Wireless Connectivity:
An Intuitive and Fundamental Guide

Chapter 4: The Networking Cake: Layering and Slicing

Petar Popovski

Connectivity Section

Department of Electronic Systems

petarp@es.aau.dk

Contributions to the slides:

Israel Leyva-Mayorga

Radoslaw Kotaba

Abolfazl Amiri

Alexandru-Sabin Bana

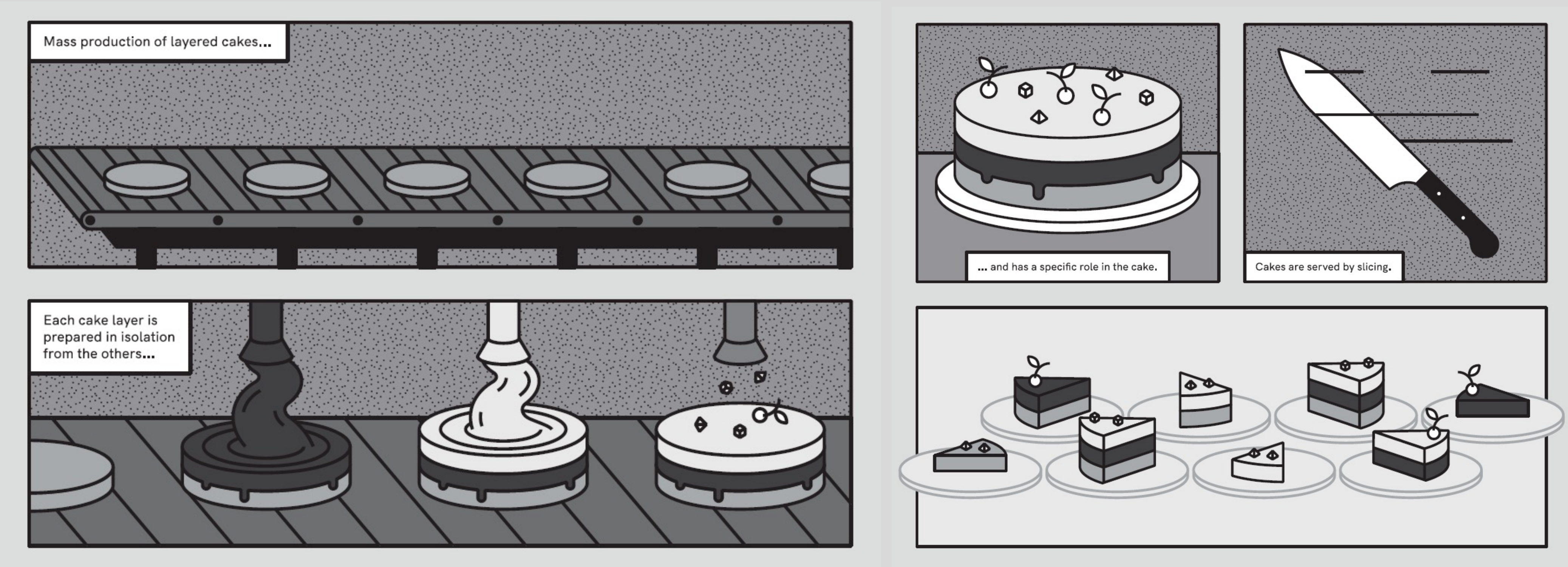
Robin J. WIlliams

AALBORG UNIVERSITY

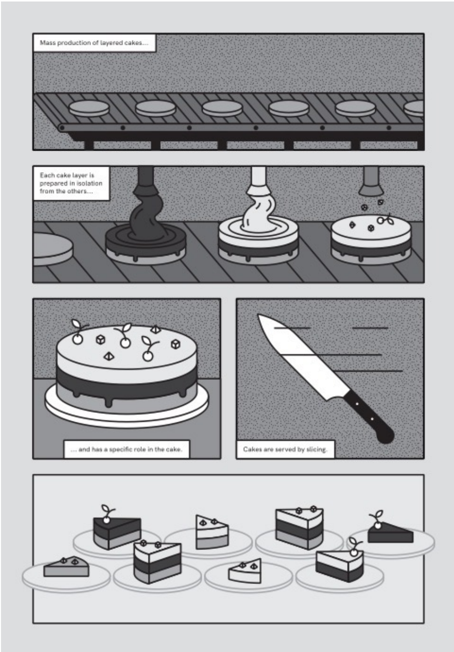
DENMARK

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


Mass production of layered cakes...
Each cake layer is prepared in isolation from the others...
... and has a specific role in the cake.
Cakes are served by slicing.

How to make protocols for a scalable communication architecture



- Mass production of communication protocols and their modules
- Universal support over a large number of services
- Possibility to customize the protocol and support the actual requirements of a service

What will be learned in this chapter

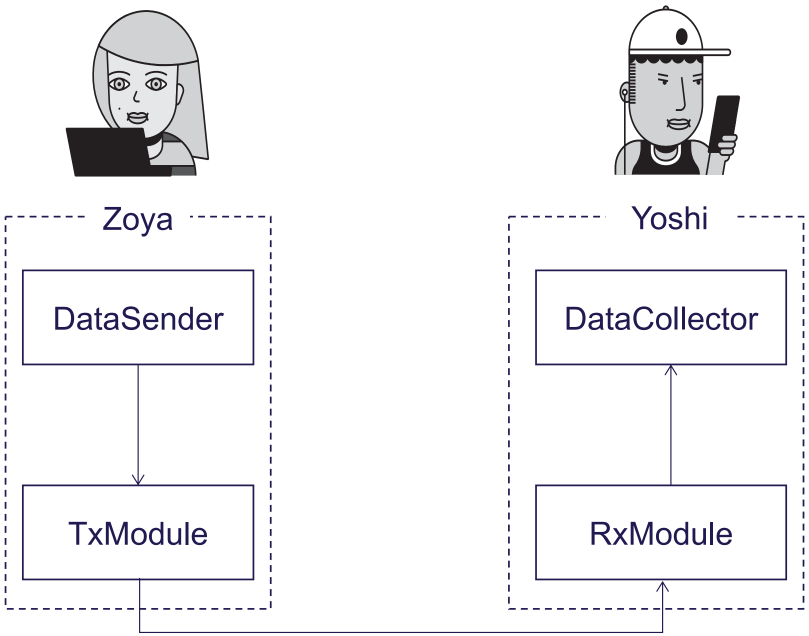
- How to implement the algorithms/protocols discussed in the previous chapters
- The fundamental ideas behind layering: modules as black boxes that can be reused by various services
- From simple to standard layering models
- The concept of cross-layer optimization
- Slicing and sharing of communication resources by heterogeneous services

Components of a wireless node

Which components are needed
to run a certain protocol?

A simple architecture leading
to a **good** layered system design:

Each component is a black box
that fulfills a **specific** task



Components of a wireless node

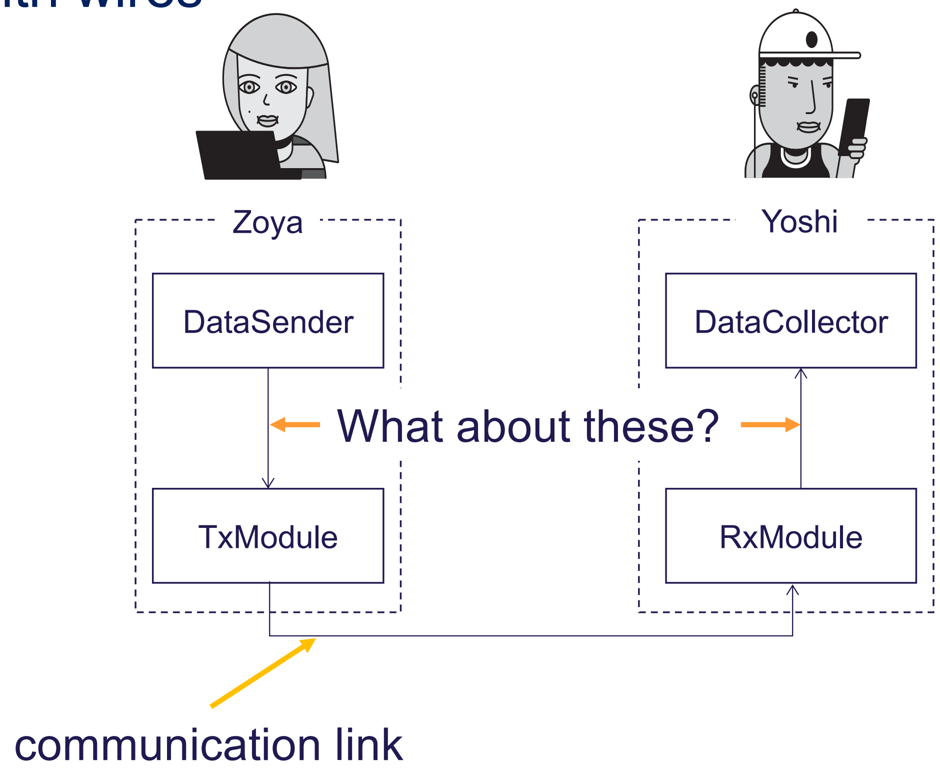
Assume modules are interconnected with wires

Known source and destination

- No address requirement

No protocol requirements

Perfectly reliable



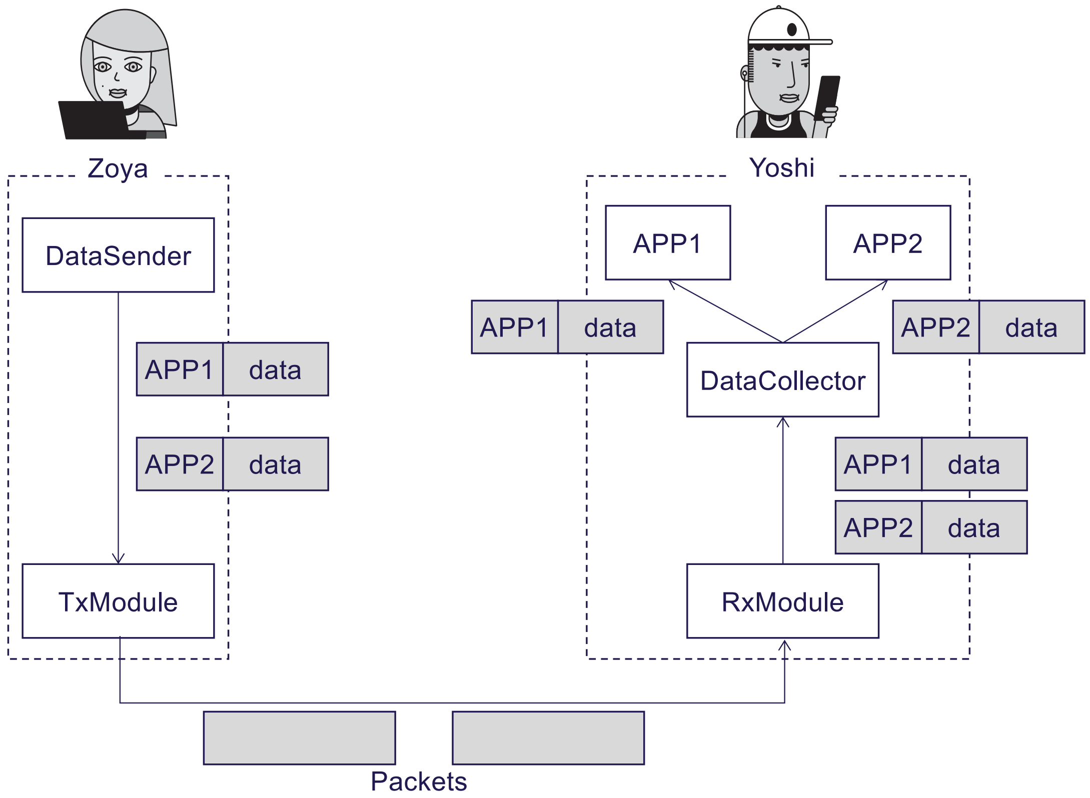
More than one application

Apps include metadata

Sender packs metadata + data

Transfer between TX-Rx modules

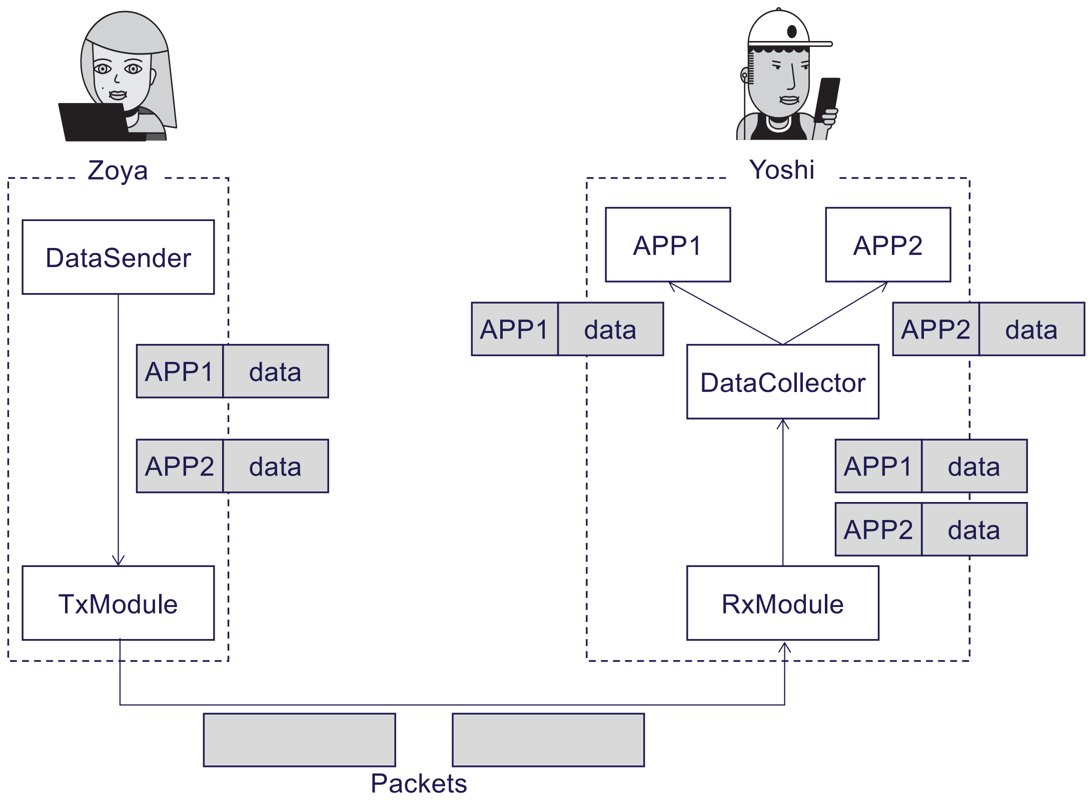
Data collector differentiates APP1 and APP2 data



Three important concepts in layering

1. **Module reuse**
   by different services
2. **Information hiding**
   remove unnecessary complexity
3. **Service through a black box**
   implementation arbitrary
   as long as it follows interfaces

Example of a two-layer system
through a telegraph service.



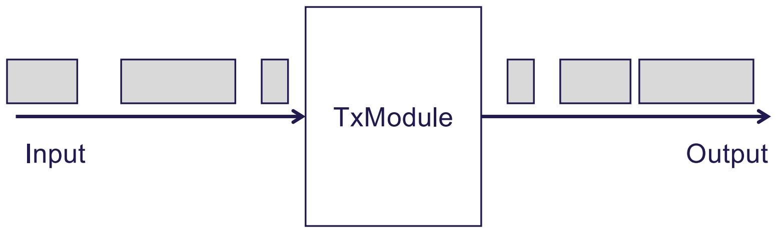
Layers and cross-layer

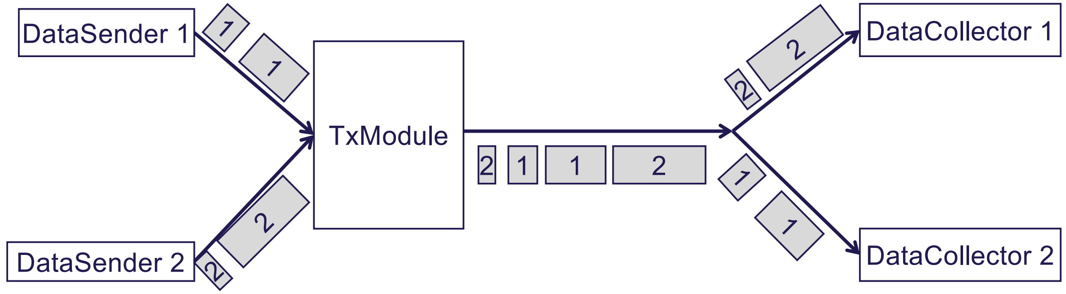
Layers may **surprise:** ordering, buffering…

Solution: add sequential numbering and an expense of **extra overhead**

OR… IF DataSender knows internal scheduling policy of TxModule

- Supply L packets to meet the internal scheduling:
  this is an instance of **cross-layer optimization**
- Introducing the need for two-way communication





Two-way communication

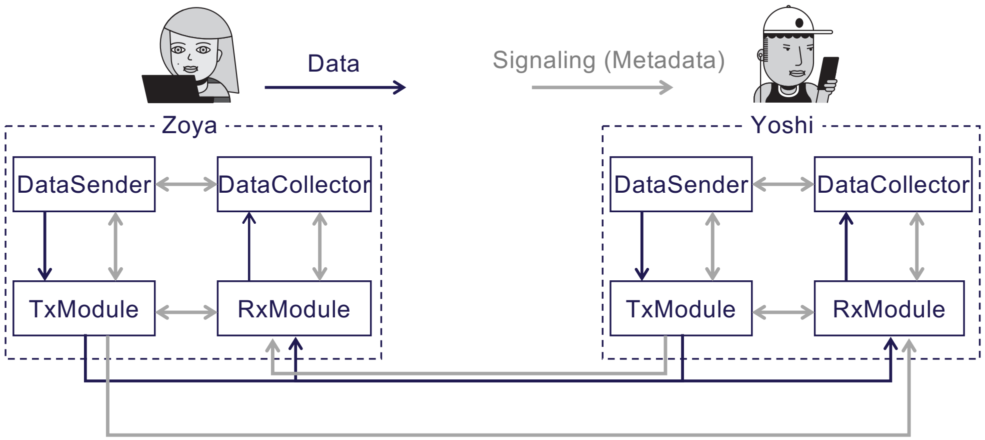
When DataSender needs to know that DataCollector has received the data

→ **signaling**

There is **intra**-device signaling over wired connections as well as **inter**-device wireless signaling over the same medium as the data *(recall the dark room from Chapter 2)*

The errors as most likely to occur over the wireless link

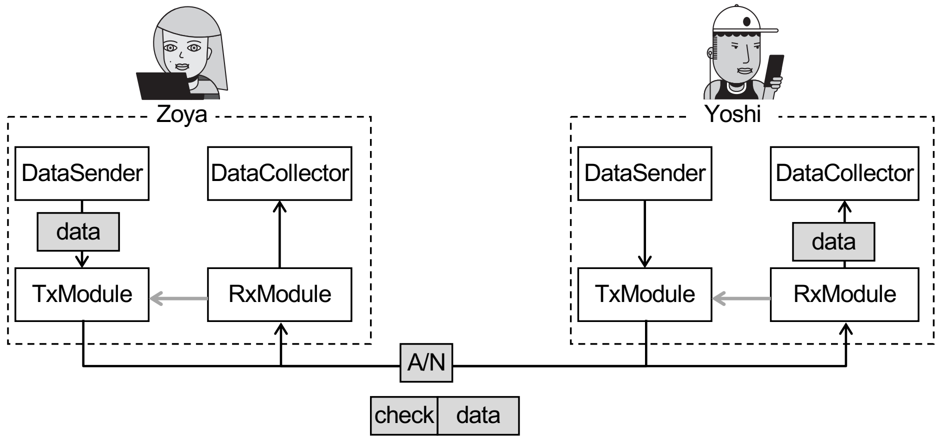
- How to design a robust system?



Reliable service from a layer

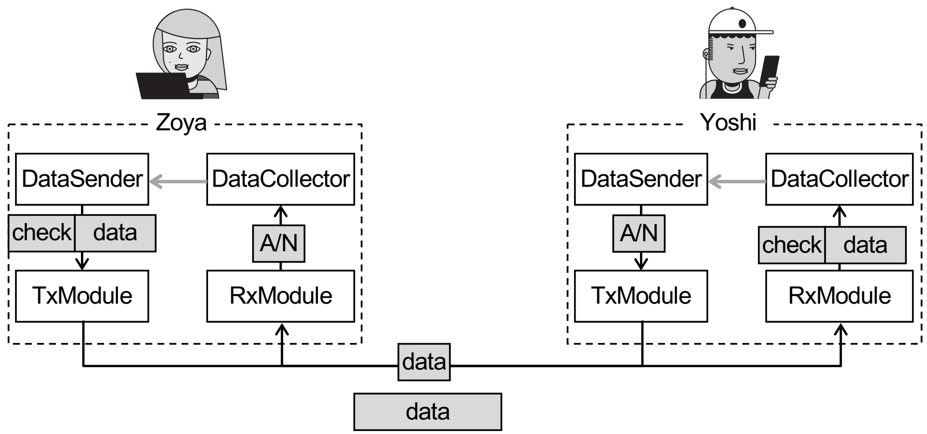
Reliable black box

- One that **informs the higher layer** upon the delivery or failure of a packet
- Can be done by using ARQ with 1-bit ACK or NACK



Unreliable black box

- Transmits packet once
- Higher layer ensures reliability
- Lower layer unaware
- **End-to-end principle**



Layers in communication protocols

PHY: physical layer

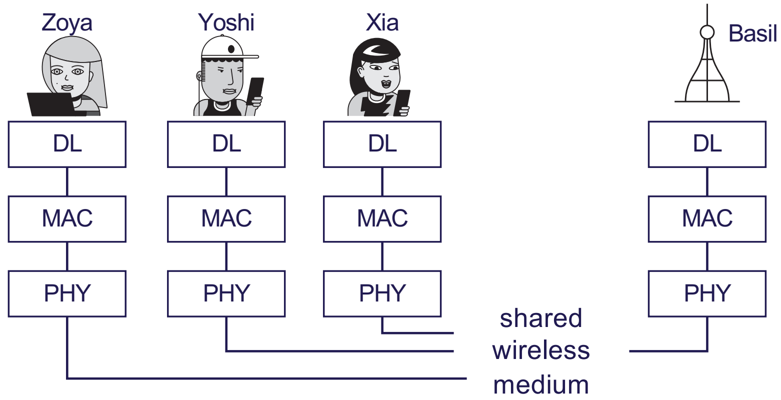
- Idle, Collision, Single Tx

MAC: medium access control layer

- Perform desired random access
- Store S-slots, and pass higher

DL: data link layer

- Integrity check
- Individual ACK



Strictly following the layered structure may not be optimal:

an example is not being able to decide if the source of error is noise or collision

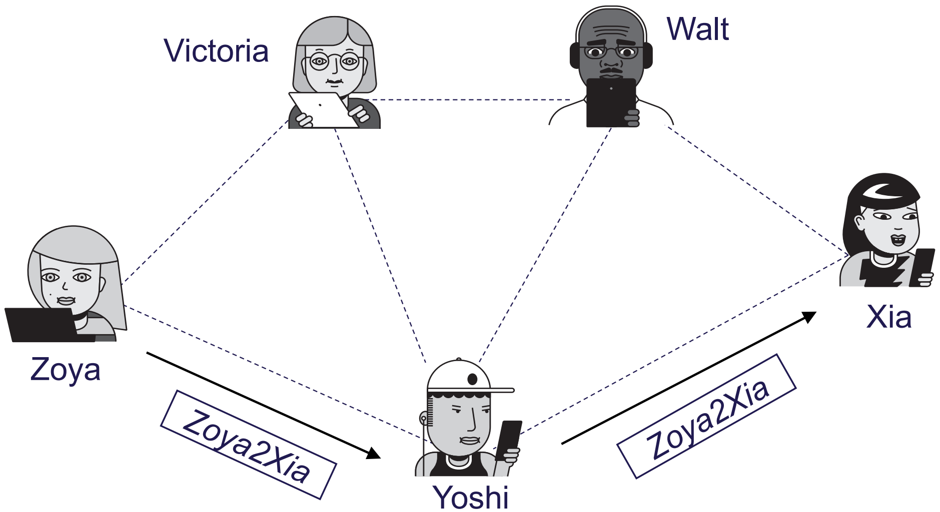
Cross-layer design: merging MAC and DL

- Highly dependent on PHY being able to tell between S and C

Layering models for multi-hop connections

Introducing the **network layer**

- Passes the packet **Zoya2Xia** to the ZoyaDL, instructing it to send to Yoshi
- YoshiDL unaware of contents, but **YoshiNetwork** is
- **YoshiNetwork** supplies **Zoya2Xia** to YoshiDL instructing it to send to Xia



OSI model	TCP/IP model
7-Application layer	Application
6-Presentation layer	
5-Session layer	
4-Transport layer	Transport
3-Network layer	Internet (IP)
2-Data link (DL) layer	Network interface
1-Physical layer (PHY)	

a protocol stack

Connection and connectionless protocols

Connection-oriented

✗ **Initial handshake** to establish

✓ **Low** metadata afterwards

✓ Suitable for longer, frequent exchanges

Connectionless

✓ **No prior setup**

✗ **No readiness** to receive, e.g., random access

✓ Suitable for multicast

The standard layering models

Network layer (IP)
for path discovery

PHY (works with bits)
+
DL (works with packets)

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network interface

MAC – intersection of PHY and DL

OSI model	TCP/IP model
7-Application layer	Application
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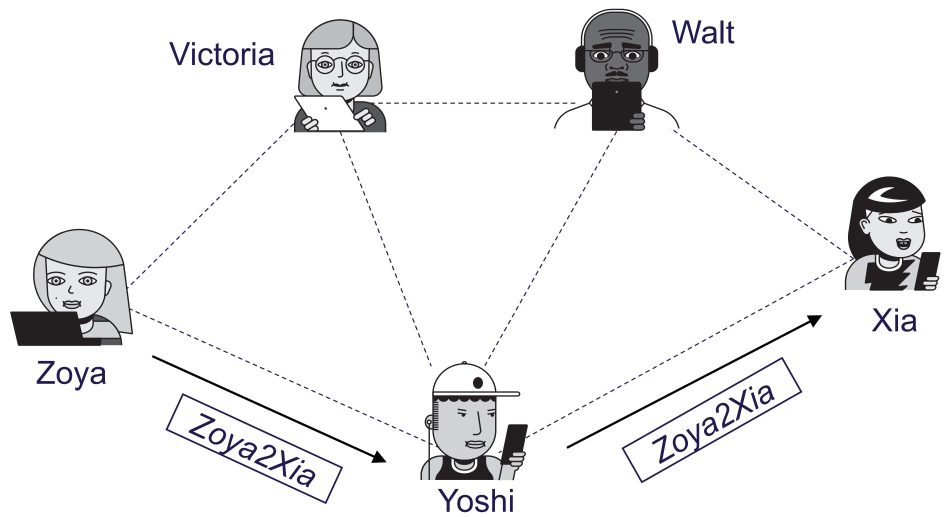
The network layer



Path preference from Zoya to Xia

- Knowledge on path properties

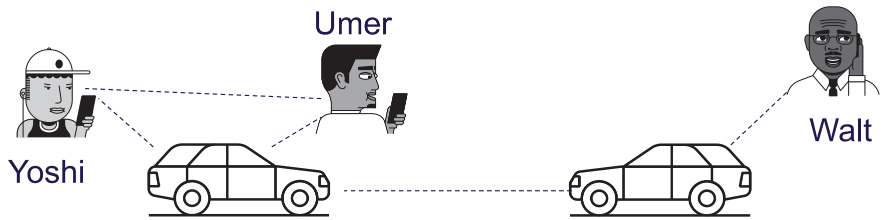
Route discovery and **overhead**

Multi-path **diversity**

- **Encoding and sending** information through **two or more** communication **resources**
- Ideally, these resources should be statistically independent

Route discovery

Incurring **overhead**



Most communication is **dynamic**

- Feasibility of route discovery determined by the rate of change

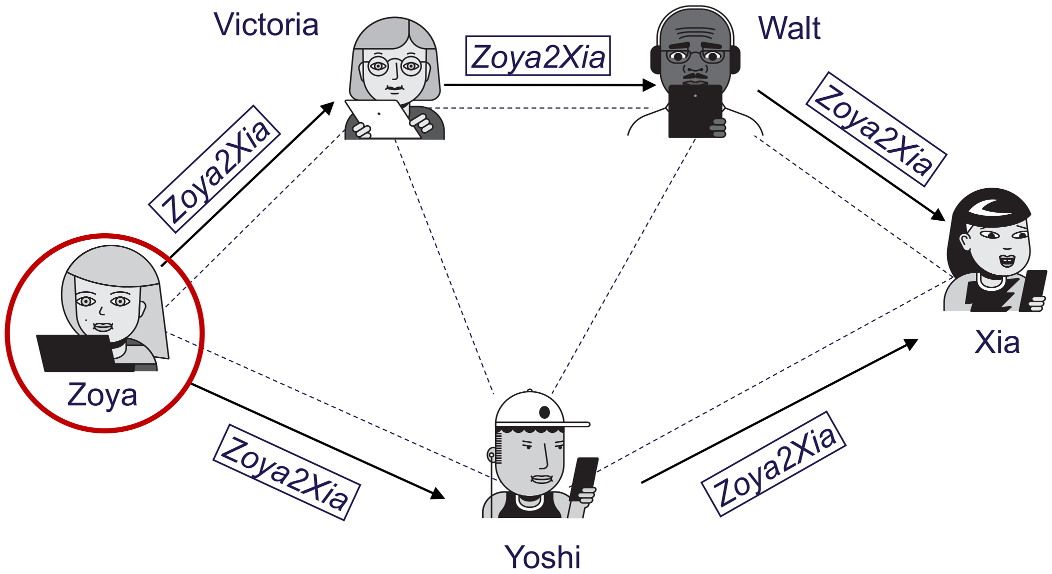
Flooding – each node forwards overheard packets

Hybrid solution: **clustering**

Alternative wireless layering

Protocol stacks oriented towards wired networks

Diversity eases moving the packet **closer** to the destination

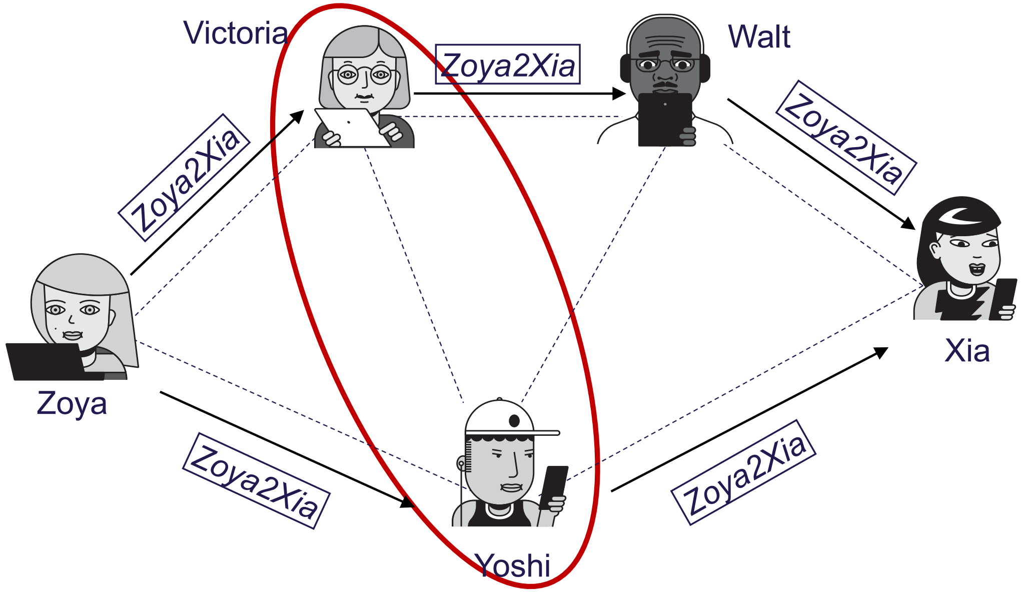


Alternative wireless layering

Protocol stacks oriented towards wired networks

Diversity eases moving the packet **closer** to the destination

Union of devices = super-device



Alternative wireless layering

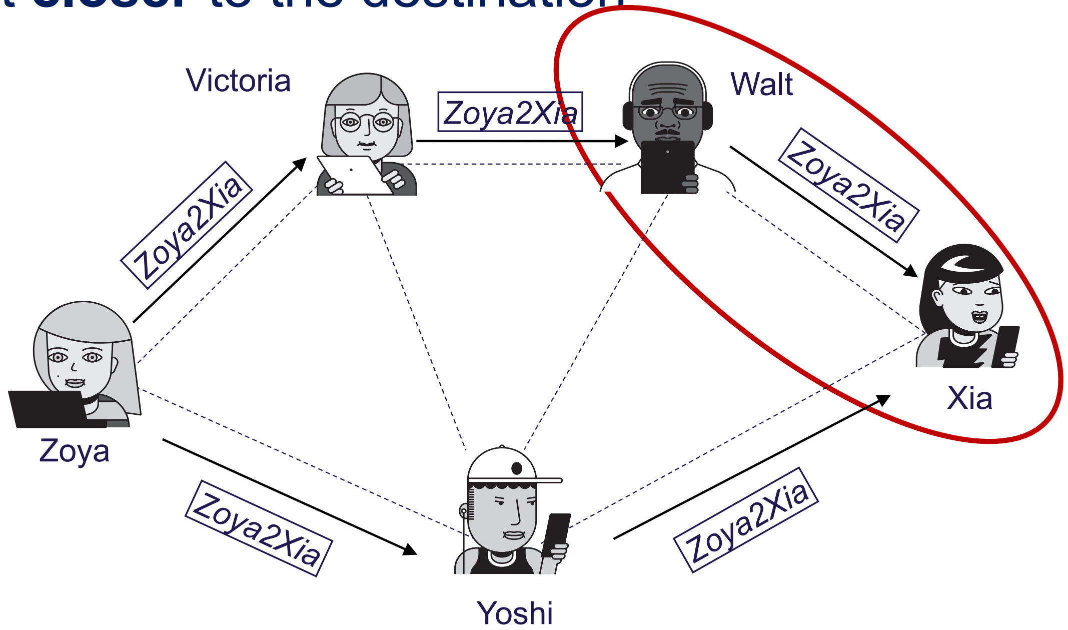
Protocol stacks oriented towards wired networks

Diversity eases moving the packet **closer** to the destination

Union of devices = super-device

Efficiency can be **increased**:
Coordination within a super-device in dedicated resources

- Better integration of data and coordination
- How to make scalable protocols applicable to universal scenarios



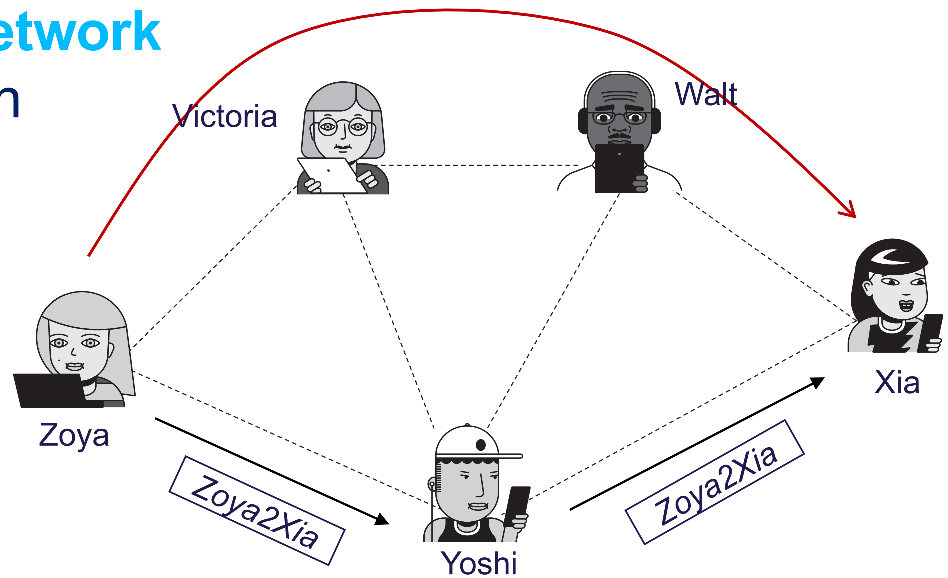
Cross-layer design for multiple hops

Single routing Z-V-W-X

MAC collision at V between Z & W

Network layer is aware of Z-V-W being in range

When both Z AND W want to send, **network** may inform **MAC** to mitigate a collision



Cross-layer design for multiple hops

Single routing Z-V-W-X

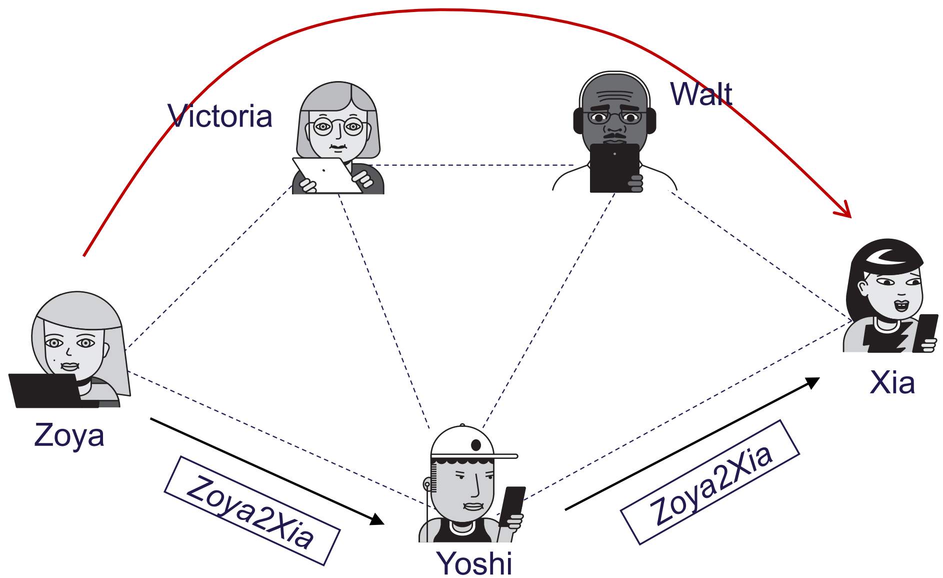
MAC collision at V between Z & W

More efficient x-layer solution:

V knows the packet W will send

If Z AND W collide, V performs **SIC**

- decodes packet from Z
  while W delivers a packet to X
- pipelining the communication

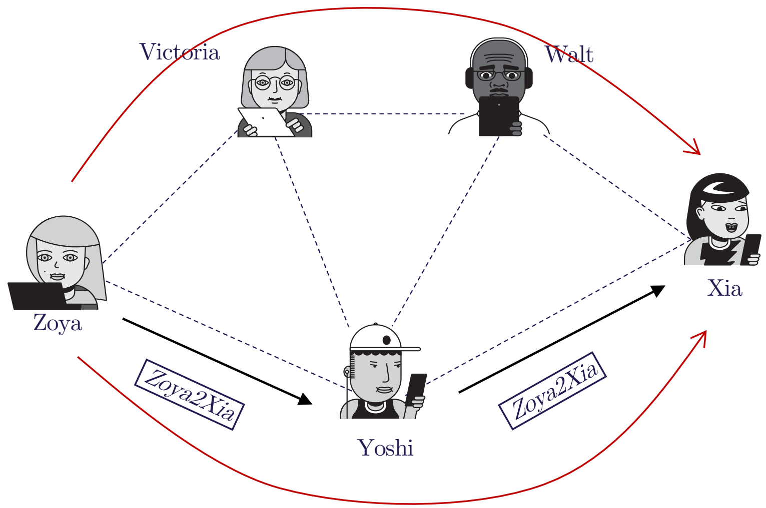


Cross-layer design for multiple hops

Assume multi-path diversity:
Z-Y-X and Z-V-W-X

- Probability *p* that a link is in outage
- Users send ACK, allowing others to overhear and cease transmission of an already known packet
- Y acks V, W hears ack and ceases TX.

However, this loses the advantage of multi-path diversity

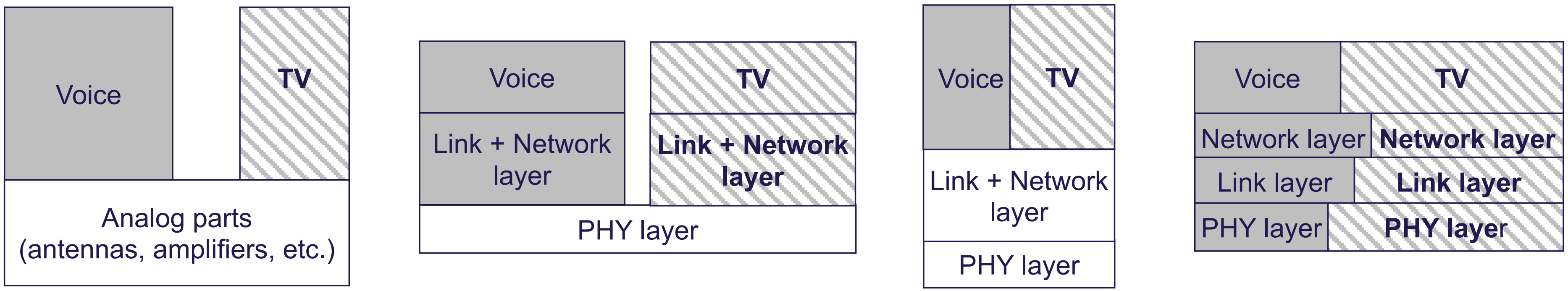


Slicing the wireless resources

Modular layered architecture offers multiple points for services to converge

Various requirements of services

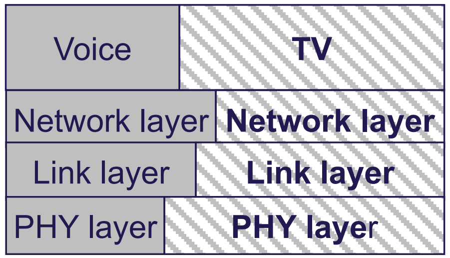
Slicing offers flexible adjustment of the convergence throughout the layers



Slicing the wireless resources

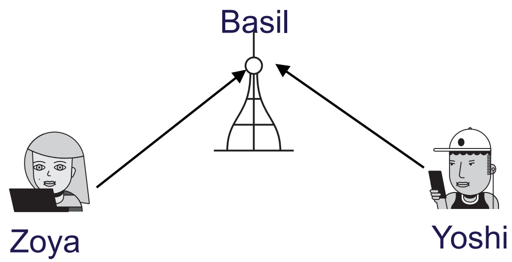
in general, sharing of

- computation
- data storage
- connectivity



The networking cake in action

A primer on wireless slicing



Broadband: Zoya

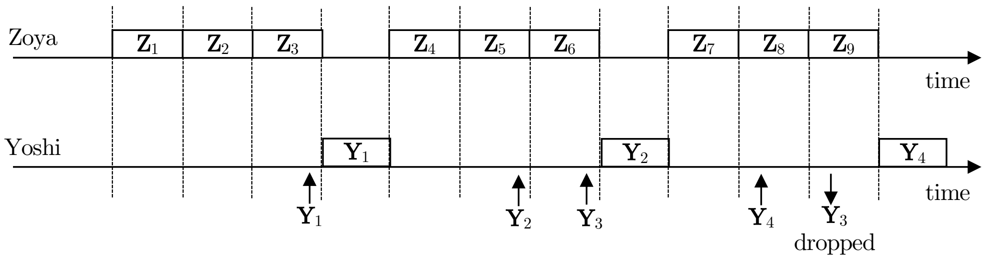
Low-latency reliable control: Yoshi

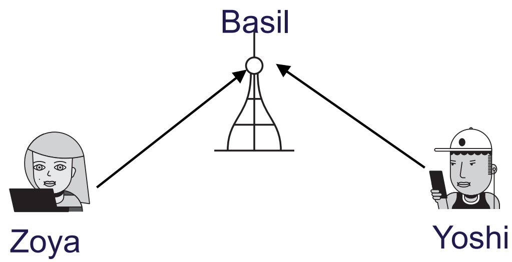
Uplink more interesting than downlink

- Users are competing for resources without coordinating with each other
- Full coordination in the downlink

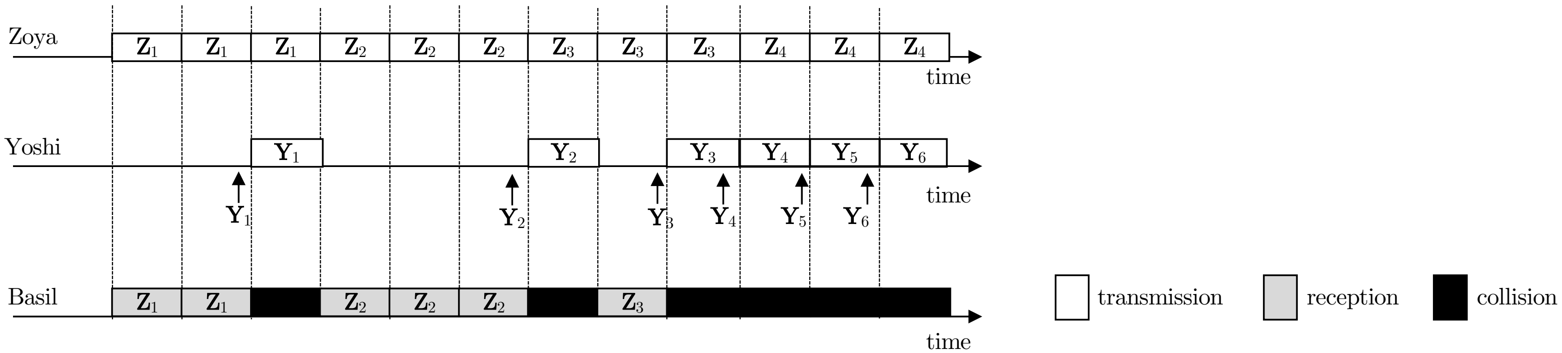
A primer on wireless slicing

Orthogonal slicing

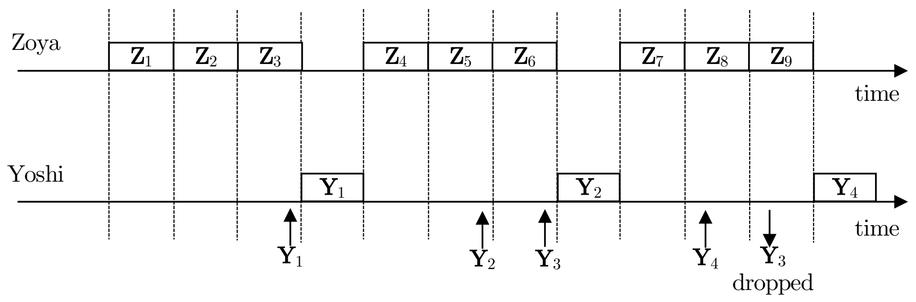




Non-orthogonal slicing



Orthogonal wireless slicing



$$G = \frac{L-1}{L} R \text{ [bps]}$$

Yoshi has arrival probability a

- If $a < \frac{1}{L}$, Yoshi succeeds

- If $a \geq \frac{1}{L}$, queueing delay tends to infinity

What if Yoshi's packets should have **zero latency**? $L = 1$, and then $G = 0$

We have reached the **limit of orthogonal slicing**

Non-orthogonal wireless slicing

Using extra-collision **SIC**

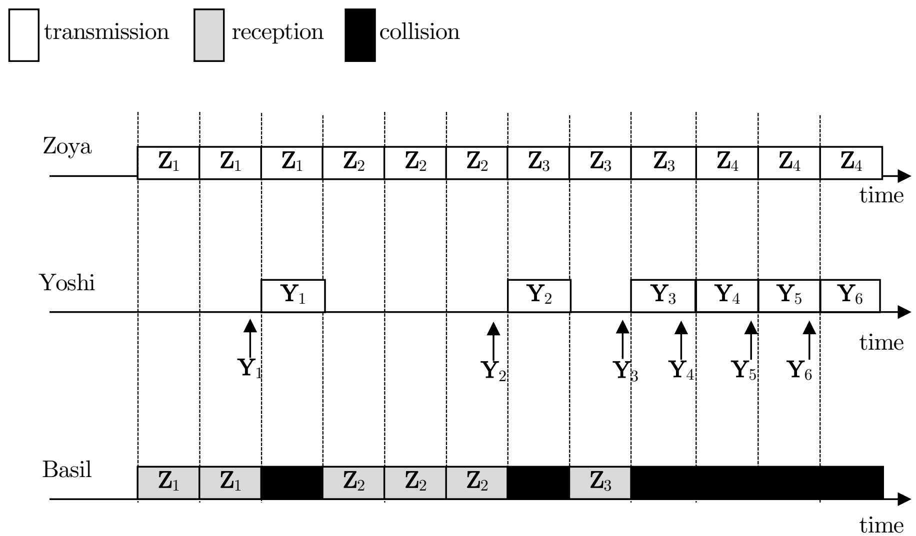
Zoya uses relaxed requirements, allowing ϵ_Z error probability

Yoshi also allows ϵ_Y error probability

Zoya repeats her packets $L = 3$ times

$a^L \leq \epsilon_Z$, then $G = \frac{R}{L}(1 - a^L)$ [bps]

and $a^{L-1} \leq \epsilon_Y$



(c)

Outlook and takeaways

- Modularization of the design and implementation of a communication system
- Three key concepts in layering
- Multi-hop, route discovery, alternative layering
- Cross-layer design of protocols
- Orthogonal and non-orthogonal wireless resource slicing