Wireless Connectivity: An Intuitive and Fundamental Guide

Chapter 3: Access Beyond the Collision Model

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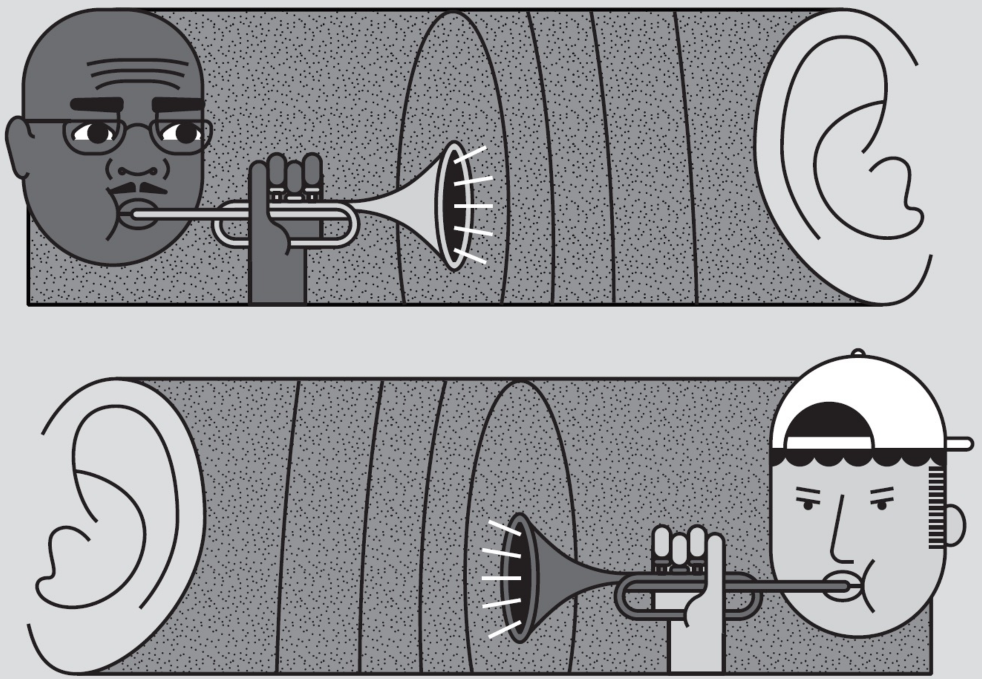
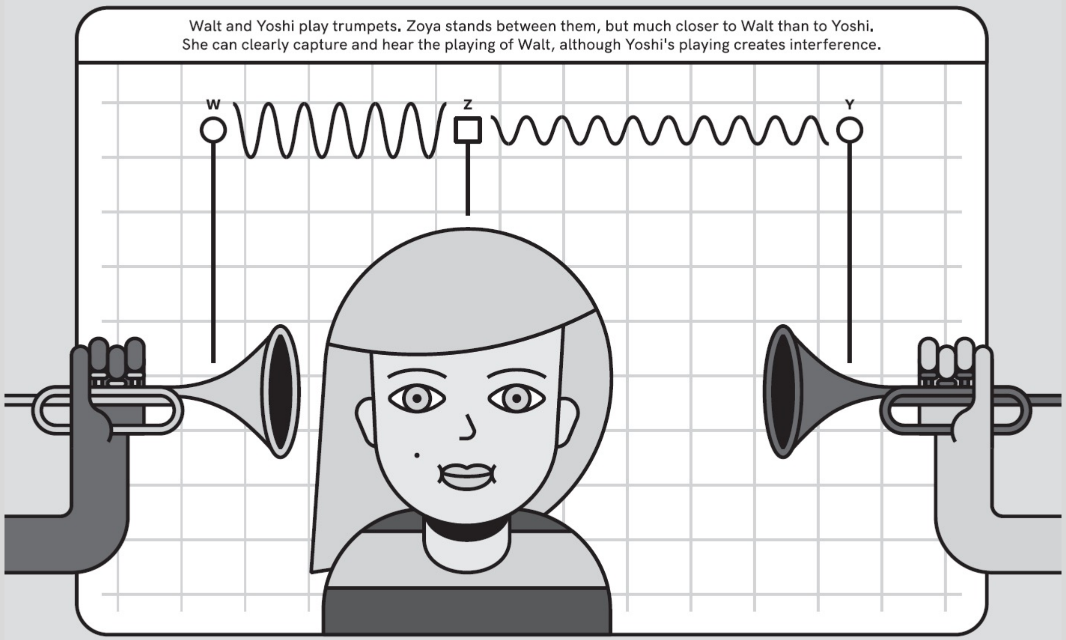
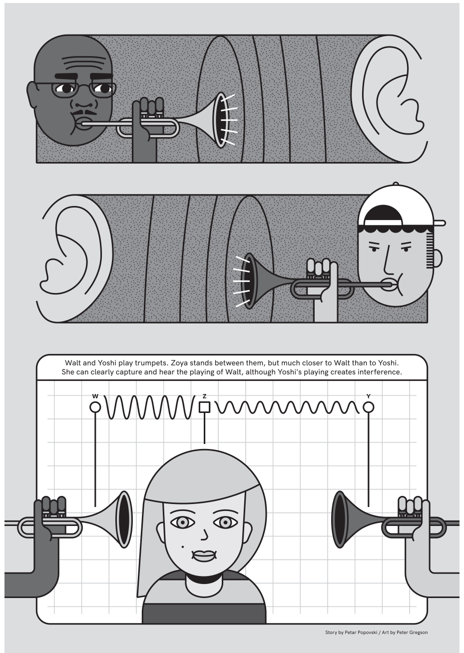
Modules

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




Walt and Yoshi play trumpets. Zoya stands between them, but much closer to Walt than to Yoshi.
She can clearly capture and hear the playing of Walt, although Yoshi's playing creates interference.
W
Z
Y

Limitation of the collision model



- As with the trumpet analogy, all is not lost even when collisions and interference occur
- Intuitively different signals are perceived differently by the receiver
    - Distance
    - Power
- What if one tune is longer and the person keeps playing after the other has finished?

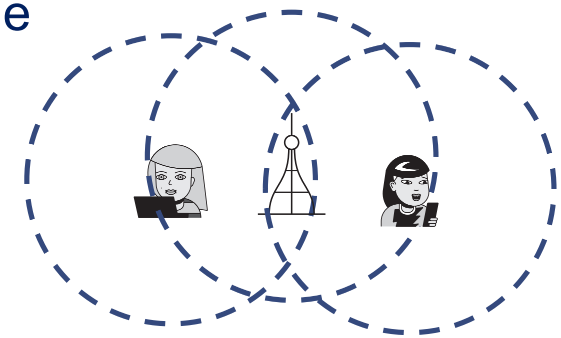
What will be learned in this chapter

- Gradually adding some more reality to the collision channel
- Effects of distance and interference on the communication models
- Capture and Successive Interference Cancellation (SIC)
- How to benefit from buffering collisions and use them in the future
- Unwrapping the data packets and introduction of integrity check

Introducing distance to the model

Perhaps, the model in which communication is perfect up to distance d is too simplistic

- The first cracks in the model: sensing vs. data reception range



Intuitively, as the distance d increases, more and more data is lost through ***graceful degradation***

For now, we still treat packet of size $D = RT$ as the smallest unit, so no possibility of receiving only some of the bits correctly

- Instead, let's assume packet is received correctly with probability $1 - p_e$ and lost with probability p_e and observe a long sequence of L packets over time

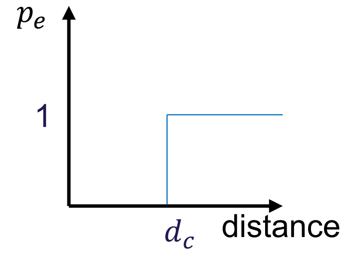
Introducing distance to the model

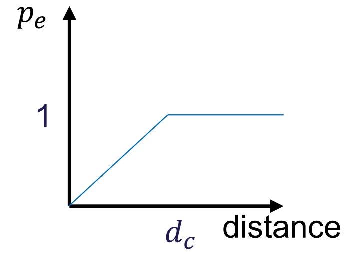
After observing large number of packets L, the **throughput** is

$$Th(p_e) = \frac{L(1-p_e)RT}{LT} = (1-p_e)R$$

if we make now $p_e = p_e(d)$ then, consequently, $Th = Th(d)$.

The function $p_e(d)$ can have various forms.





The notion of finite distance might seem counterintuitive as the radio waves propagate infinitely so the received power is never 0

- However, receivers are characterized by their **sensitivity,** i.e. the minimum power P_{th} (w.r.t. the noise) beyond which decoding is not possible
    - As such, d_c can be understood as the distance where $P_{received} = P_{th}$

Distance and interference

The packet's error probability dependence on the distance is inherently tied to the signal strength.

However, even when the signal is too weak to be received properly, it might still cause interference

- Another reason why simple collision model is insufficient → one active device in the universe

Introducing: the **capture effect** and **successive interference cancellation (SIC)**

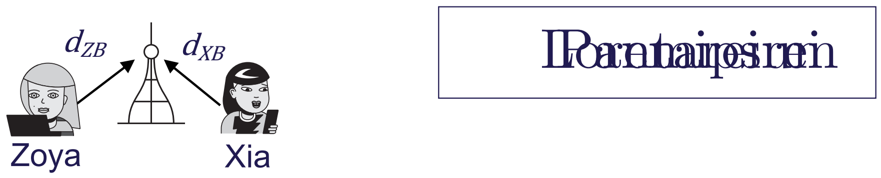
Distance and interference

Consider Zoya and Xia transmitting simultaneously

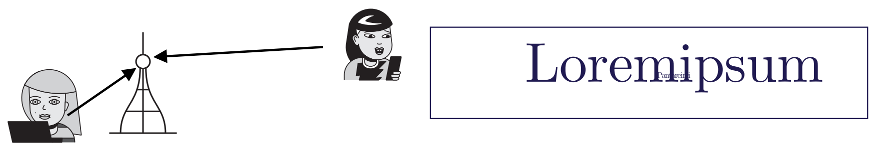
Their distance to the base station is d_{ZB} and d_{XB} respectively

We can distinguish 4(5) outcomes

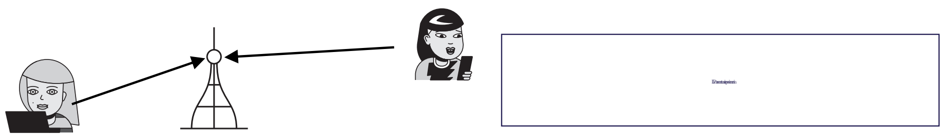
Collision



Capture effect



Idle



SIC

Distance and interference

The price for using the enriched wireless model, is a significant increase in complexity necessary to describe it

Consider K devices with their respective distances to the base station being $d_1, \dots, d_K$

- At any time, k devices can be active (and $k = 0, \dots, K$) $\rightarrow \sum_{k=1}^{K} \binom{K}{k}$ scenarios
    - In each scenario 2^k possible outcomes
      (more outcomes if we want to distinguish between collision and idle)
        - $\sum_{k=1}^{K} \binom{K}{k} 2^k$ different parameters p need to be defined
            - Almost 60000 already with just 10 devices present!

Models with lower complexity however can still be useful

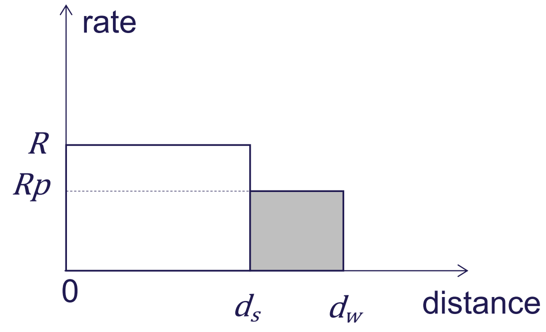
Double disk model

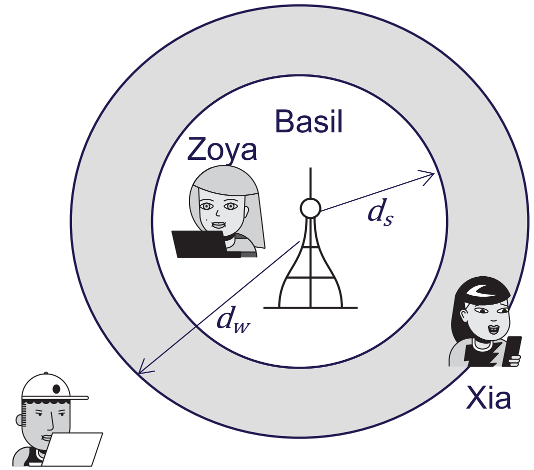
We define **two** distances d_s and d_w

We observe different behavior (outcome, probability) depending on:

- The number of simultaneous signals
- Which distance class they belong to

Zoya	**Others**			
	none	≥ 1 weak, no strong	1 strong	≥ 2 strong
Strong	Received, 1	Received, p	Collision, 1	Collision, 1
Weak	Received, p	Idle, 1	Received, p if the strong is received otherwise 0	Collision, 1

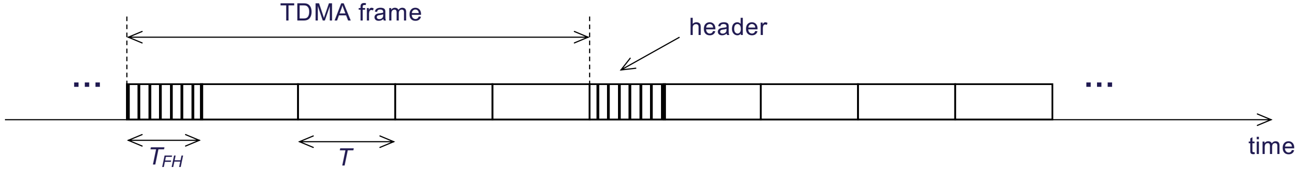


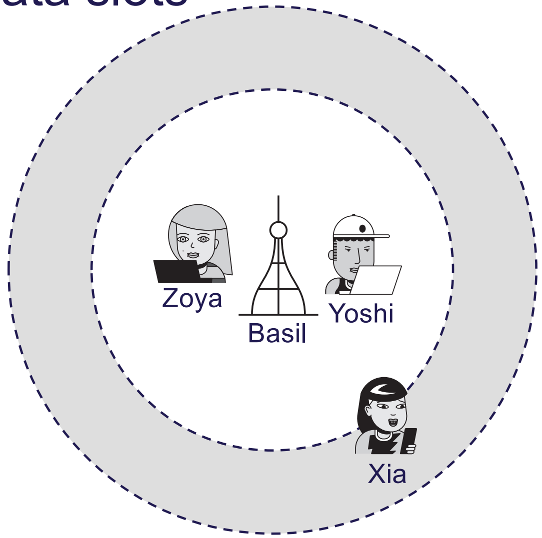


Double disk model: downlink

Introducing the probability of reception has many implications

- Consider downlink transmissions from Basil to the terminals and the frame structure from Chapter 1, a header followed by data slots
- If Xia is in the weak region and does not receive the frame header, then she ignores the data content of the frame
  - Clearly, the reception of the header, being a form of control information, is crucial





Double disk model: Downlink

Consider the frame in which a header is followed by 3 data slots meant for Xia

- If header is received correctly (probability p), then Xia proceeds to receive the data
- Otherwise Xia ignores all the data
    - Expected number of received data packets is $L_p = p \cdot 3p + (1-p) \cdot 0 = 3p^2$
    - Consequently, the goodput is $G_p = \frac{L_p D}{T_{FH} + 3T} = \frac{p^2 R}{\tau + 1}$, where $\tau = \frac{T_{FH}}{3T}$

One could consider a frame where header is repeated to increase its reliability

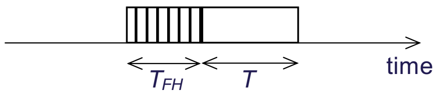
- The expected number of received packets increases to $L'_p = \left(p^2 + 2p(1-p)\right) \cdot 3p = 3p^2(2-p)$
- The situation with goodput is not as straightforward $G'_p = \frac{L'_p D}{2T_{FH} + 3T} = \frac{p^2(2-p)R}{2\tau + 1}$

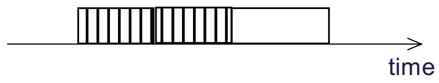
Double disk model: Downlink

Small improvements such as header repetition can be taken even further
but we should be aware of the complications

Header repetition is needed only if
there is some data in the frame intended for users in the weak reception zone

- Idea: introduce two types of frames
  - Marginal gains if $\tau = \frac{T_{FH}}{T} \approx 0$
  - Requires the knowledge of who is in which zone
  - Header must be distinguishable from data

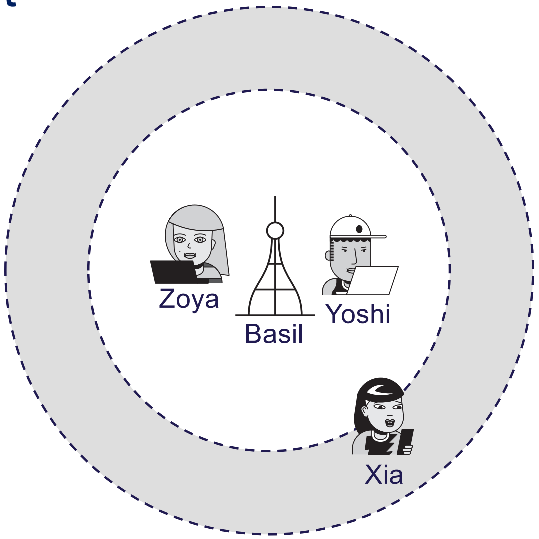




Double disk model: Uplink

The uplink scenario further highlights the importance of the header

- Xia can only transmit if she correctly receives the header and is assigned a slot
- No response from Xia can mean two things: no data or error receiving the header
    - Important to distinguish those two cases → dummy packet
        - If Basil is aware of the error
          then he can assign extra slots to Xia in the next frame
        - Basil might also be interested in periodically “pinging”
          the devices that are connected to it



Beyond the collision model: SIC

Distance can be used to our advantage by employing ***multi-packet reception***

Assume two packets in the same slot: **Strong** from Zoya and **Weak** from Xia

0: With probability $1-p$, Zoya's packet is not received correctly

- Thus, Xia's packet is not received either

1: With probability $p(1-p)$, only Zoya's packet is received correctly

- Basil applies SIC, but Xia's packet is not received correctly

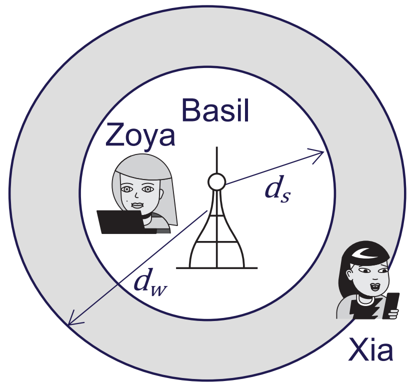
2: With probability p^2, **both packets are received correctly**

- First Zoya's and then Xia's after SIC

Ultimately, the expected number of received packets is

$$0 \cdot (1-p) + 1 \cdot p(1-p) + 2 \cdot p^2 = p(1+p)$$

which is greater than 1 when $p > 0.618$



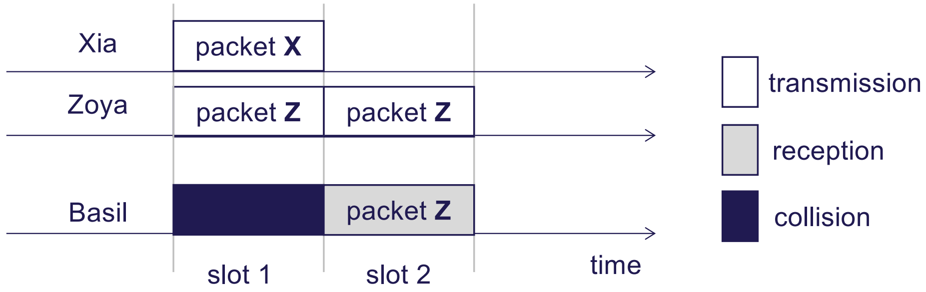
Beyond the collision model: SIC

In addition to the intra-SIC, with **sufficient memory and processing power,** the receiver could go even further:

If a collision cannot be immediately resolved through intra-SIC, buffer the signal for future use.

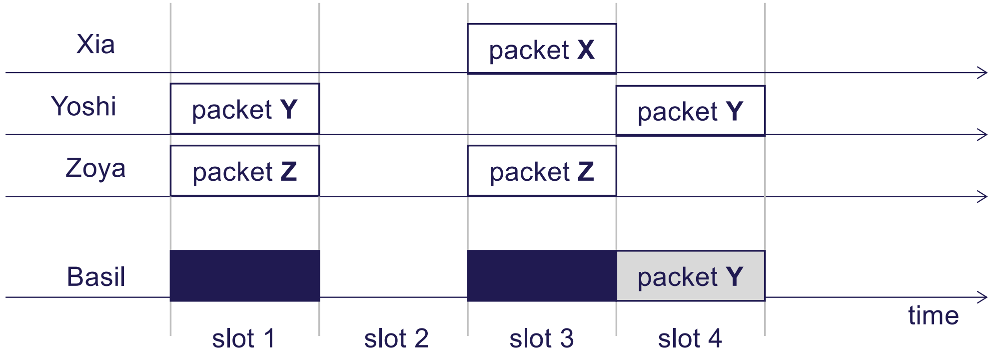
Use one of the retransmissions to remove the corresponding signal from the ***stored collision***

Use **Z** to recover **X**



Beyond the collision model: SIC

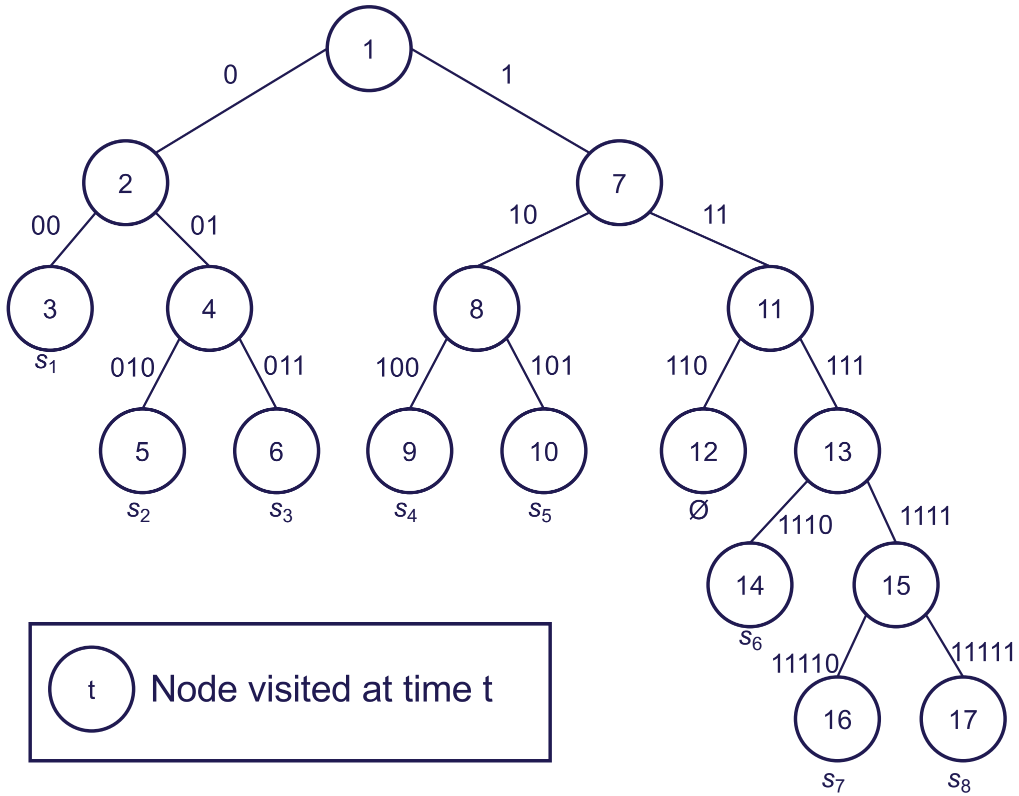
Use **Y** to recover **Z**, then **Z** to recover **X**



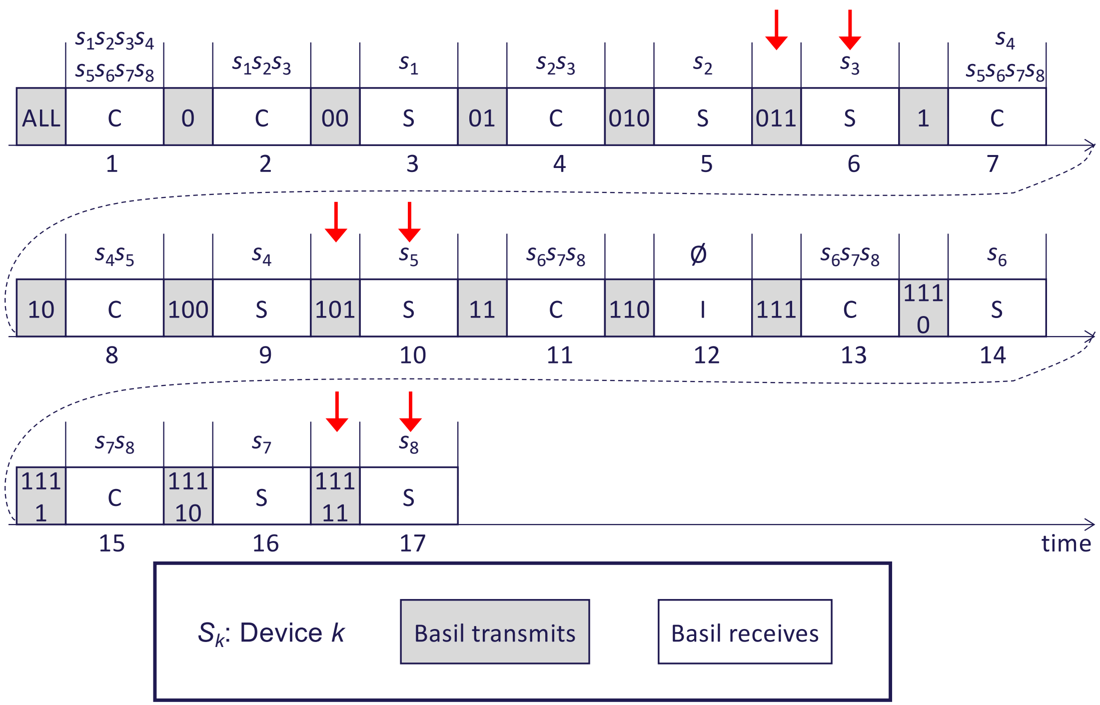
Note: The receiver needs to know which signals were involved in the collision

Probing: revisited

Tree



Tree in time: collision (C), single (S), idle (I)



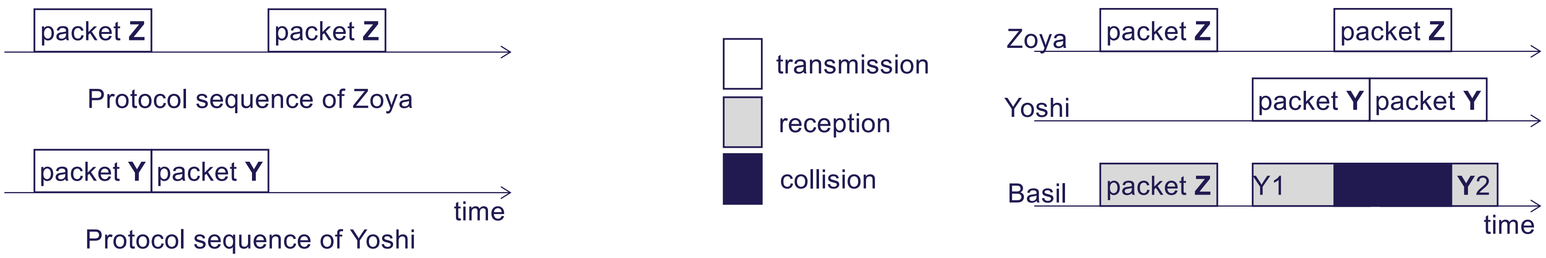
Packet fractions and protocol sequences

In the collision model: no matter how small is the mutual overlap, all data is lost

Idea: Ensure successful communication by transmitting replicas and **taking fractions of them to reconstruct the packet**

Devices transmit according to preassigned sequences

- Lack of synchronization not an issue
- Good for low-complexity devices that only transmit (predictable battery lifetime)



Unwrapping the packets

Until now, we were not concerned with the bit/byte structure of the packets

In practice it is impossible to have each bit carry actual data

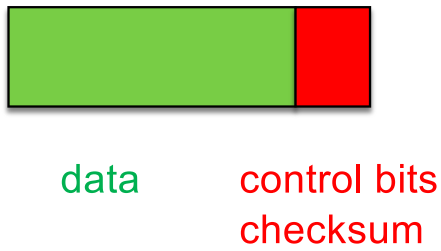
- Assume we need to send a single byte of information D, which can have 2^8 = 256 different values
- The reception of this data is subject to errors, manifested by flipping the value of a bit from 0 to 1 or vice versa
- *Since all 256 possibilities represent valid information, receiver has no guarantees that this is indeed the information that was sent*

Similar to the fact that not every 16-digit number is a valid credit card number.

Unwrapping the packets

Packets need **integrity check!** Either:

1. Make only some of the bit sequences valid or
2. Add dedicated **redundant bits $\boldsymbol{C}$**
   - These do not carry information,
     but are a function $f(\boldsymbol{D}) = \boldsymbol{C}$ of the data bits $\boldsymbol{D}$
   - This is called an **error detection code**



Example for $D = 8$ and $C = 2$: The number of possible values is to $2^{10} = 1024$, but only 256 sequences are valid packets and represent valid information

The redundancy bits introduce **overhead**:
the rate at which the packets are transmitted R_c is higher than the useful data rate R

$$R_C = \frac{D + C}{T} > \frac{D}{T} = R$$

Unwrapping the packets

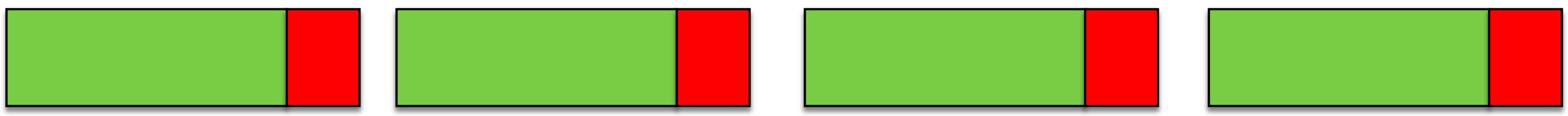
Even with redundancy bits an error may pass undetected.

This happens when:

1. A combination of errors transforms packet $[\boldsymbol{DC}]$ into another packet $[\boldsymbol{D'C'}]$ and
2. Packet $[\boldsymbol{D'C'}]$ is also valid (i.e. $f(\boldsymbol{D'}) = \boldsymbol{C'}$)

This convinces the receiver that $\boldsymbol{D'}$ was the actual message: undetected error

While these situations cannot be avoided,
practical error detection codes,
such as ***Cyclic Redundancy Check*** **(CRC),** offer very high reliability (error of 10^{-12})



Outlook and takeaways

Introducing distance in the model **expands the possibilities** for new protocols

- Collisions are not necessarily treated as waste

Mechanisms: capture, SIC, packet fractions, etc.

We have reached the point at which:

1. We cannot look at the packets as atomic units
2. Not every arbitrary array of bits is considered a valid packet
3. We consider the overhead of integrity check