Wireless Connectivity:
An Intuitive and Fundamental Guide

Chapter 12: Wireless Beyond a Link: Connections and Networks

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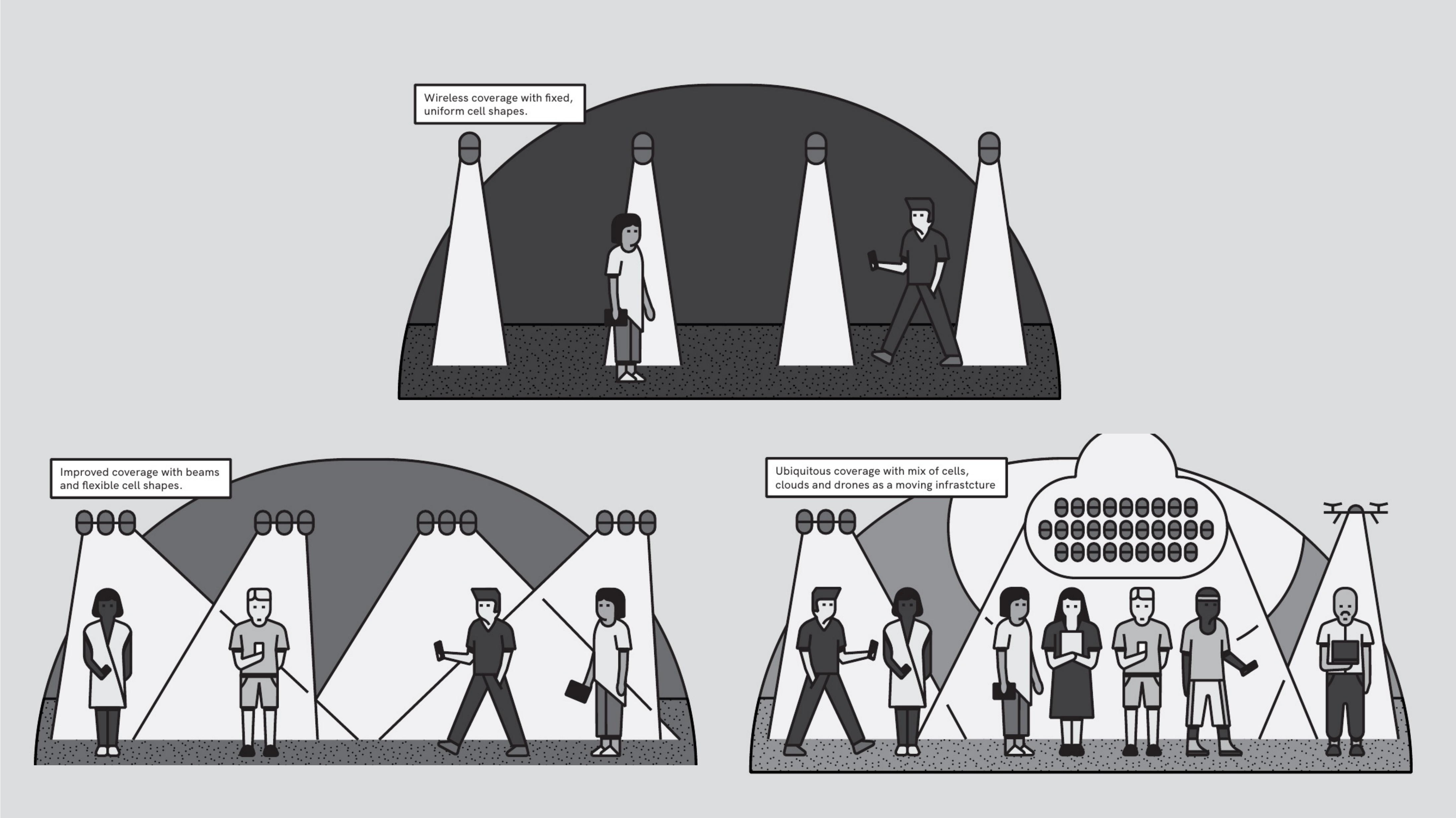
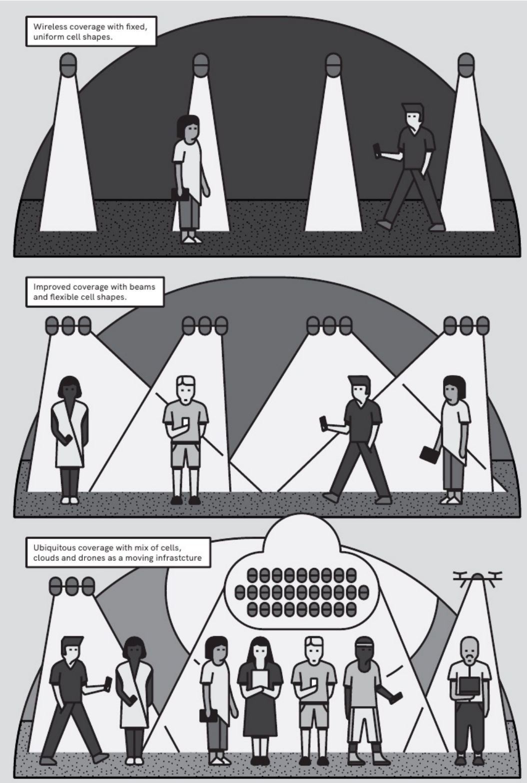
Modules

1. An easy introduction to the shared wireless medium
2. Random Access: How to Talk in Crowded Dark Room
3. Access Beyond the Collision Model
4. The Networking Cake: Layering and Slicing
5. Packets Under the Looking Glass: Symbols and Noise
6. A Mathematical View on a Communication Channel
7. Coding for Reliable Communication
8. Information-Theoretic View on Wireless Channel Capacity
9. Time and Frequency in Wireless Communications
10. Space in Wireless Communications
11. Using Two, More, or a Massive Number of Antennas
12. **Wireless Beyond a Link: Connections and Networks**


Wireless coverage with fixed, uniform cell shapes.
Improved coverage with beams and flexible cell shapes.
Ubiquitous coverage with mix of cells, clouds and drones as a moving infrastcture

Wireless infrastructure that adapts to the users



- An infrastructure with fixed and moving elements is able to adapt to the requirements of the scenario
- Cooperation between network elements is needed to ensure an efficient wireless coverage and operatio.

What will be learned in this chapter

- Types of network infrastructures and connection types
- Spatial reuse and types of cells in cellular infrastructures
- Backhauling
- Distributed MIMO
- Access through cloud and fog architectures

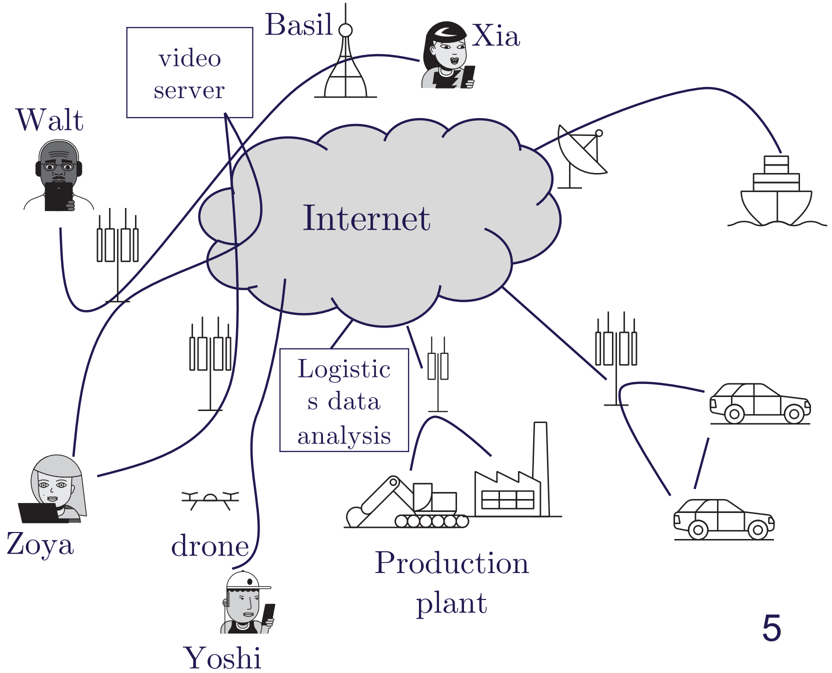
Wireless beyond a link

Throughout the course we've focused on **link-level communication:**
Devices on the opposite sides of the **link** are the **communicating parties**

In practice, the main purpose is to give access to a larger **infrastructure** and connect distant devices

The infrastructure has to provide and deal with:

- End-to-end connectivity
- Wireless coverage
- Mobility
- Interference management



Classification of wireless connections

First, we introduce the following classification of connections

Human-to-Human communication (H2H): voice, messaging, etc.

Most of the time we were implicitly or explicitly considering this one

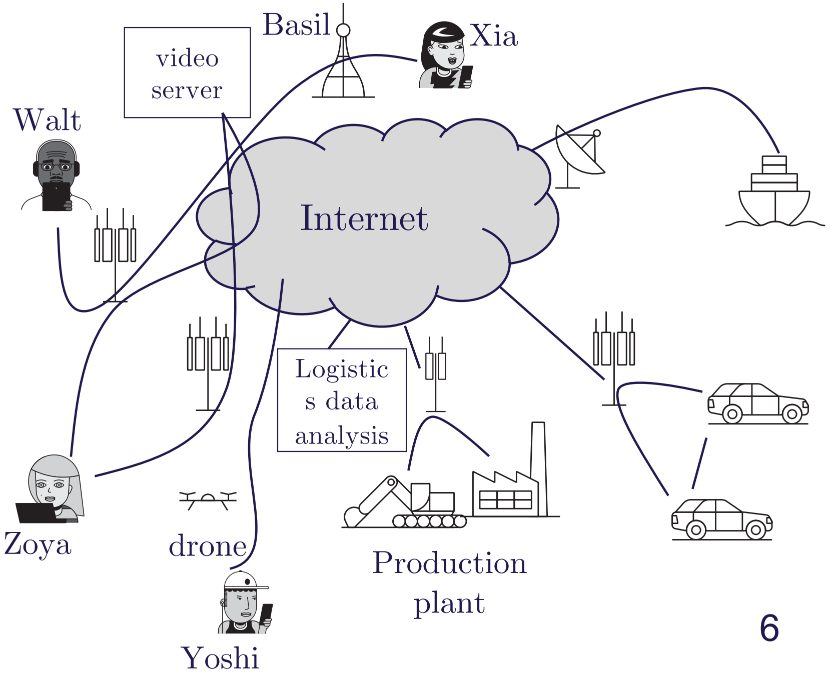
Human-to-Machine (H2M):

Browsing and streaming fall in this category

Machine-to-Machine (M2M):

Gathering most attention lately due to the popularity of **IoT** devices

A more general term is **Machine-Type Communication (MTC)**



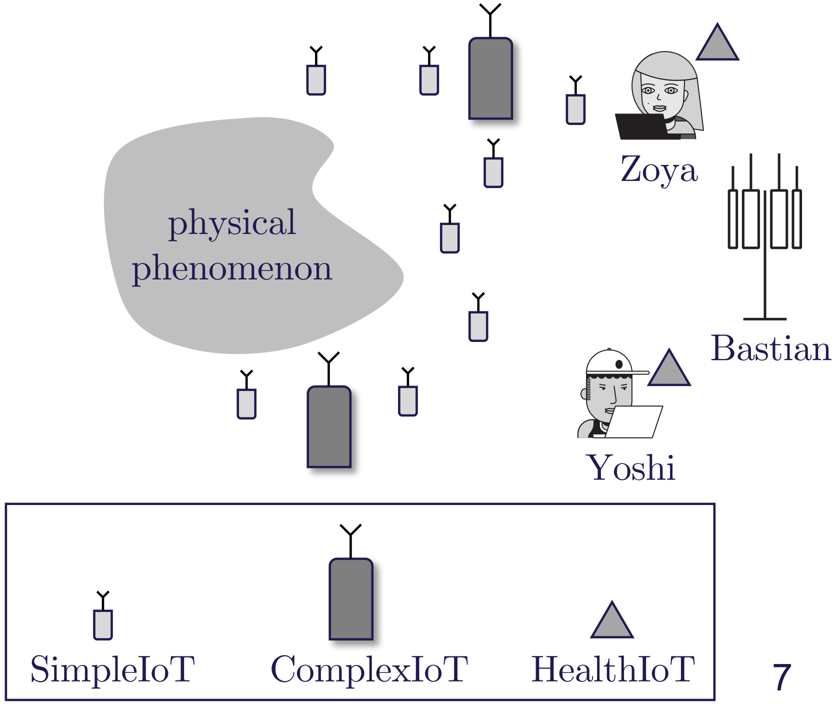
Classification of wireless connections

The different connections have different characteristics

Can be represented through a set of **heterogeneous requirements**

Typical and most relevant dimensions:

- **Rate:** few kbps vs. Mbps
- **Number of devices:** few vs. thousands
  - Impacts random access
- **Reliability:** critical vs. best-effort applications
- **Latency:** absolute value and jitter



Classification of wireless connections

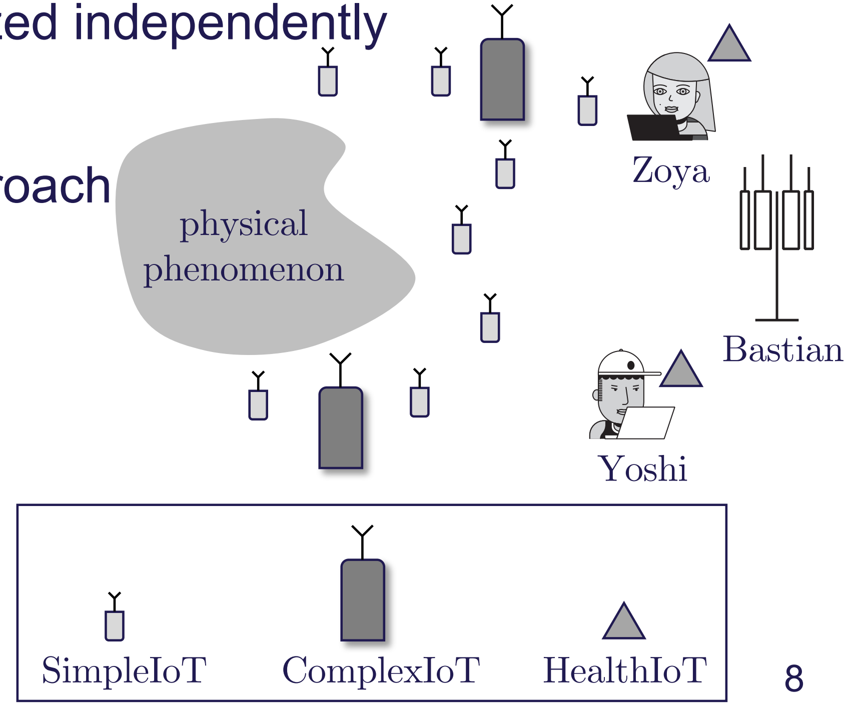
Heterogeneity can be addressed with **silo** approach:

Akin to layering and which allows to operate on higher level of abstraction

Silos, or interfaces, are separated and optimized independently

Another distinction method is the **platform** approach

- Core services/use cases defined by ITU
  - enhanced Mobile Broadband (eMBB)
  - massive MTC (mMTC)
  - ultra-reliable low-latency communication (URLLC)



Providing wireless coverage

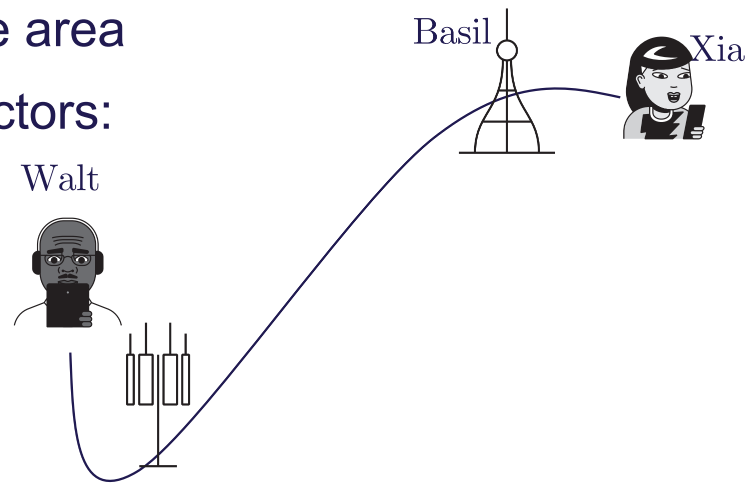
Different types of connections expect **different coverage** support:

Low-power IoT, VR applications, high-mobility cars and trains

A single BS is not enough as it has a limited coverage area

The range itself is not fixed as it depends on many factors:

- Environment
- Power used
- Number of antennas and beamforming capabilities

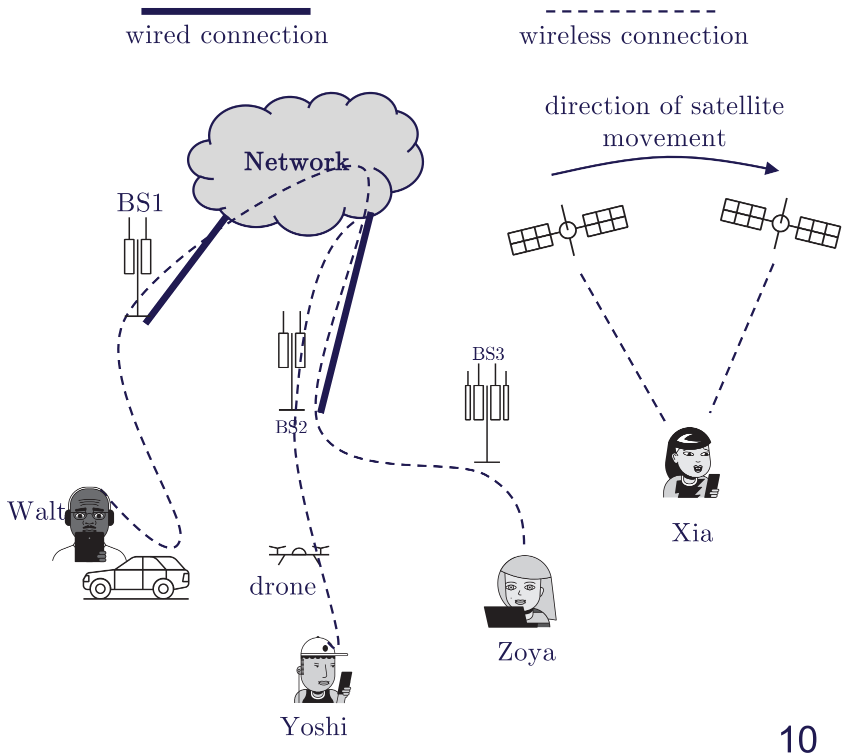


Moreover, available bandwidth **limits** the number of supported users

Types of infrastructure

Operators have three options whenever they need to provide coverage

1. Static wireless infrastructure
   - Requires strategic planning
2. Moving infrastructure
   - LEO satellites, drones
3. Hybrid infrastructure



The mobility of terminals and/or infrastructure requires **handover procedure**

Cells and cellular networks

The coverage area of the base stations is known as **cell**

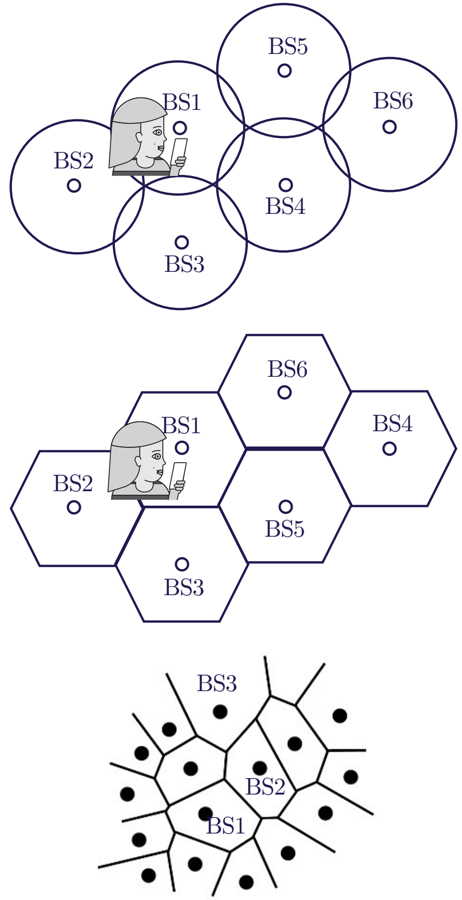
- A grid of interconnected cells create a **cellular network**

In the free-space propagation model:
the coverage area is a circle

- The radius is determined by the power threshold
- The users connect to the closest base station (BS) i as it offers the highest SINR

$$\text{SINR} = \frac{P_i}{\sum_{j \neq i} P_j + N}$$

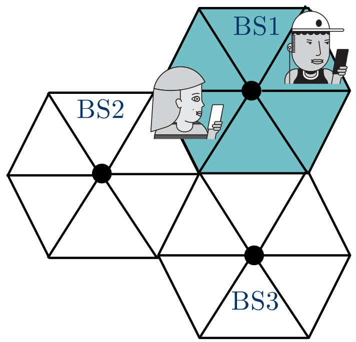
We can redefine the cell as a collection of spatial points that are closer to a specific BS than to any other



Spatial reuse

Previous examples assumed BSs with **omnidirectional antennas**
✗ Simultaneous transmissions within a cell will cause **interference**

Spatial reuse: use directed antennas to divide a **cell** into **sectors**

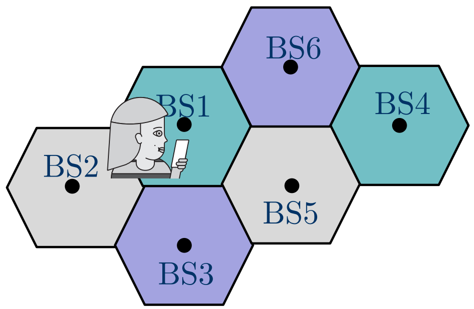


In a network, **spatial reuse** of frequencies is also called **frequency reuse**, which also applies to omnidirectional antenna systems

Defines minimum distance between cells that can operate at the same frequency

This problem is called graph **coloring**

Tradeoff between **interference** and **efficient reuse**



Spatial reuse

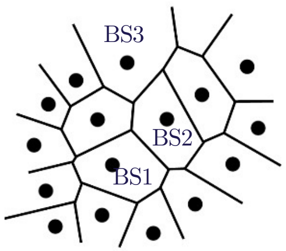
Some practical comments:

Code Division Multiple Access (CDMA) is a specific type of access where devices use the whole spectrum by design and yet the interference is mitigated

✓ Particularly good for systems with high reuse factor

Even in relatively static scenarios, the structure of a cell fluctuates over time

- Interference, movement (dynamic environment), obstacles all have their impact
- How do devices know what are the current SINRs and which BS to connect to?
    - BS need to broadcast periodic reference signals
    - If needed, change of cell association (handover) can be initiated



Cell sizes

Cells can be classified by the size of their coverage area

Intuitively, large **macrocells** are desirable

✓ Less hardware, fewer handovers…

✗ … but may have low spectral efficiency

Other types of cells include **micro-**, **pico-**, and **femtocells**

These are particularly suitable in urban environments

Network densification:

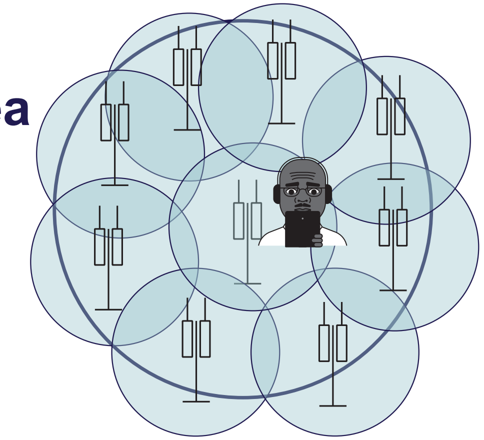
✓ **Better frequency reuse**

✓ Smaller average distance from the BS

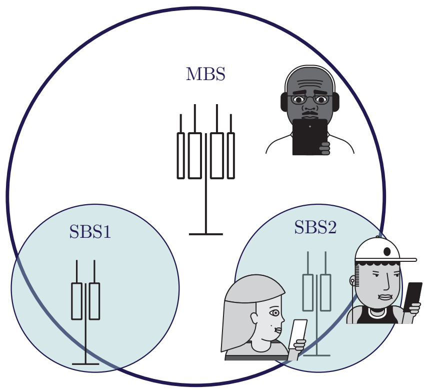
✗ Increase the **probability of interference**

Heterogeneous networks (HetNets) are hybrid designs

Densification



HetNet



Two-way communication

In terms of coverage, **uplink** and **downlink** are not necessarily symmetrical

Let P_M, P_S, P_W be the Tx power of macro (MBS), small (SBS), and Walt respectively

Additionally, denote the signal power loss between Walt and

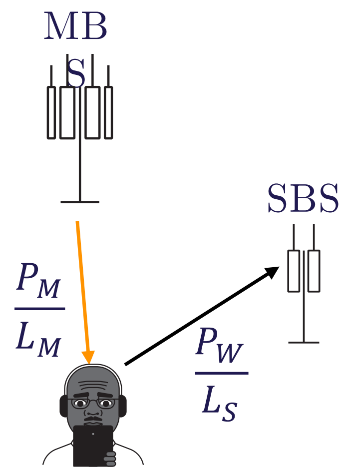
1) MBS as L_M and 2) SBS as L_S

It is possible that: in the **uplink** $\frac{P_W}{L_M} < \frac{P_W}{L_S}$ while in the **downlink** $\frac{P_M}{L_M} > \frac{P_S}{L_S}$

- The solution could be a **decoupled downlink-uplink**

The discussion naturally extends to the concepts of FDD and TDD

- **Flexibility** vs. **interference** management



No cell is an island

The behavior of each cell affects all others around it

Interconnection of cells is needed to:

Support handover, coordinate resource allocation, and allow frequency reuse

Recall the concept of relaying

- Access to the larger infrastructure is provided by relays (**backhaul links**)
  - We will differentiate relays from **access links between devices and BS**
  - In-band vs. out-of-band wireless backhaul
- Not limited to wireless, in fact **wired backhaul** has certain advantages
  - ✗ But lacks flexibility and introduces extra hardware costs

One-way relaying and half-duplex cost

Simplest case with in-band relaying

Zoya transmits packets of size D bits over T seconds

Reference: maximum goodput when Zoya communicates directly with the MBS

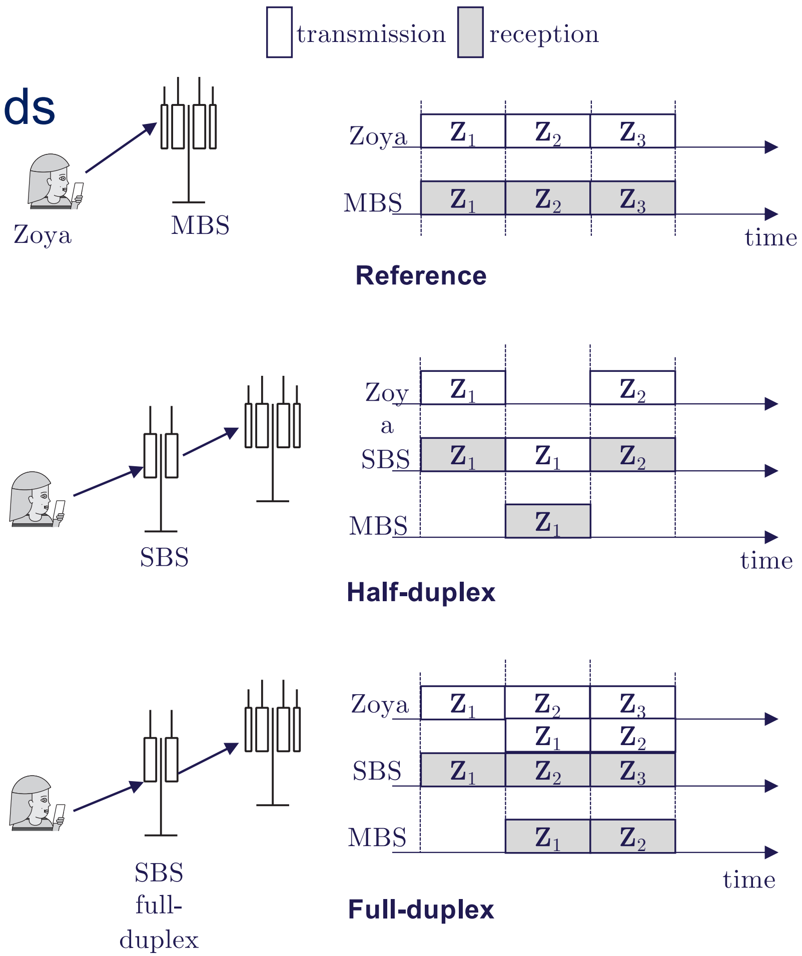
$$\mathrm{Gp} = R = \frac{D}{T}$$

Half-duplex relay: goodput drops to

$$\mathrm{Gp} = \frac{LD}{2LT} = \frac{R}{2}$$

Full-duplex: pipelining is possible such that

$$\mathrm{Gp} = \frac{LD}{(L+1)T} \approx R$$



What changes with two-way relaying?

With direct connection, Zoya and MBS send every other slot so

$$\mathrm{Gp} = \mathrm{Gp}_Z + \mathrm{Gp}_M = R$$

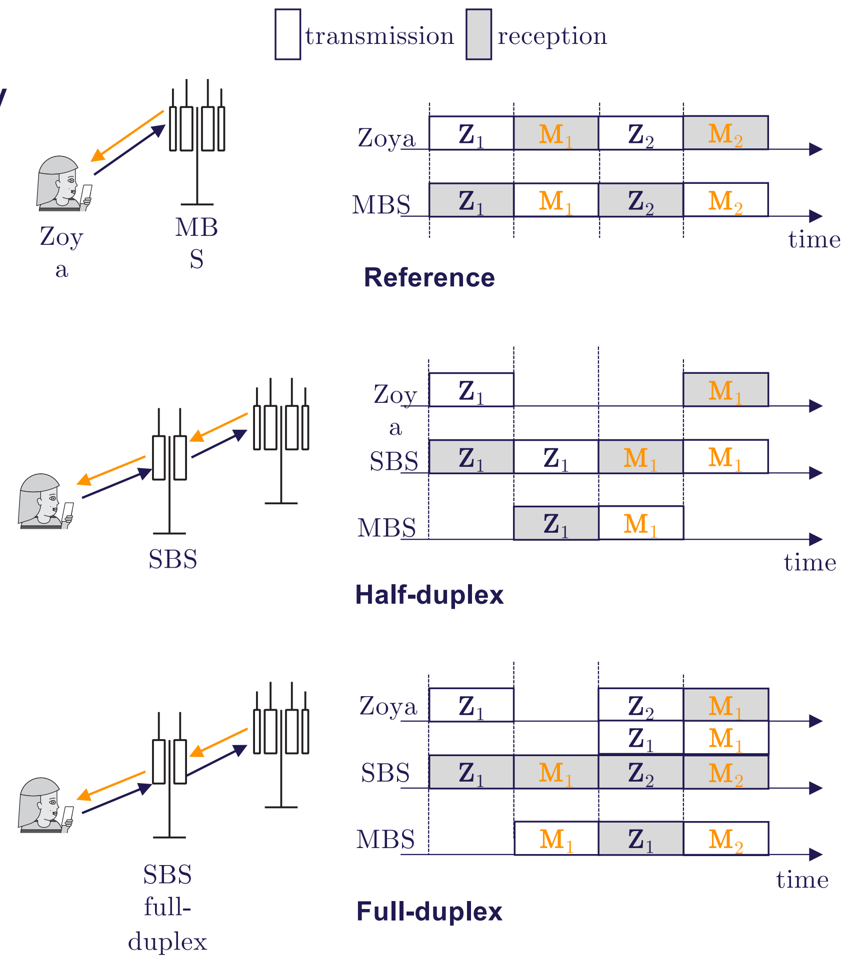
Half-duplex: a full transaction requires 4 slots, so

$$\mathrm{Gp} = \frac{2LD}{4LT} = \frac{R}{2}$$

Full-duplex: the full rate is achieved

$$Gp = \frac{2LD}{2(L+1)T} \approx R$$

However, something interesting can be done to improve half-duplex mode…



Two-way relaying with a *twist*

After the relay obtains both Z_1 and M_1, rather than forwarding one at a time it can broadcast

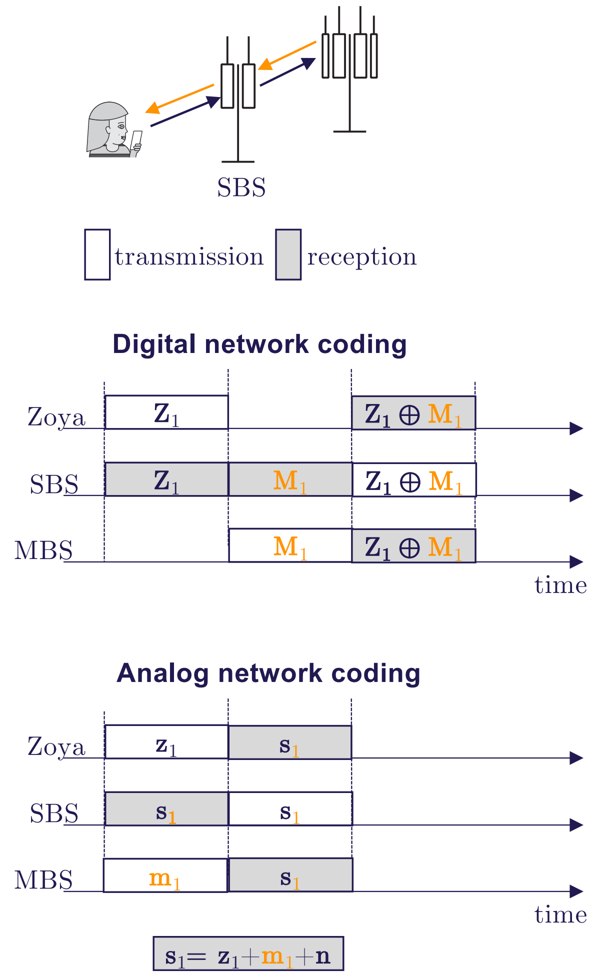
$$S_1 = Z_1 \oplus M_1$$

- Since Zoya knows Z_1, she can recover M_1 as

$$Z_1 \oplus S_1 = M_1$$

- The goodput increases to $\mathrm{Gp} = 2R/3$
- This is known as *digital network coding*
- The *analog* variant has two further subtypes:
    1. *Decode-and-forward*
    2. *Amplify-and-forward*

In principle, full rate can be reclaimed!



Cooperation and coordination

Simple: cooperative **handover**

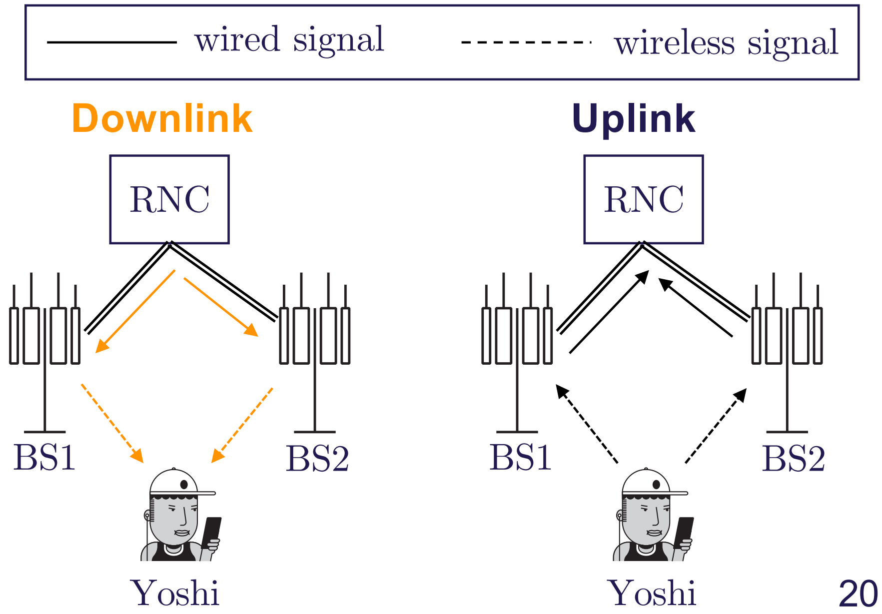
More complex: wireless resource management by a Radio Network Controller (RNC)

- Coordination to mitigate **interference**, for example, between neighboring TDD cells

In the downlink: soft handover and multipath

In the uplink, we can have each BS to:

1. Attempt decoding
2. Convert to bits and forward
3. Amplify-and-forward (AF)
   - As in Maximal Ratio Combining (MRC)
   - Macro-diversity due to the **spatial separation** of the antennas



Distributing and networking the MIMO concept

Cooperation with wired backhaul:

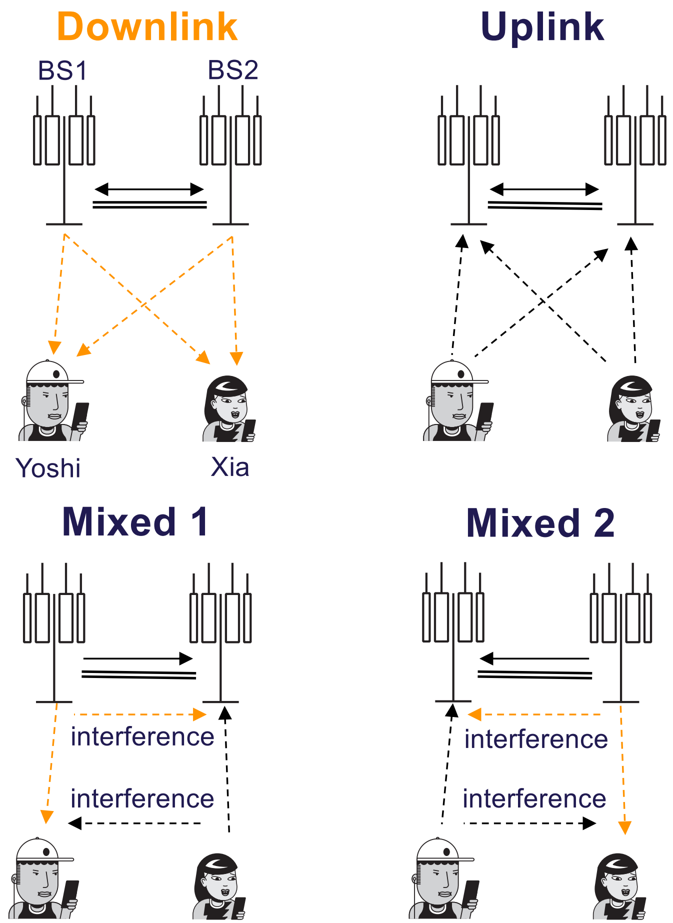
Assume infinite backhaul capacity

Coordinated Multipoint (CoMP) or Distributed MIMO

✓ Interference mitigation

Two-way communication through TDD switching

1. Traditional
2. Mixed **uplink-downlink**
   - Emulates full-duplex



wired signal | wireless signal

Cooperation through a wireless backhaul

✗ No more infinite backhaul capacity

MBS transmits first, followed by SBS

MRC @ Zoya: $\gamma_Z = \gamma_{Z,M} + \gamma_{Z,S}$

Highest rate: $R_{M,Z} = \frac{1}{2}\log_2(1 + \gamma_Z)$

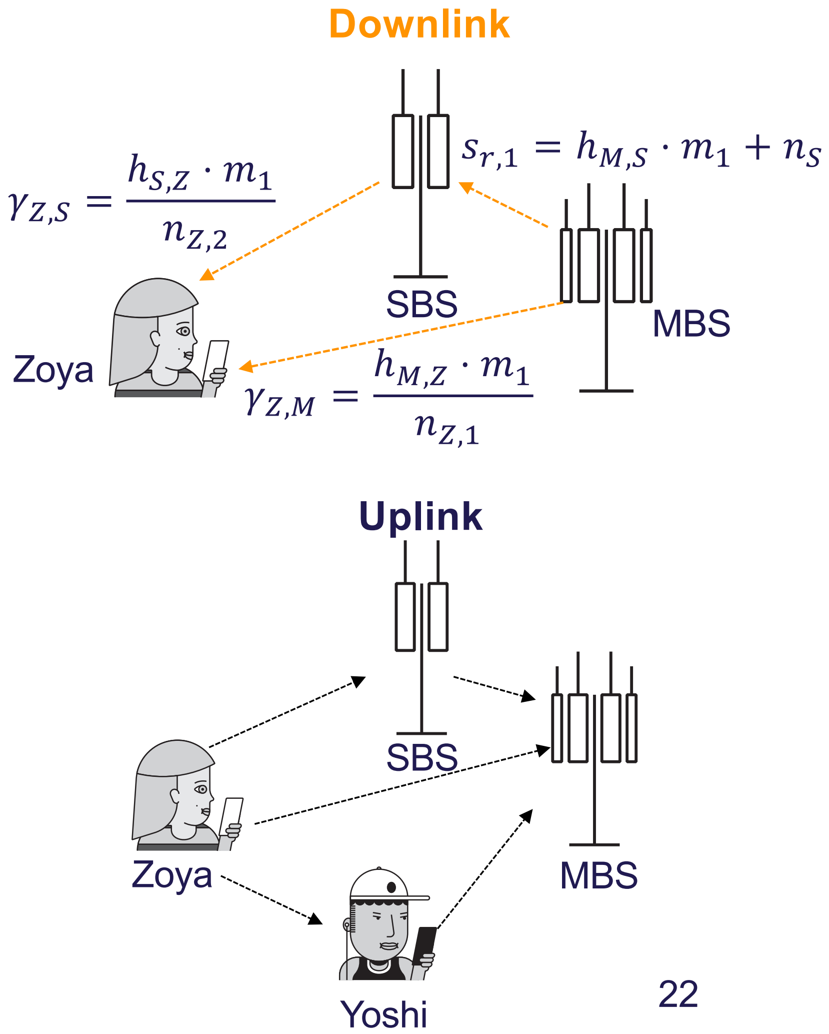
✗ More complex:

MBS can broadcast also in 2nd stage

✗ Cooperative methods require:

1. Various level of message exchange
2. Revision of the classic **layering:**

It combines network, link, MAC and PHY



Dissolving cells into clouds and fog

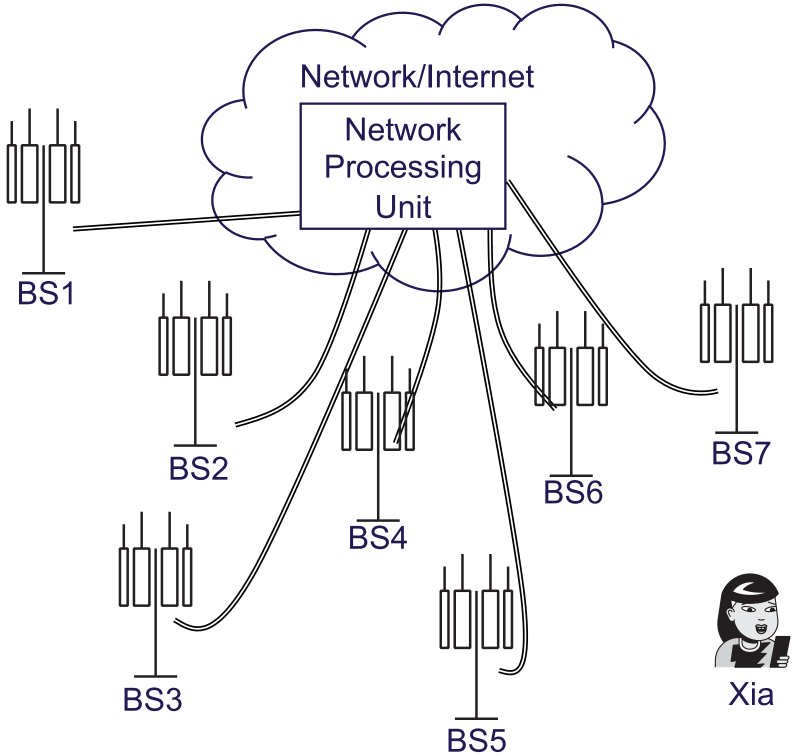
Abandoning the **cell** concept

Replace with set of interconnected (wired) BS to act as a distributed multi-antenna system

Ideal assumptions should be questioned

Finite capacity backhaul (and **latency**>0)

Noisy cooperation



Finite capacity backhaul links

If links carry data in digital form $R = \min(R_B, R_D)$,

where the capacity of the backhaul and of the direct links are R_B and R_D, respectively

Else if links carry data in analog form because:

1. BS needs to transfer **CSI** coefficients for **each user**
2. Baseband signals must be transferred to network processing unit

Example: Walt sends a symbol w to Victoria

Victoria recovers $v = w + n_Q$, where

n_Q is the **quantization noise** with σ_Q^2 decreasing with the rate as 2^{-R}

Tradeoff: Multi-antenna processing gain **enhances SINR**

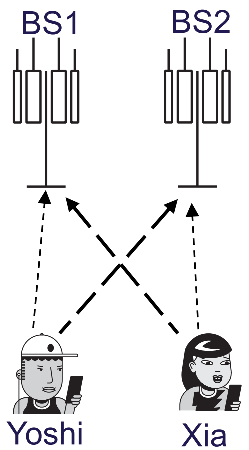
But **additional noise** is infused through quantization of analog signals

Noisy cooperation with finite backhaul

No cooperation

✗ **Interference** decreases SINR

$$b_{r,1} = h_{Y,1} \cdot y + h_{X,1} \cdot x + n_1$$
$$b_{r,2} = h_{Y,2} \cdot y + h_{X,2} \cdot x + n_2$$

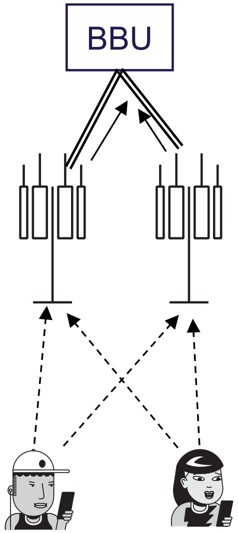


Quantize and forward

Baseband unit (BBU)

✗ Adds quantization noise

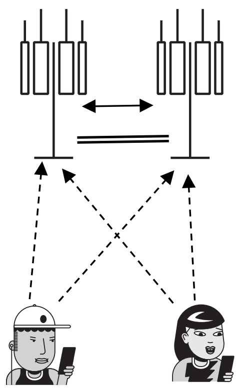
$$b_{q,1} = b_{r,1} + n_{q,1}$$
$$b_{q,2} = b_{r,2} + n_{q,2}$$

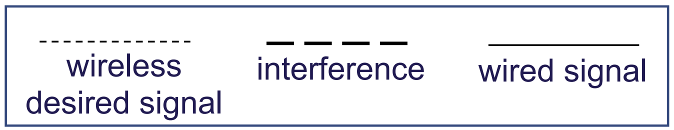


Cooperation

Exchange of quantized signals

✓ Allows the use of MIMO techniques

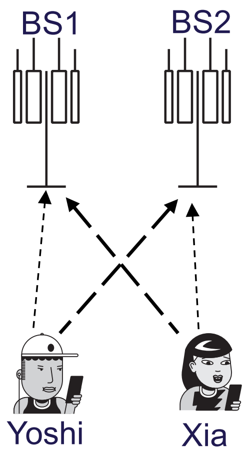


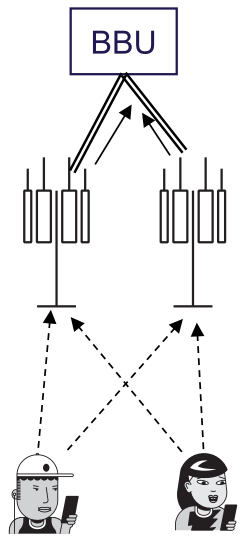


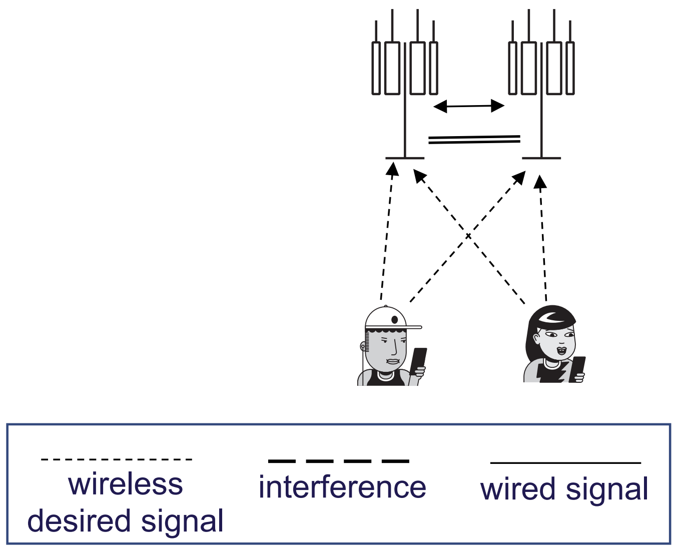
Access through clouds and fog

Seems that cooperation by exchanging quantized signals is best, but:

- What about hardware **cost**?
- May not be scalable to many BSs







Access through clouds and fog

Cloud-RAN (C-RAN) = Baseband Units (BBUs) + Remote Radio Heads (RRHs)

✓ Joint processing of **interference**

✓ Higher density of RRHs (with **limited** BS functionality)

✓ Adaptation of communication and computing to user density

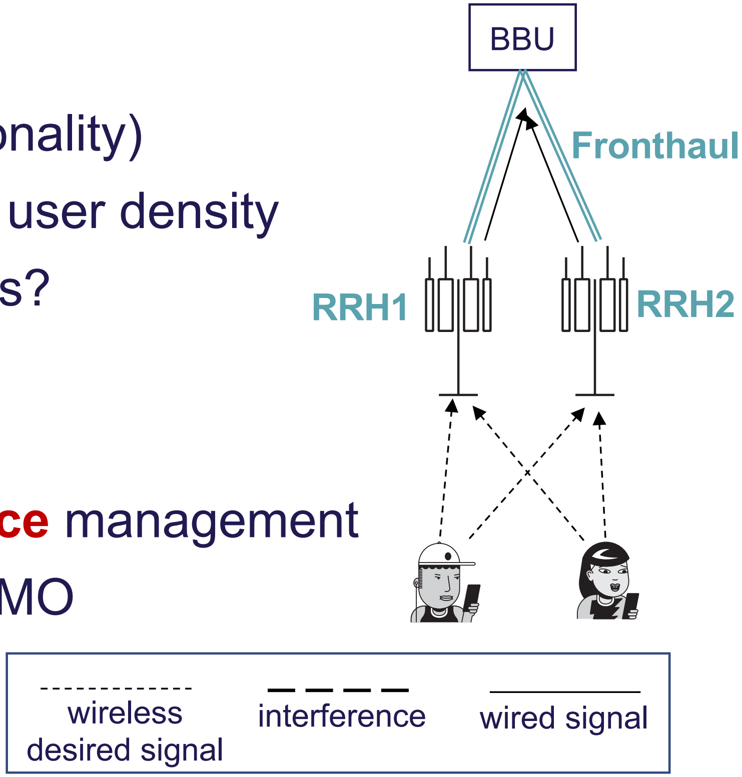
Functionality split between central unit and RRHs?

Fog RAN: more functionality to the RRHs

✓ Mobile Edge Computing and very low latency

Tradeoff: low latency of local traffic vs. **interference** management

Cell-free massive MIMO: cloud/fog + massive MIMO



External interference

Unrelated links may **interfere** with each other

$$\mathrm{SINR} = \frac{S}{N + I}$$

Frequency spectrum is scarce, so it must be managed

Spectrum licenses allow to control **interference**

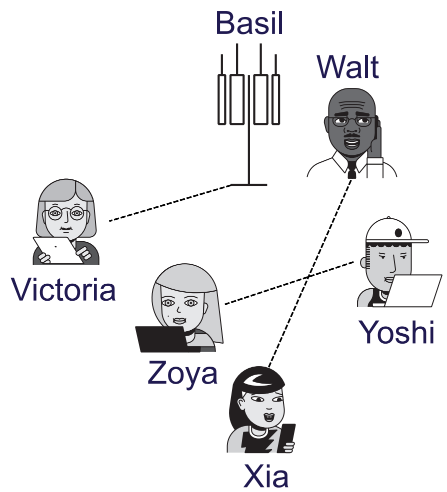
Many factors involved: technological, political, economic…

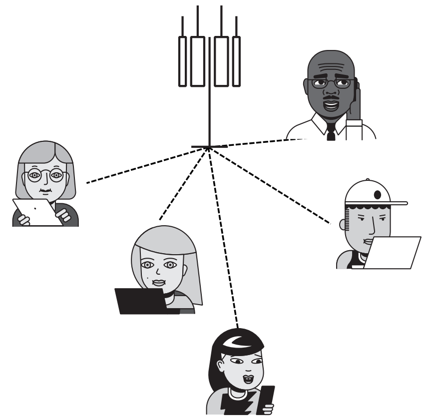
Lower frequencies are highly valued, why?

- More desirable for some applications

Not all spectrum is licensed (high **cost**)

- Unlicensed spectrum





Spectrum sharing and caring

Unlicensed spectrum

✓ No license cost

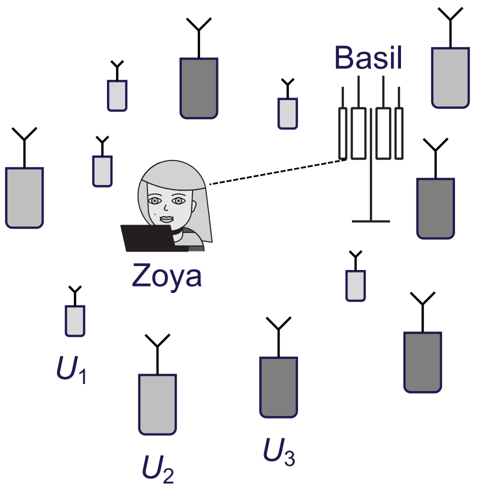
✗ Unpredictable interference

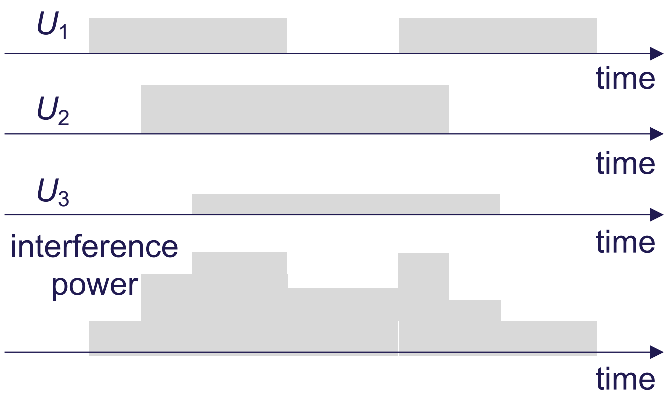
Spectrum regulations: based on simple, minimal rules

- Maximum transmit power limit
- Maximum spectrum usage over time

Coordination and cooperation

Deviates from the idea of minimal rules





Duty cycling, sensing, and hopping

Without cooperation, the devices can: self-restraint or coordinate implicitly

Duty cycling: Limit the transmissions in the channel to a certain percentage of time

Carrier sensing or Listen Before Talk (LBT): Wait for the channel to be **idle**

- ✗ Requires receiving capabilities of the device!
- ✗ Less technology neutral compared to duty cycling

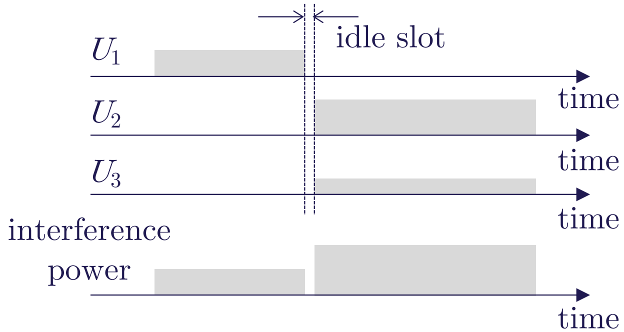
Frequency hopping: Similar to duty cycling but with several frequencies

- ✓ Graceful degradation with respect to the number of devices
- ✗ Requires multiple frequency capability
- ✗ Less neutral compared to duty cycling

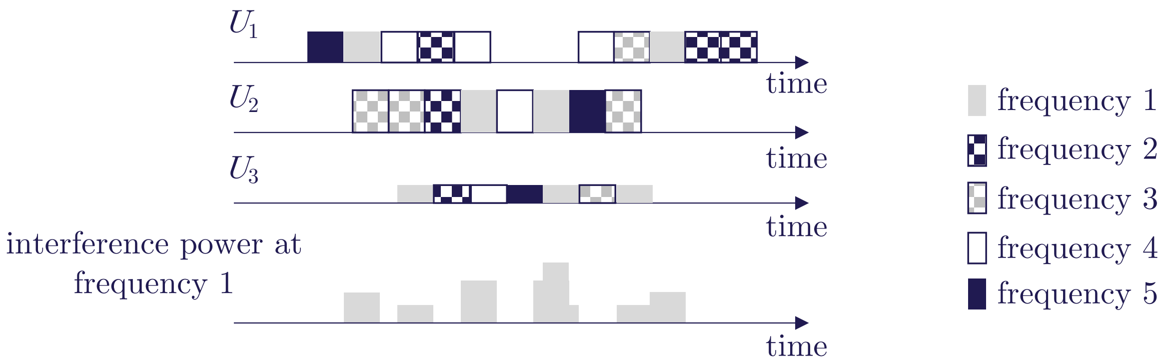
Duty cycling, sensing, and hopping

Duty cycling

LBT



Frequency hopping



Some final words

Licensed and unlicensed spectrum are the two extremes in the way spectrum is used

Dynamic spectrum access: Channels may not always be used

Abandon the static licensing and allow agile access to the spectrum resources

Cognitive radio:

- **Primary (incumbent) user:** license to use the frequency band
- **Secondary user:** must find out the way to use the spectrum without disturbing

Technology axioms:
minimal assumptions upon which the whole wireless ecosystem is built

- These can change over longer periods, reflecting the change in the minimal technology level of the wireless systems

Outlook and takeaways

- There are many types of traffic, connections, and infrastructure
- Spatial reuse, frequency reuse, and cell sizes to maximize coverage and capacity while mitigating interference
- Relaying is essential for reliability but requires coordination and increases the elements in the system (**cost**)
- Cloud/fog RAN and massive MIMO offer great possibilities
- Licensed vs. unlicensed systems