EE 5410 High Speed and Embedded Computer Networking

Syllabus (Tentative)

- Introduction
- High-speed networking in the network backbone
  - Basic switch/router architectures
  - QoS Support
  - Interconnection architectures
- On-chip switches and networking
- Packet processing and table look-up
- Networks for embedded systems
  - Basics of real-time networks
  - In-vehicle networking
  - CAN bus
  - FlexRay
- Real-time Ethernet
  - AFDX
  - TSN
- Other Topics according to available time

Course Philosophy

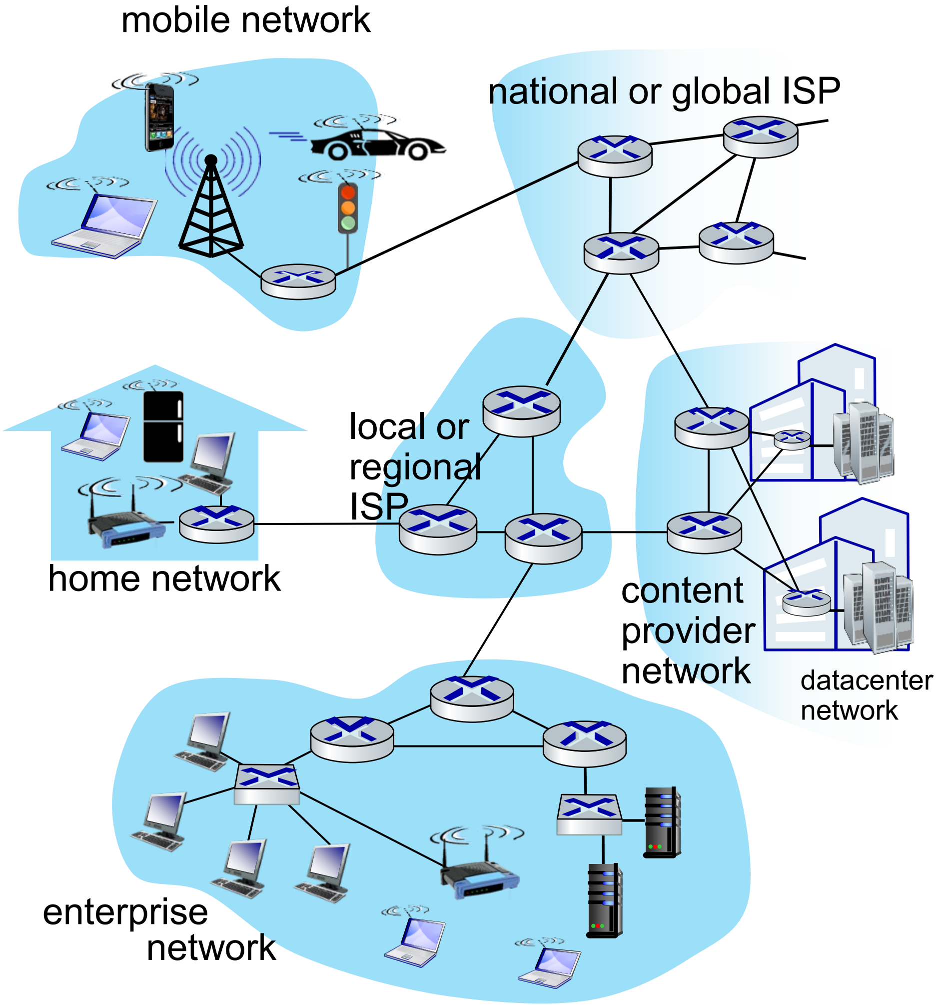
- High Speed Networking:
  - Relaxed constraint: No limit on hardware, use the most expensive highest end devices
  - Tight constraint: 100s of Gbps data rates, nanosec times
- Embedded Networking
  - Relaxed constraint: Lower data rates (10s of Kbps, Mbps)
  - Tight constraint: Life critical, time sensitive applications

EE 5410 High Speed and Embedded Computer Networking

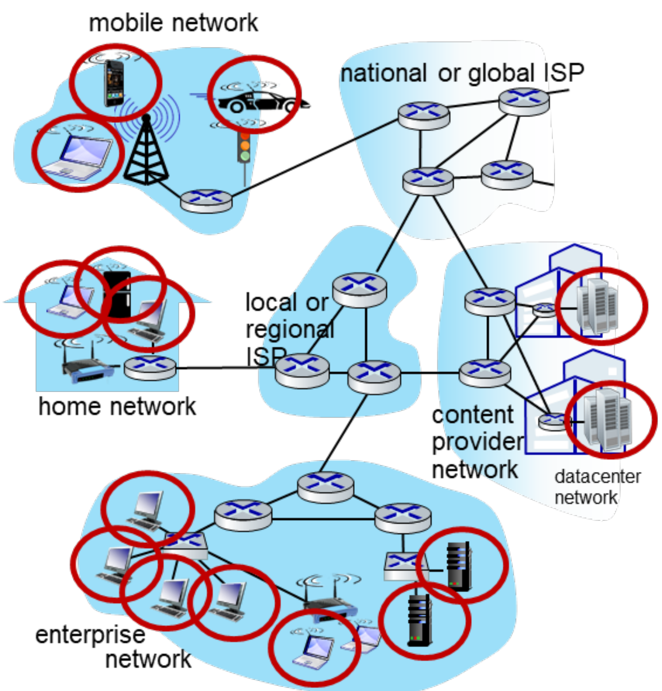
Introduction 1: Basic Networking Concepts for the Wide Area Networking

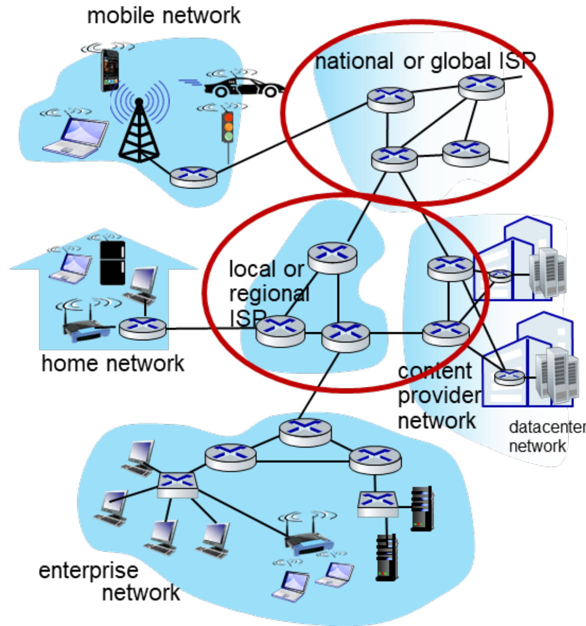
What's the Internet?

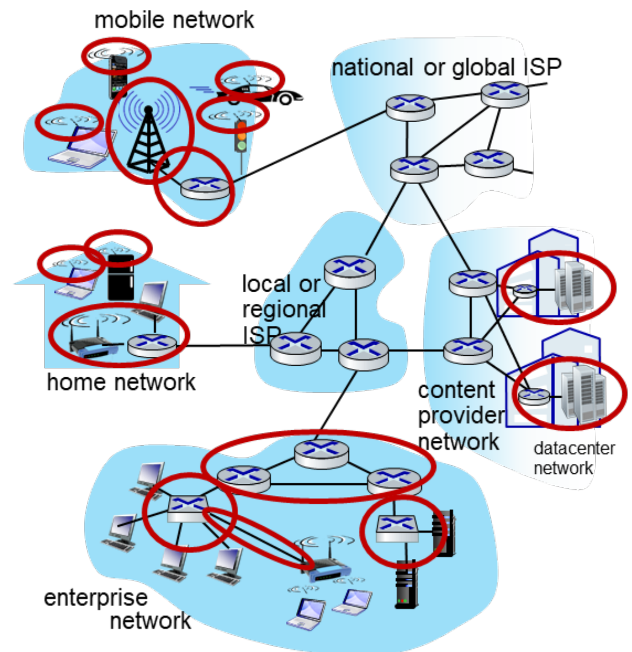
- millions of connected computing devices: *hosts = end systems*
  - running *network apps*
- *protocols:* rules of communication
- *routers:* special network devices
  - On demand connection
- *communication links*
  - fiber, copper, radio, satellite
  - transmission rate = *bandwidth*



A closer look at network structure







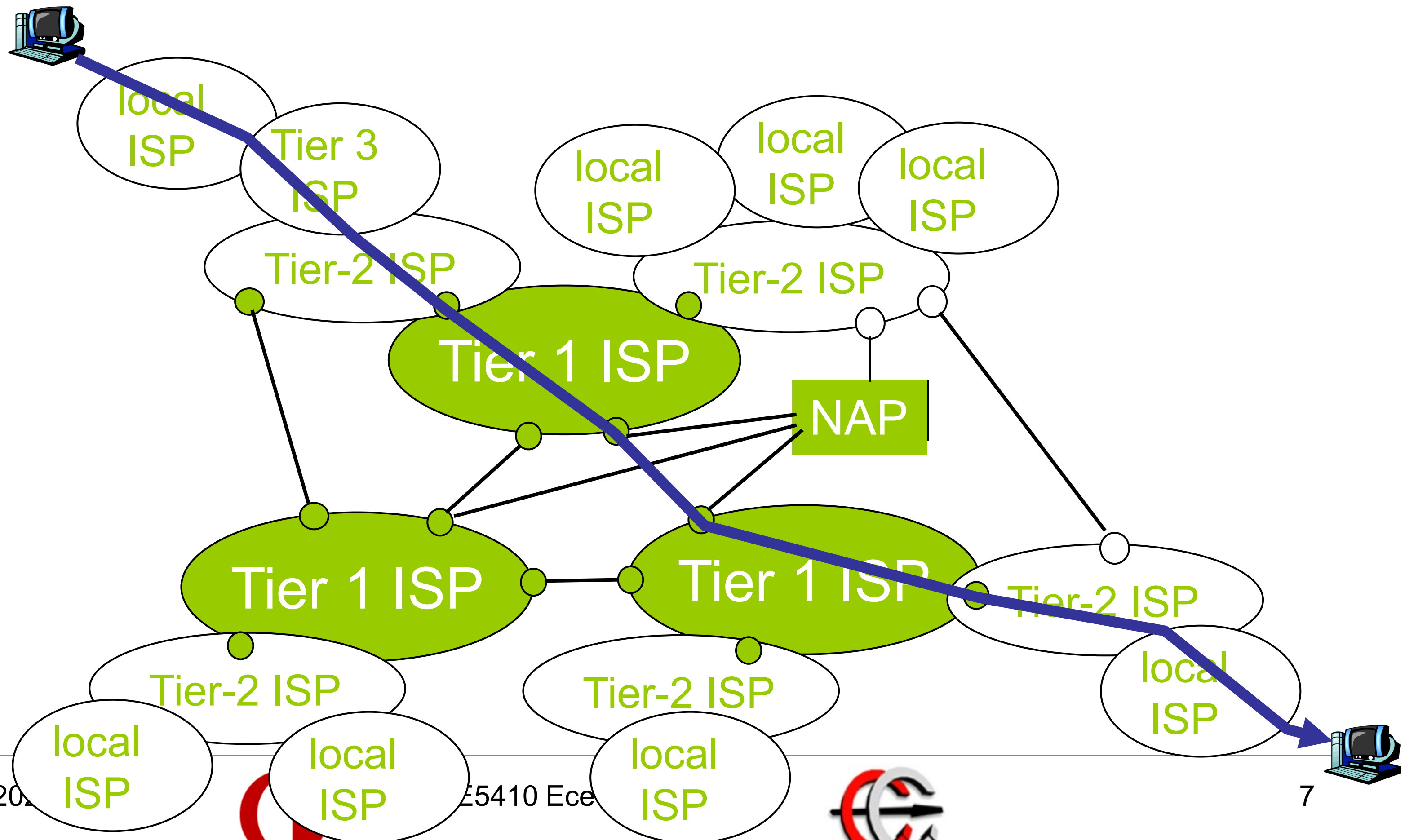
network edge:
- Low-speed
- applications and hosts

network core:
- High-speed
- interconnected routers
- network of networks

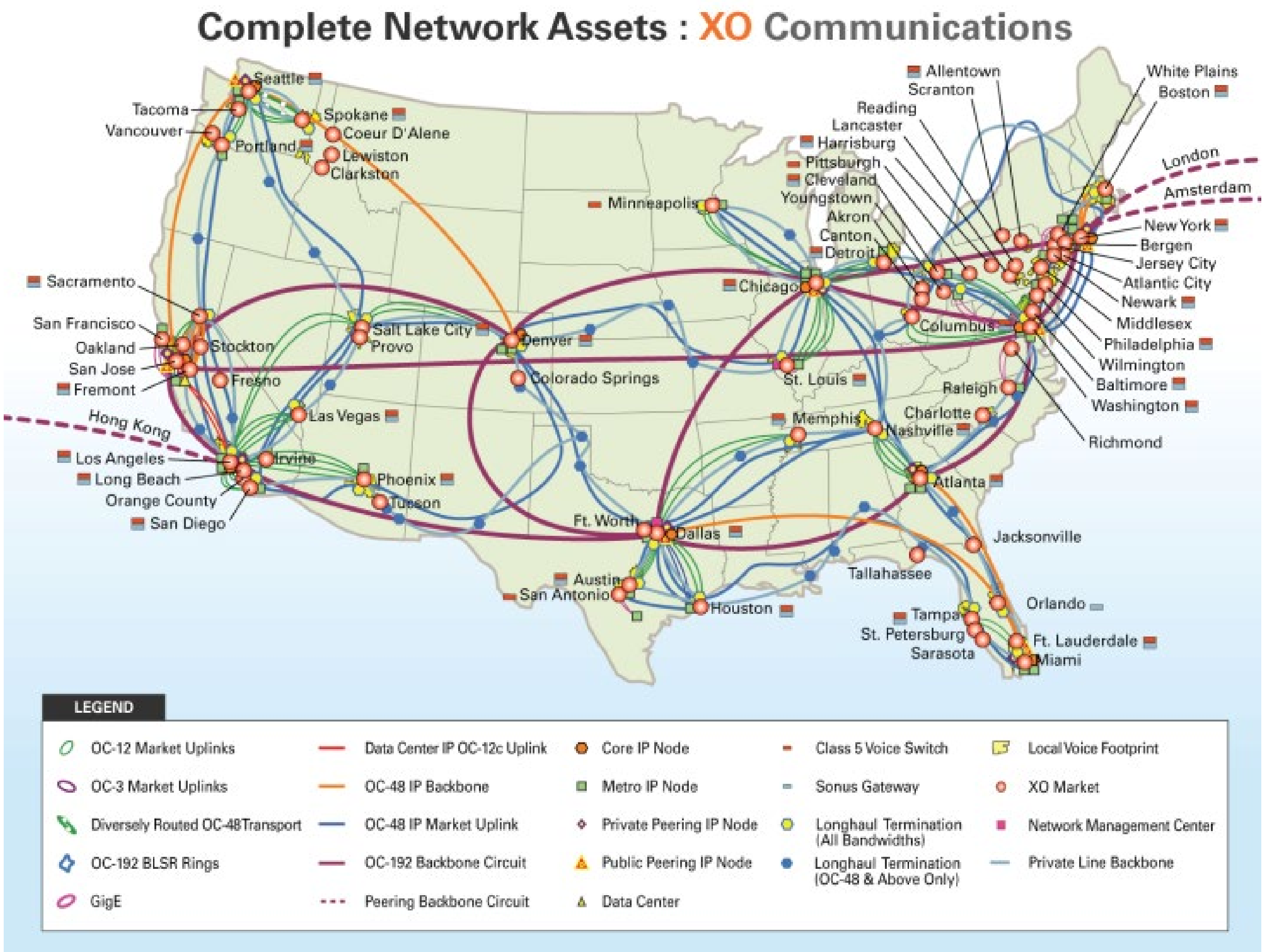
access networks, physical media:
- Connection between edge and core
- Edge routers
- wired, wireless communication links

Internet structure: network of networks

- a packet passes through many networks!

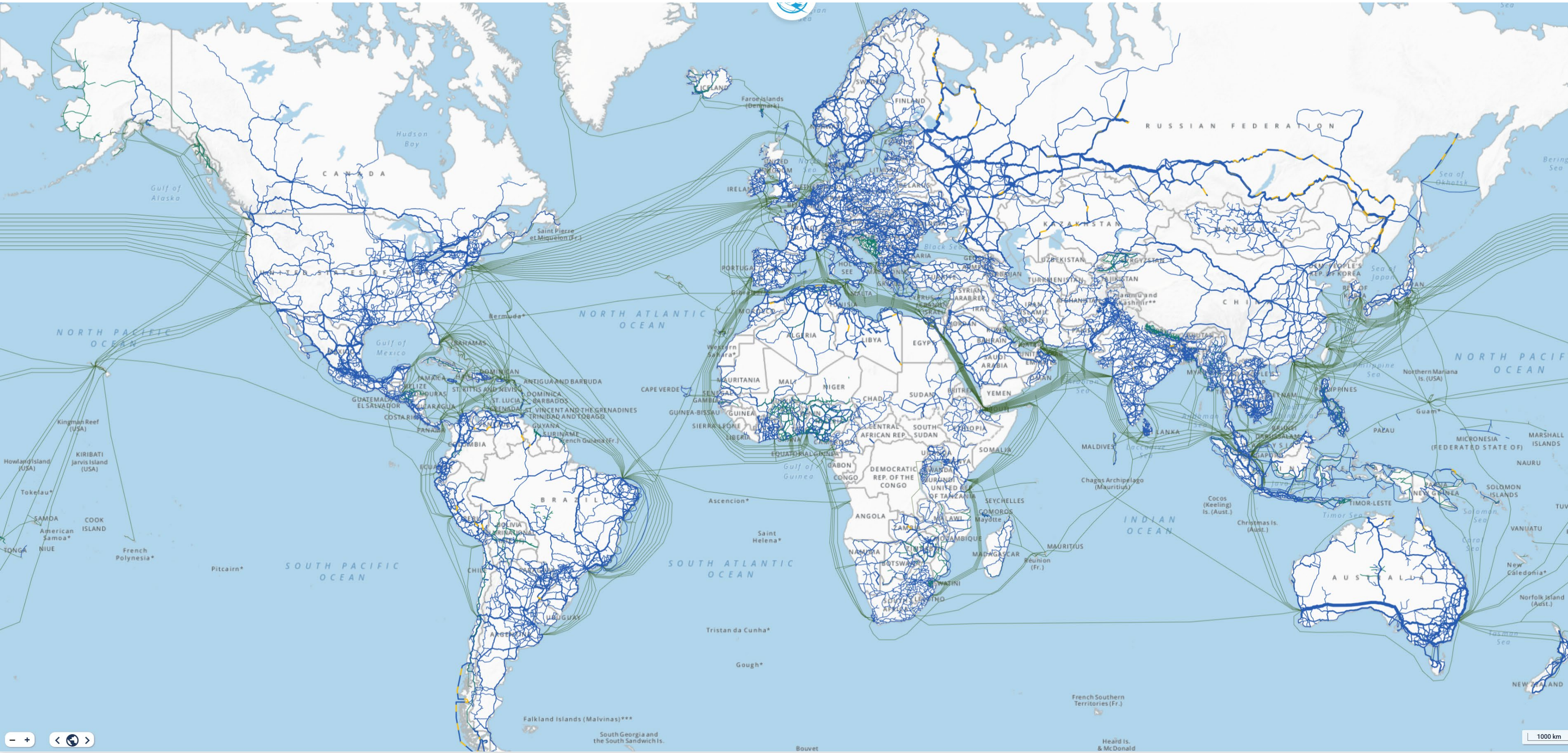


Tier-1 ISP



Complete Network Assets : XO Communications
Seattle
Tacoma
Vancouver
Portland
Spokane
Coeur D'Alene
Lewiston
Clarkston
Minneapolis
Sacramento
San Francisco
Oakland
San Jose
Fremont
Stockton
Fresno
Salt Lake City
Provo
Denver
Colorado Springs
Las Vegas
Hong Kong
Los Angeles
Long Beach
Orange County
San Diego
Irvine
Phoenix
Tucson
Ft. Worth
Dallas
Austin
San Antonio
Houston
Chicago
Detroit
St. Louis
Memphis
Nashville
Atlanta
Columbus
Allentown
Scranton
Reading
Lancaster
Harrisburg
Pittsburgh
Cleveland
Youngstown
Akron
Canton
White Plains
Boston
London
Amsterdam
New York
Bergen
Jersey City
Atlantic City
Newark
Middlesex
Philadelphia
Wilmington
Baltimore
Washington
Richmond
Raleigh
Charlotte
Jacksonville
Tallahassee
Orlando
Tampa
St. Petersburg
Sarasota
Ft. Lauderdale
Miami
LEGEND
OC-12 Market Uplinks
OC-3 Market Uplinks
Diversely Routed OC-48Transport
OC-192 BLSR Rings
GigE
Data Center IP OC-12c Uplink
OC-48 IP Backbone
OC-48 IP Market Uplink
OC-192 Backbone Circuit
Peering Backbone Circuit
Core IP Node
Metro IP Node
Private Peering IP Node
Public Peering IP Node
Data Center
Class 5 Voice Switch
Sonus Gateway
Longhaul Termination (All Bandwidths)
Longhaul Termination (OC-48 & Above Only)
Local Voice Footprint
XO Market
Network Management Center
Private Line Backbone

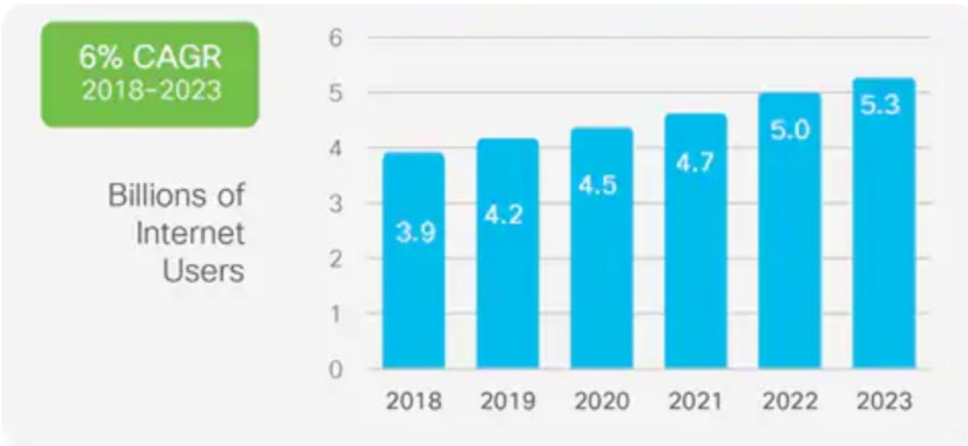
Current Internet



https://bbmaps.itu.int/bbmaps/

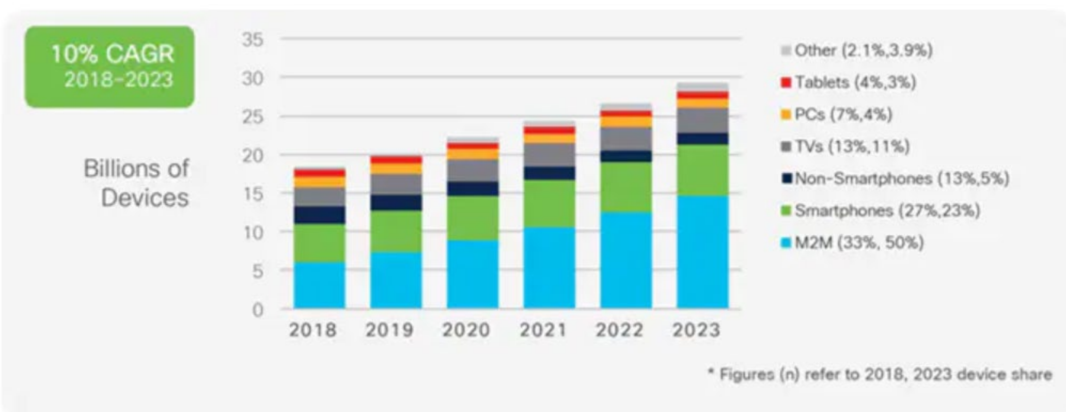
Users and Hosts

Figure 1. Global Internet user growth



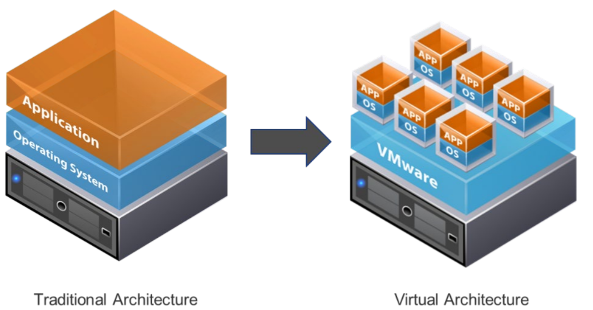
https://www.cisco.com/c/en/us/solutions/collateral/executive-perspectives/annual-internet-report/white-paper-c11-741490.html

Figure 2. Global device and connection growth

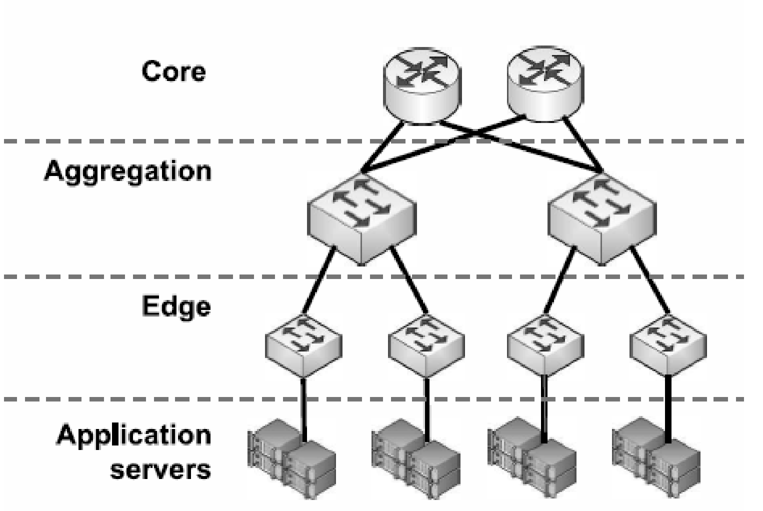


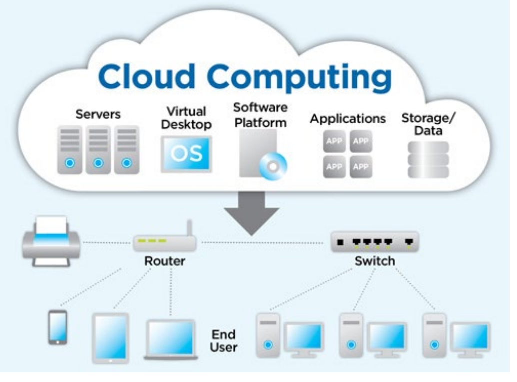
Architecture Trends

Virtualization



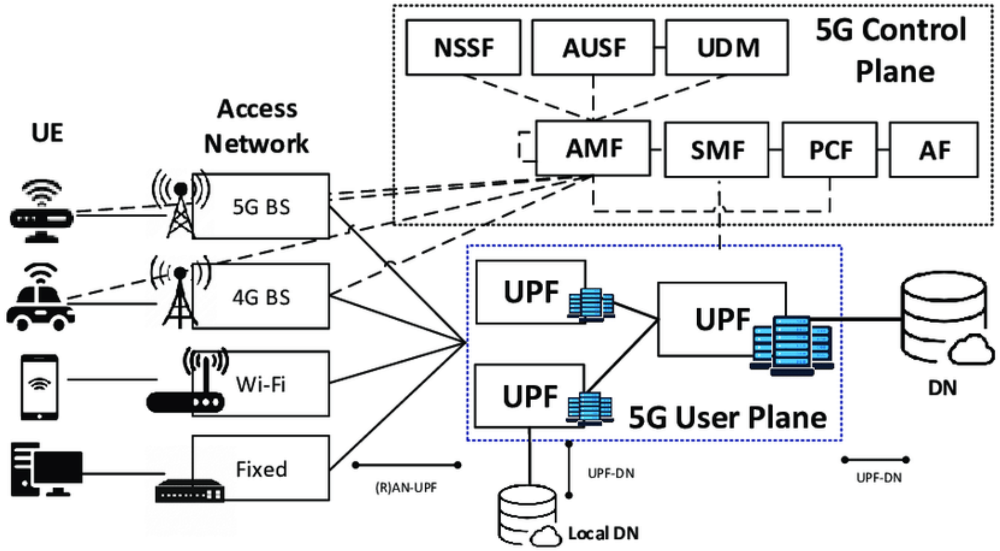
Data Centers



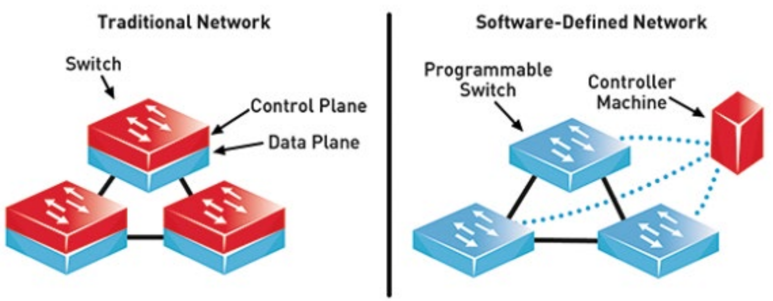


Cloud

Architecture Trends

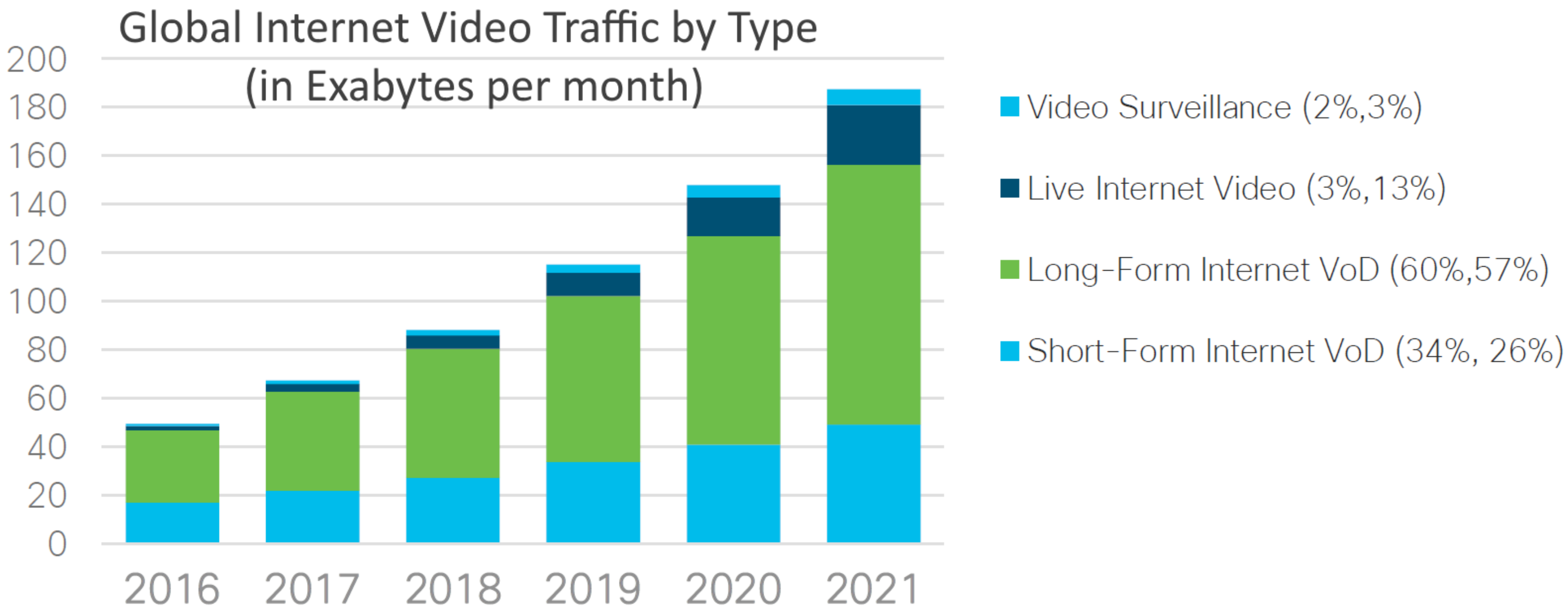


5G



SDN

Application Trends



Source: Cisco VNI Global IP Traffic Forecast, 2016-2021

Requires Quality of Service

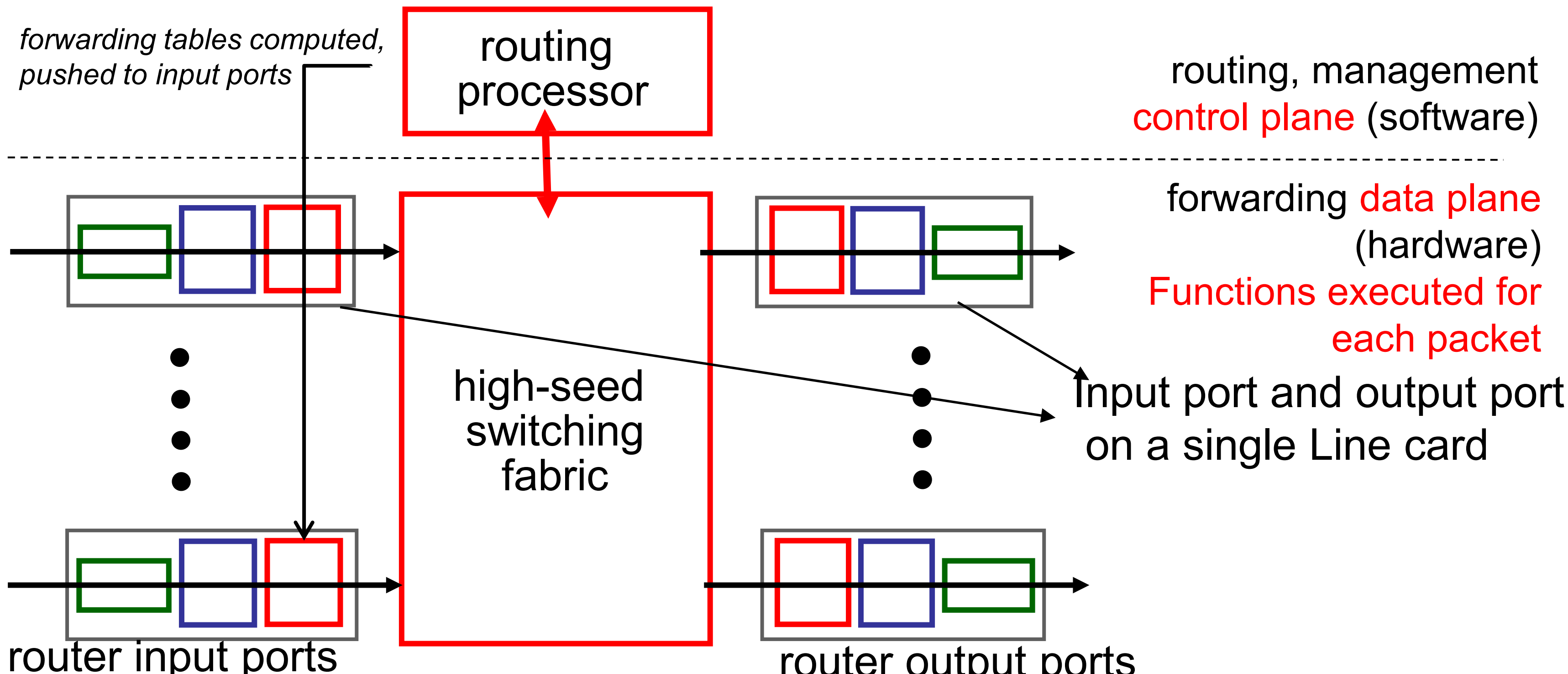
Quality of Service

- Performance metrics:
  - Delay
  - Bandwidth: minimum, average, variance
  - Packet loss
  - End-to-end (source node to destination node)
- QoS: Given the application sends data with certain properties to the network, the network provides certain service guarantees
- Example: End-to-end delay < 50ms if the average input data < 8Mbps

Router architecture overview

two key router functions:

- run routing algorithms/protocol (RIP, OSPF, BGP)
- *forwarding* datagrams from incoming to outgoing link



Data Plane

- Line rate operation
- The packet processing should not slow down the packet
- Example: 64 Byte IP packet@10 Gbps line rate takes 51.2 nsec
- Packet processing should be completed in 51.2 nsec/packet➔19.53 million packets/sec

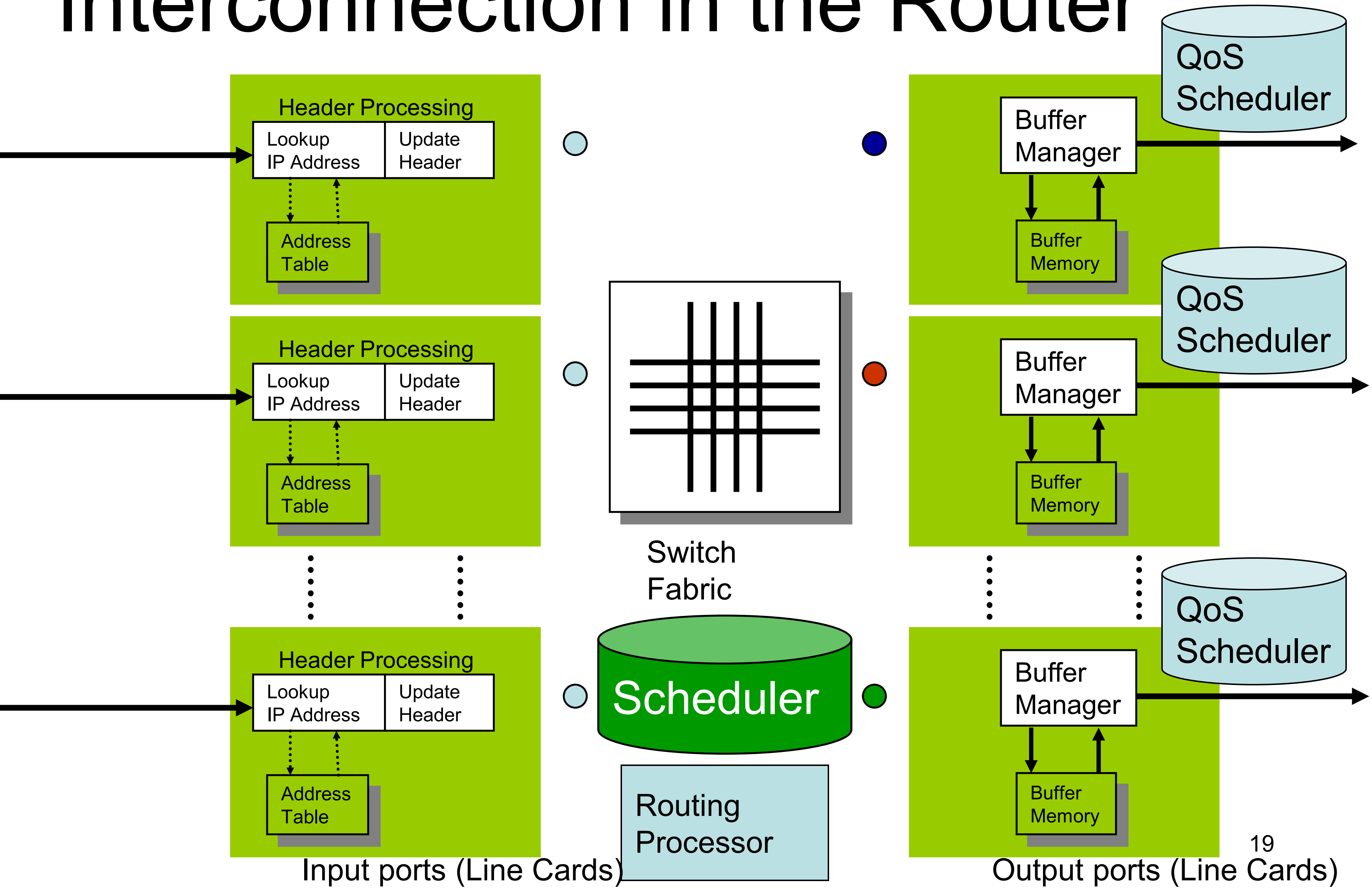
Focus

- How to transfer packets in the network core:
  - IP Router architecture as a node
  - Network Architectures as a whole
  - High-speed data transfer with QoS
  - High-speed table look-ups

Interconnection Networks

- Routers
- Multiprocessor systems
- Network on chip systems

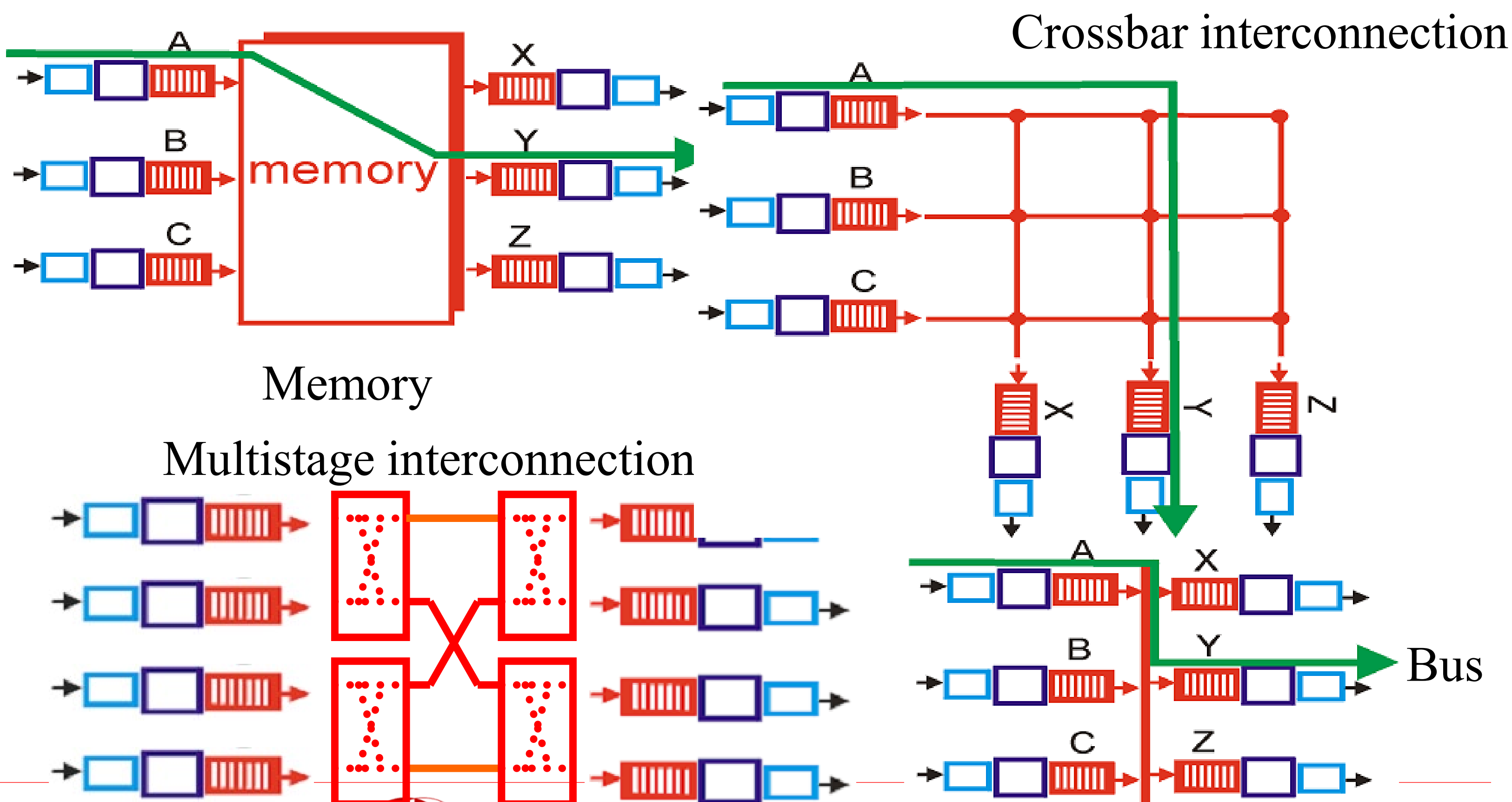
Interconnection in the Router



Switch Fabric

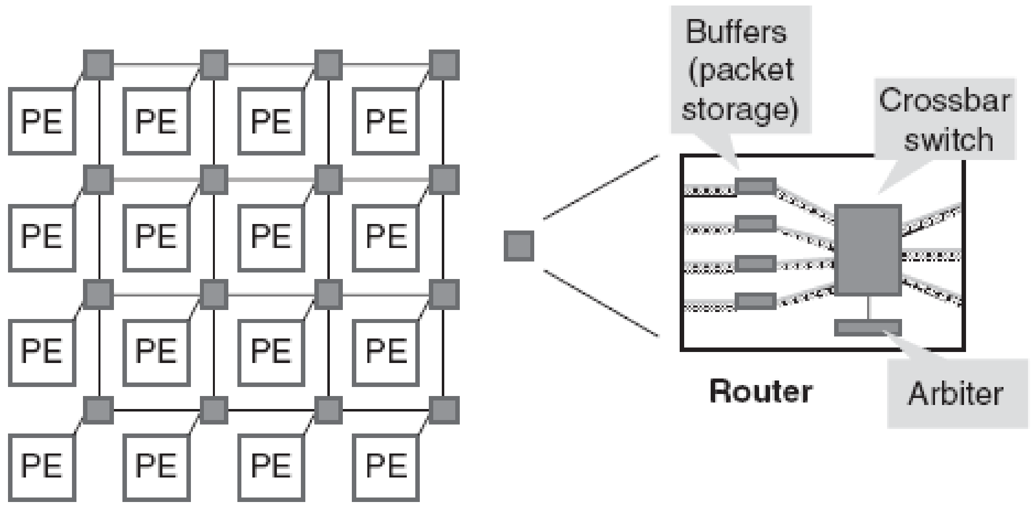
Switch Fabric:

- **Combination of hardware & software that move incoming data to the correct output port**
- **Usually a complex interconnected structure of switching paths and ports-> analogy to woven textile fabric**
- **Examples: memory, bus, interconnection networks**



Network on Chip

- Network-on-chip (NoC) is a packet switched on-chip communication network designed using a layered methodology
- NoCs use packets to route data from the source to the destination PE via a network fabric that consists of
  - switches (routers)
  - interconnection links (wires)



Focus

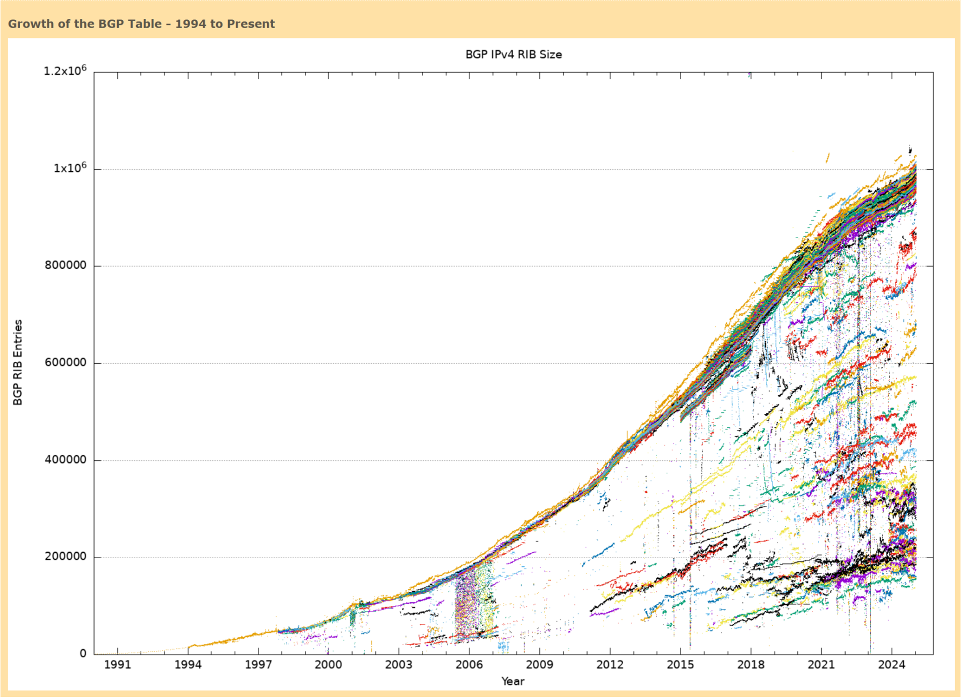
- To link line cards, processors, memory banks, on chip processing elements (PE)
- Objective function and constraints:
  - Maximize bandwidth
  - Minimize latency
  - Minimize power consumption
  - Volume and cost constraints
- Service:
  - Easy to repair
  - Robustness

Packet Processing

- IP look-up
- SDN look-up
- 5G UPF look-up
- Deep Packet Inspection

Focus

- Data plane line rate operation➔Millions of look up per sec
- Large Tables



https://bgp.potaroo.net/

Similar courses

- https://www.csl.cornell.edu/~jiaxinl/ece6960/fa25/
- https://tusharkrishna.ece.gatech.edu/teaching/icn_s22/
- https://web.stanford.edu/class/ee384x/EE384X/Home.html

Reference Material

- Selected Journal Papers
- High Performance Switches and Routers, H. Jonathan Chao, Bin Liu, 2007, John Wiley & Sons, Inc
- Switch/Router Architectures: Shared-Bus and Shared-Memory Based Systems, Dr. James Aweya, 2018 Wiley-IEEE Press
- Aweya, J. (2022). Designing Switch/Routers: Fundamental Concepts and Design Methods (1st ed.). CRC Press.
- On-Chip Networks, Second Edition, Natalie Enright Jerger,Tushar Krishna, and Li-Shiuan Peh, Synthesis Lectures on Computer Architecture, June 2017
- Principles and Practices of Interconnection Networks, William Dally, Brian Towles, Morgan Kaufmann Publishers Inc. ,2003.

EE 5410 High Speed Computer Networking

Introduction 2: Basic Networking Concepts for Real-time Embedded systems, Automobile networking, Industrial Networking

Networking for Real-time Embedded Systems

- Complex functionalities, demanding performance requirements of applications such as DSP, network, and multimedia processors.
- Requirement for real-time operation: Respond within a predefined period, mandated by the dynamics of the process under control

Networking for Real-time Embedded Systems

- Emergence of distributed embedded systems: networked embedded systems
  - a collection of spatially and functionally distributed embedded nodes
  - interconnected by means of wireline and/or wireless communication infrastructure and protocols
  - interacting with the environment (via a sensor/ actuator elements) and each other
  - there can be a master node performing some control and coordination functions, to coordinate computing and communication to achieve certain goal(s)

Networking for Real-time Embedded Systems

- The networked embedded systems appear in a variety of application domains:
  - automotive, train, aircraft
  - office buildings, and industrial areas (factory floor)
  - primarily for monitoring and control

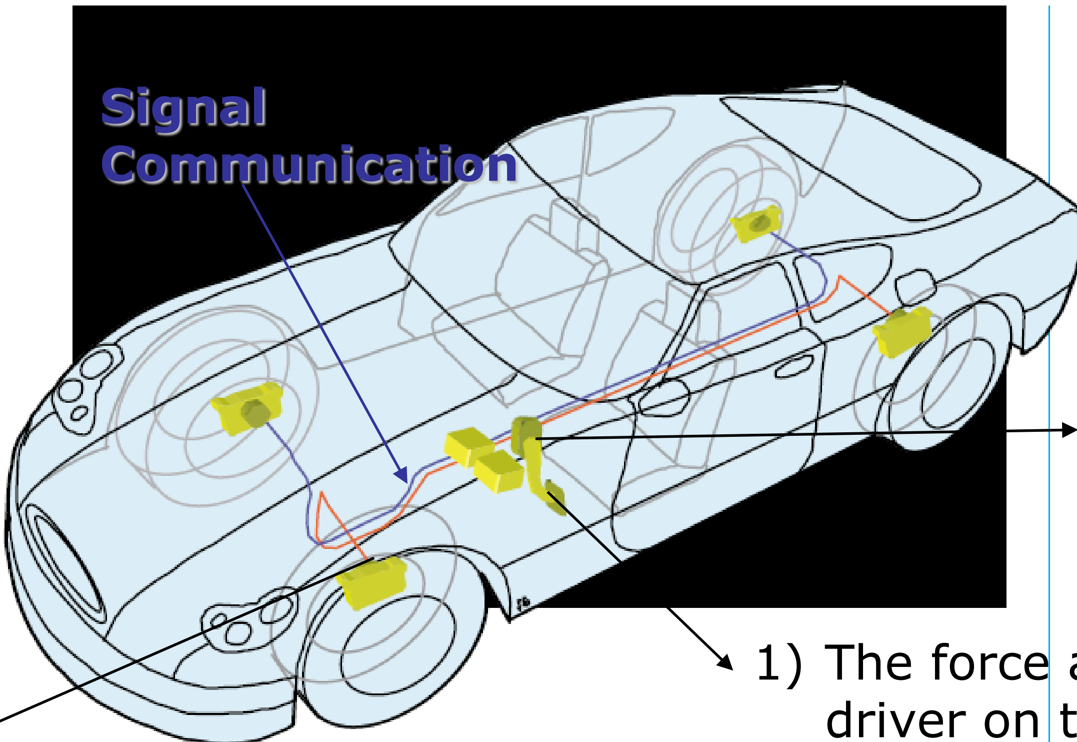
High-speed networking in automobiles

- Question1: What percentage of the manufacturing cost in (luxury) vehicles go to electronics?
- Answer: More than 23%
- Question 2: What percentage of the innovation in the automotive field is in electronics?
- Answer: More than 80%
- The electronic systems in vehicles:
  - Increase exponentially in number and dollar amount
  - Get more complicated

Implications for vehicle engineering

- Focus: developing electronic systems that safely and efficiently **replace entire mechanical and hydraulic applications**.
- Support with sensors and communication

X-by-wire Systems:Brake-by-wire Example



3) The microcontroller sends the appropriate brake signal to the electromechanical actuator on each wheel.

1) The force applied by the driver on the brake pedal is read by the sensors.

2) Sent to microcontroller.

4) The modular actuators squeeze the brake pads against the brake disk to slow and stop the car.

In-vehicle networks

- The vehicle's electronic equipments are interconnected
  - Sharing of information and resources among the distributed applications.
- Interconnection in the past:
  - wiring one element to another
  - N^2 problem

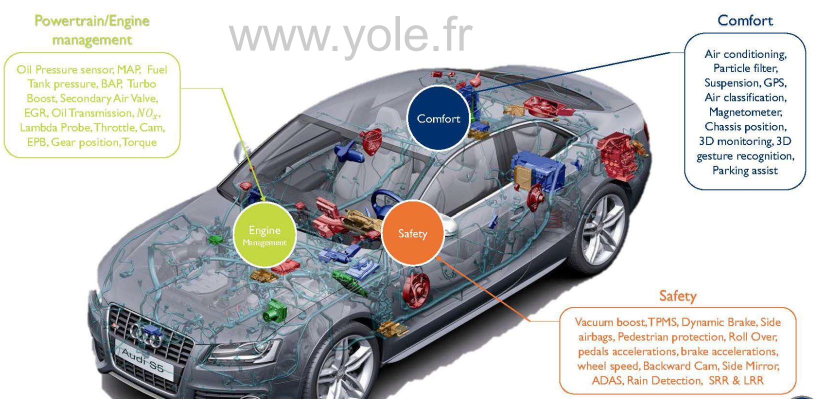
In-vehicle networks

- Problems:
  - Increased vehicle weight
  - Required vehicle volume
  - Difficult to maintain reliability
- Example: Every extra 50 kilograms of wiring, for each 100 kilometers traveled:
  - Consumes extra 100 watts of power
  - Increases fuel consumption by 0.2 liters

In-vehicle networks

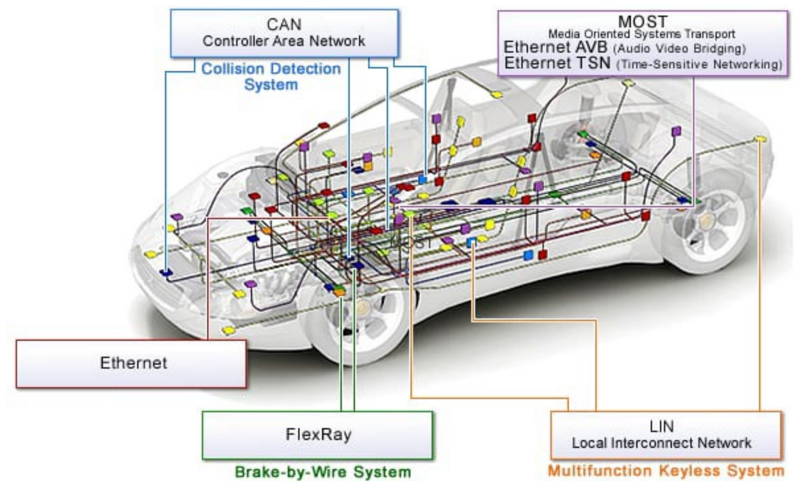
- Solution:
  - Replace one-to-one dedicated wiring by a network similar to computer LANs.
- In a 1998 press release, Motorola reported:
  - Replacing wiring harnesses with LANs in the four doors of a BMW reduced the weight by 15 kilograms while enhancing functionality.
- Beginning in the early 1980s, centralized and then distributed networks have replaced point-to-point wiring.

Today's Vehicle: Internal Connectivity



ECU (Electronic Control Unit):

- Gets Sensor Inputs
- Computes outputs for actuators, motors, relays, LEDs



https://www.renesas.com

Contemporary vehicle:

- up to 70 ECUs
- tens of millions of lines of code
- ECUs connected by in-vehicle networks

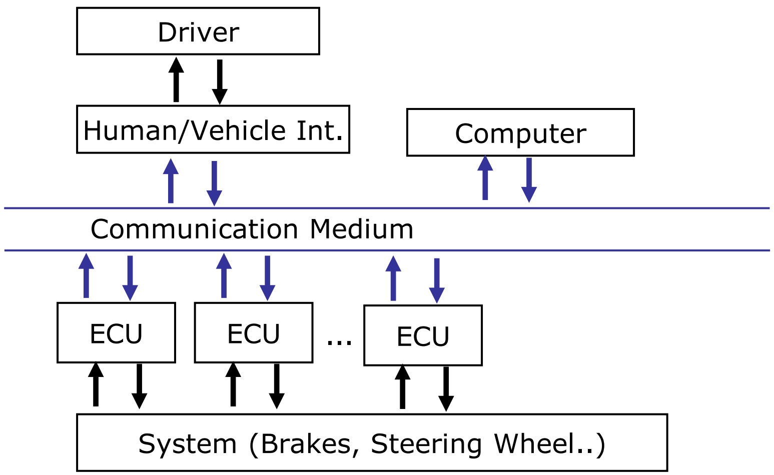
Speed of data transfer in automobiles

Technology	Speed	Application
LIN	Less than 10Kbps	Body" domain (seat control, door lock, lighting, trunk release, rain sensor, etc.).
CAN	250kbps-1Mbps	Power train
CAN-FD	Up to 10 Mbps in data transmission phase	Power train
MOST	24.8 Mb/s.	Point-to-point audio and video data transfer
FlexRay	10Mbps	X-by wire

Speed of data transfer in automobiles

Technology	Speed	Application
LIN	Less than 10Kbps	Body" domain (seat control, door lock, lighting, trunk release, rain sensor, etc.).
CAN	250kbps-1Mbps	Power train
CAN-FD	Up to 10 Mbps in data transmission phase	Power train
CAN-XL	Up to 20 Mbps in data transmission phase	Power train
Ethernet 100BaseT1	100Mbps	In Development
MOST	24.8 Mb/s.	Point-to-point audio and video data transfer
FlexRay	10Mbps	X-by wire

In-vehicle Communication for the Next Generation Applications

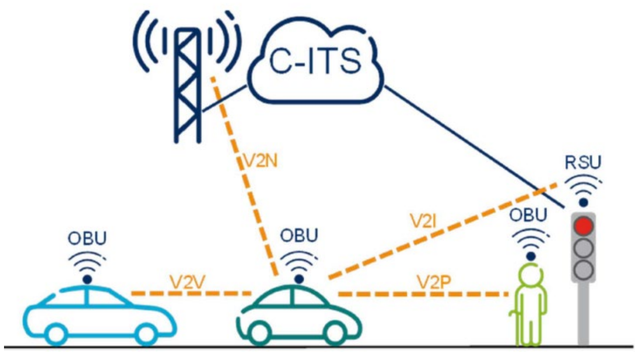


- Signals:
  - Information sharing, coordination, commands
  - Periodic
  - Event-triggered, sporadic

- Amount of traffic among the components is increasing
- Requirements for signal communication:
  - Fast
  - Real-time
  - Deterministic
  - Supports periodic communication
  - Reliability and stability

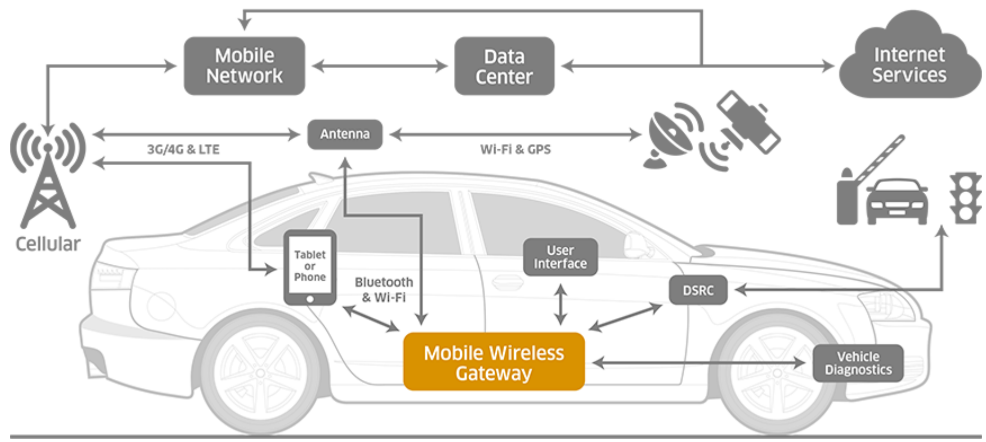
Today's Vehicle: External Connectivity

Connectivity Modes



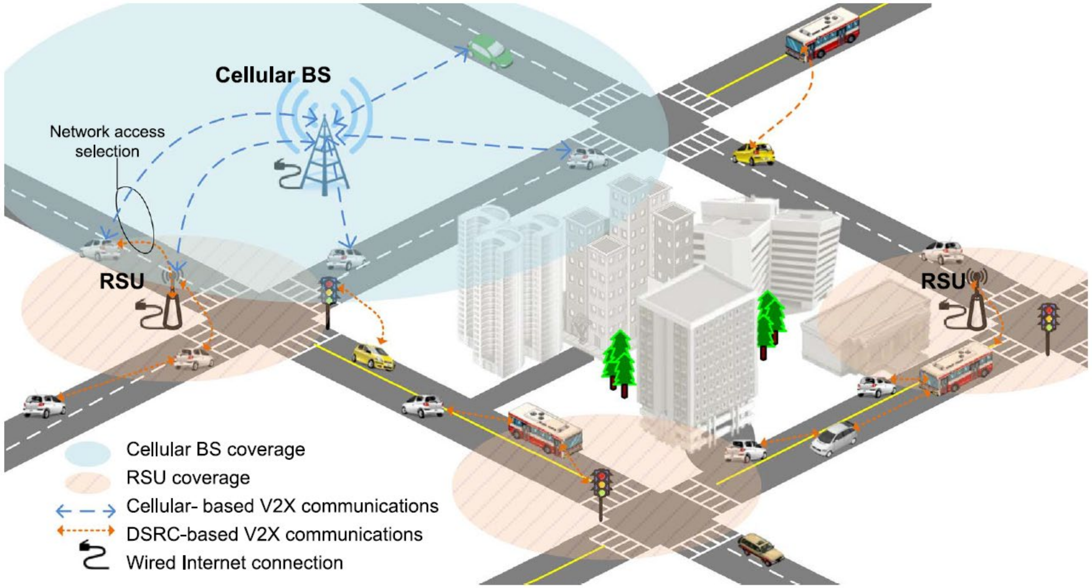
C-ITS: Cooperative ITS
V2N: Vehicle to Network
V2I: Vehicle to Infrastructure
V2V: Vehicle to Vehicle
V2P: Vehicle to Pedestrian
OBU: On Board Unit
RSU: Road Side Unit

Connectivity Interfaces of the Vehicle



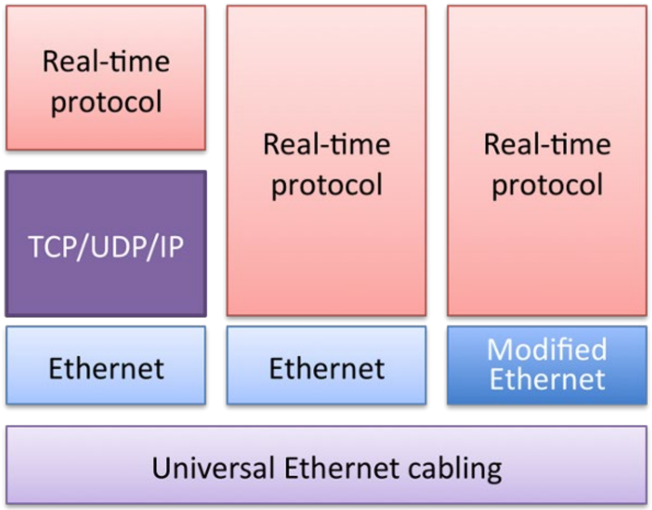
http://design.avnet.com/axiom/autorama-connecting-your-car-to-the-internet-of-tomorrow/

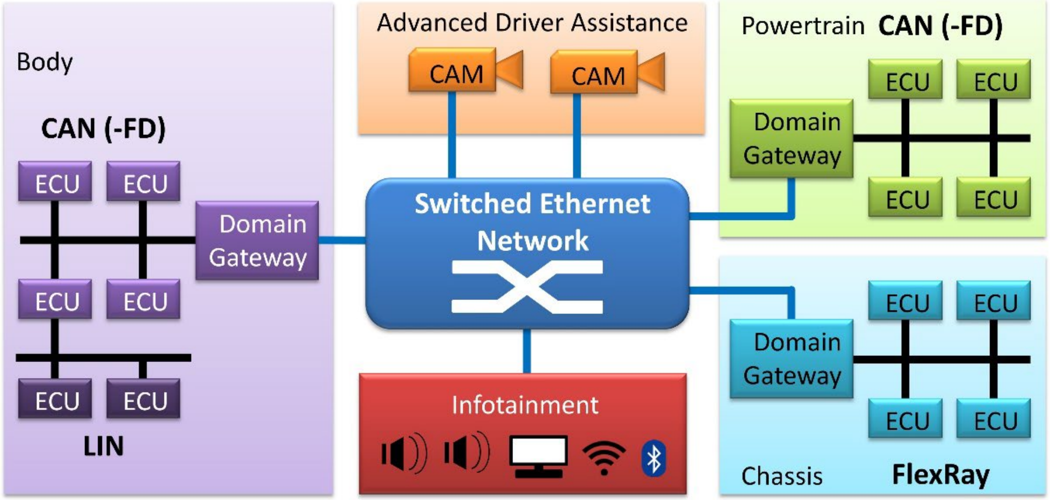
V2X Heterogeneous Communications



- DSRC:
  - Low delay
  - V2V and V2I are realized by DSRC
- Cellular network:
  - Connects fragmented DSRC segments
  - Acts as a backup for V2V
  - Access network to the Internet for Infotainment

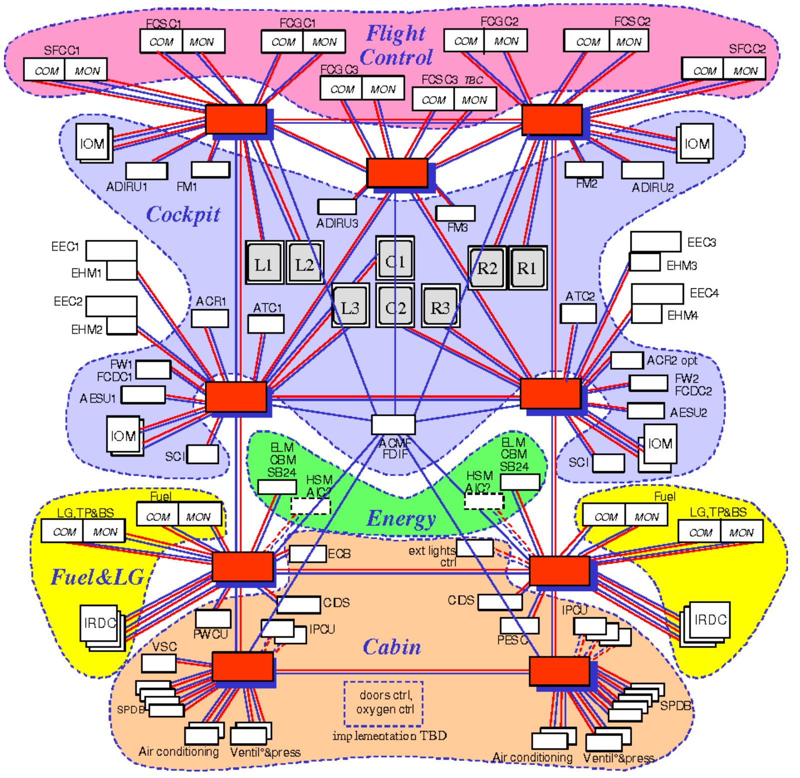
Real-time Ethernet





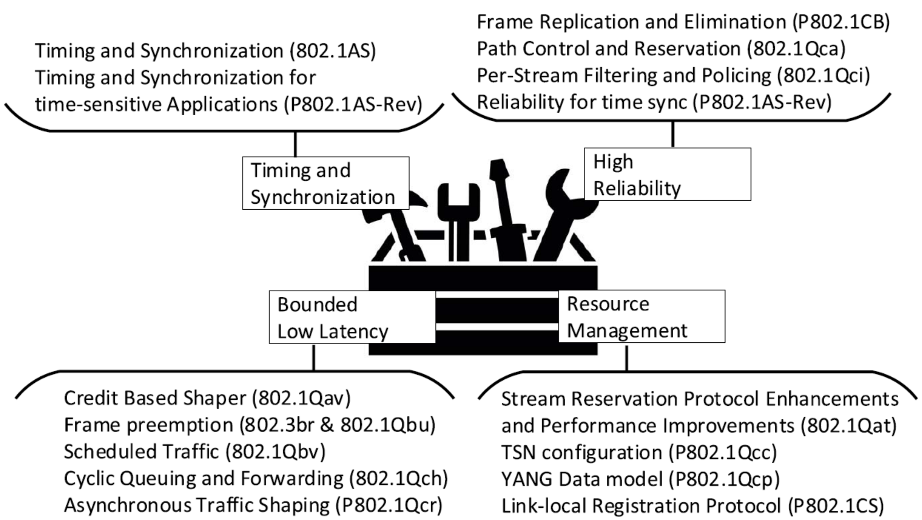
AFDX

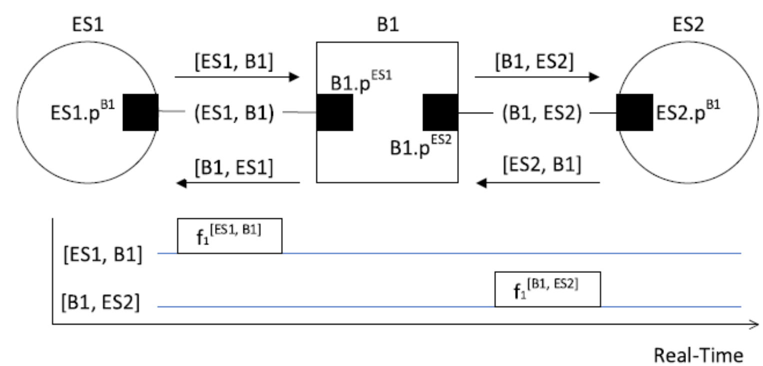
- Avionics Full Duplex Switched Ethernet
- 100Mbit/sec / 10Mbit/sec, first 1GBit/sec implementations
- Built around commercial Ethernet (MAC, IP, UDP, SNMP) with provisions for deterministic behavior
  - Connection oriented
  - Shaped traffic



TSN

- Collection of IEEE Protocols
- Timed switching function with strict bounds (gates)





IEEE 802.1 TSN toolbox.

Focus

- How to transfer packets in the embedded networks:
  - At high speeds or limited hardware resources
  - Guaranteeing application requirements
- Using legacy standards if possible
- How to establish D2X (Device to Any) communications

Similar courses

- http://users.ece.cmu.edu/~koopman/lectures/index.html#649

Reference Material

- Selected Journal Papers
- Industrial Communication Technology Handbook, 2nd Edition, Richard Zurawski, CRC Press, 2017
- Autonomous and Connected Vehicles: Network Architectures from Legacy Networks to Automotive Ethernet Editor(s):Dominique Paret, Hassina Rebaine, Benjamin A. Engel First published:31 March 2022

Grading

- Midterm: 30%
- Paper presentation: 5%
  - Students will select a paper from the recent research papers and present it in the class
- Final: 40%
- Class Project: 25%
  - A development on the presented research paper (simulation, analytical computation, FPGA realization)
  - A suitable research problem from the student's thesis or workplace

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