Wireless Connectivity: An Intuitive and Fundamental Guide

Chapter 2: Random Access: How to Talk in Crowded Dark Room

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Chapters

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
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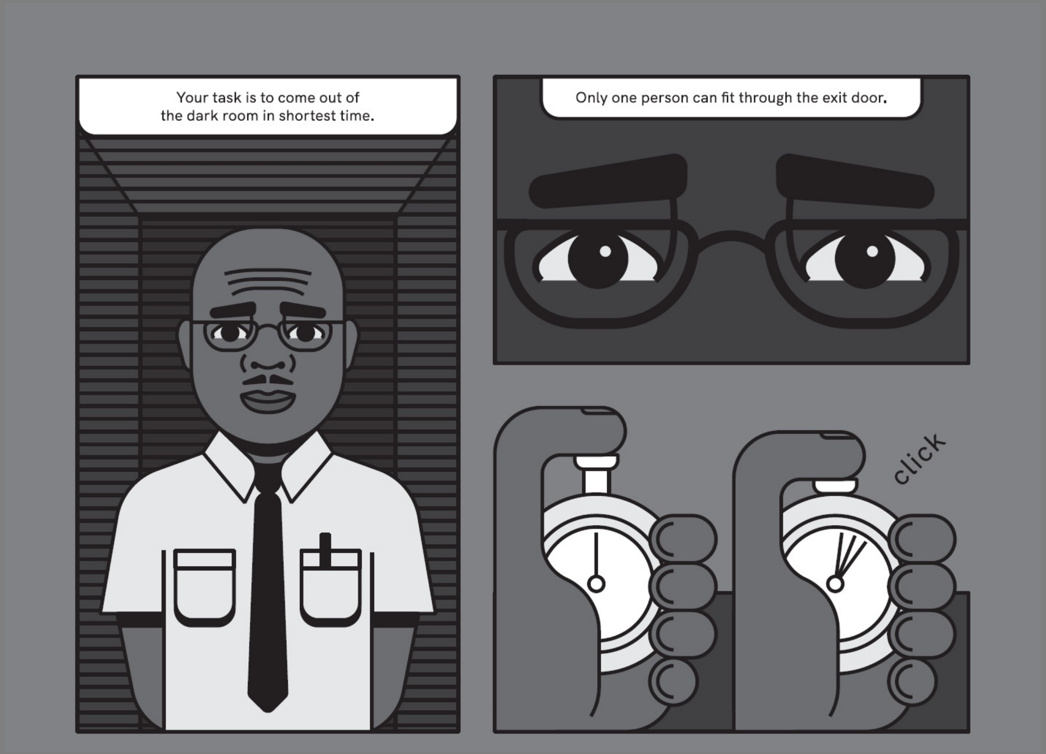
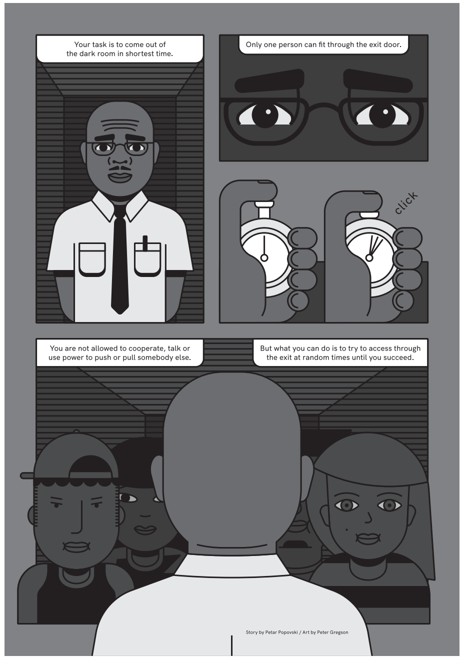
8. Information-Theoretic View on Wireless Channel Capacity
9. Time and frequency in wireless communications
10. Space in wireless communications
11. Using Two, More, or a Massive Number of Antennas
12. Wireless Beyond a Link: Connections and Networks


Your task is to come out of
the dark room in shortest time.
Only one person can fit through the exit door.
click


You are not allowed to cooperate, talk or use
power to push or pull somebody else.
But what you can do is to try to access through the
exit at random times until you succeed.

The essential properties of a random access setup



- Randomized transmission decisions
- The problem of initial access:
  - Could be solved trivially if Walt uses the names of the people in the room to coordinate them
  - When the names are unknown, randomized distributed algorithm should be used
- Efficiency problem when the set of potentially active transmitters is large; the set of actually active transmitters is small and uknown

What will be learned in this chapter

- When and why to use random access over a shared communication medium
- (framed) ALOHA protocol and the main ideas behind its analysis
- Probing over a shared channel and its connection to group testing
- Carrier sensing: how to take an advantage of a short (cheap) idle slot
- Random access in multi-hop scenario, hidden and exposed terminals

Canonical scenario for random access

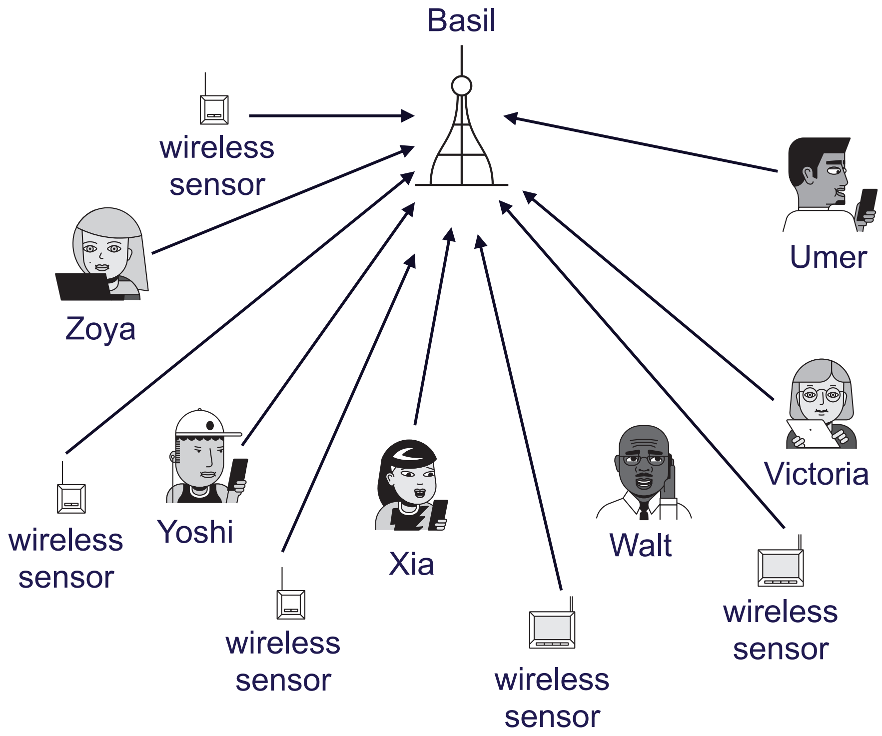
Assume that Basil is in a dark room and other people in that room want to talk to him

- Dark room = same channel for communication (data) and coordination (metadata)

Techniques discussed last time work very well for **deterministic traffic**, especially in the downlink

Problems

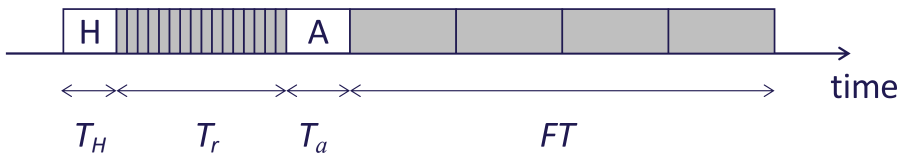
- Initial access
- Lack of coordination in the uplink



Basic tradeoffs in random access

Scenario with $K \gg 1$ devices
out of which only **very few**
have data to send at a given time

- Basil does not know
  who will be active at a specific time



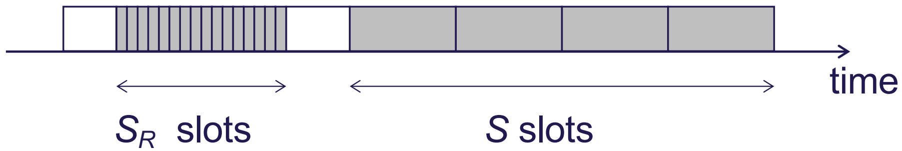
Tradeoffs

- Allocating an exclusive slot to
  each of the K devices
  may lead to idle (wasted) resources
- … and having a
  fixed number of data slots
  may lead to unnecessary
  waste or packet drops

Framed ALOHA with reservation frame and data slots

Create a short reservation FRAME with $S_R < K$ slots

1. An **active user** selects one of them at random (possibility of collision)
2. The $S \leq S_R$ successful devices are granted a dedicated data slot
3. The data phase consists of $F = S$ slots, which is dynamically adjusted
   - Recall: Flexibility requires signaling



In absence of reservation frame, users perform grant-free access and apply random access in the data frame.

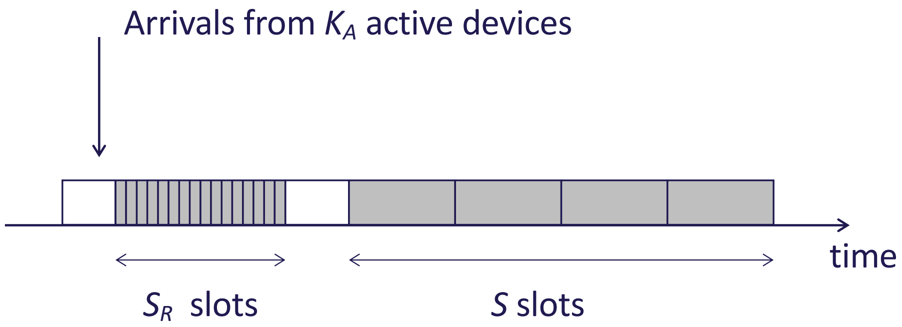
If K is known, how long should S_R be?

Framed ALOHA: Size of the reservation frame

Let K_A be the number of active devices

Probability of a successful transmission in a given slot = the probability that **any** of the devices selects this **particular** slot while **others** do not

$$P(K_A) = \binom{K_A}{1}\frac{1}{S_R}\left(1-\frac{1}{S_R}\right)^{K_A-1}$$

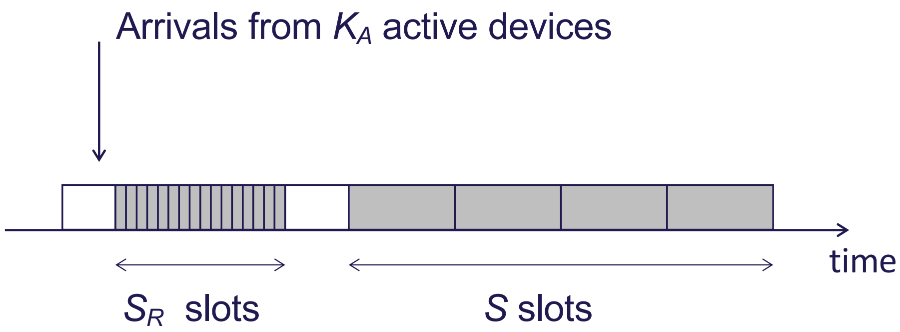


A simple maximization of this expression w.r.t. S_R leads to $S_R = K_A$

Framed ALOHA: Dependence on # of active devices

We have assumed that Basil knows K_A

- Still does not know **which** K_A devices
- In practice, K_A should be estimated



Optimized success probability

$$P(K_A) = \left(1 - \frac{1}{K_A}\right)^{K_A - 1}$$

approaches e^{-1} as K_A goes to infinity

Framed ALOHA: Estimating # of active devices

Relation among the average numbers of

active $\overline{K}_A$, newly arrived $\overline{K}_N$ and retrying/collided $\overline{K}_C$

$$\overline{K}_A = \overline{K}_N + \overline{K}_C$$

For large numbers we can remove the bars and work with the average values as if exact

$$K_A = K_N + K_C$$

In a stationary regime

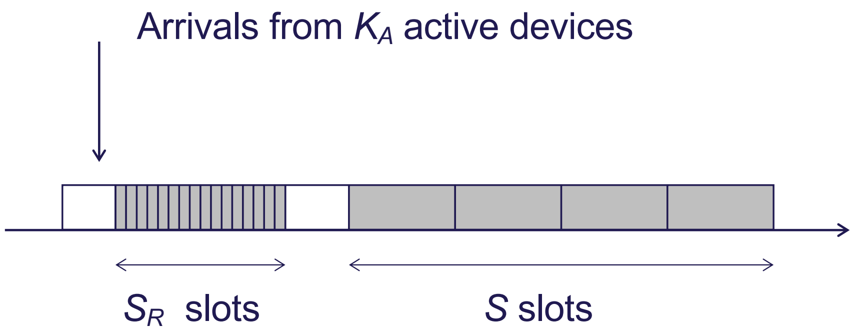
$$K_C = K_A\left(1 - \mathrm{P}(K_A)\right) \approx K_A(1 - e^{-1})$$

such that the relation between new and active is

$$K_A = K_N \cdot e$$

Throughput (=goodput)

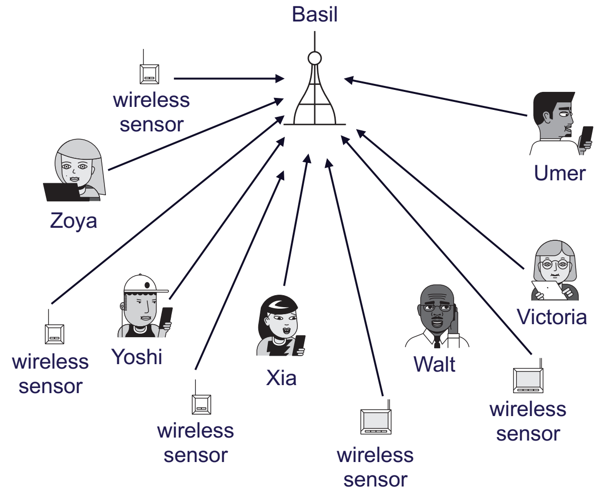
$$G = \frac{K_N}{K_A T} = \frac{K_A e^{-1}}{K_A T} = \frac{e^{-1}}{T} \quad \text{[packet/s]}$$



In the book it is shown how to take into account past collisions for throughout calculation

But can we use the knowledge/memory of past collisions to get more efficient access?

Probing

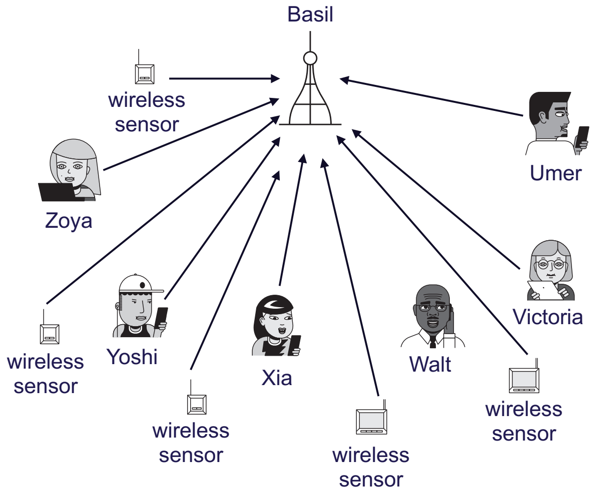


For framed ALOHA we (optimistically) assume that K_A is known or at least a *good* estimate is available

Back to the cartoon from this chapter

- People in the dark room do not know each other, otherwise a predefined contract or hierarchy could be used
- Walt says “one of you come out of the room”, but who feels entitled to be “the one”?
- The question of Walt is in fact probing, not scheduling

Probing/polling



Probing/polling mechanism

1. Basil probes by sending an invite message
2. The K_A devices with data respond

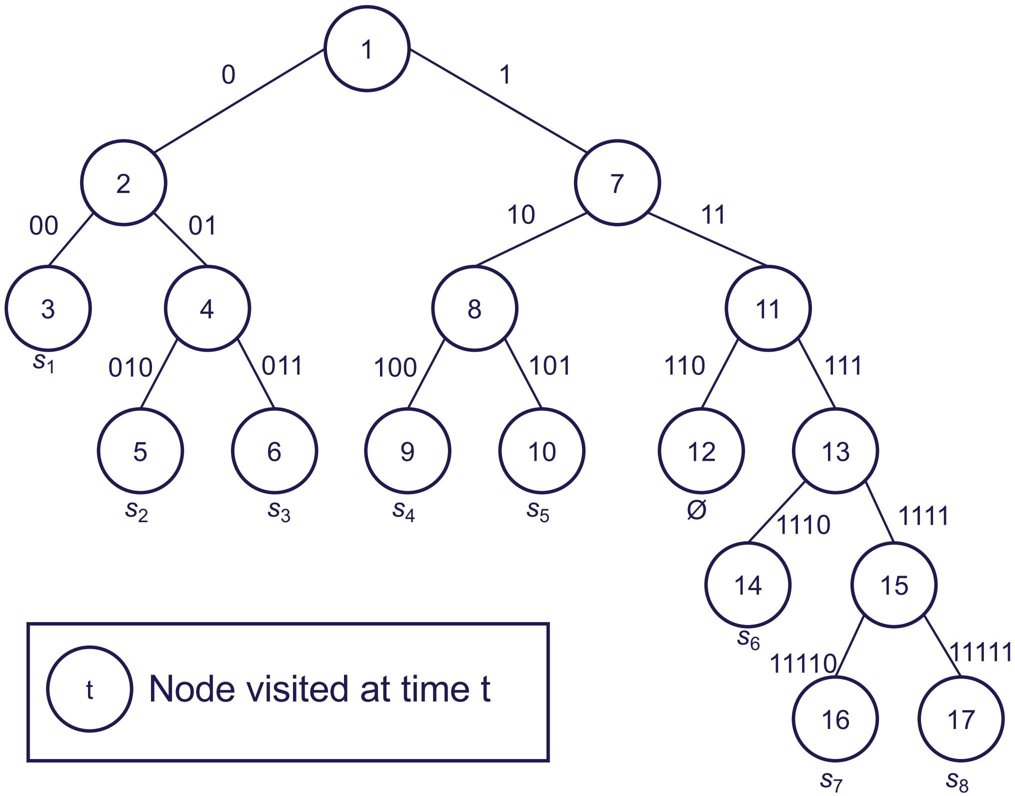
   if $K_A = 0$ no new packets and the data phase is idle; BS goes back to 1

   else if $K_A = 1$ there is no collision; device will be assigned a data slot

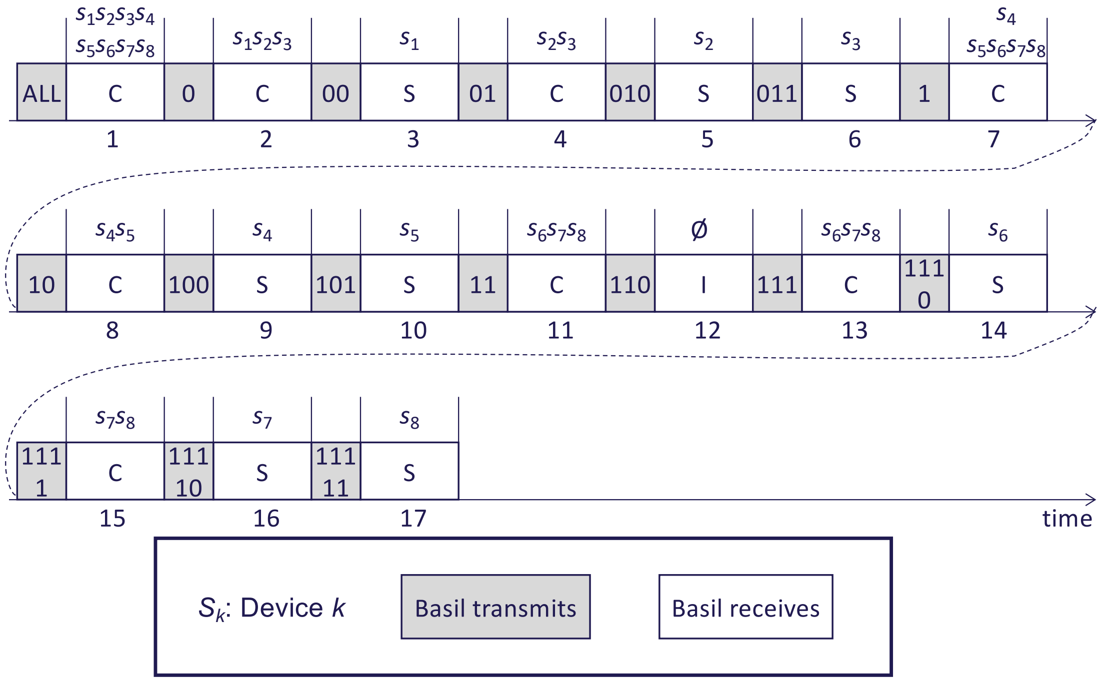
   else $K_A > 1$ collision occurs; polling is initiated

Probing: Example for $K_A = 8$

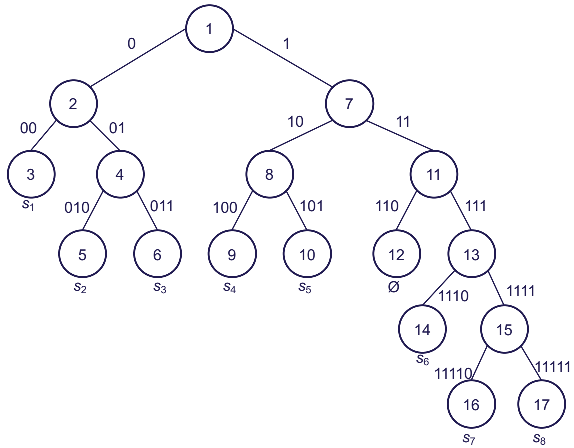
Tree



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



Remarks on probing

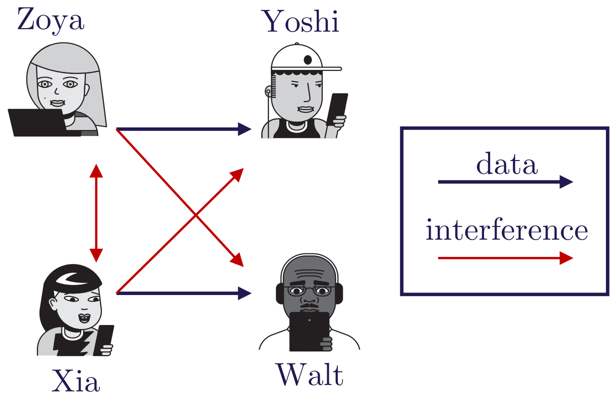


- Instead of randomization,
  the devices can use unique addresses for probing
- Probing process allocates short ad hoc addresses
  to the active devices
- Using of a feedback (collision, single, idle) instead of a probe offers equivalent traversal of the tree
- Combining ALOHA and probing
  - ALOHA uses memoryless randomization
  - Probing retains memory

Carrier sensing

The problem of spectrum sharing
requires also randomization

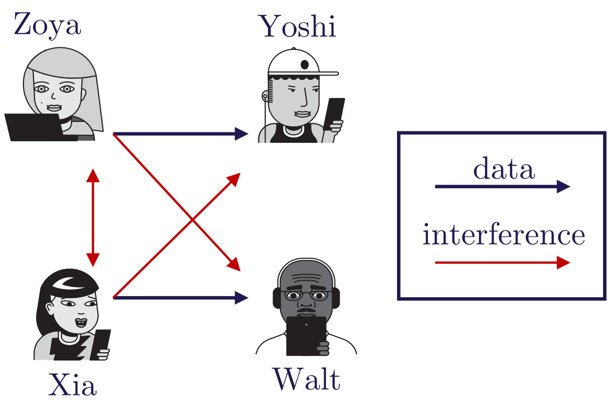
- Proximate links that share the same channel may cause interference
- Lack of coordination among links that are not logically connected and can only communicate through interference
- Example: the Wi-Fi access points of two neighbors

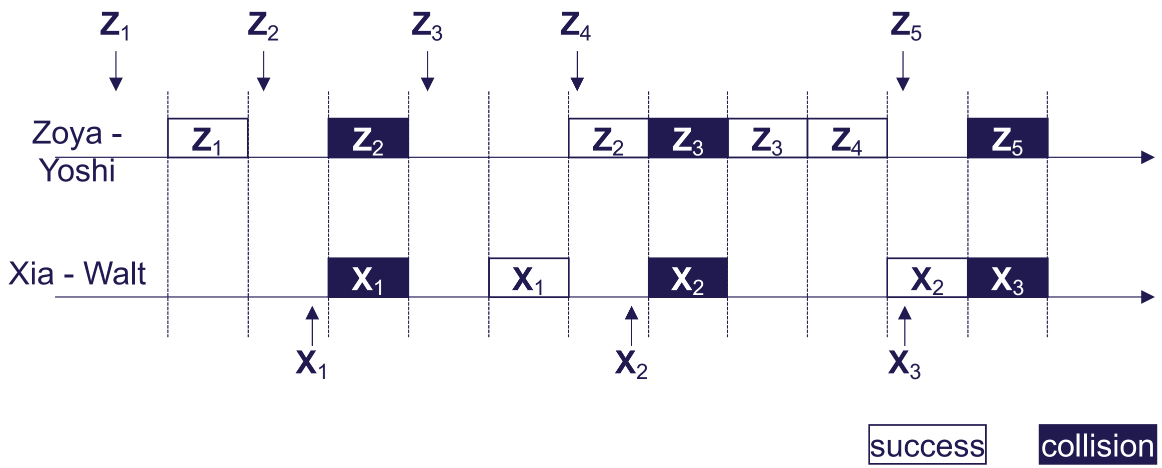


Carrier sensing

Spectrum sharing with a slotted synchronized structure

- Questionable to assume that two independent systems are a a priori synchronized, but synchronization can occur through the access of a shared medium
- New packets **always need to wait** at least until the start of a new slot
- Enforced **waiting synchronizes the packets to collide**





Carrier Sense Multiple Access (CSMA)

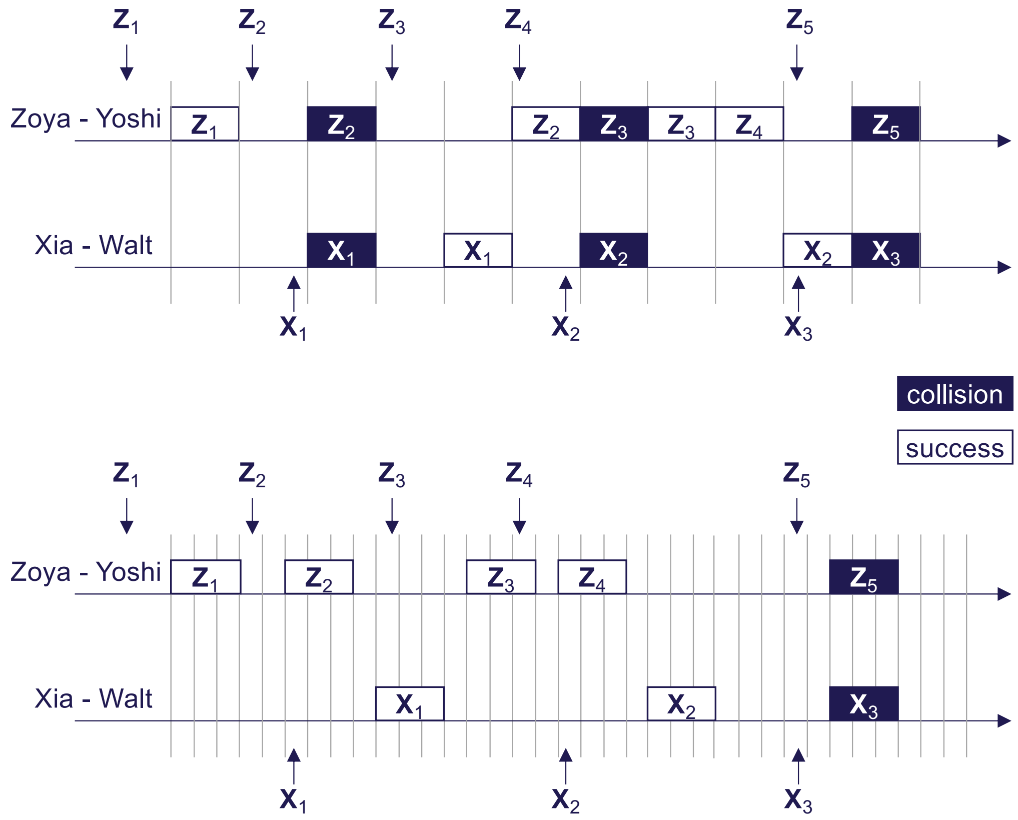
Idea: Make the *idle slots* short (cheap!)

Finer time resolution
preserves asynchronism of arrivals

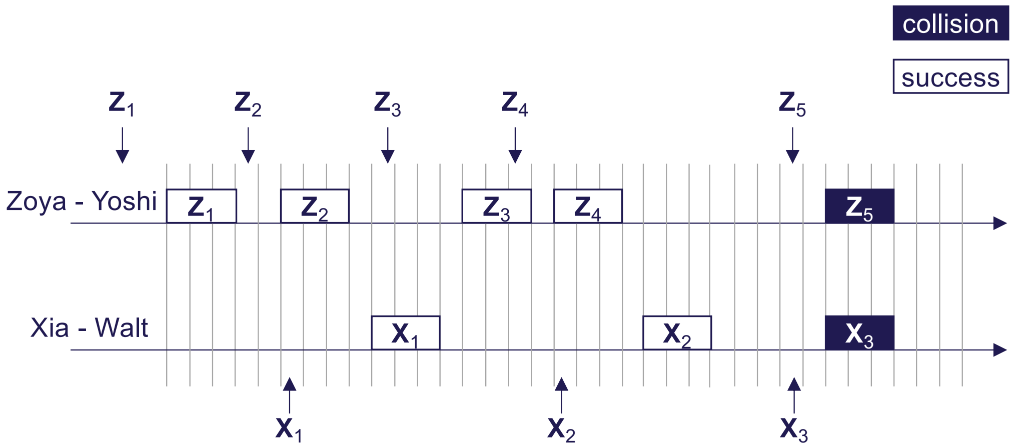
Devices not currently transmitting
must listen to **sense** if carrier is free

- If the medium is busy,
  device waits for a random time
  =
  countdowns
  a random number of idle minislots

Carrier sensing obviates the need
for fixed-length packet



Elements of CSMA

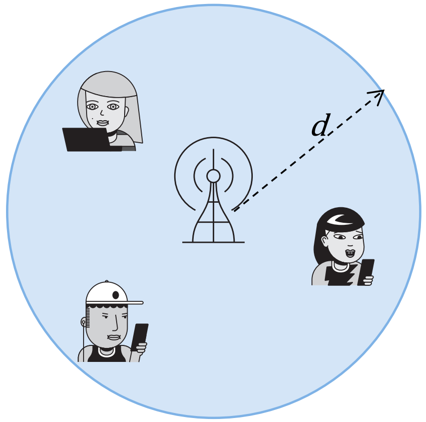


Random number of waiting minislots

- Pausing countdown during sensed carriers to avoid aligning of the access instants after the medium is sensed idle

Choosing the idle slot size

- Carrier should be reliably detectable
- Propagation delay $T_I = \frac{d}{c}$ or $T_I = \frac{2d}{c}$ if the sensing range is larger than the communication range



Feedback to the transmitter

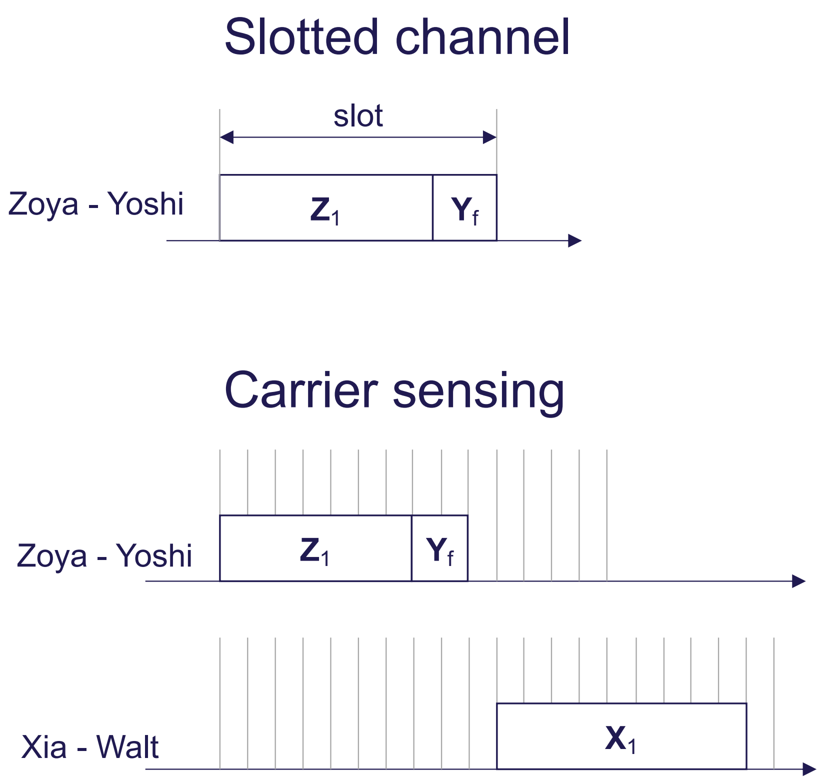
The possible outcomes:
collision and **success**

The transmitter must be informed of the outcome through **feedback:**

- Acknowledged (**ACK**)
- Not acknowledged (**NACK**)

Implemented differently
in a slotted channel
and in carrier sensing.

In carrier sensing,
Yoshi's feedback can **skip sensing**,
making it **HIGH** priority

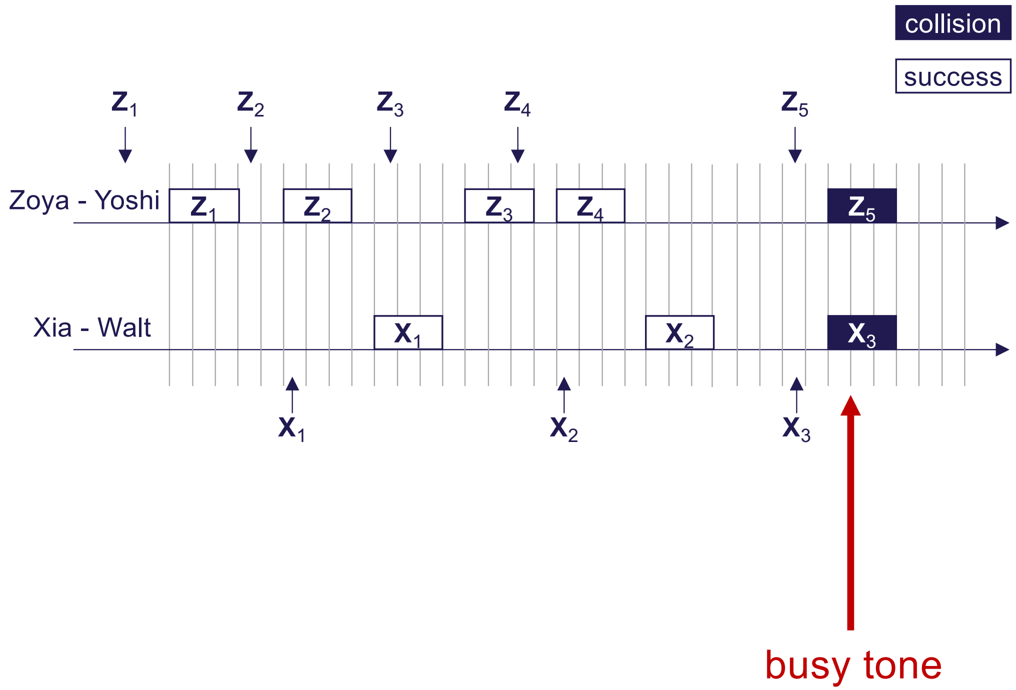


Feedback to the transmitter

Idle slots are basis for different prioritization levels:

- Users of a given priority need to wait for a priority-dependent number of idle slots
- Malicious users could exploit this

Full-duplex and used of busy tones



Carrier sensing and multiple hops

Potential **weakness** **of carrier sensing:** assuming that everyone can hear everyone else.

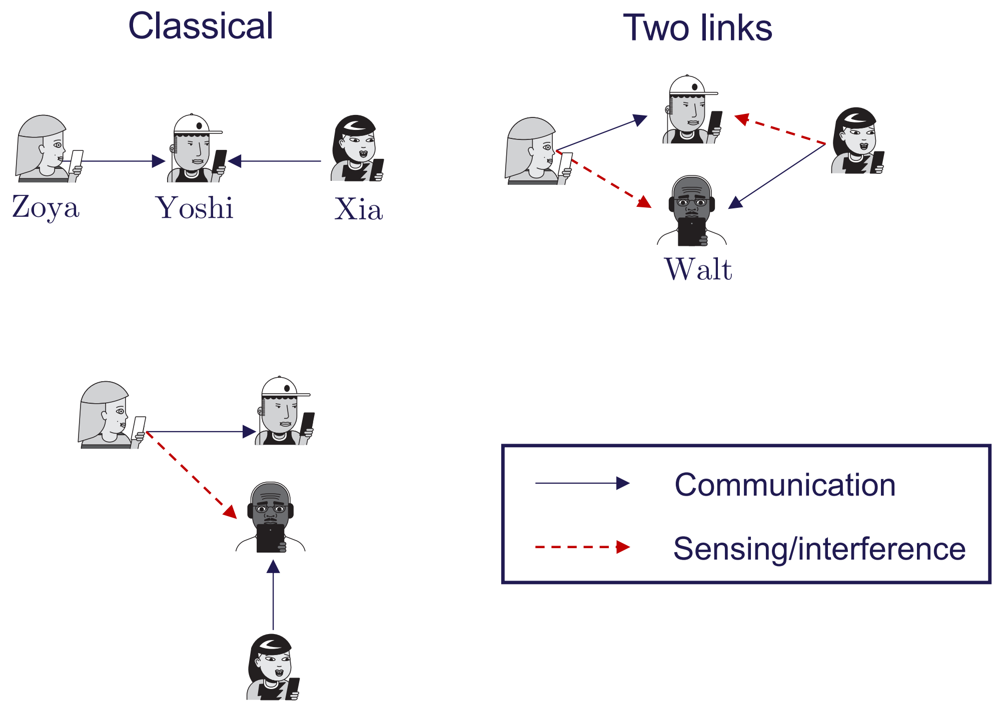
Actual setup is rarely single-hop

Hidden terminal problem:

The carrier seems to be idle when it is actually being used

✓ Could be tackled by an increased sensing range

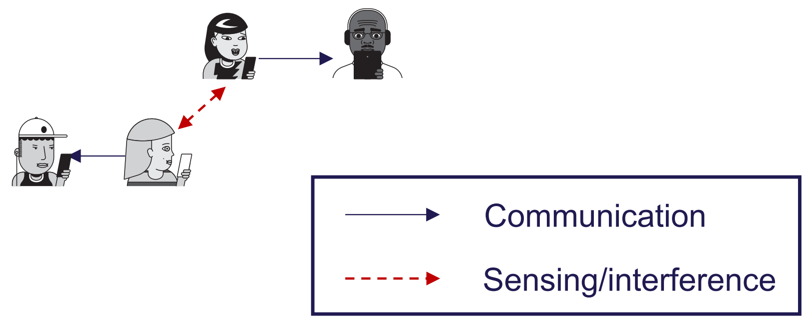
Hidden terminal



Two links, but one receiver is a victim

Carrier sensing and multiple hops

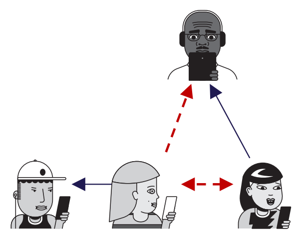
Exposed terminal



Exposed terminal problem:

The carrier seems busy when it is not and a transmission can be carried out

Sensing works



There are multi-hop setups in which sensing still works well

Carrier sensing and multiple hops

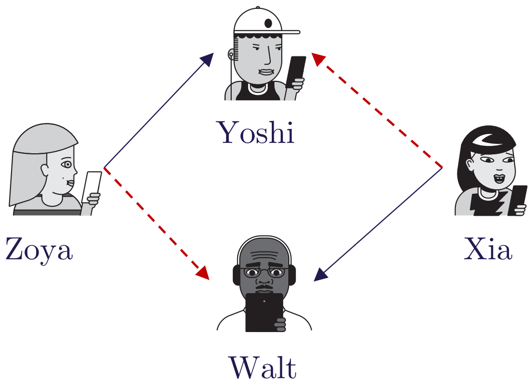
Short reservation packets can make collisions **cheaper**

First, Zoya transmits a *Request-to-send (RTS)* to Yoshi

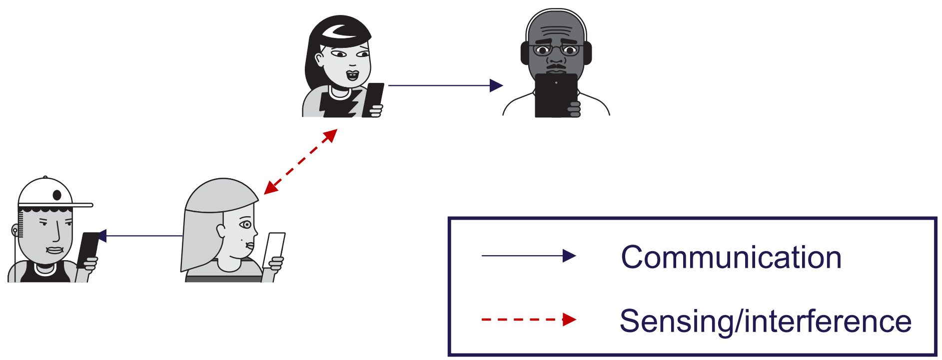
Then, Yoshi responds with a *Clear-to-send (CTS)* to Zoya.

CTS signals potential interferers to refrain from transmitting because the medium will soon be busy

Hidden terminal: Xia receives CTS



Exposed terminal: Xia only receives RTS



Outlook and takeaways

Random access protocols

ALOHA: memoryless randomization, useful for sporadically active devices

Probing: collision resolution with memory based on tree splitting
Related to Group Testing (COVID-19!)

Carrier sensing makes the idle slots cheap

Multi-hop scenarios bring the issues of hidden/exposed terminals