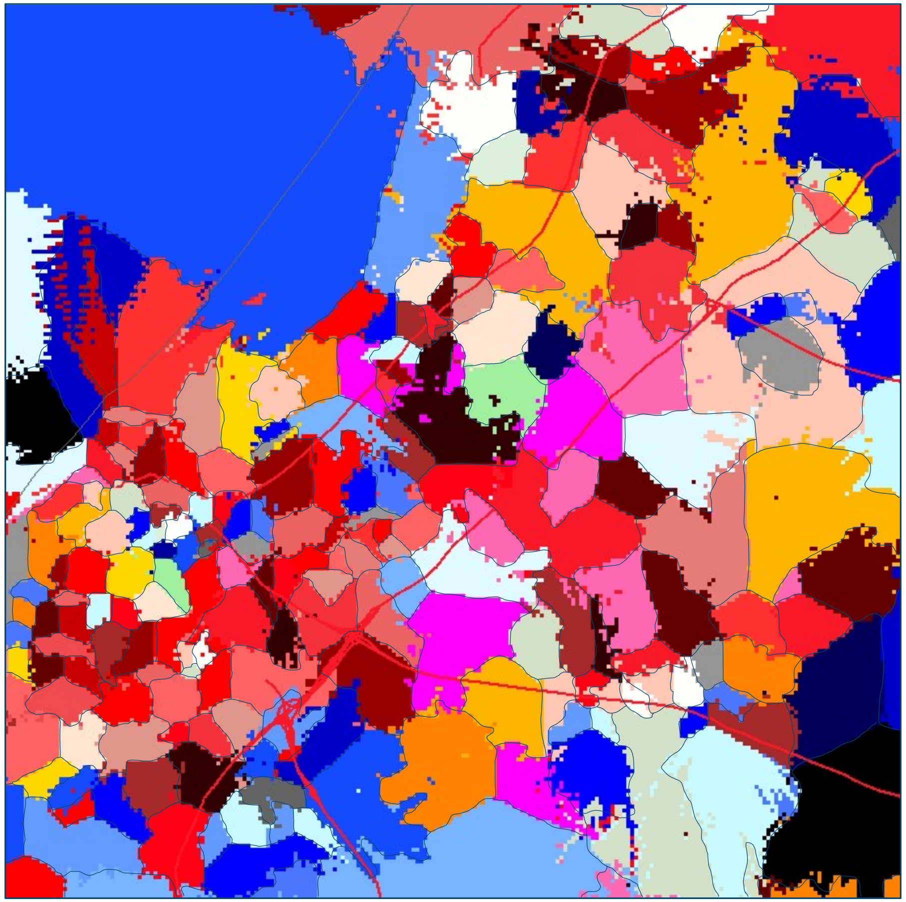
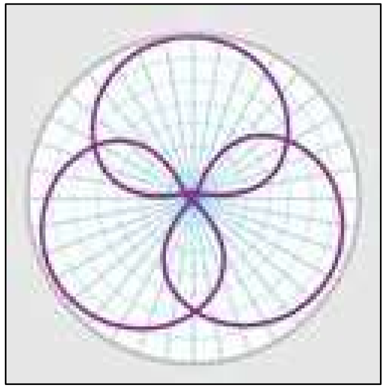
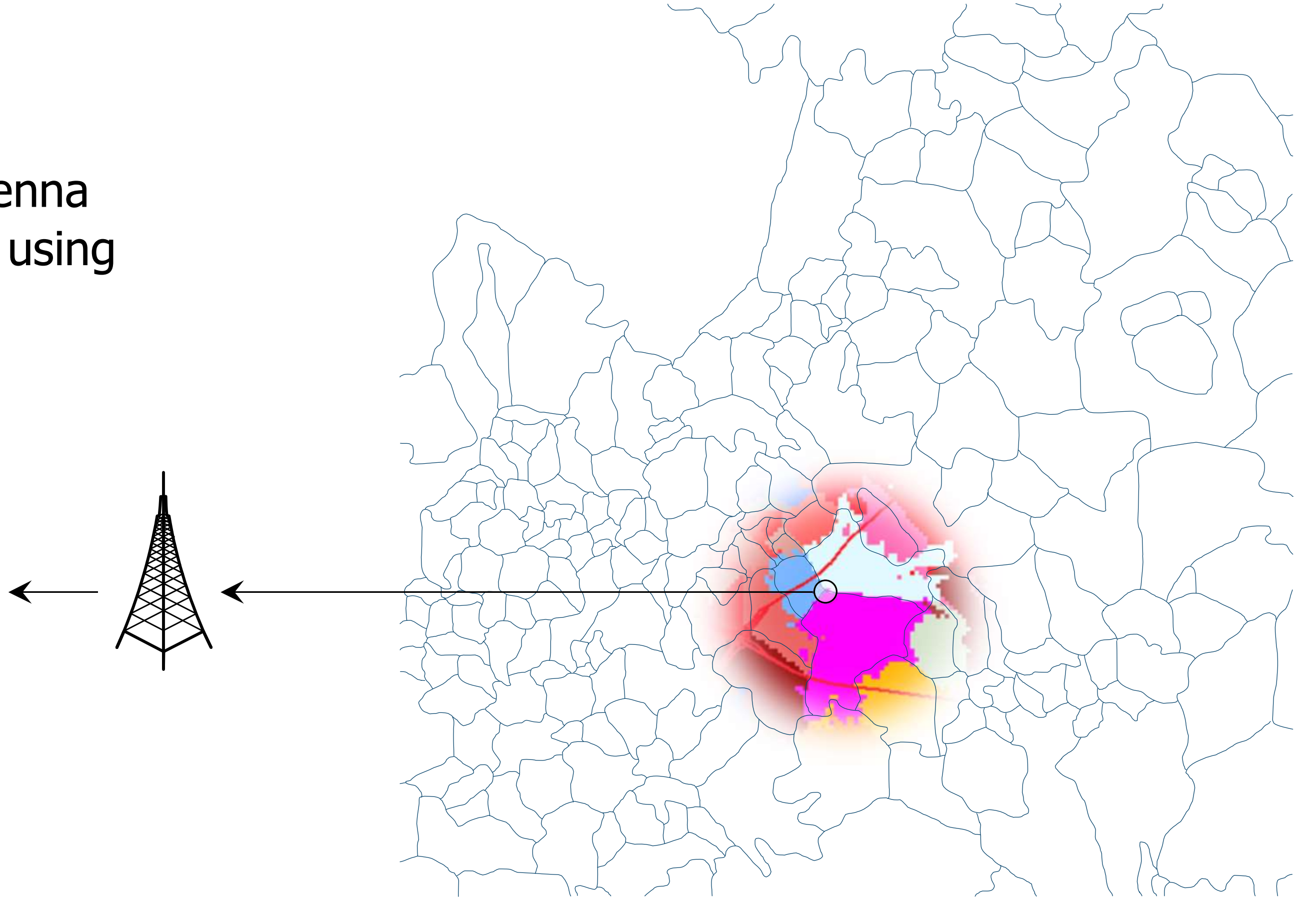


A mobile cellular network

Some terminology

- Each colored area is a *cell*, i.e. the service area of a given antenna
- A typical *site* serves three cells using *directional antennas*

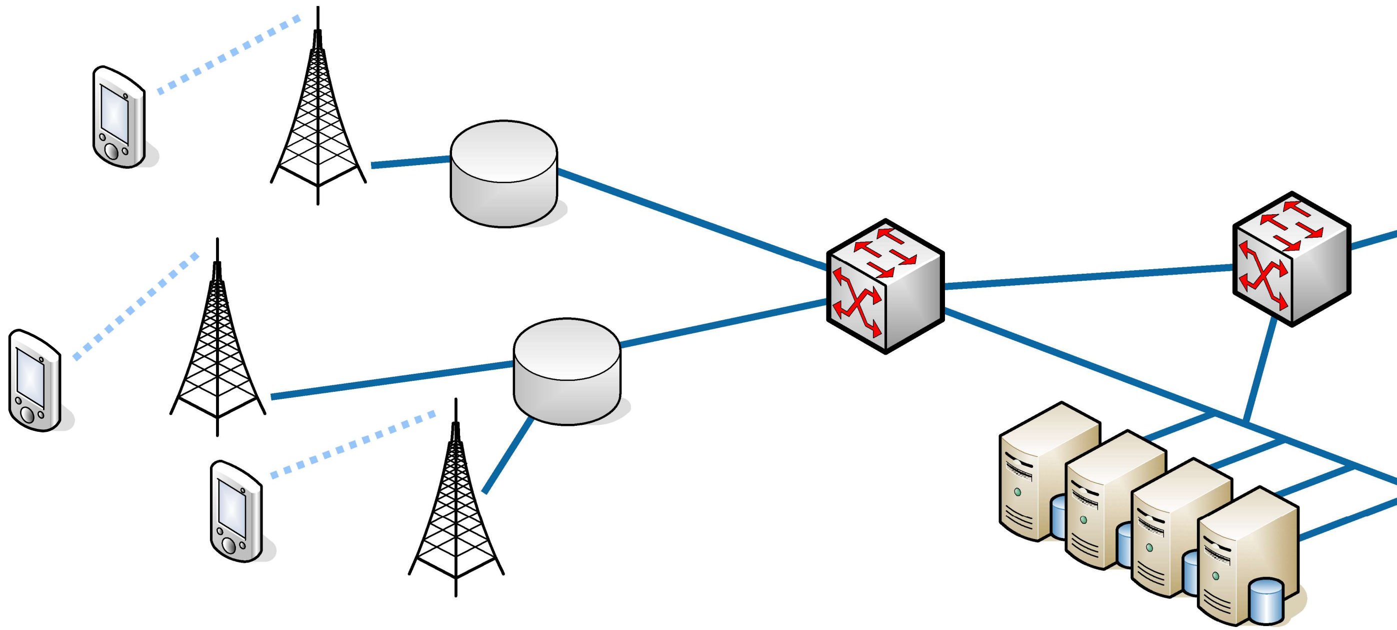




A mobile cellular network

Some terminology

- The antenna sites are connected to a *core network*
- The core network provides *gateways* to *external networks*

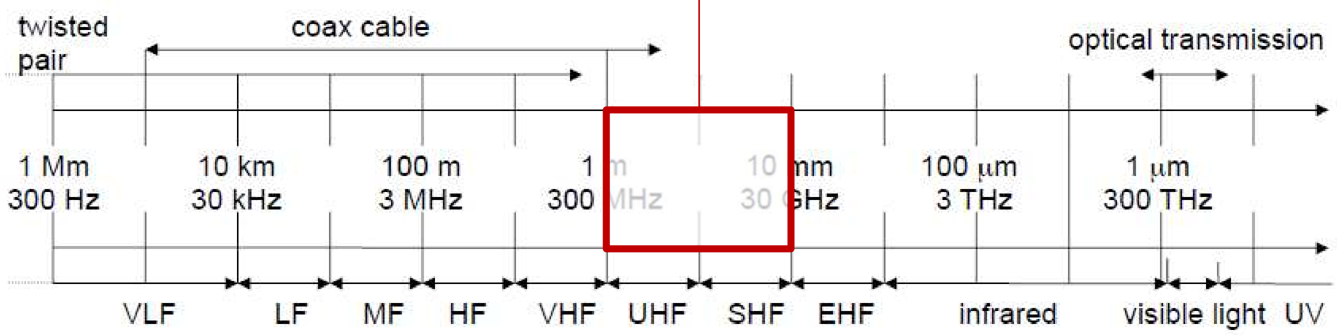


The wireless channel

Spectrum aspects

- Where?

2/3/4G networks use the UHF band (800/900/1800/2100/2600 MHz)
5G networks (will) use the UHF/SHF bands (700/3500/26000 MHz)



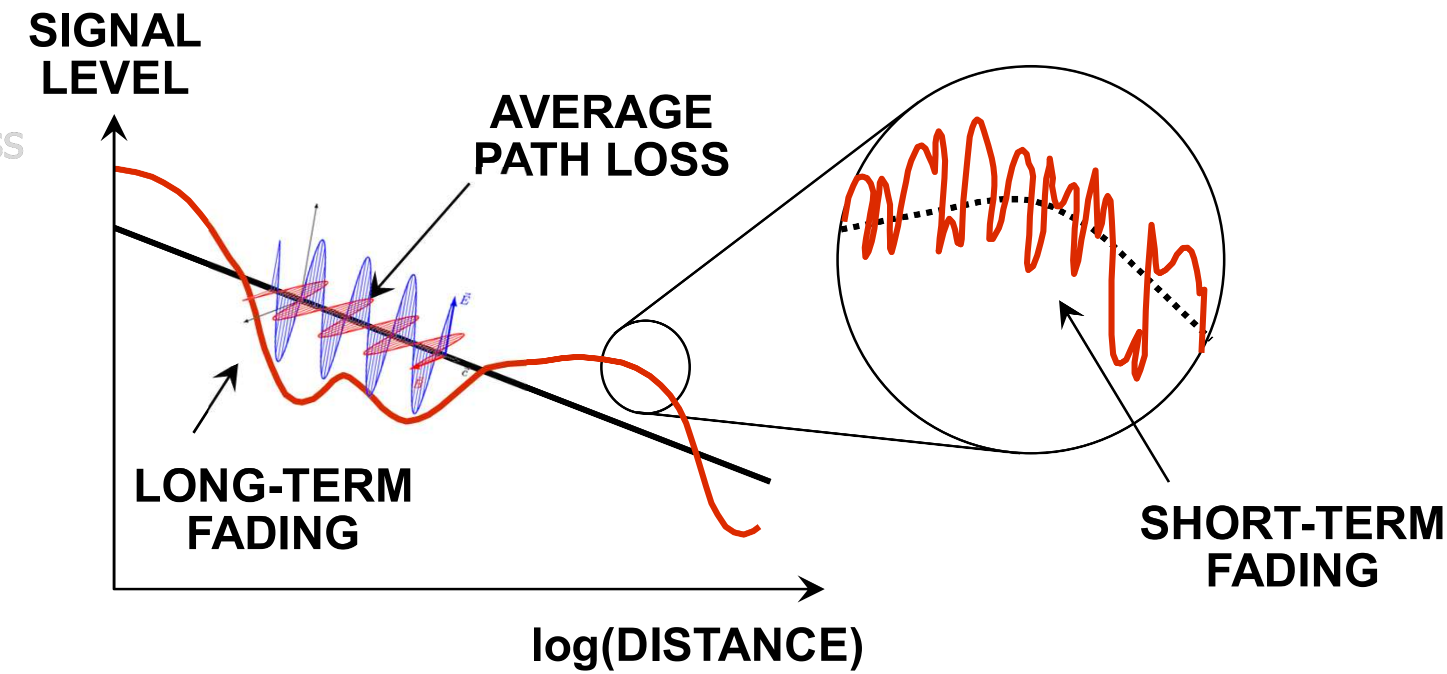
VLF = Very Low Frequency
LF = Low Frequency
MF = Medium Frequency
HF = High Frequency
VHF = Very High Frequency

UHF = Ultra High Frequency
SHF = Super High Frequency
EHF = Extra High Frequency
UV = Ultraviolet Light

The wireless channel

Propagation aspects

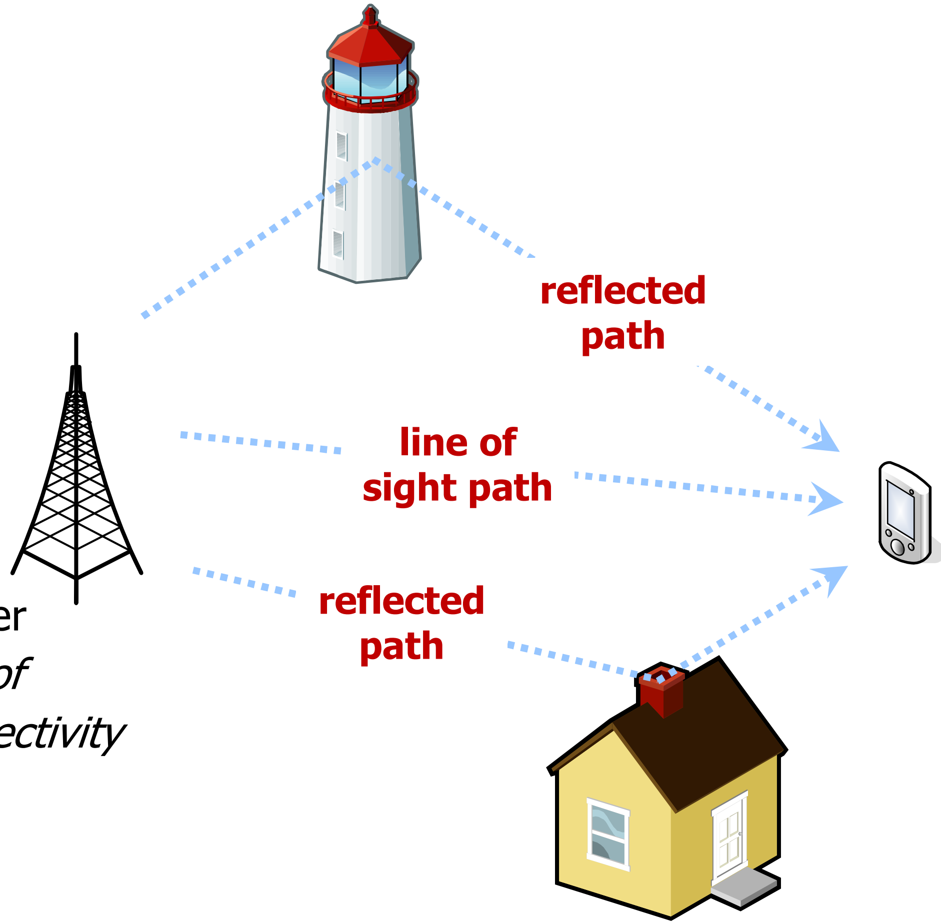
- Path loss
- Shadowing
- Multipath fading
- Indoor penetration loss
- Body loss
- Cable loss
- …



The wireless channel

Propagation aspects

- Multipath fading
  - A broadcast signal typically travels multiple paths from the transmitter to the receiver
  - As different paths have different lengths, these copies of the same signal experience different delays
  - When aggregated at the receiver, these signals may strengthen or weaken each other
  - Effectively, this creates a *spatial landscape of high/low signal strengths* and *frequency-selectivity*



The wireless channel

Propagation aspects

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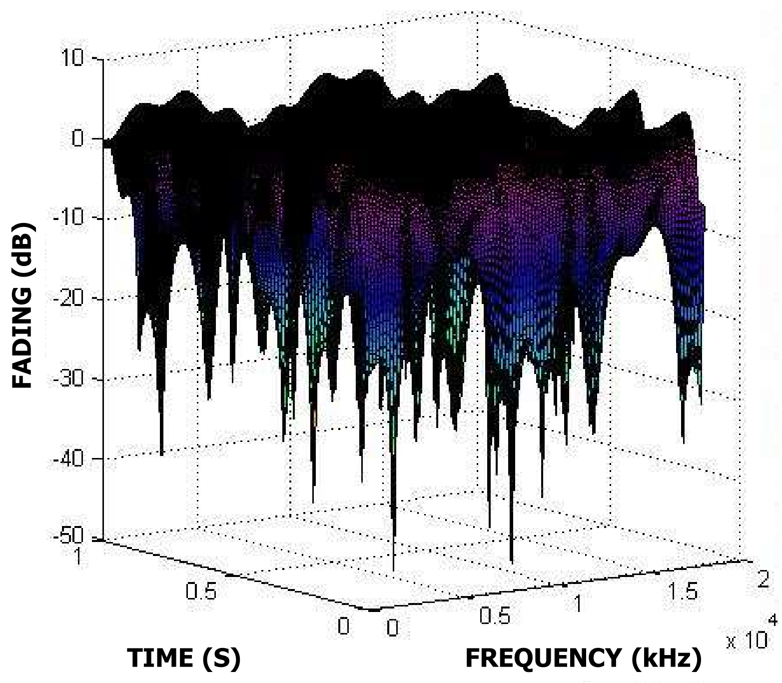
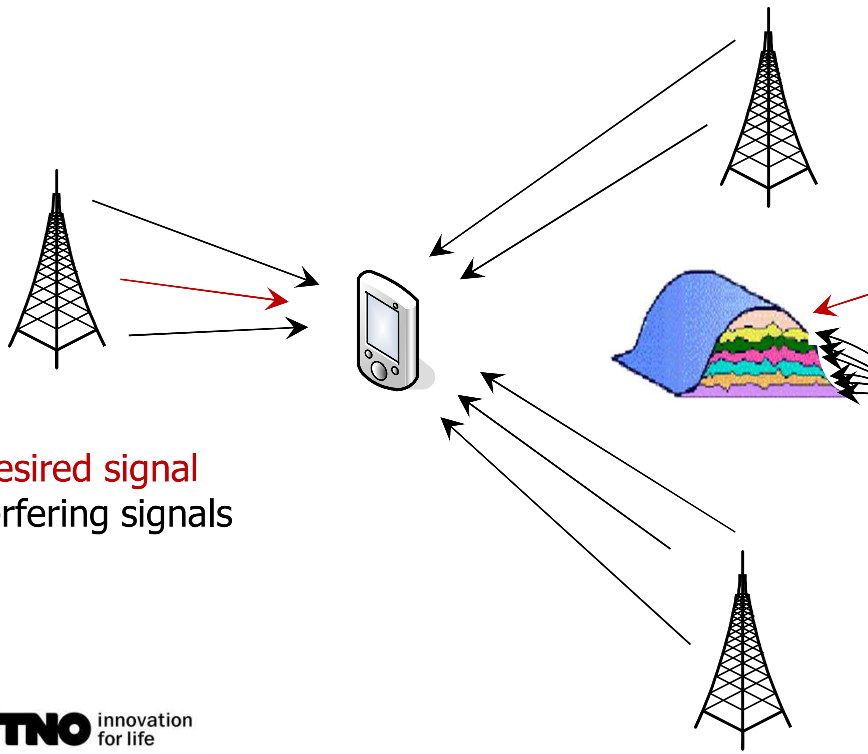
  - Effectively, this creates a *spatial landscape of high/low signal strengths* and *frequency-selectivity*
  - A pedestrian-speed user may experience something like this



The wireless channel

Link quality

- SINR = Signal-to-Interference-plus-Noise Ratio



desired signal
interfering signals

$$SINR = \frac{p_{\text{received,desired}}}{\sum p_{\text{received,interfering}} + N}$$

The wireless channel

Link quality

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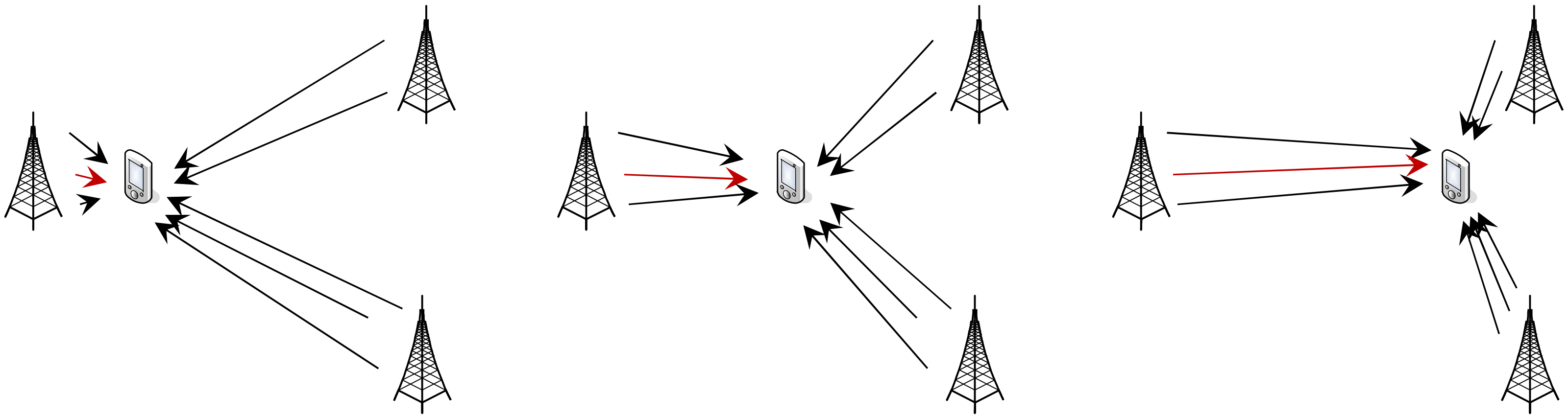

near site →
high SINR

near cell edge →
low SINR

beyond cell edge →
unlikely!!

Radio resource management

A suite of management mechanisms

- Radio resource management comprises a suite of mechanisms designed and tuned to *efficiently* and *effectively* assign *resources* to users at different time scales
  - Resources: time, spectrum, power, antennas
  - Mechanisms: admission control, handover control, congestion control, adaptive modulation & coding, packet scheduling, beamforming, power control
  - Efficiently: do not waste resources
  - Effectively: provide good service quality

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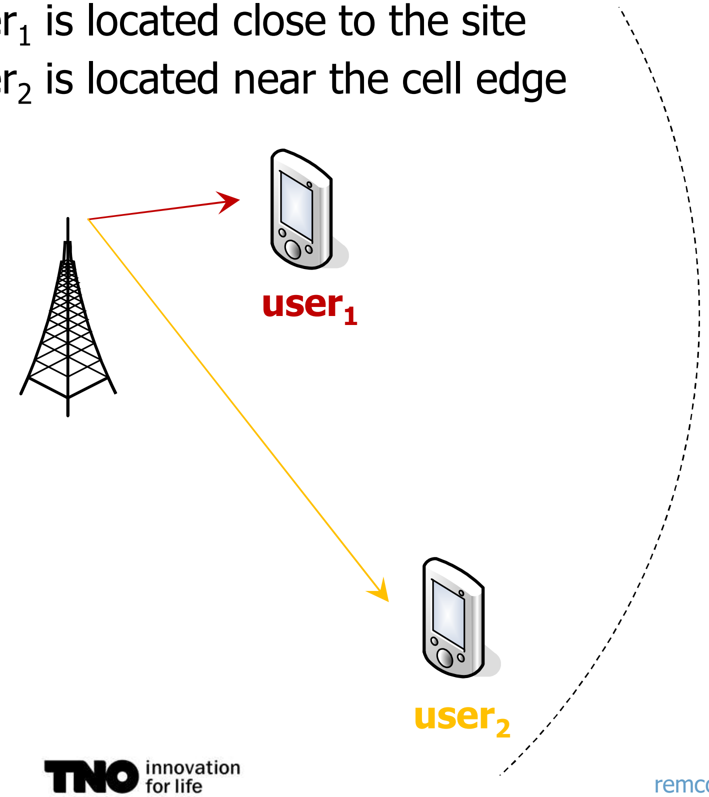
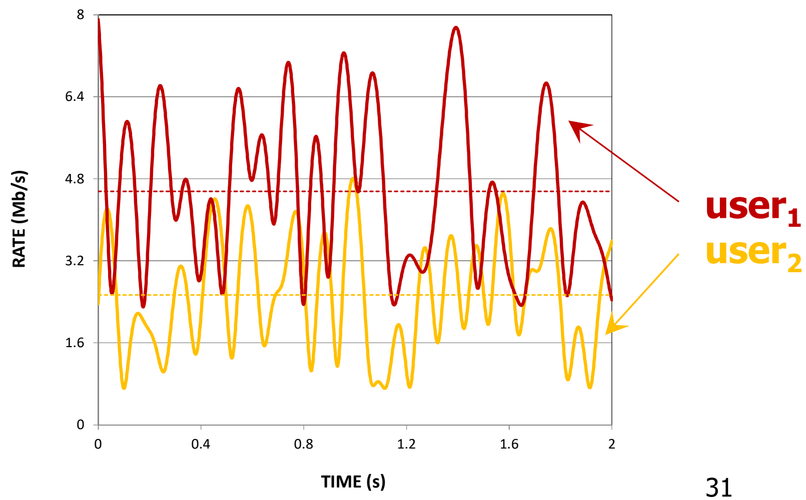
Packet scheduling

A key radio resource management mechanism

- Consider a cell serving two users
  - $User_1$ is located close to the site
  - $User_2$ is located near the cell edge



- Consider example link quality traces
  - Recall distance-based path loss: *on average $user_1$ has a better channel*
  - Recall multipath fading: *the per-user SINR varies over time; the attainable bit rates $R_i(t)$ vary accordingly*



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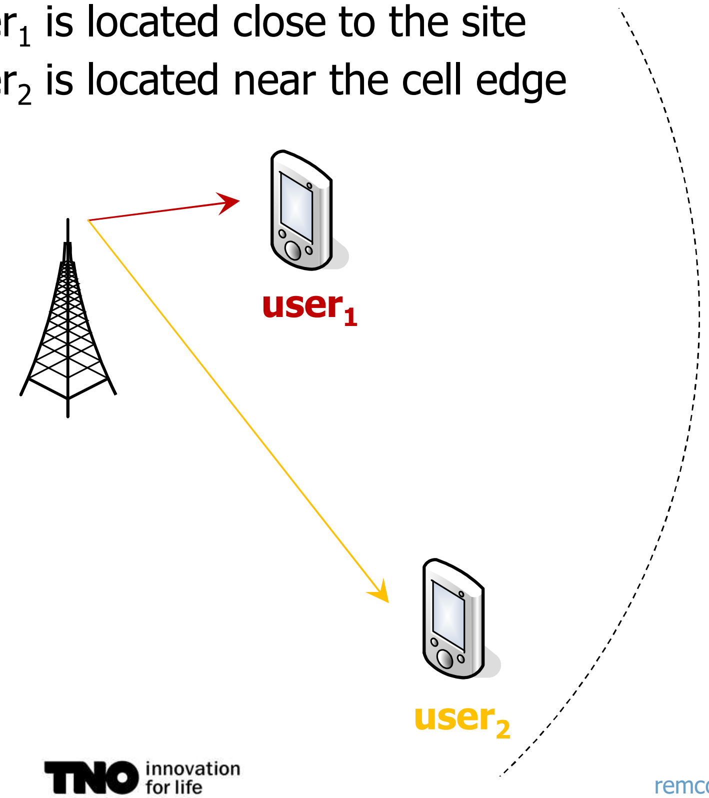
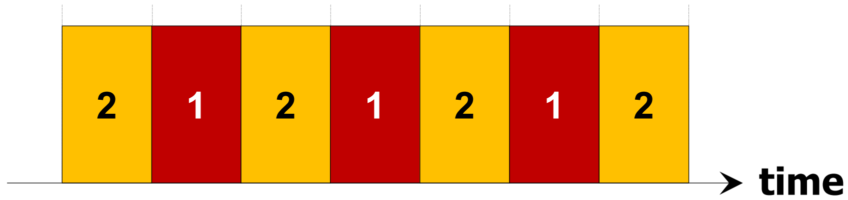


- Consider a purely time-shared channel
  - Scheduler decides in each time slot (~ 1 ms) which user to serve
  - Example of cyclic scheduling: 'round robin'
  - *How else could you do it?*



Packet scheduling

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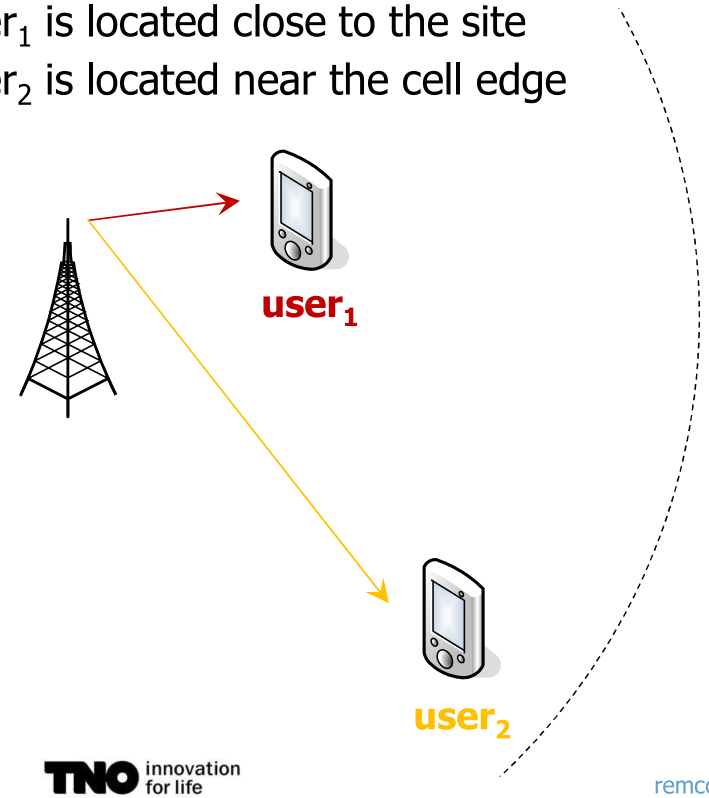
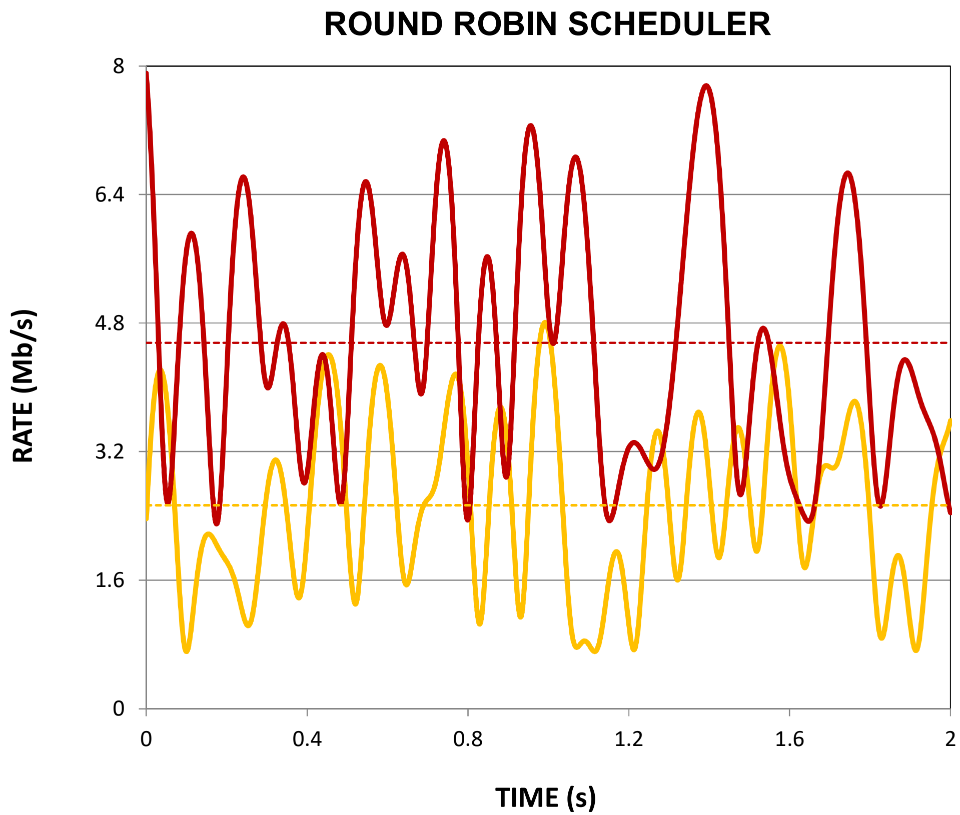


cyclic scheduling: just alternate



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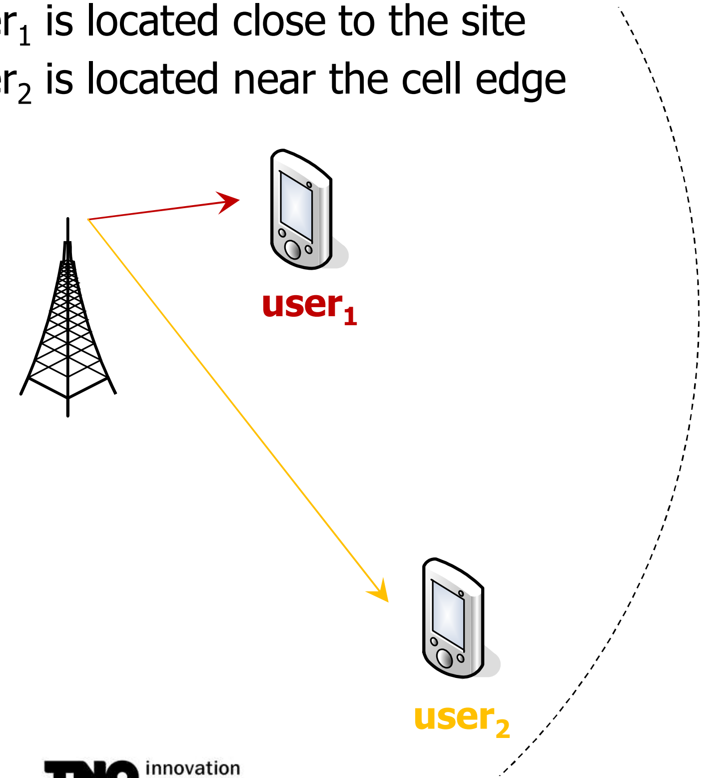

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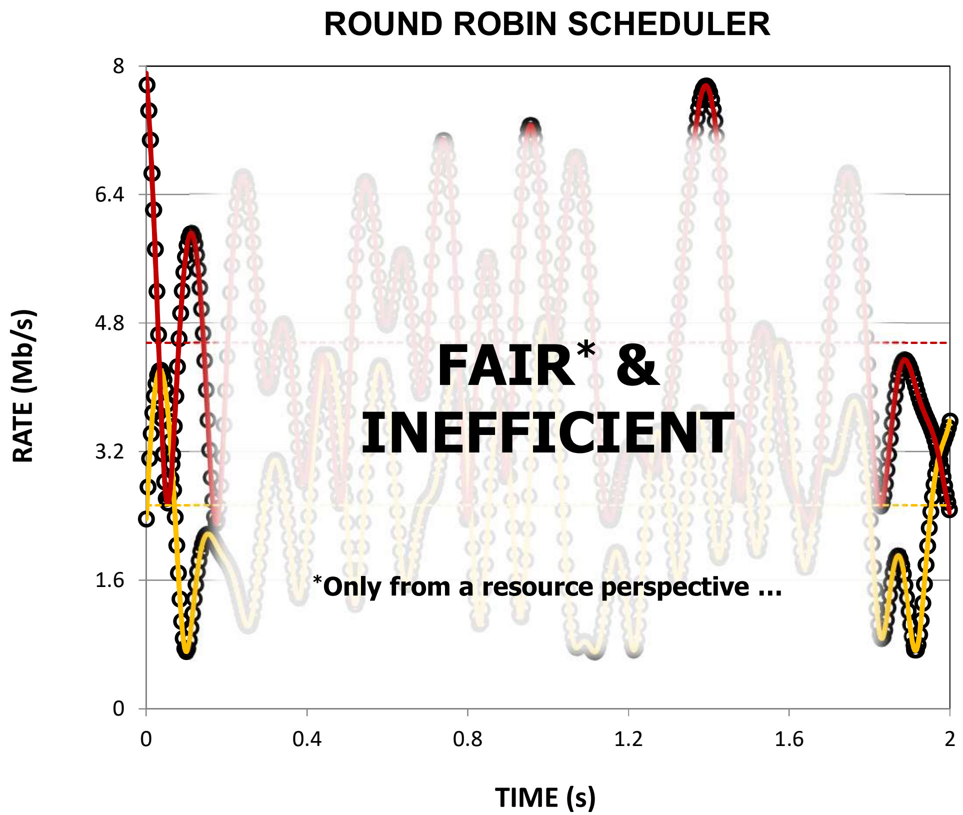

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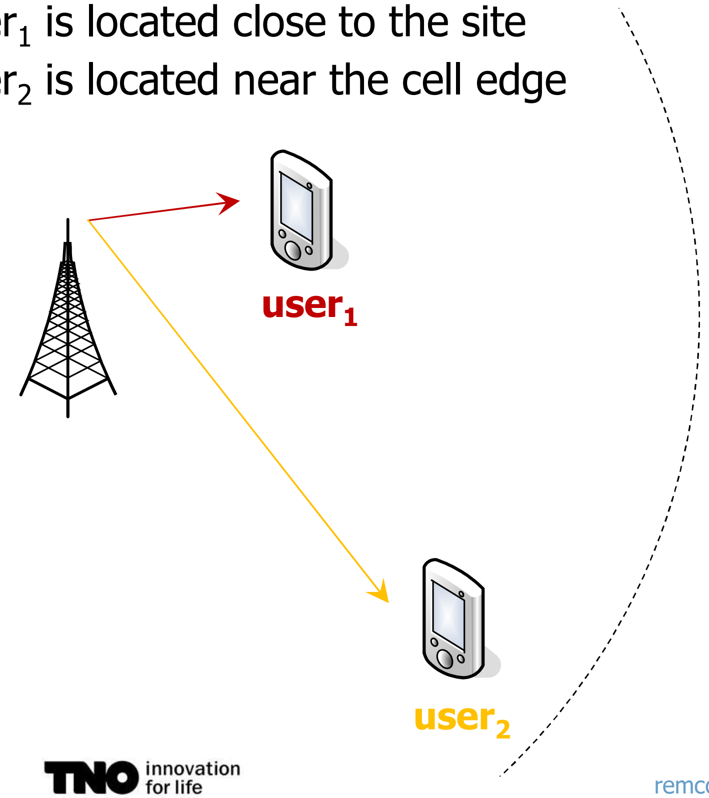
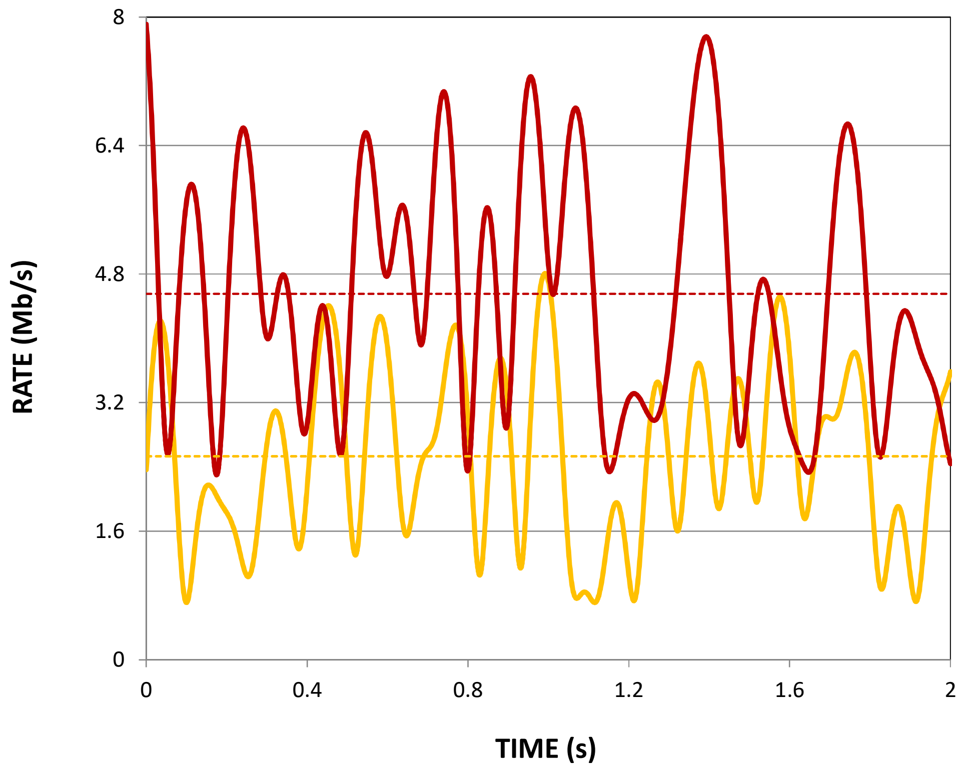


always serve the user with
the highest attainable bit rate

$$i^* = \arg\max_i R_i(t)$$

MAXIMUM RATE SCHEDULER



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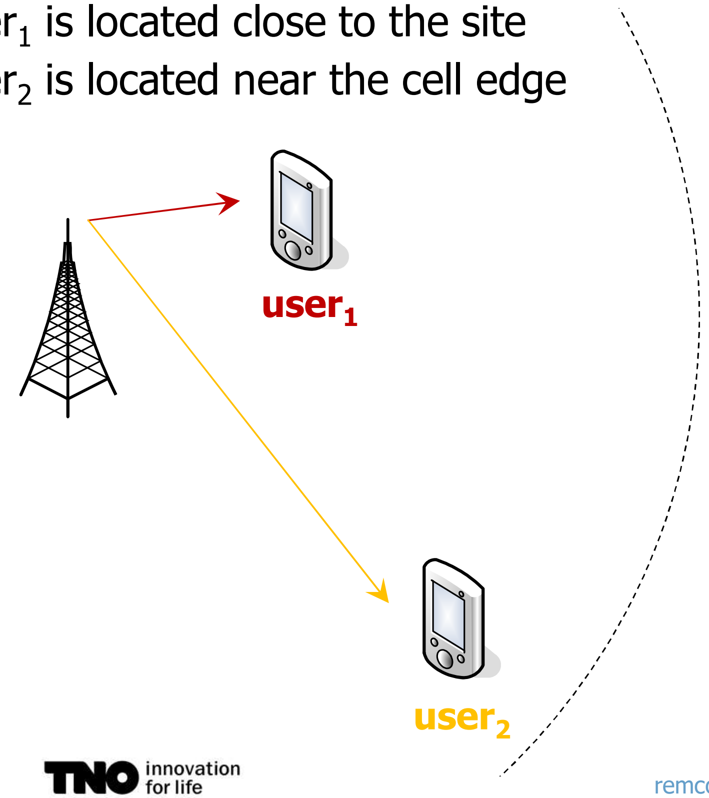

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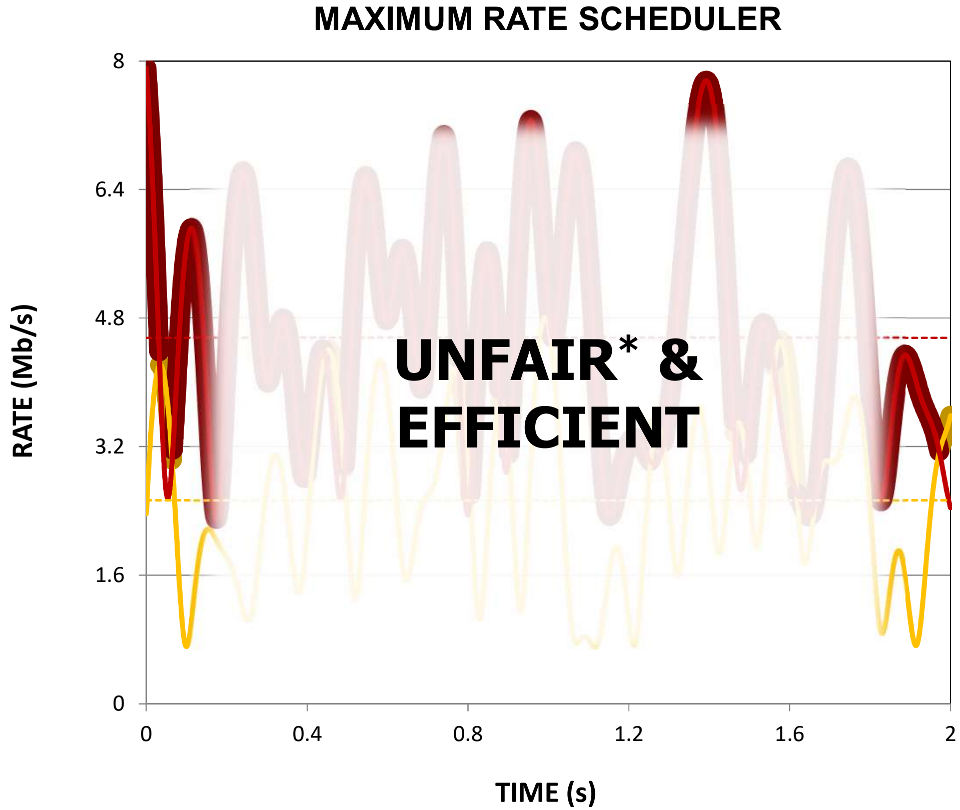

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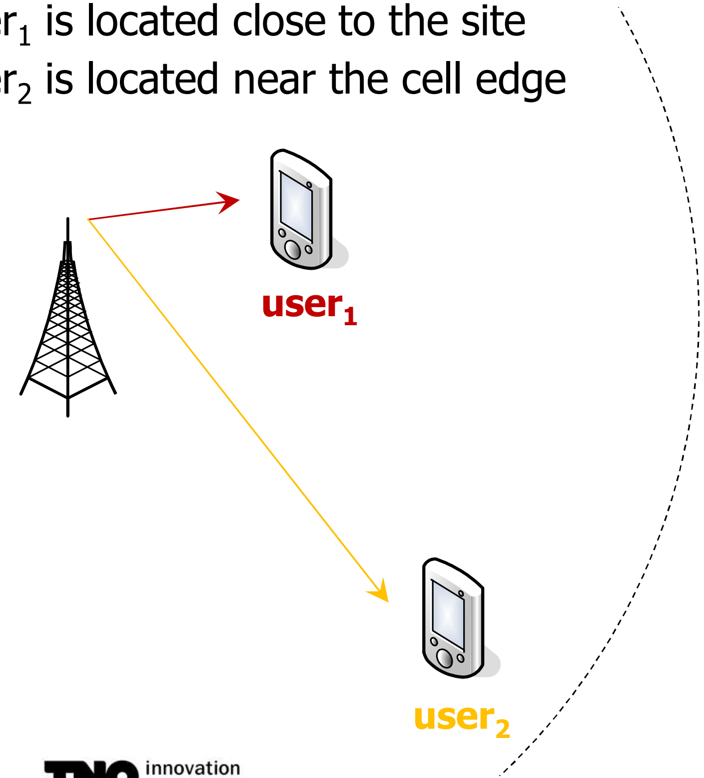
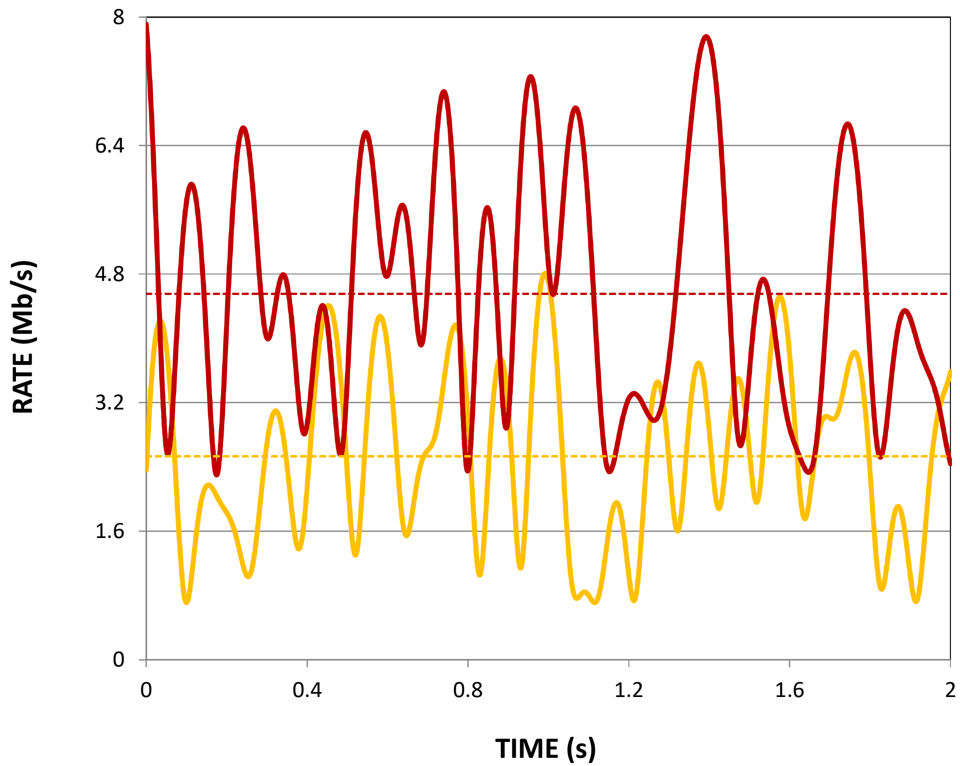


serve the user with the highest relative attainable bit rate

$$i^* = \arg\max_i \frac{R_i(t)}{\hat{R}_i}$$



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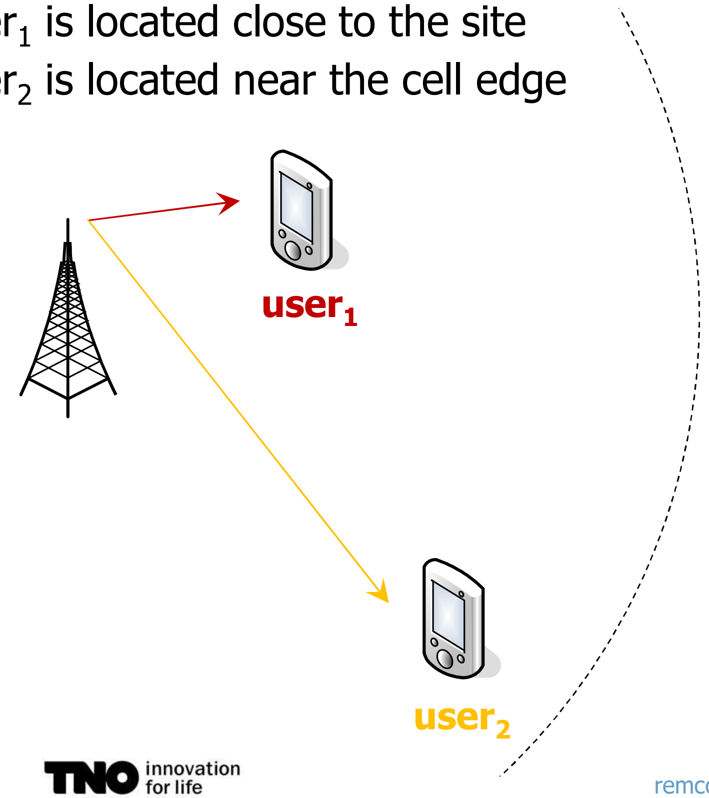

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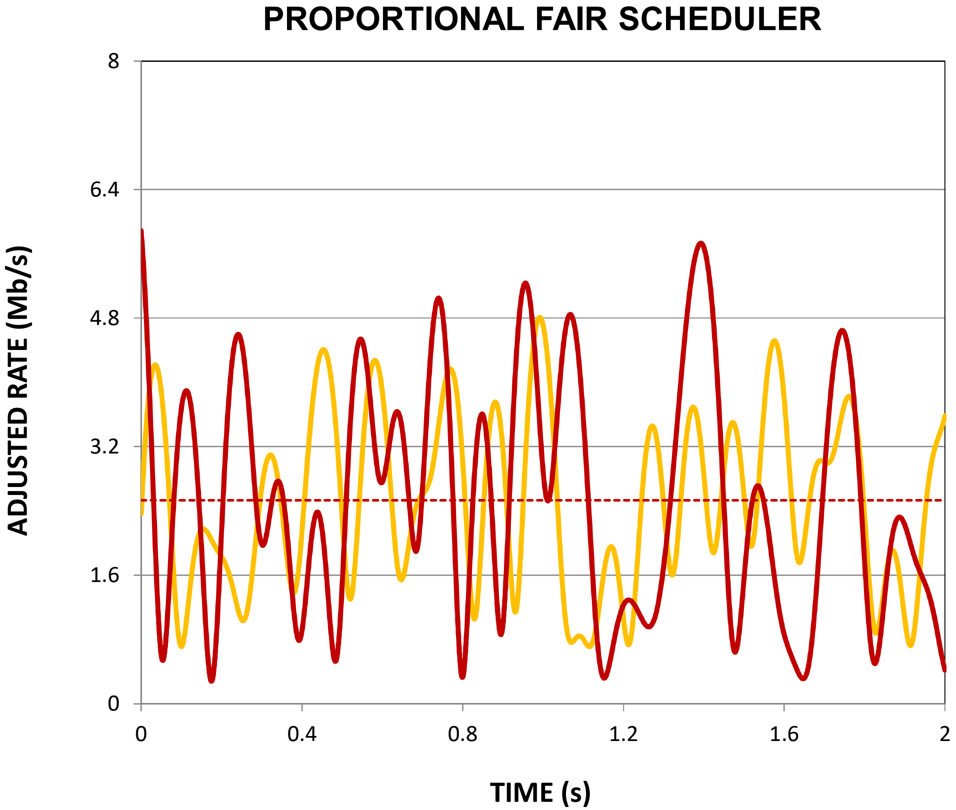

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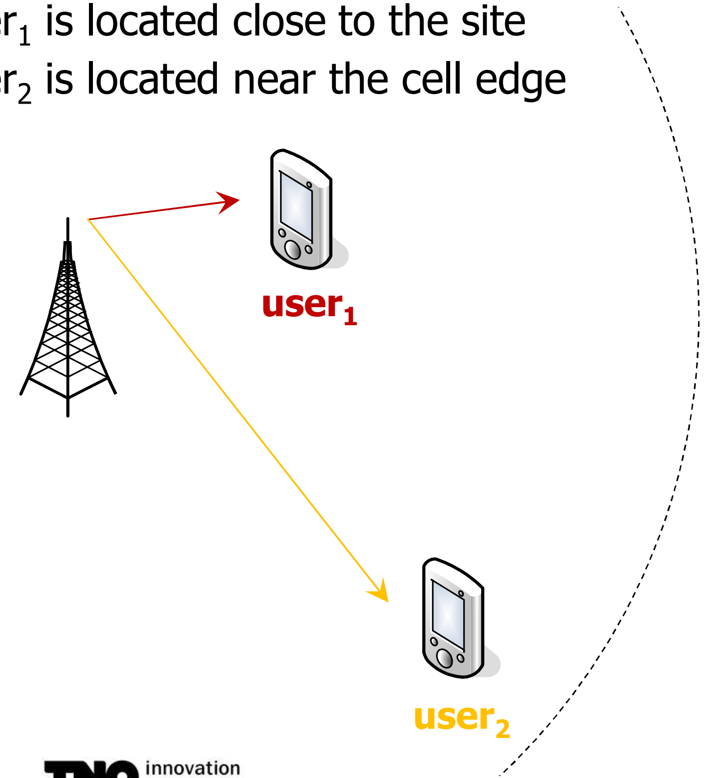

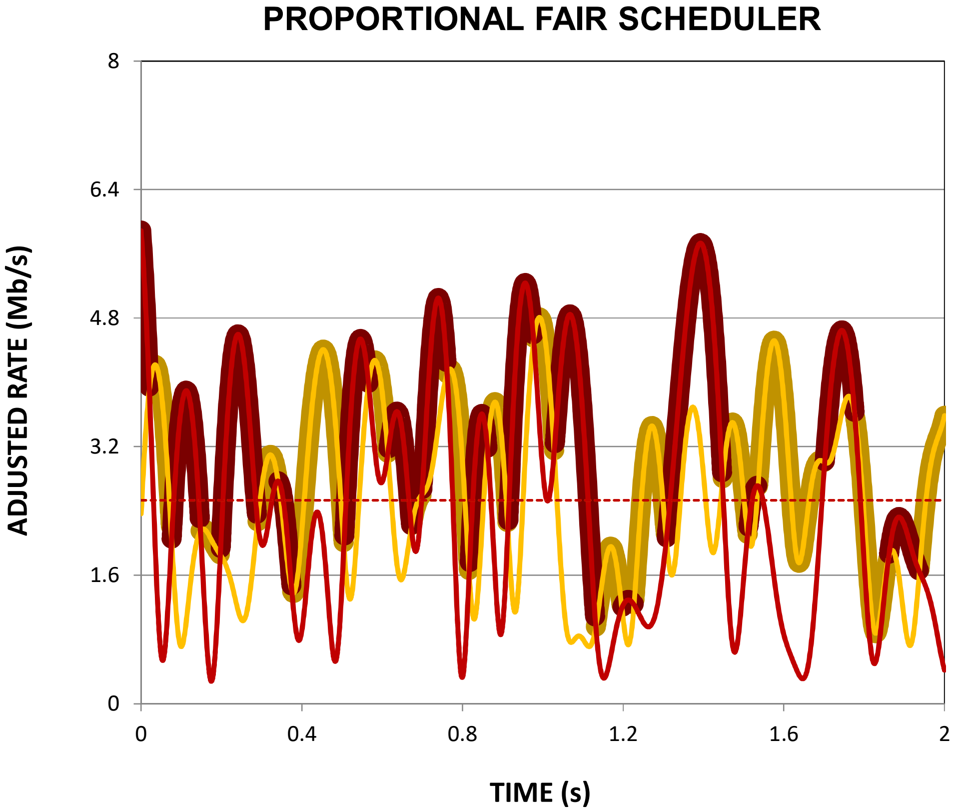

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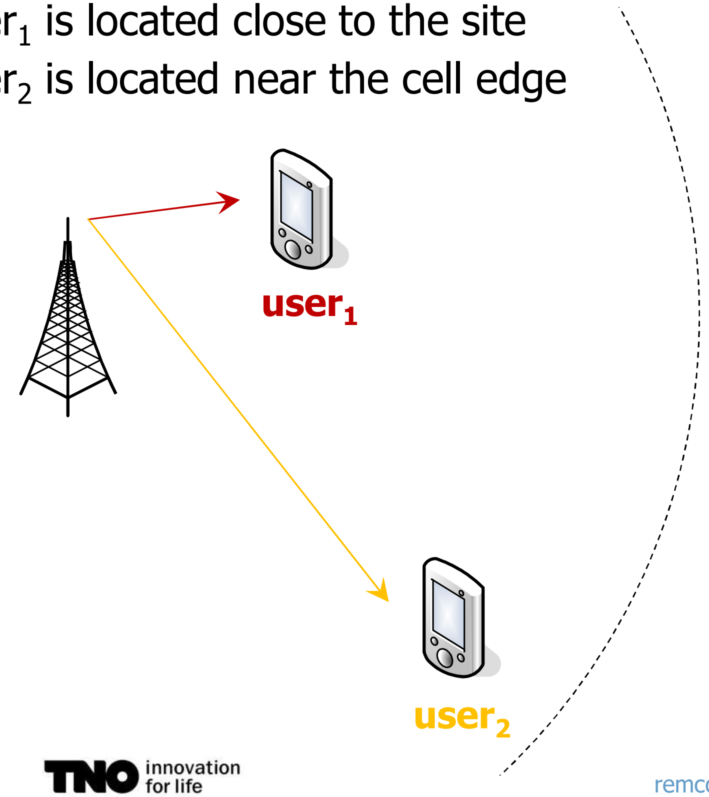

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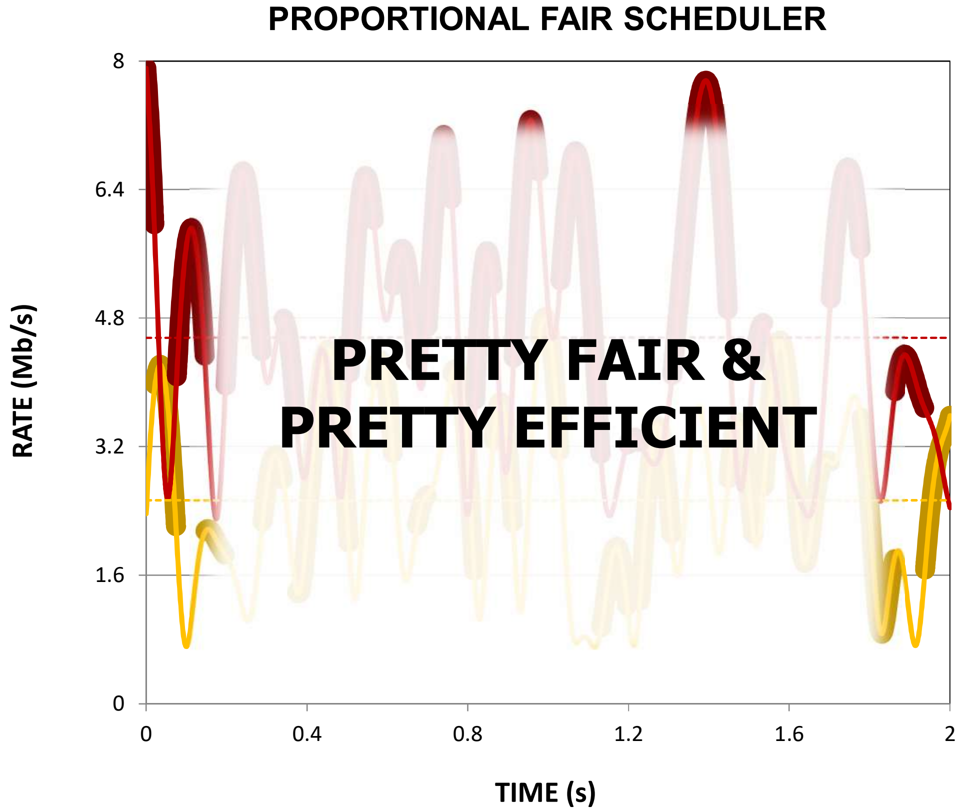

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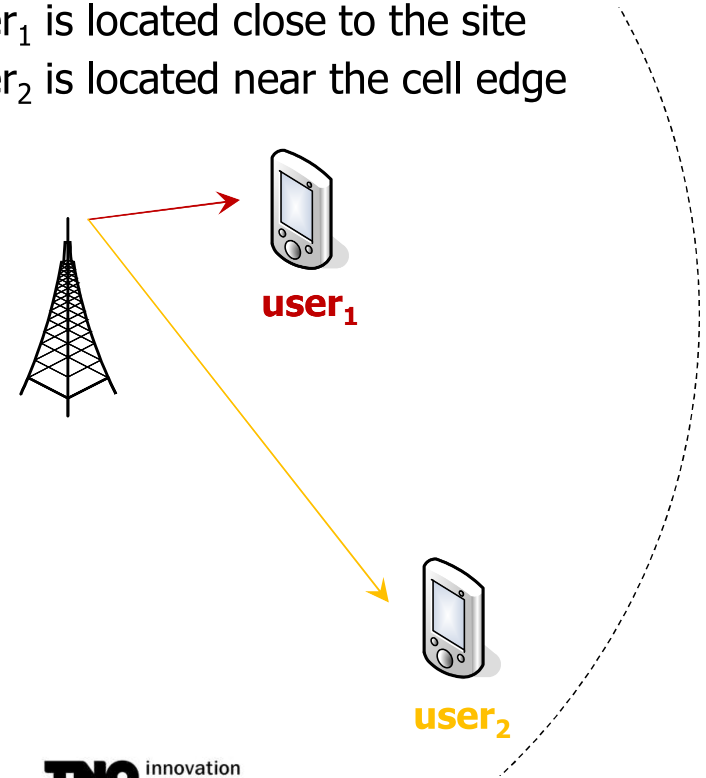
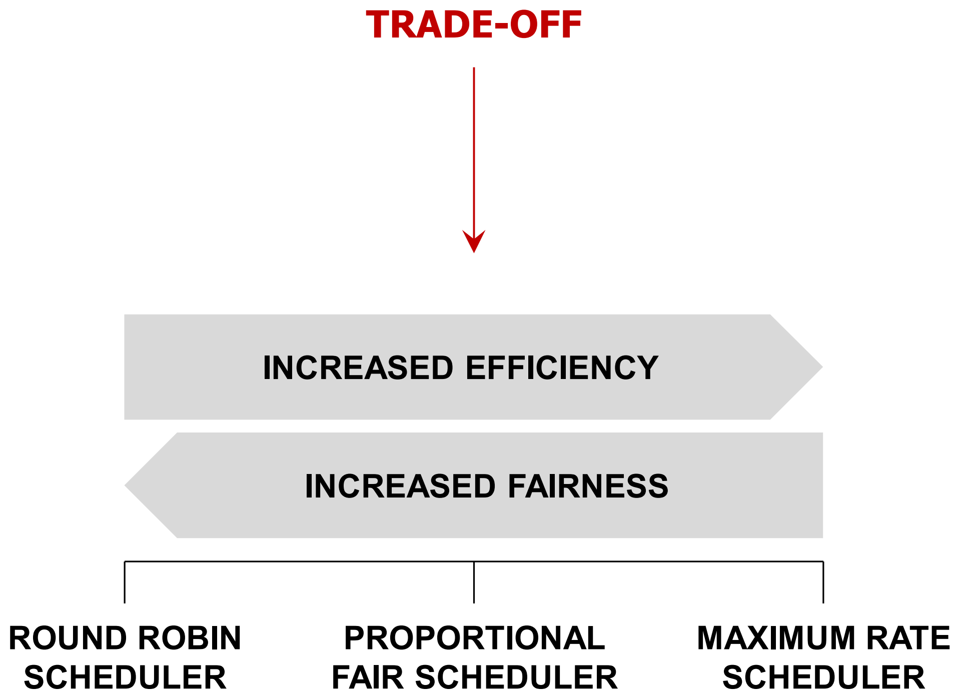


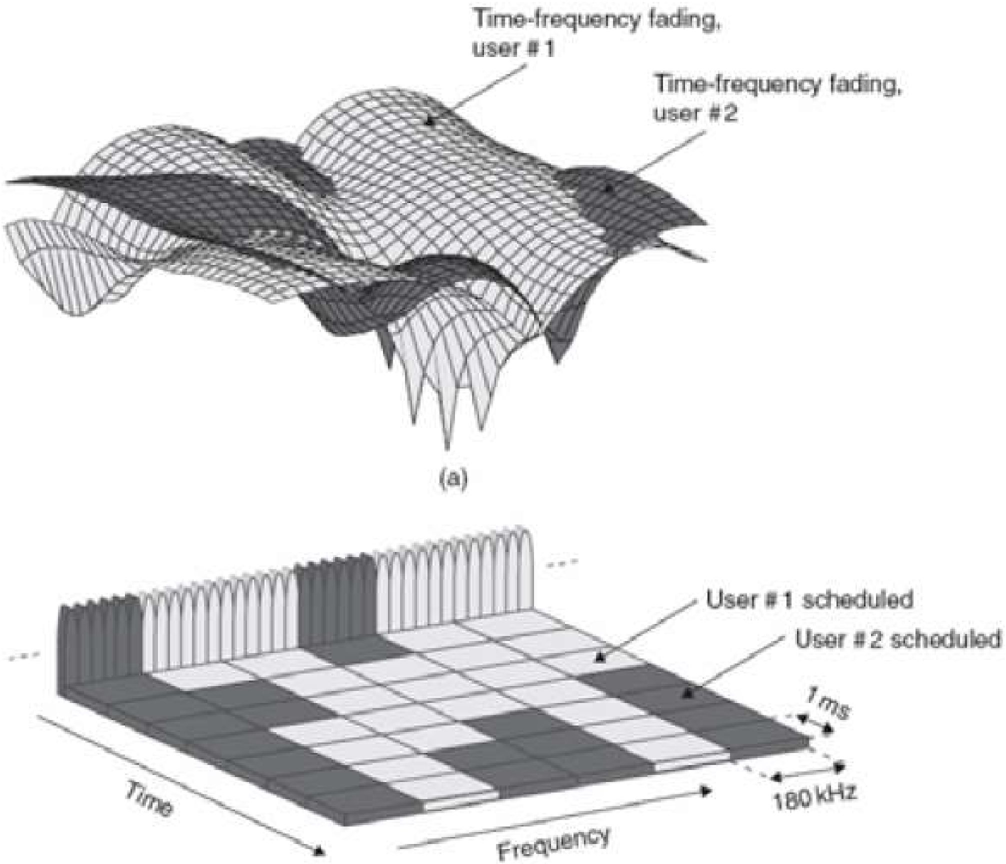


Packet scheduling

A key radio resource management mechanism

- Scheduling challenges in 5G networks
  - Scheduling is done jointly in the *time-frequency* domain
  - Delay-sensitive services require the scheduler to also satisfy stringent end-to-end *delay requirements*
  - Using a feature called *'MU-MIMO'* we can schedule multiple users in a given time-frequency resource

BEAMFORMING



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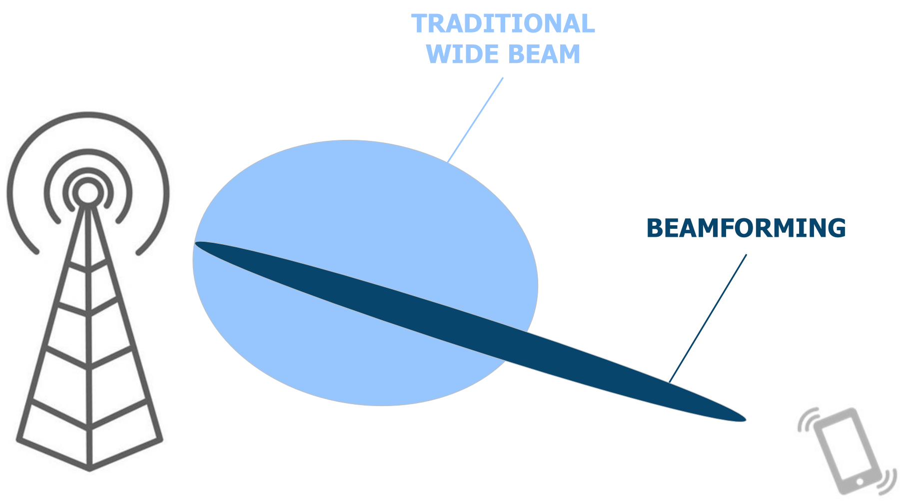
Beamforming

A key transmission mode in 5G networks

- In 5G networks, so-called 'massive MIMO' antenna arrays can be used to form highly directive and hence powerful beams towards the targeted users



Beamforming

A key transmission mode in 5G networks

- In 5G networks, so-called ‘massive MIMO’ antenna arrays can be used to form highly directive and hence powerful beams towards the targeted users
- Have a look at a few seconds of an NOS news item of 25-01-2019

Beamforming

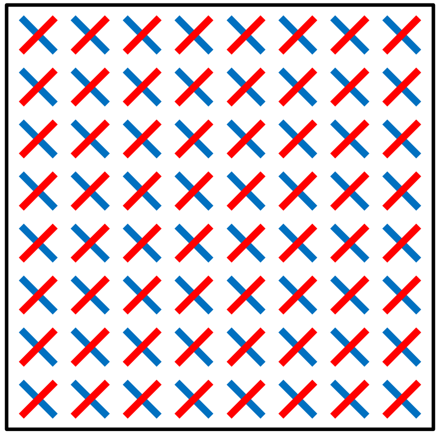
A key transmission mode in 5G networks

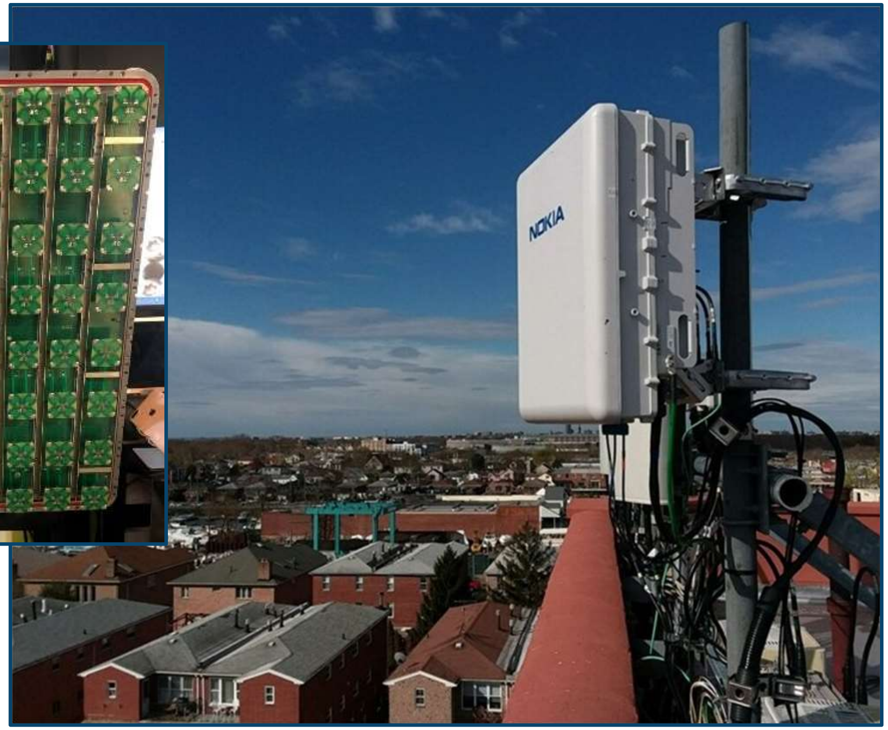
- In 5G networks, so-called ‘massive MIMO’ antenna arrays can be used to form highly directive and hence powerful beams towards the targeted users
- Have a look at a few seconds of an NOS news item of 25-01-2019

Beamforming

A key transmission mode in 5G networks

- Beamforming is a physical phenomenon that occurs when the same signal is transmitted by multiple identical and synchronised antennas
- Example: planar array of 128 antennas





- We will ignore the distinct antenna polarisations today …

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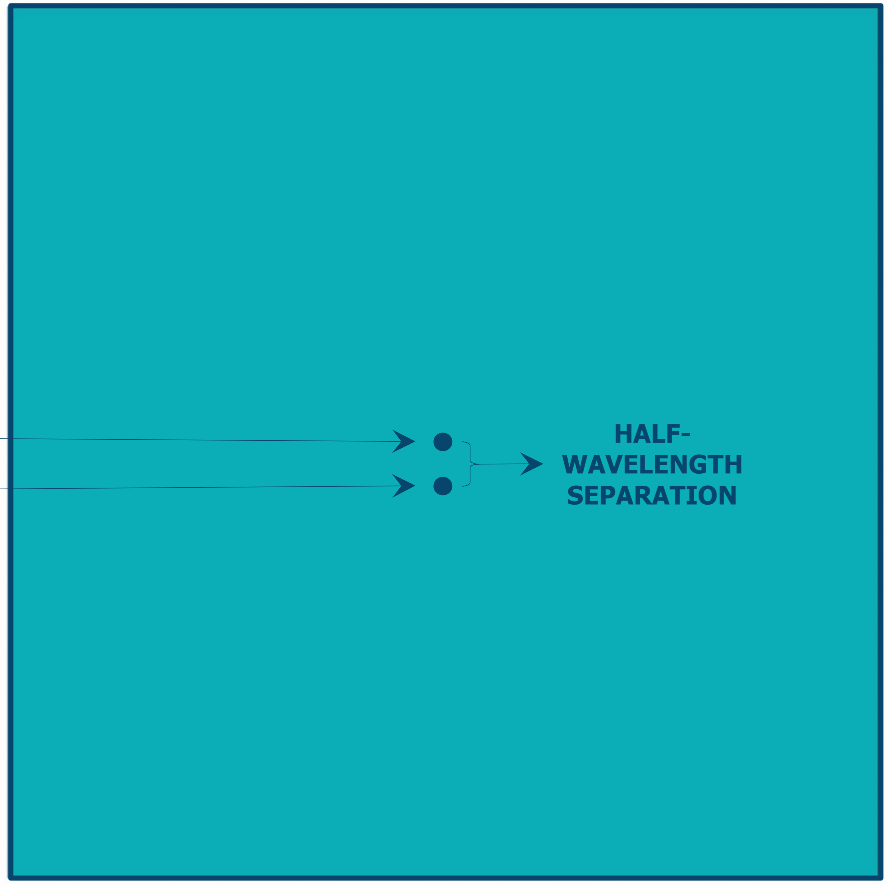
Beamforming

A key transmission mode in 5G networks

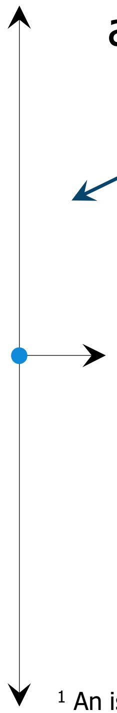
- The beamforming phenomenon is illustrated with an analogy of water waves, generated by two distinct sources
  - 1st source
  - 2nd source
- Along the horizontal axis wave amplitudes increase: beamforming gains
- Along the vertical axis the two waves cancel each other out, due to the half-wavelength separation

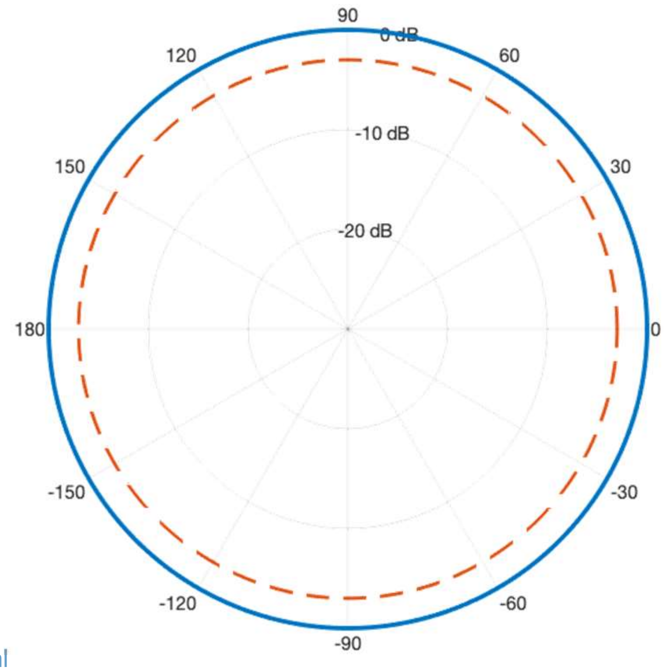


Beamforming

A key transmission mode in 5G networks

- The net effect is generally represented by the *radiation pattern* of an antenna array: a diagram showing the received power at all possible angles around the antenna array
  - *Example:* if a signal is transmitted by **one** isotropic antenna[1], the horizontal cut of the radiation pattern looks like this



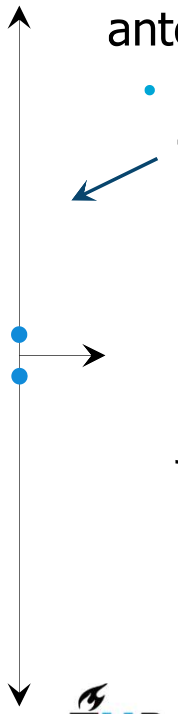


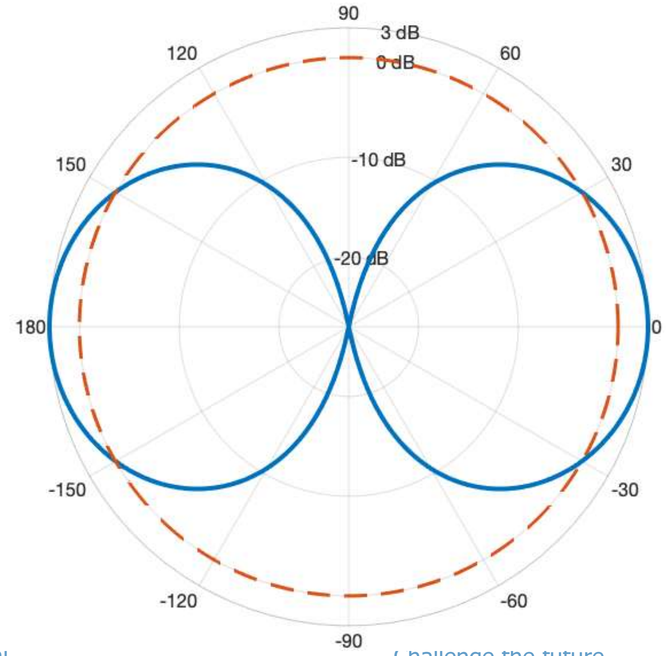
[1] An isotropic antenna is an ideal antenna which radiates its power uniformly (also backwards) in all directions; AE gain = 0 dBi

Beamforming

A key transmission mode in 5G networks

- The net effect is generally represented by the *radiation pattern* of an antenna array: a diagram showing the received power at all possible angles around the antenna array
    - *Example:* if the same signal is transmitted by **two** isotropic antennas vertically spaced half a wavelength apart, then there is *constructive* interference along the horizontal axis and *destructive* interference along the vertical axis, just like in the water waves analogy

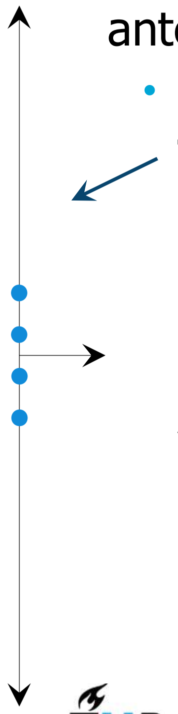


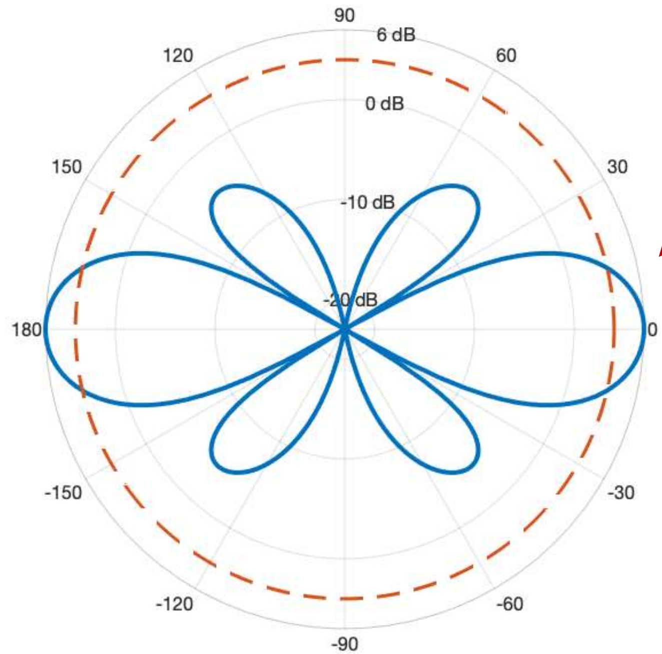


Beamforming

A key transmission mode in 5G networks

- The net effect is generally represented by the *radiation pattern* of an antenna array: a diagram showing the received power at all possible angles around the antenna array
  - *Example:* if the same signal is transmitted by **four** isotropic antennas vertically spaced half a wavelength apart, then there is *constructive* interference along the horizontal axis *and two other axes*, and *destructive* interference along vertical axis *and two other axes*



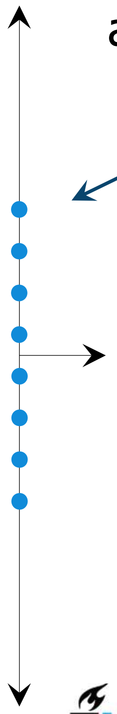


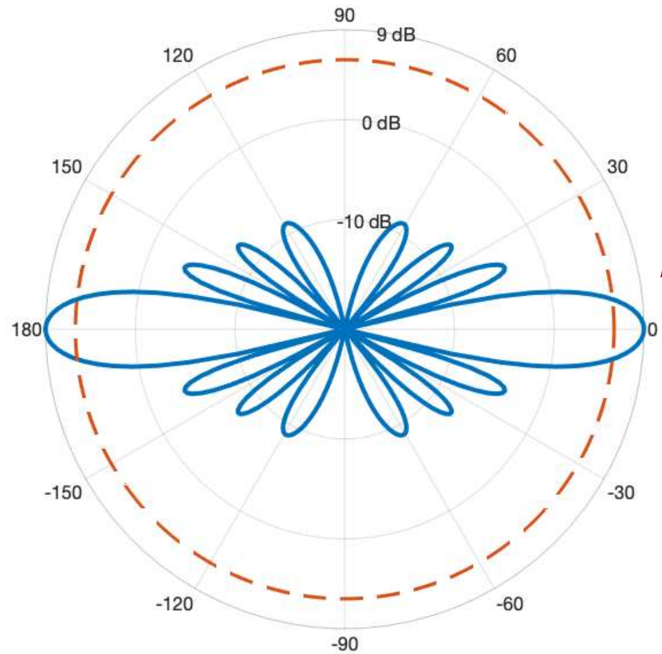
ever narrower and stronger main lobe

Beamforming

A key transmission mode in 5G networks

- The net effect is generally represented by the *radiation pattern* of an antenna array: a diagram showing the received power at all possible angles around the antenna array
  - *Example:* if the same signal is transmitted by **eight** isotropic antennas vertically spaced half a wavelength apart, then there is *constructive* interference along the horizontal axis *and six other axes*, and *destructive* interference along vertical axis *and six other axes*



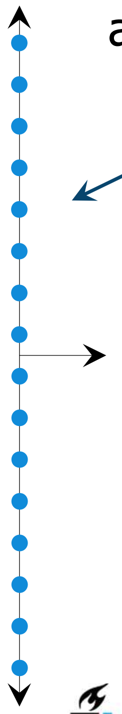


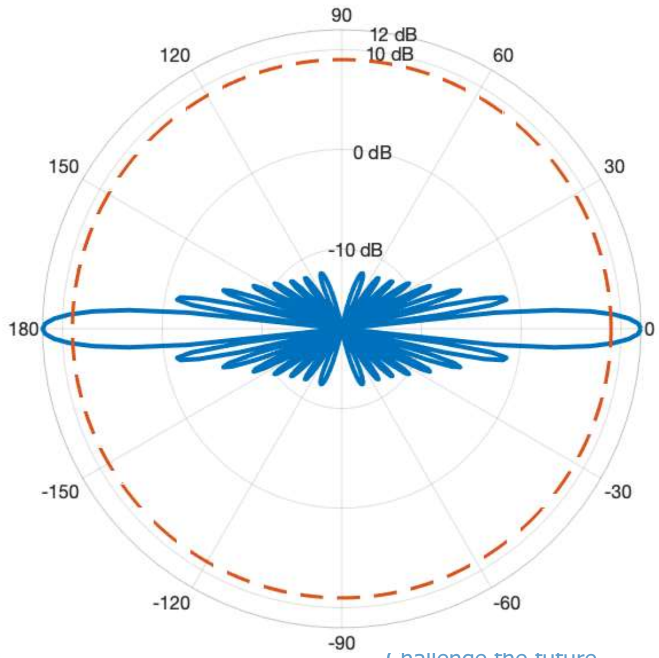
ever narrower and stronger main lobe

Beamforming

A key transmission mode in 5G networks

- The net effect is generally represented by the *radiation pattern* of an antenna array: a diagram showing the received power at all possible angles around the antenna array
    - *Example:* if the same signal is transmitted by **sixteen** isotropic antennas vertically spaced half a wavelength apart, then there is *constructive* interference along the horizontal axis *and fourteen other axes*, and *destructive* interference along vertical axis *and fourteen other axes*





trade-off of cost versus performance

ever narrower and stronger main lobe

Beamforming

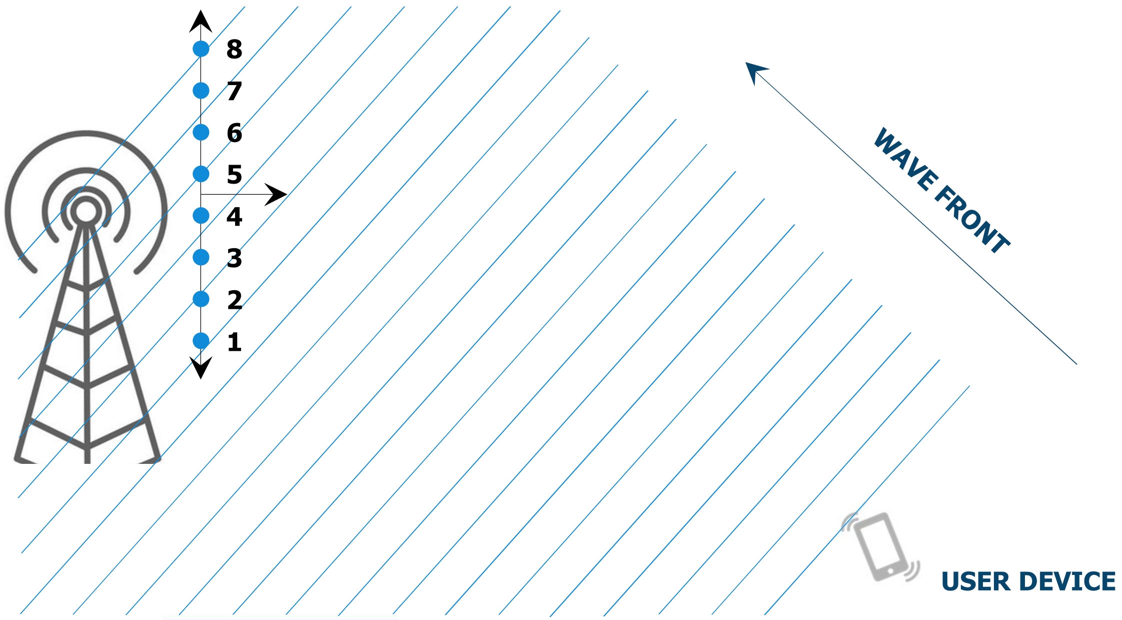
A key transmission mode in 5G networks

- In the examples the signal was transmitted in a *synchronized* manner by all antennas
- By manipulating the *relative phases* of the signal, the beam can be steered into a certain direction → how to determine these relative phases?

Beamforming

A key transmission mode in 5G networks

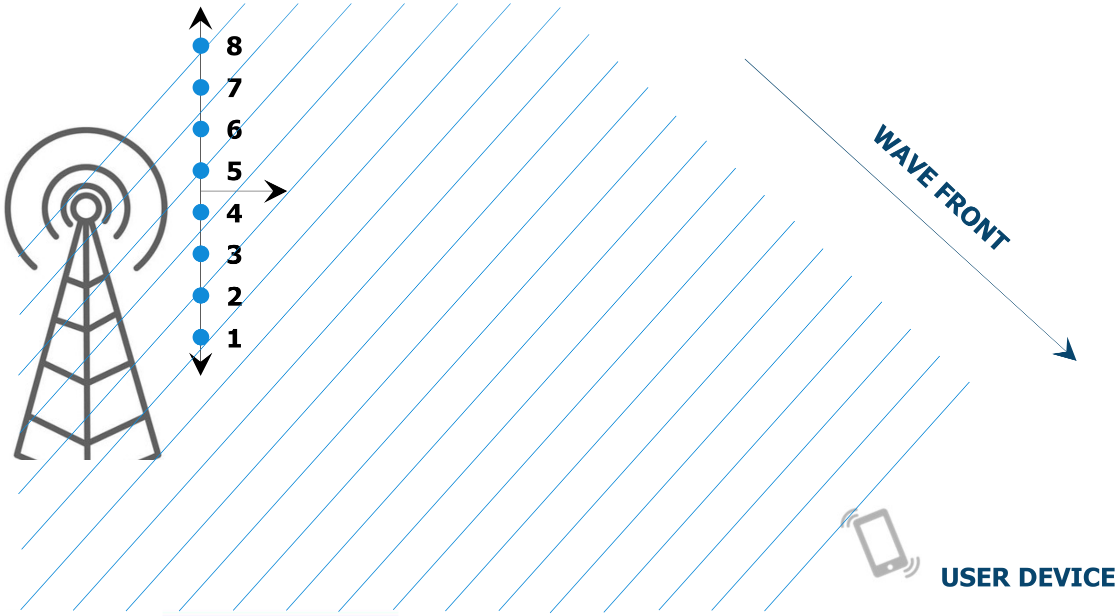
- The use device first transmits a pilot signal to the base station
- This pilot signal is received by all antennas: first by antenna$_1$, then by antenna$_2$, …, and finally by antenna$_8$: *these relative delays are perceived as phase differences*



Beamforming

A key transmission mode in 5G networks

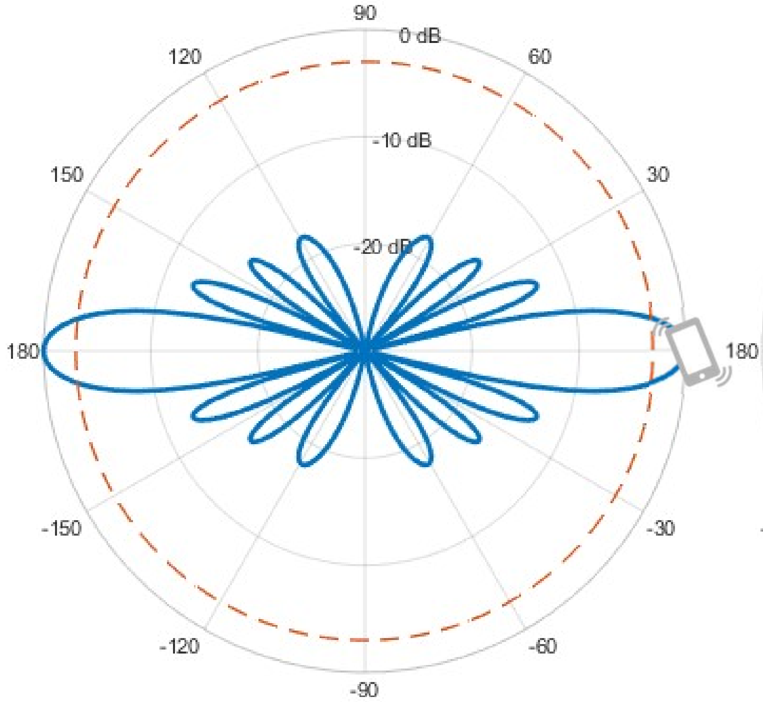
- For the beamformed transmission to the user device, the base station simply ‘flips’ these observed phase differences
- The signal is transmitted first by antenna #8, then by antenna #7, etc, and finally by antenna #1: *this creates a wave front in the direction of the user device*

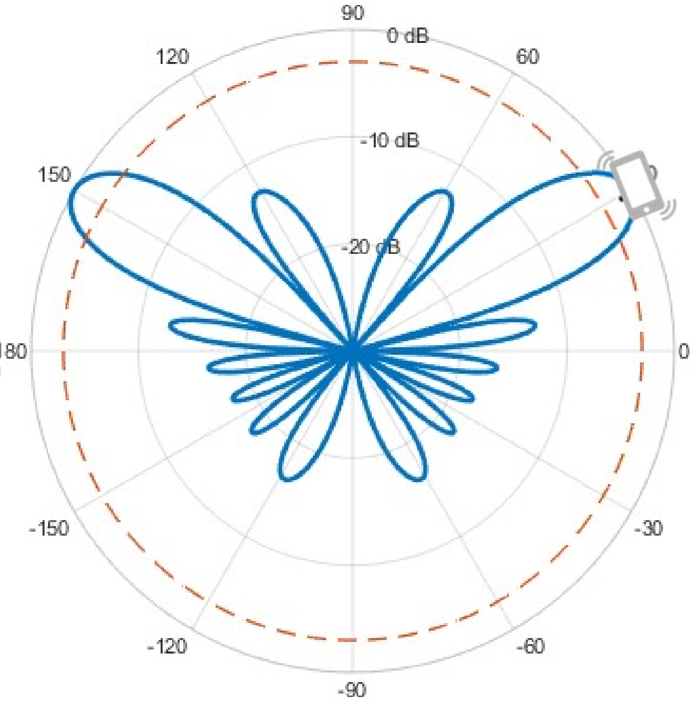


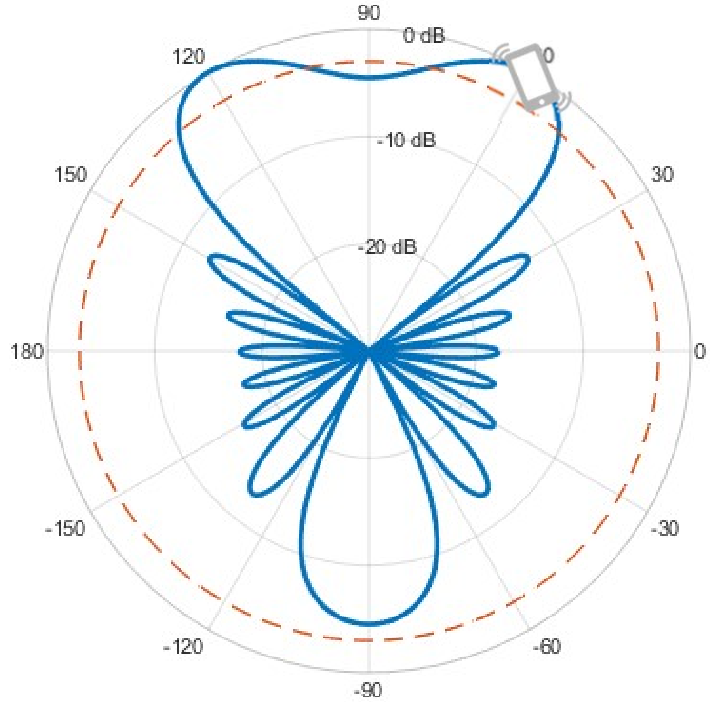
Beamforming

A key transmission mode in 5G networks

- Some examples



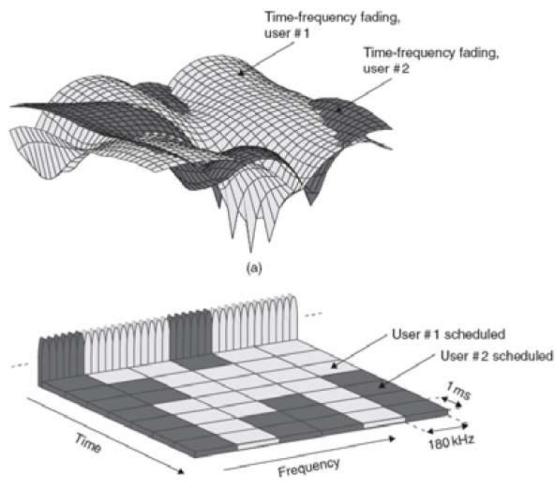




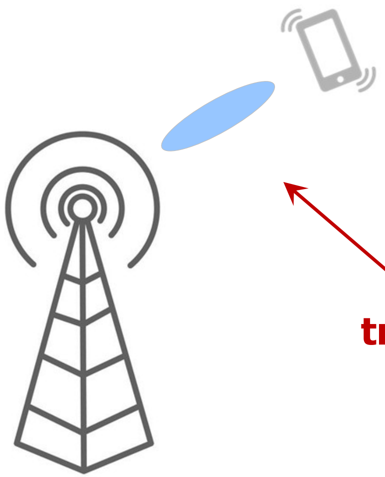
Beamforming

A key transmission mode in 5G networks

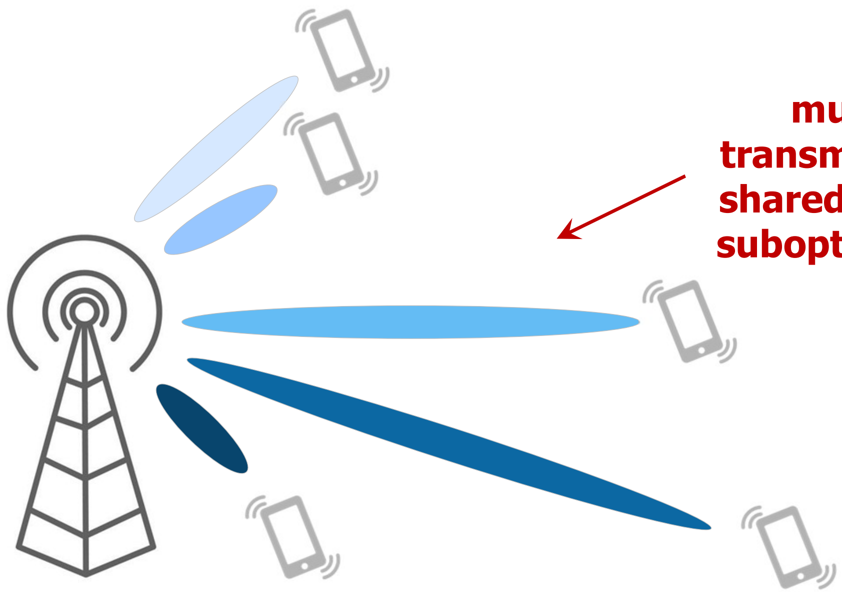
remember scheduling?



- Narrow beams enable *'MU-MIMO':* scheduling multiple users in the same time-frequency resource, sharing the transmission power
  - Multi-user *beamforming trade-off:* high gain or low interference?



single-user transmission with full power and optimal beams

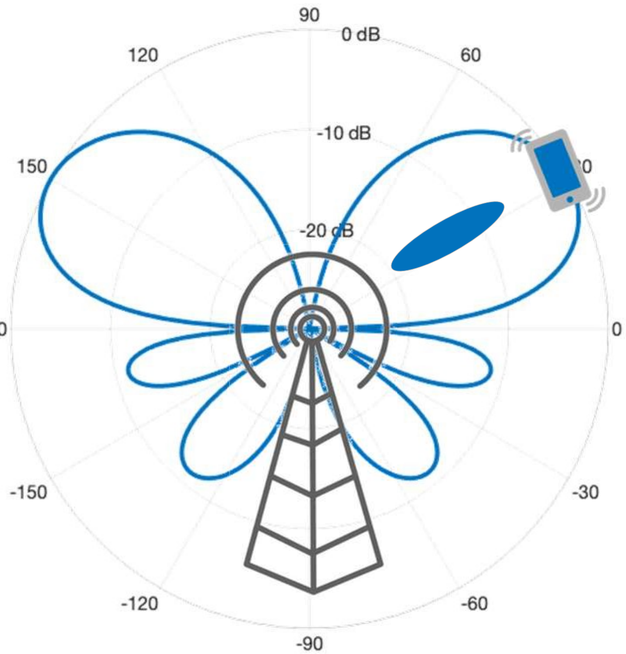


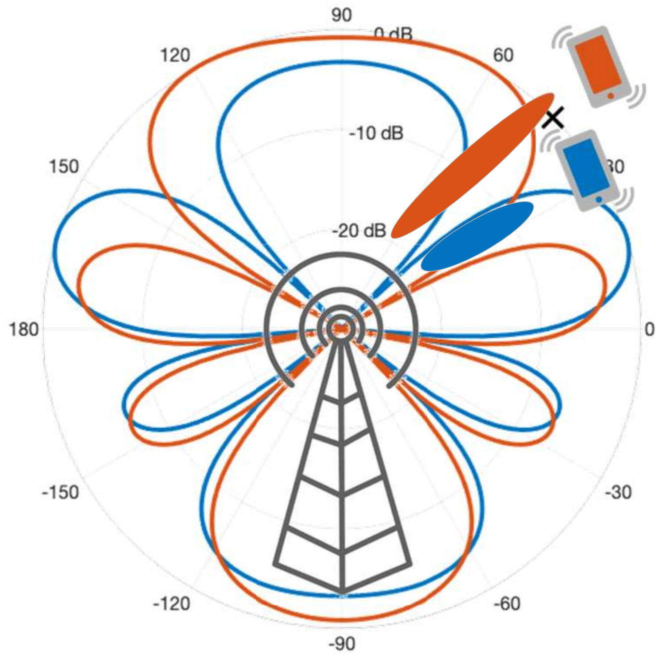
multi-user transmission with shared power and suboptimal beams

Beamforming

A key transmission mode in 5G networks

- Narrow beams enable *'MU-MIMO':* scheduling multiple users in the same time-frequency resource, sharing the transmission power
  - Multi-user *beamforming trade-off:* high gain or low interference?

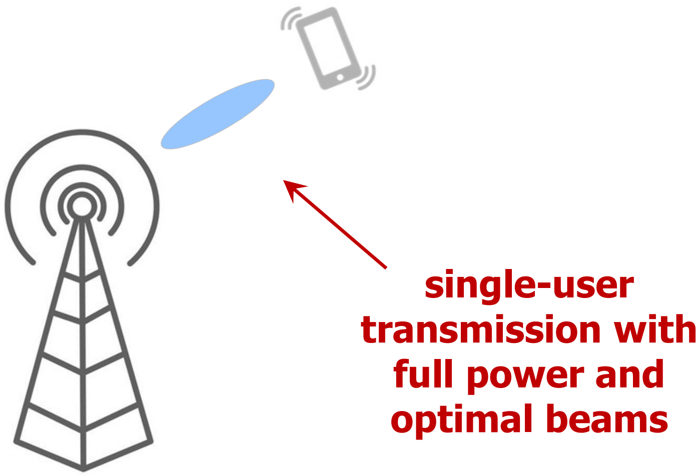


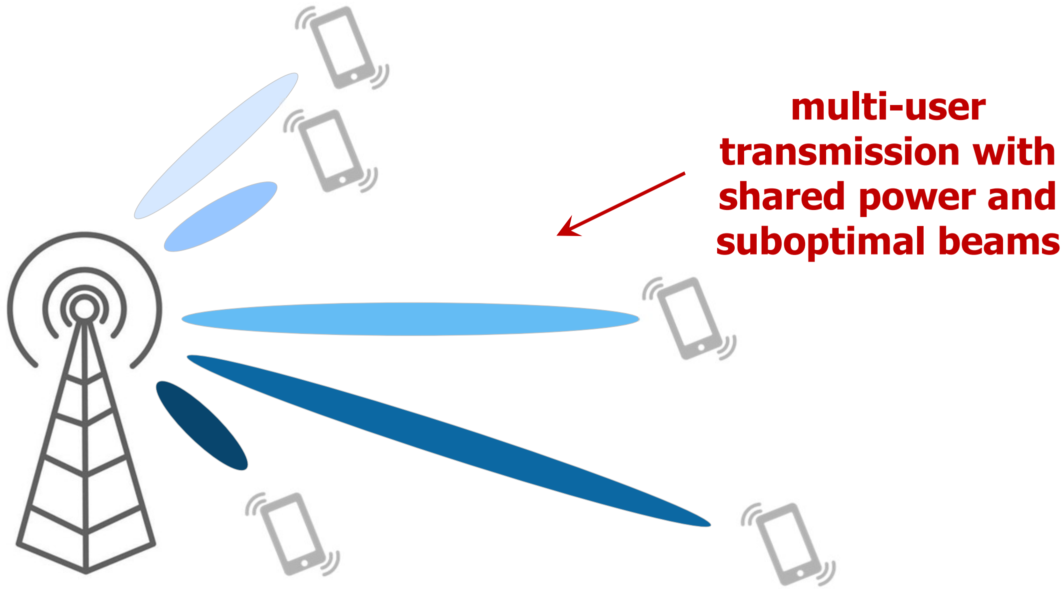


Beamforming

A key transmission mode in 5G networks

- Narrow beams enable *'MU-MIMO':* scheduling multiple users in the same time-frequency resource, sharing the transmission power
  - Multi-user *beamforming trade-off:* high gain or low interference?
  - *Scheduling trade-off:* single user at high rate or multiple users at lower rates
    - Depends on beamforming-induced SINRs

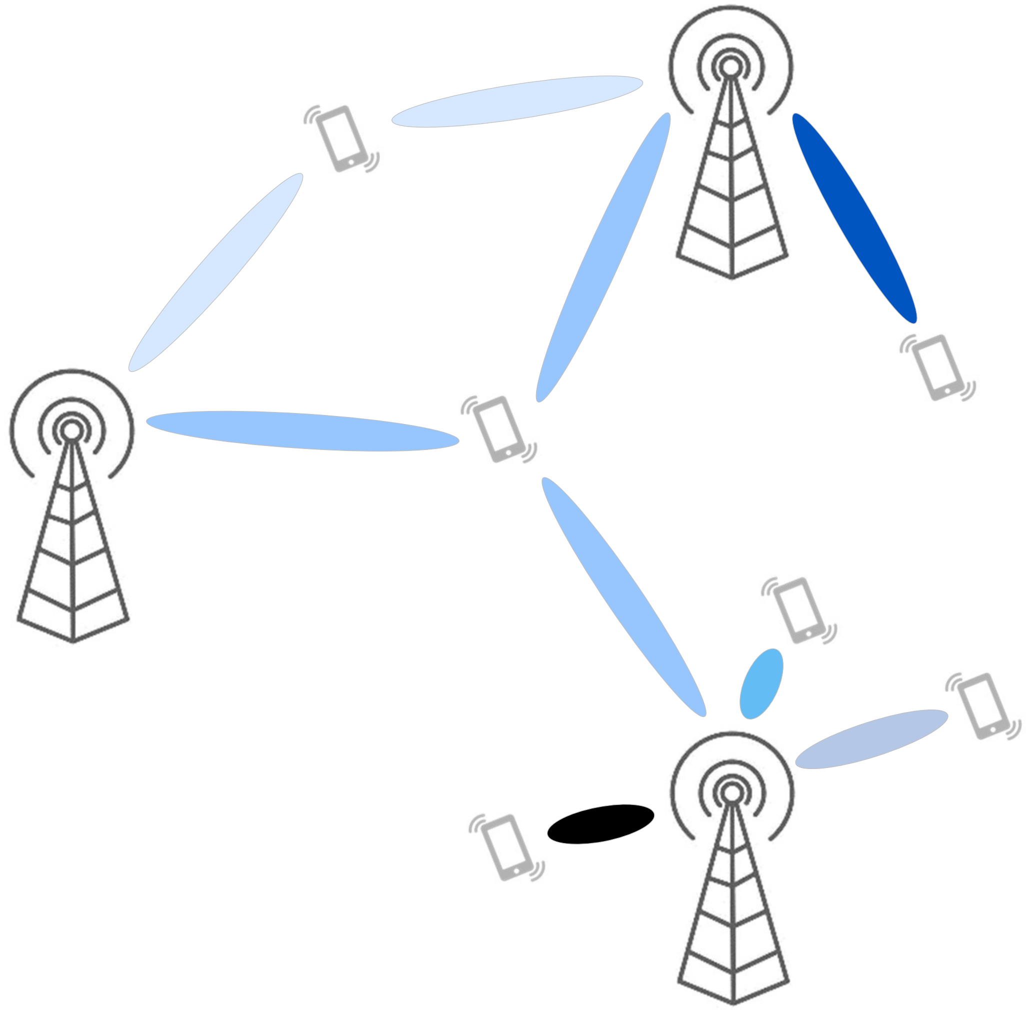




Beamforming

A key transmission mode in 5G networks

- Why only use the antenna array of a single base station to serve a user?
  - Distributed MIMO takes it to the next level
  - With new trade-offs to consider!!
  - To be discussed some other time :)



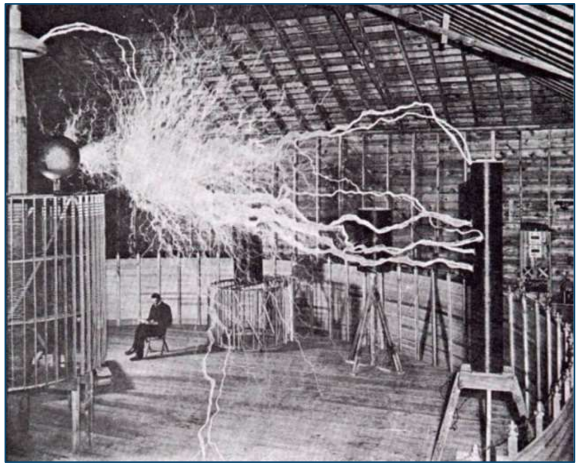
Outline

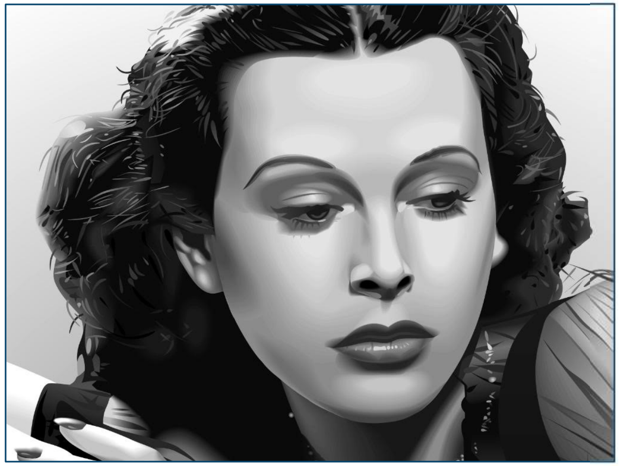
- Introduction
- Preliminaries
- Packet scheduling
- Beamforming
- Wrap-up

Wrap-up

So much more to say …

- We talked a bit about history and about the mobile networking market
- After some preliminaries, we had a teaser about two key aspects of 5G networking, involving all kinds of optimization trade-offs
- There is so much more to say …





Wrap-up

So much more to say …

Wrap-up

So much more to say …