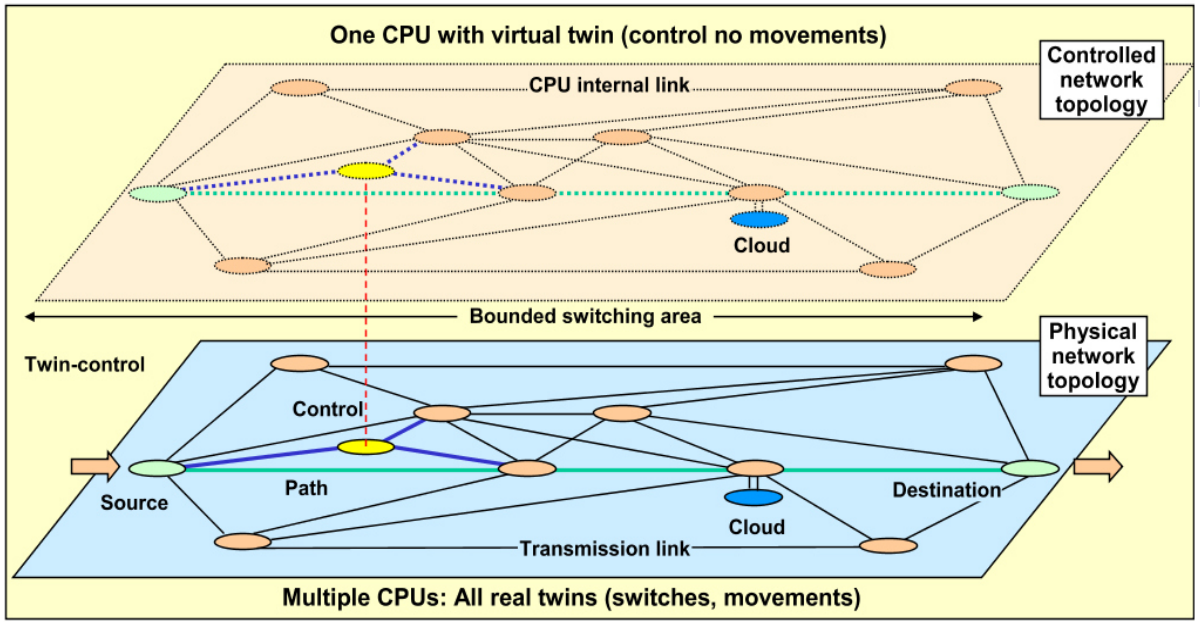
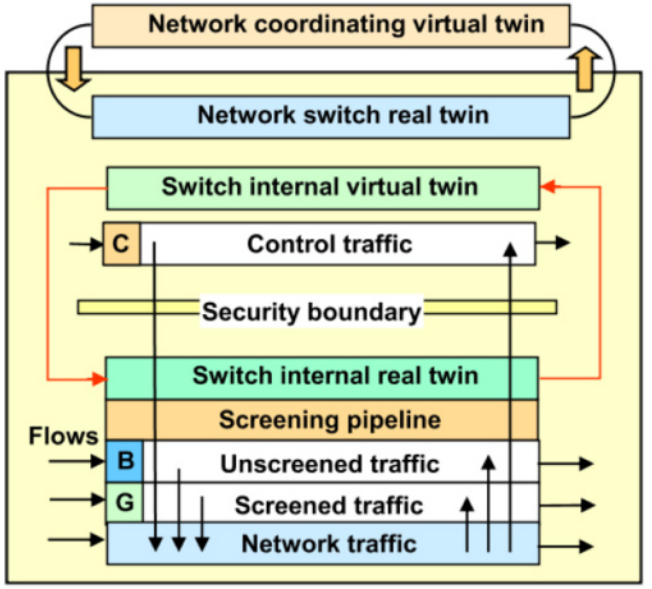




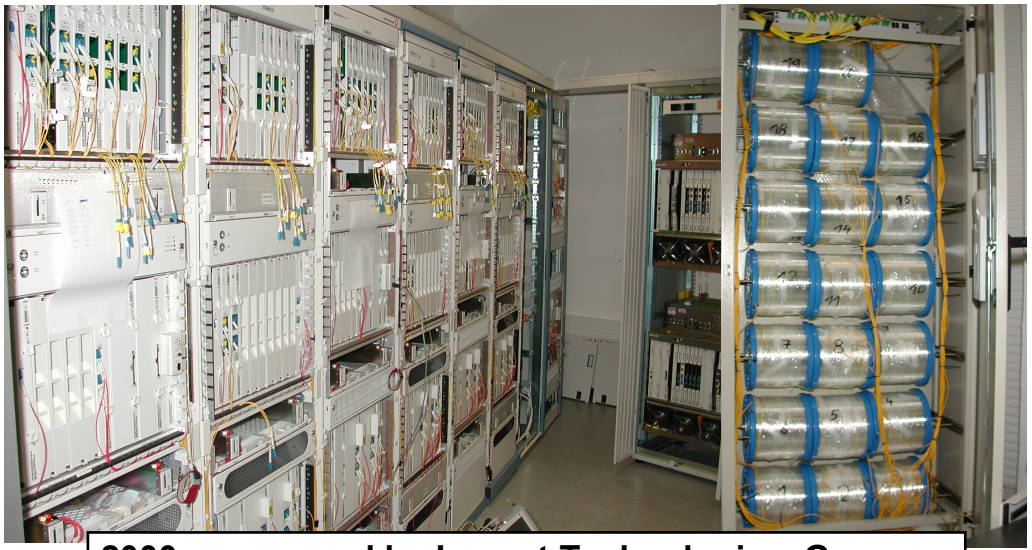
SDN-Twin: Software defined networking with digital twins

Die momentan modernste Netzarchitektur ist Echtzeitsimulator sowie Echtzeitvisualisierung

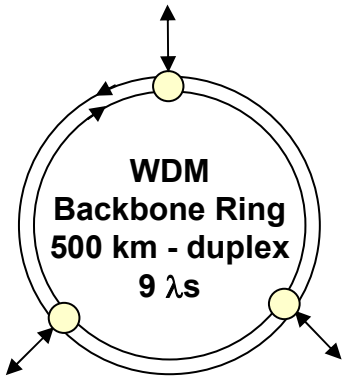
Ein historischer Meilenstein in lebenslang stabiler, rechnergestützter Planung, Konstruktion und Realisierung eines Netzkontrollsystems mit internem physischen Netz und diversen Cloud Einheiten für Datenverkehr beliebiger Geschäftszwecken, das automatisch zum realen physischen Netz mit voller Transparenz wird und somit eine kontinuierliche Überprüfbarkeit der Leistungs- und Servicequalität sowie intrinsisch Erweiterungen im Netz- oder operativen Betrieb ermöglicht.

Em. O.Univ. Prof. Dipl.-Ing. Dr.techn. Harmen R. van As

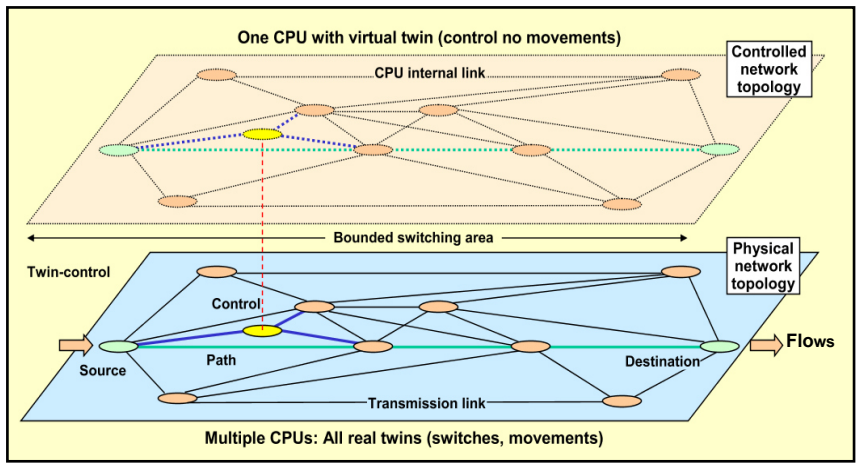
53 years in telecommunications and its mathematics



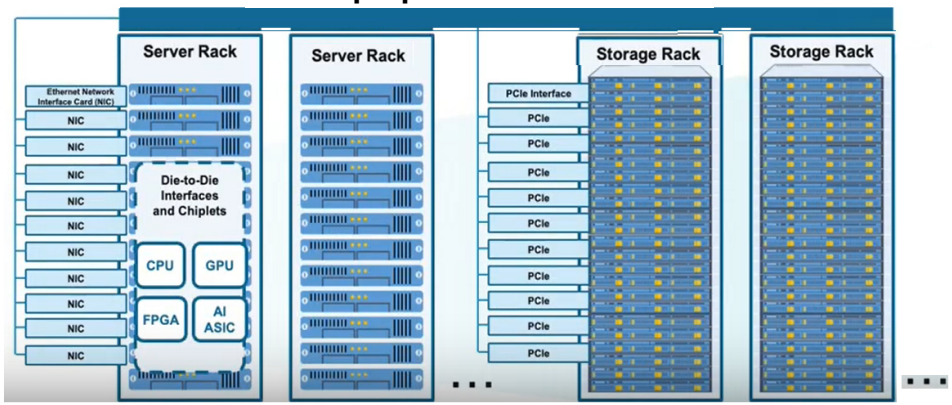
2000, sponsored by Lucent Technologies, Germany



2.5 Gbit/s, 10 Gbit/s, transparent



Rooftop optical interconnect



SDN-Twin international education, research and development

Four-line research & development

aTinaTwin

International education

Research & Development

Business

www.atinaTwin.com

CMG aggfa

Action group Gigabit fiber access

CMG - Computer Measurement Group Austria AGGFA

www.cmg-ae.com

TU WIEN SDN twin research

Scientific community

www.sdn-twin.at

international congress

www.isdn-tnc.org

First international SDN-Twin Networking Congress, 2023, Vienna
Second international SDN-Twin Networking Congress, 2024, Munich

1. Lecturing program at the Vienna University of Technology

SDN-Twin: Software-defined-networking with digital twins

15 lectures with circa 15 units each

2. International PhD program in SDN-Twin networking

- Scientific research
- Software design and programming
- Hardware design and realization
- Digital twin application fields

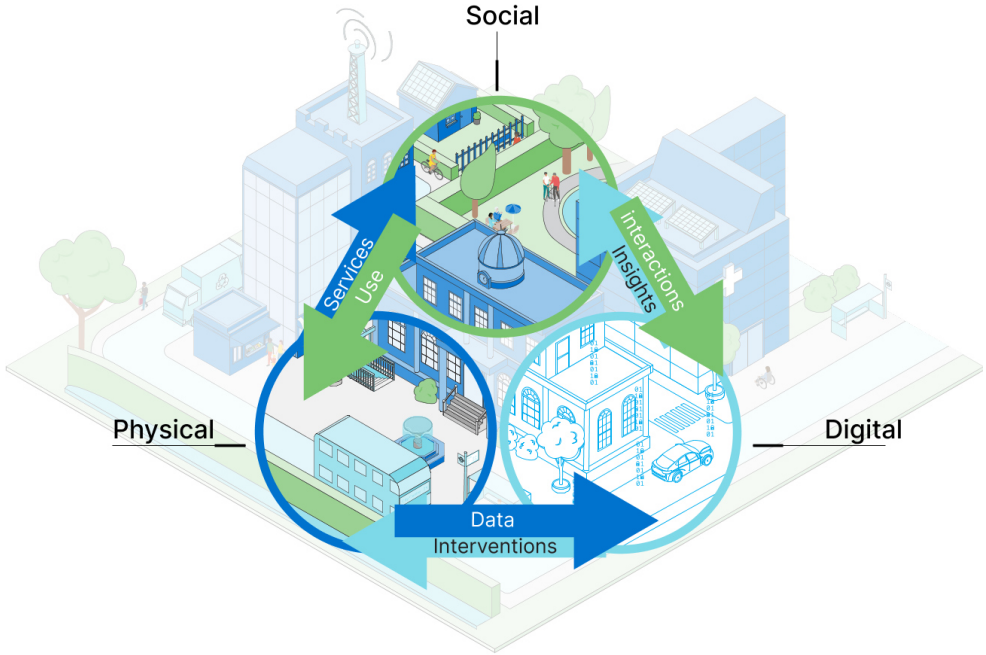
- Teletraffic theory
- Queueing theory
- Network calculus
- Optimization

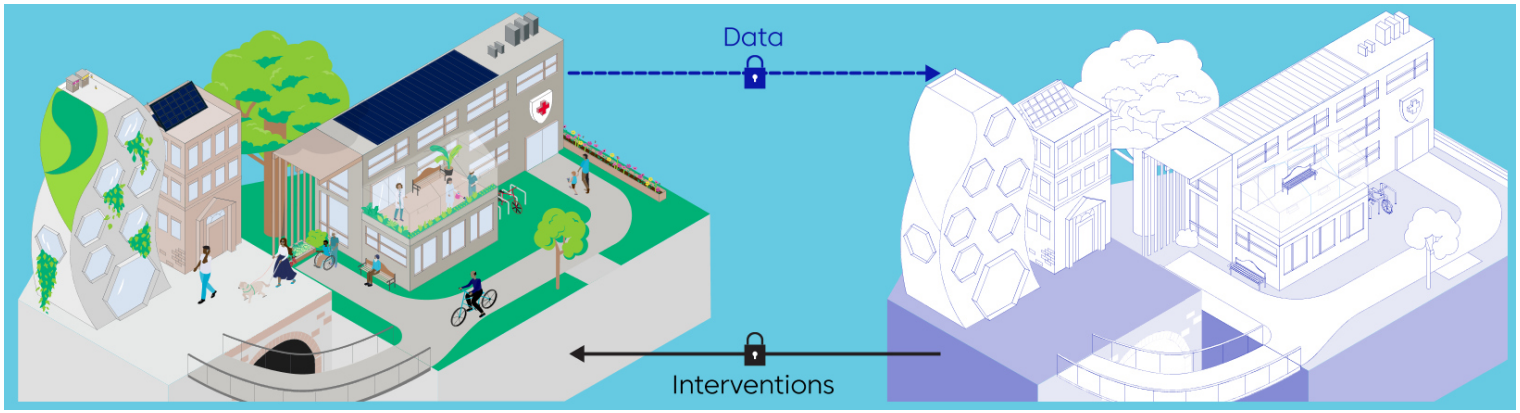
- Reliability theory
- Graph theory
- Artificial intelligence
- Deep learning

3. SDN-Twin educational research, competence and test center Vienna University of Technology

4. Industrial SDN-Twin consortium to promote standards for manufacturing bare metal switches

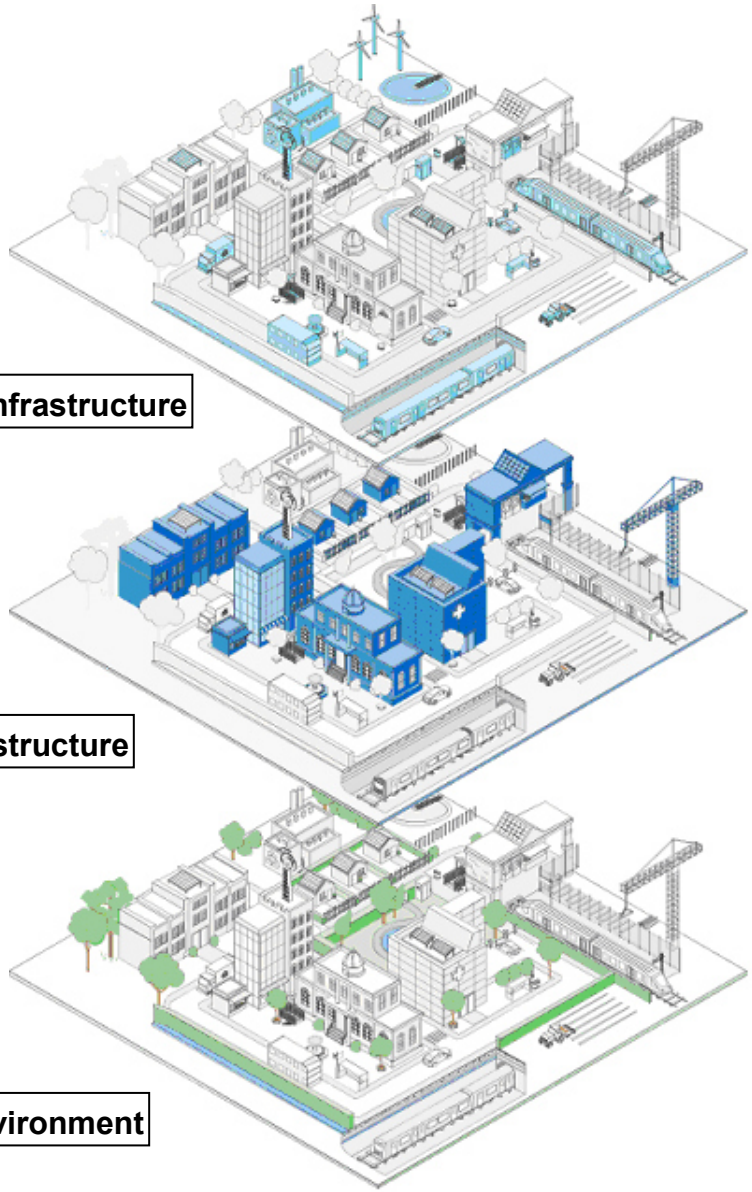
Digital twins (virtual and real)





Real: Socio-technical **Iterative** **Virtual: Cyber-physical**

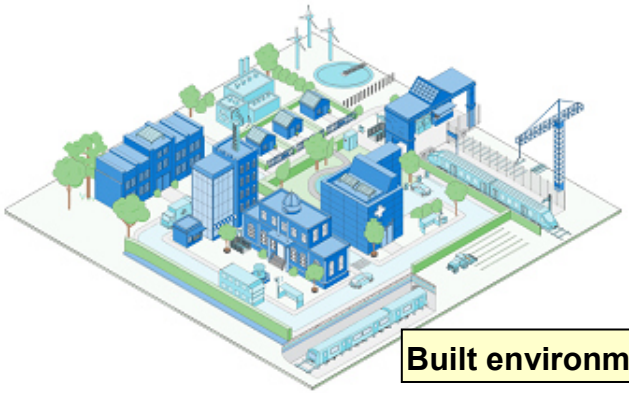
Digital twins (virtual and real)



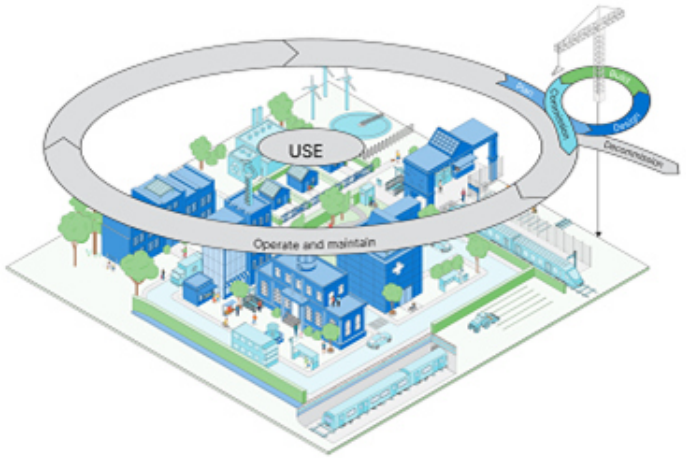
Economic infrastructure

Social infrastructure

Natural environment



Built environment

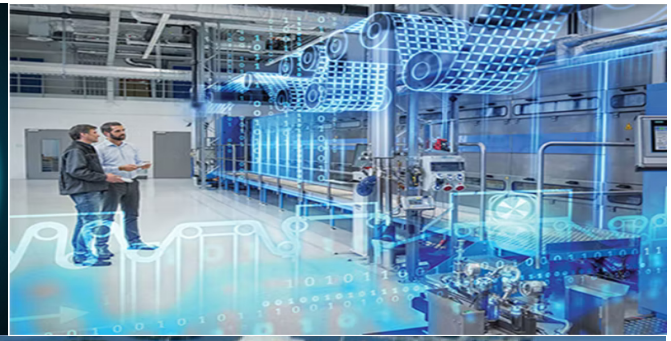
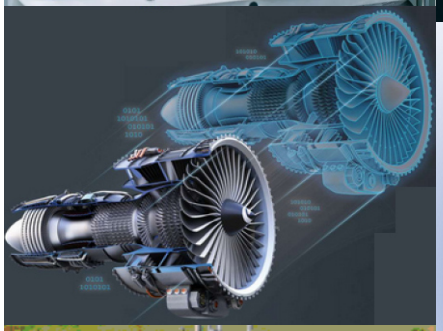


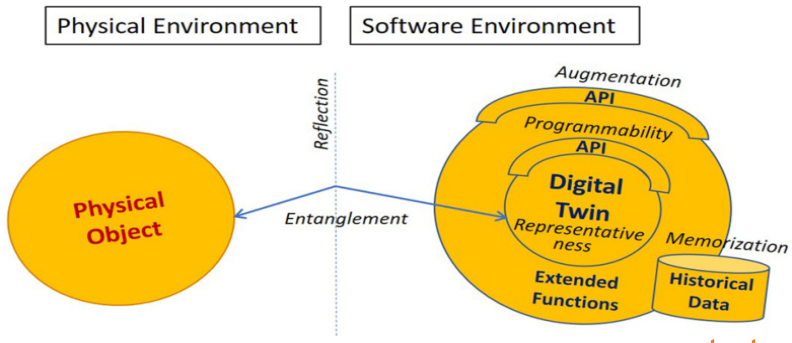
Operational environment

1970s: NASA (space projects), 2010s Digital twins

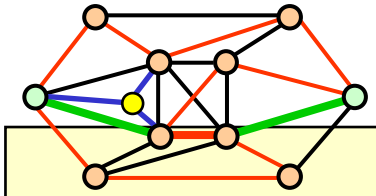
Digital twins: Not just a hype

February 19, 2019



SDN-Twin: network planning, optimization and design



p-cycle protected topology
Hamiltonian cycle

- Software design and programming
- Hardware design and realization

One CPU with virtual twin (control no movements)

CPU internal link

Controlling network model topology

Cloud

Bounded switching area

Physical network topology

Twin-control

Control

Path

Source

Destination

Cloud

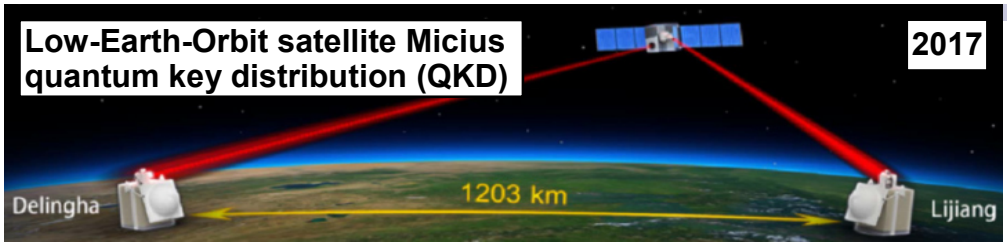
Transmission link

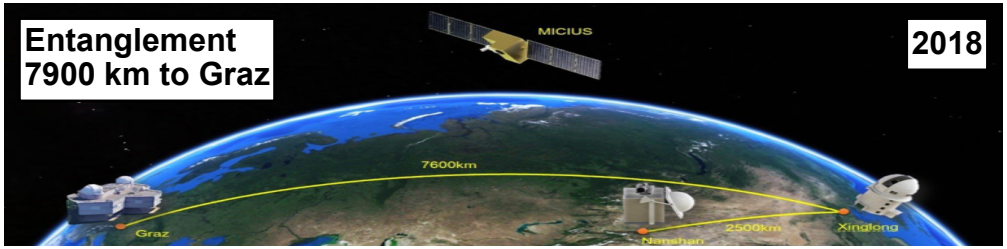
Multiple CPUs: All real twins (switches, movements)

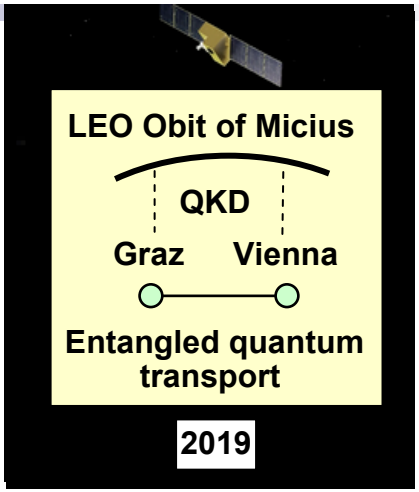
Control traffic
Control and customer traffic
Source-destination flow

Switching node with access traffic
Source-destination flow
Control unit

Quantum entanglement twins and SDN-Twin control digital twins



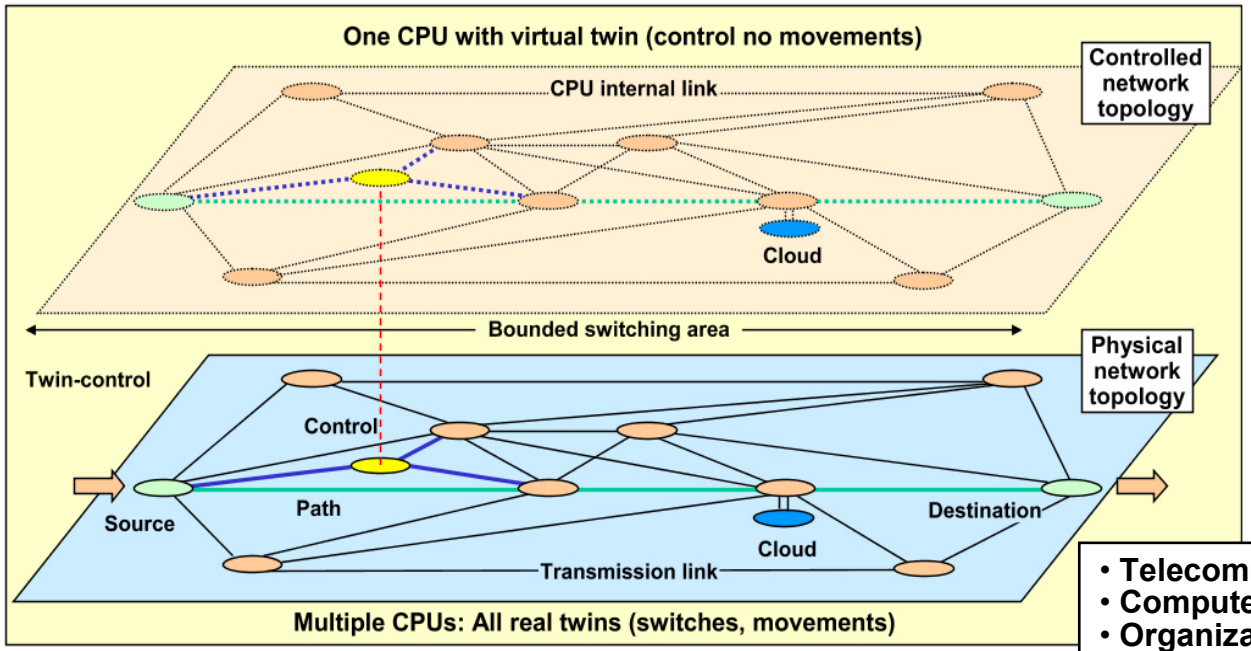


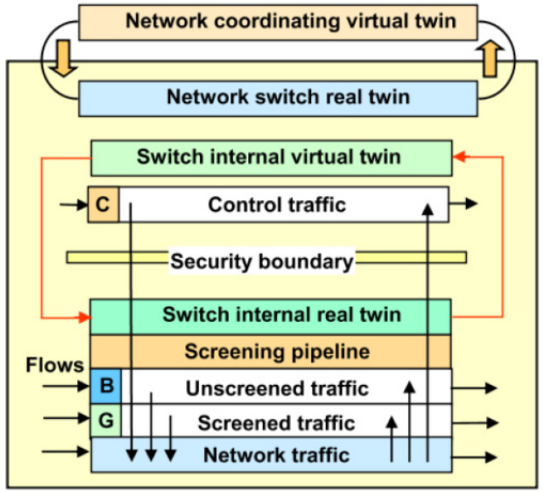


Em. O. Univ.-Prof.
Dr. Dr. h.c. Dr. h.c.
Anton Zeilinger
2022
Physics Nobel prize

Quantum entanglement twins

SDN-Twin control digital twins

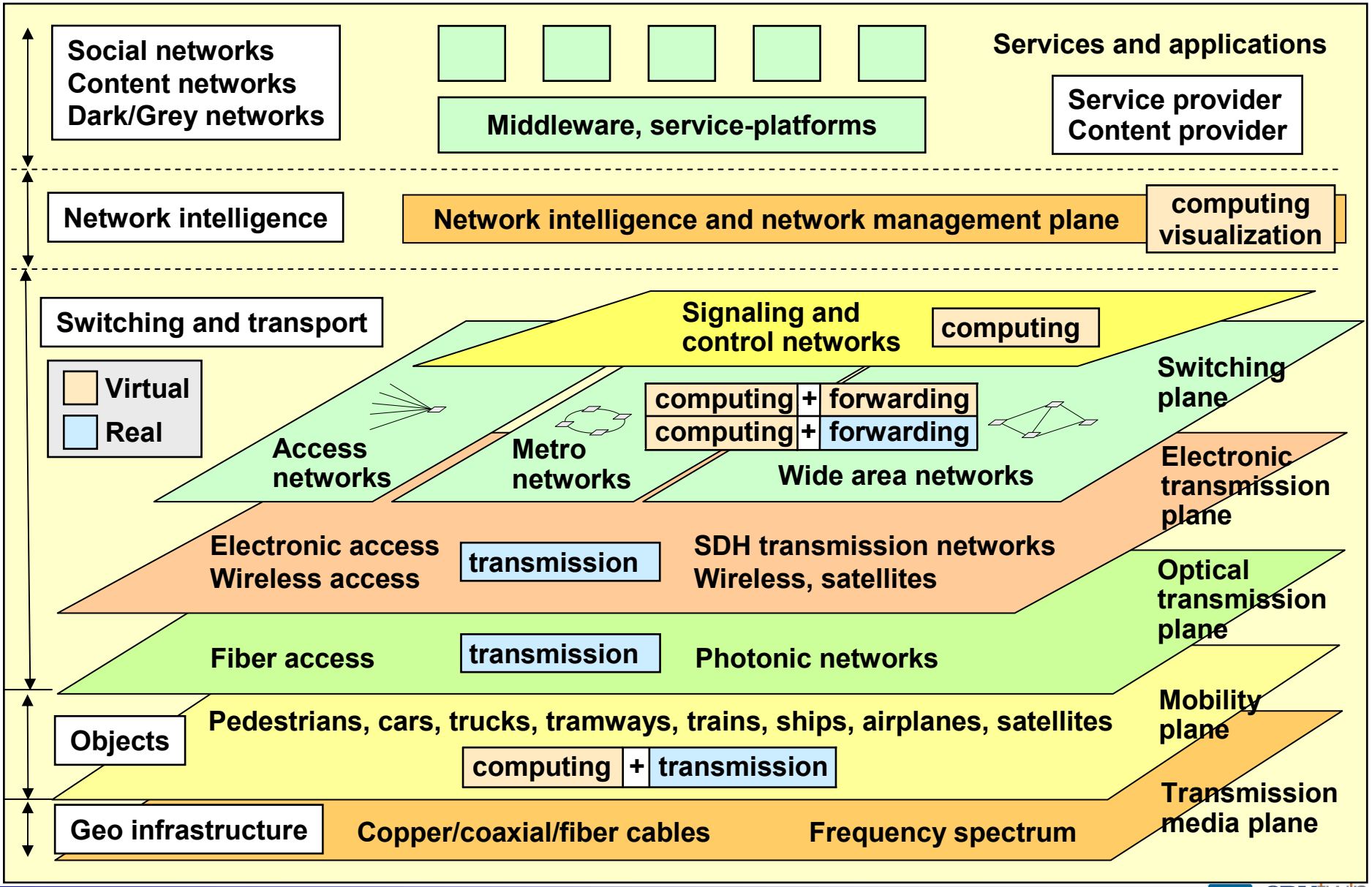




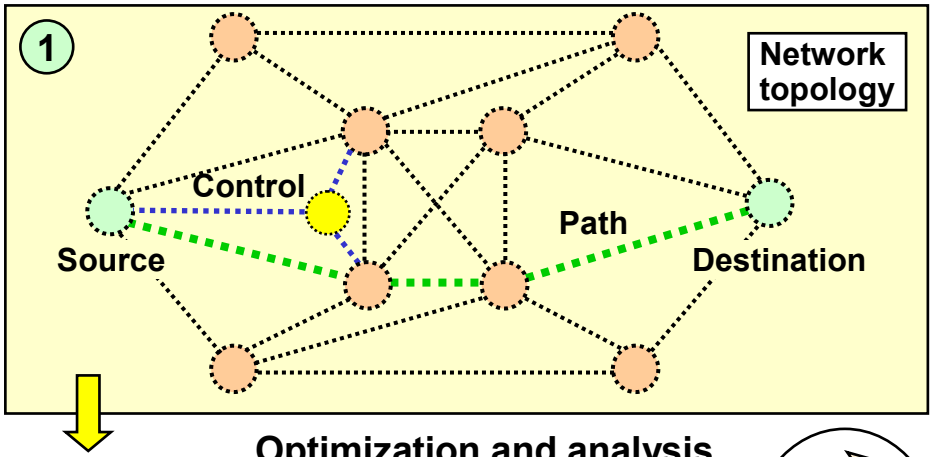
- Telecommunications
- Computer
- Organizational

- Strategic
- Social
- Logical

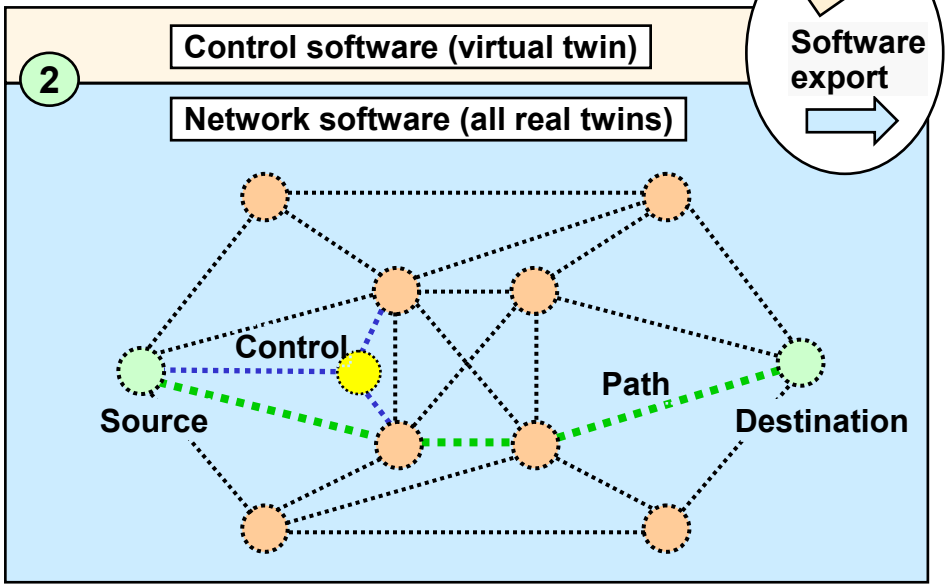
SDN-Twin network architecture



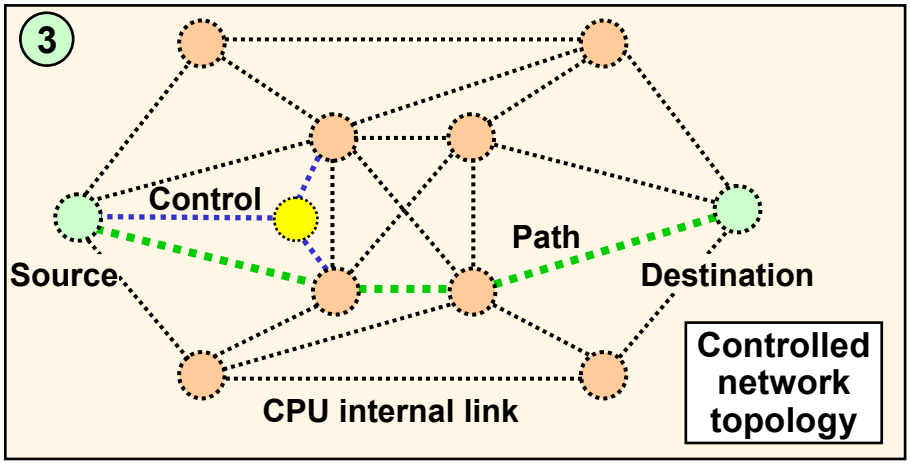
SDN-Twin: Network planning, optimization and design



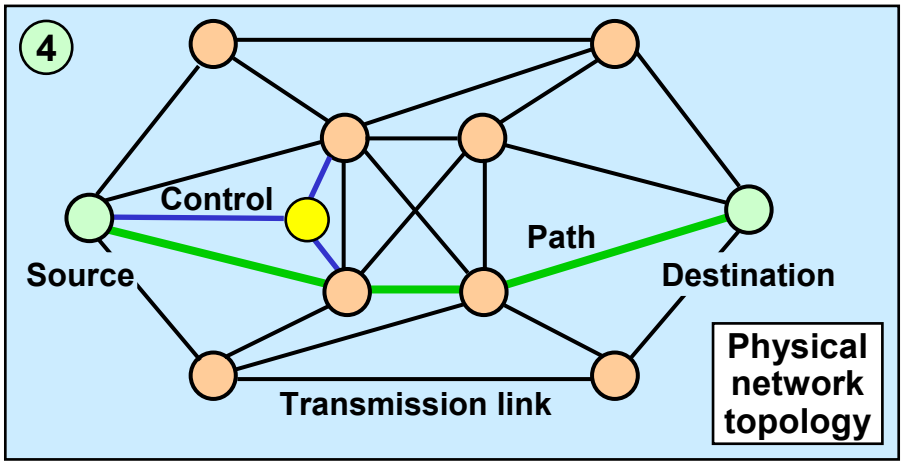
Optimization and analysis



Generation of network data structures
for the virtual twin and all physical twins



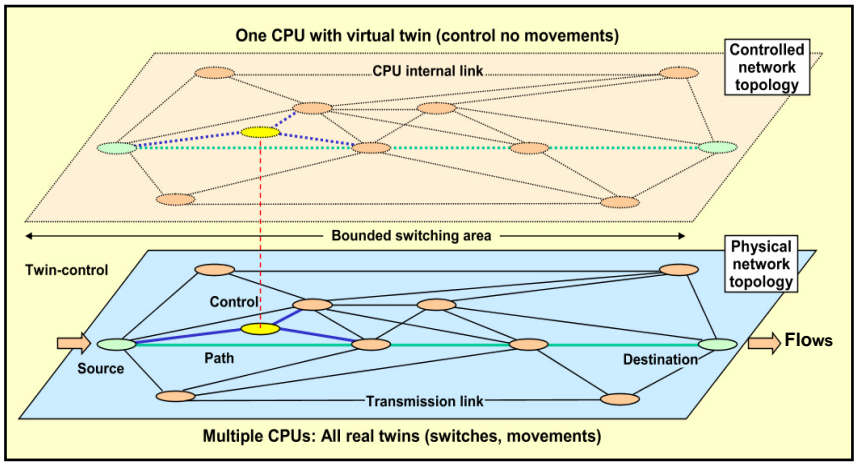
One CPU with virtual twin (control no movements)

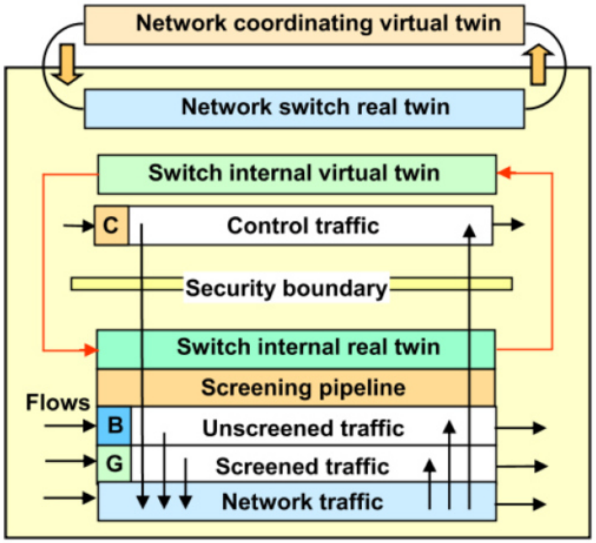


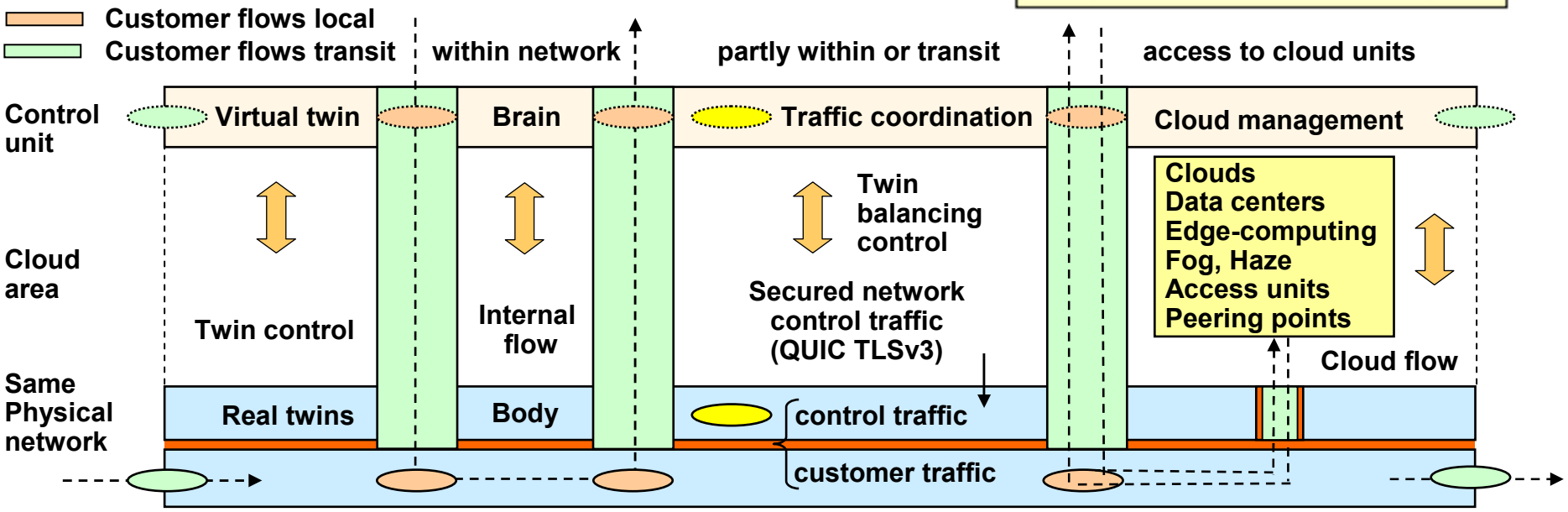
Multiple CPUs: All twins (switches, movements)

Control traffic
Control traffic and teletraffic

SDN-Twin with embedded physical network and Clouds







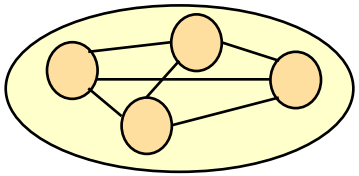
Structural anchor points in public and special-purpose IP networks

SDN-Twin public IP networks

Switching areas organized as a cellular structure

SDN-Twin computer networks will cover the public domain in concatenated and stacked manner.

SDN-Twin special-purpose IP networks



Main traffic in many cases well predictable.

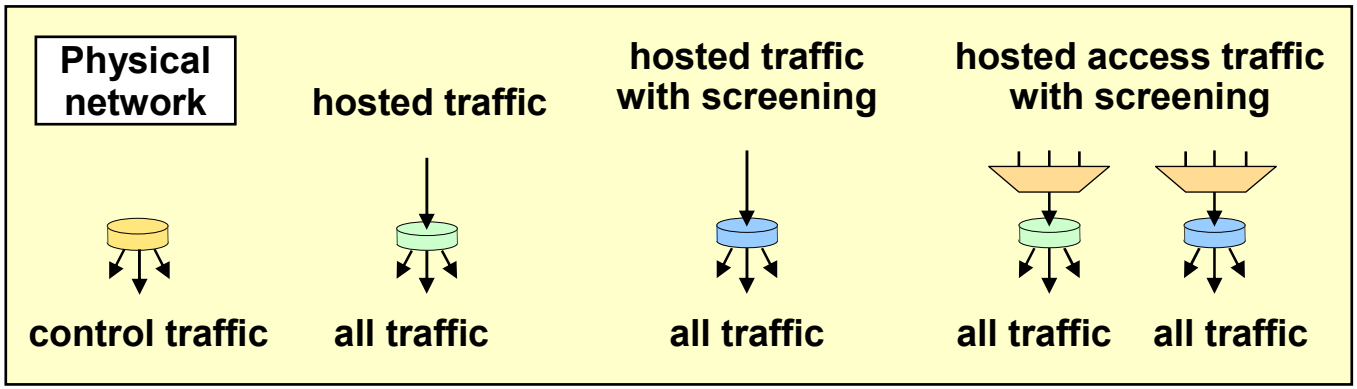
- Main traffic in many cases well predictable
- No chance to predict traffic load behavior of mobility
- Network must be able to cope with sudden changes

- Island network and their interconnection
- Five SDN-Twin networks, one over public domain and appropriately secured

One virtual twin CPU	Same network topology	[brain, control, location compact, no movements]
Set of real twin CPUs	Same network topology	[body, switches, geographic distributed, movements]

Bounded switching area

- Secured
- Computer-controlled
- Operational transparent
- Dynamic label switched
- Traffic load adaptive
- Green operation



Virtual coordination twin and real switching twins

Control together with data flow traffic over same physical network

One virtual twin CPU	Data compact	Algorithms, strategies, early detection, emergency control
	Same network topology	[brain, control, location compact, no movements]
Set of real twin CPUs	Data distributed	Routing/path data, monitoring, measurements, local actions
Control/data flow traffic	Same network topology	[body, switches, geographic distributed, movements]

Virtual plane

- Flow management
- Congestion management
- Destination arrival delay management
- Power consumption management
- Views in the future in the virtual plain
- Detection of security attacks or anomalies
- Operational transparency

SDN-Twin bare metal switches with transmission interfaces

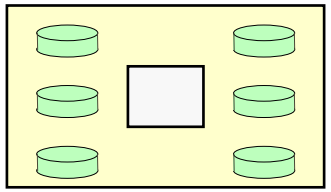
Switching fabric not required

CPU, GPU, DPU and PCIe, MVNe, CXL, RoCE, CUDA, RDDx, with MTM switching

Additional functions

Real plane

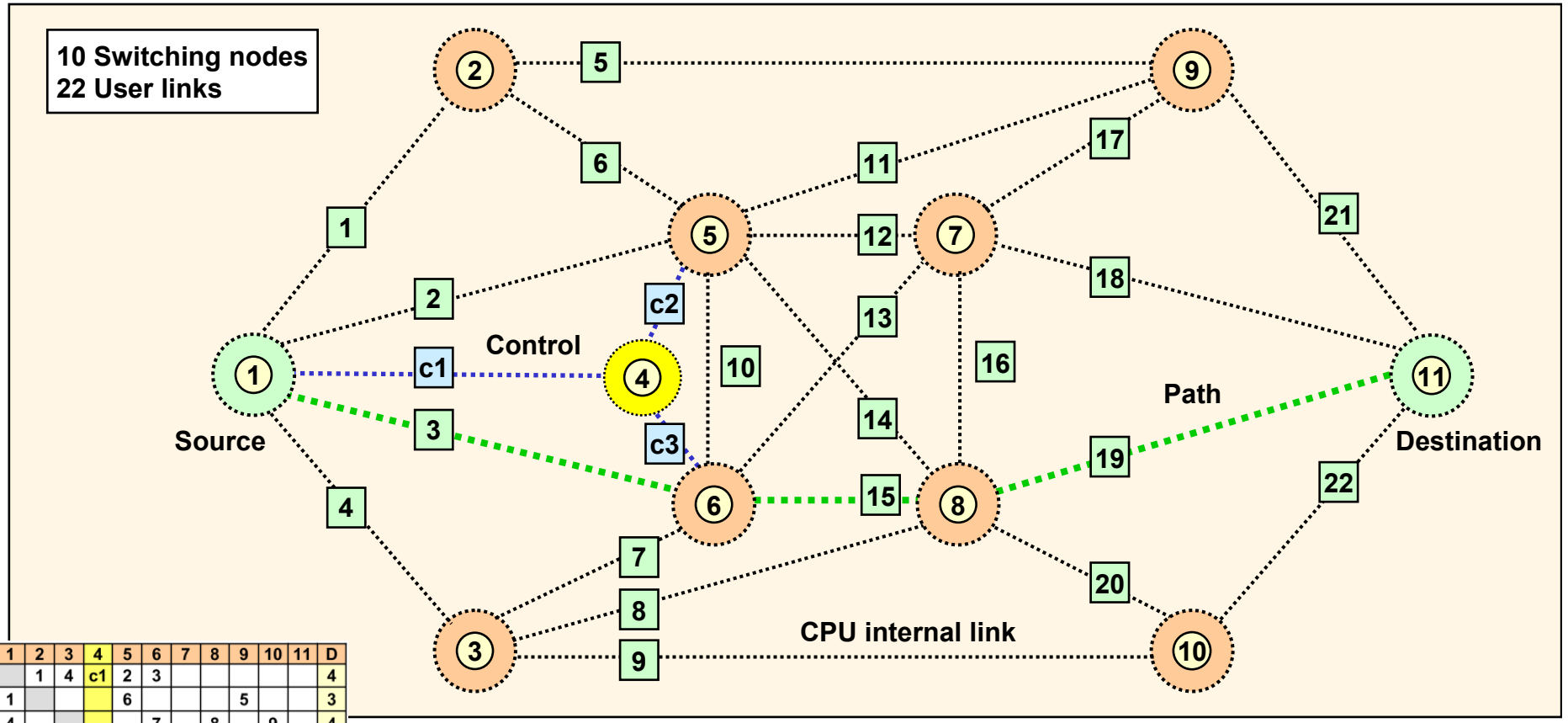
- Dynamic label switching
- Loss free packet forwarding
- Advanced forwarding functions
- Protocol behavior analysis
- Security attack detection
- Anomaly detection and analysis
- Measurements



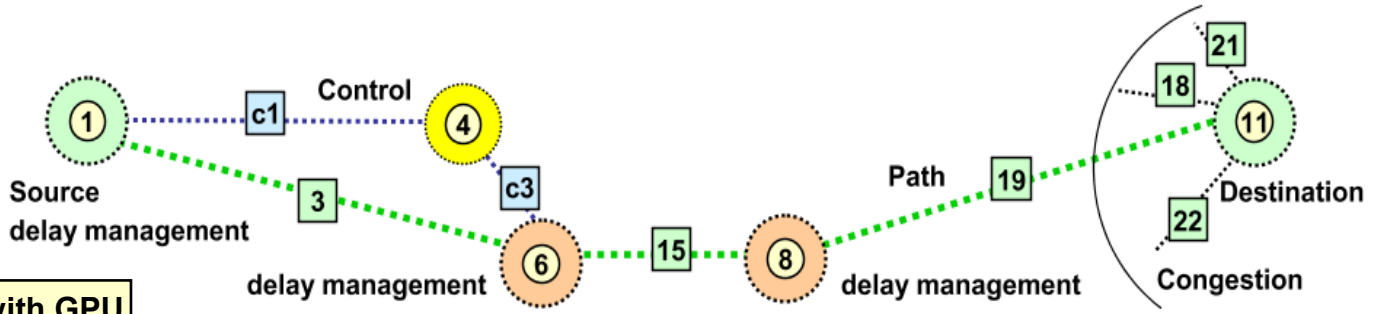
Real twin switches keep track on status of neighbor switches.

All paths that the switch can use are local available and can be used depending on load situations.

Routing and timing in virtual twin controlling computer

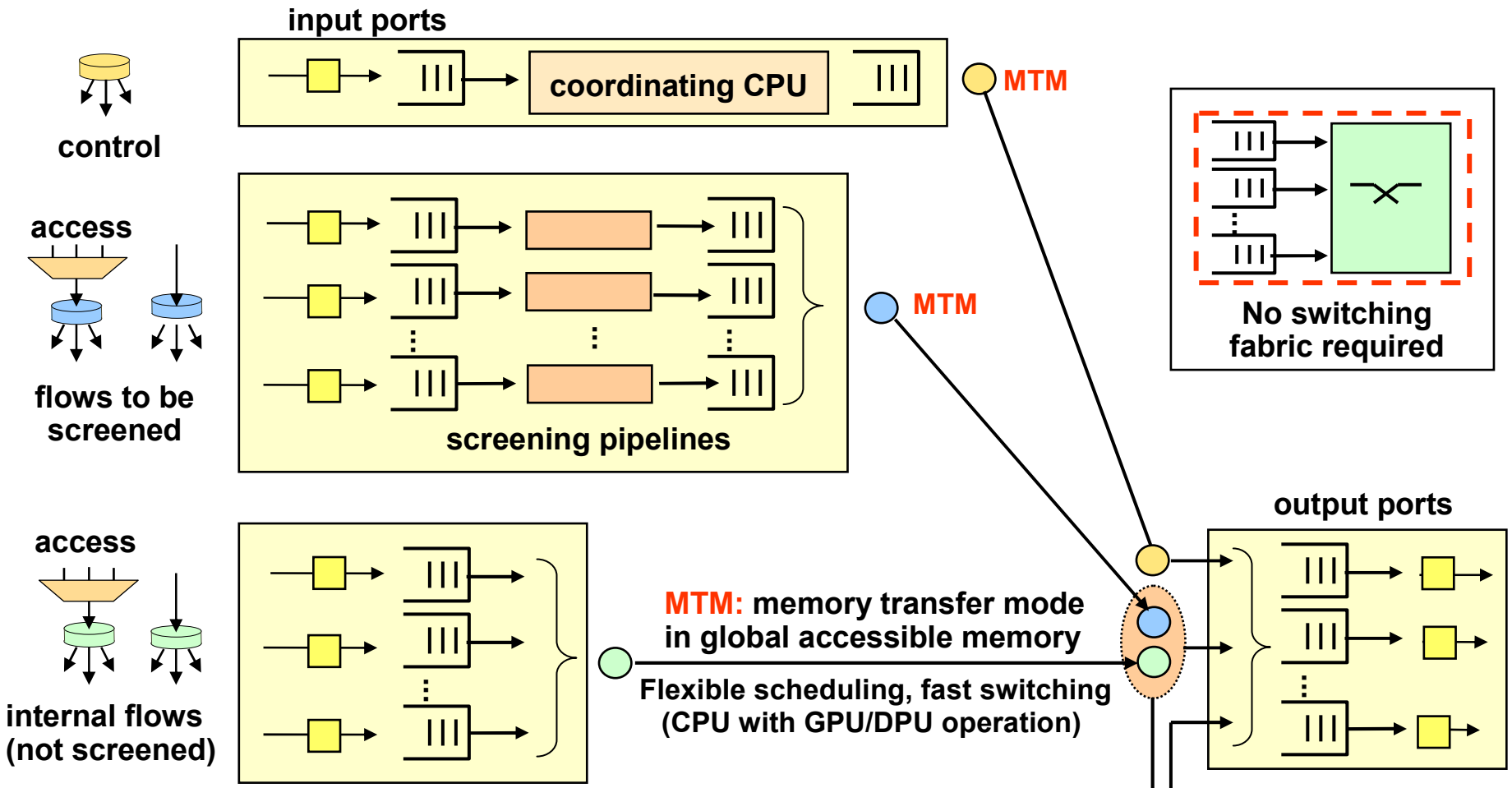


	1	2	3	4	5	6	7	8	9	10	11	D
1		1	4	c1	2	3						4
2	1				6				5			3
3	4					7		8		9		4
4	c1				c2	c3						3
5	2	6		c2		10	12	14	11			7
6	3		7	c3	10		13	15				6
7					12	13		16	17		18	5
8			8		14	15	16			20	19	6
9		5			11		17				21	4
10			9					20			22	3
11							18	19	21	22		4
D	5	3	4	3	7	6	5	6	4	3	4	



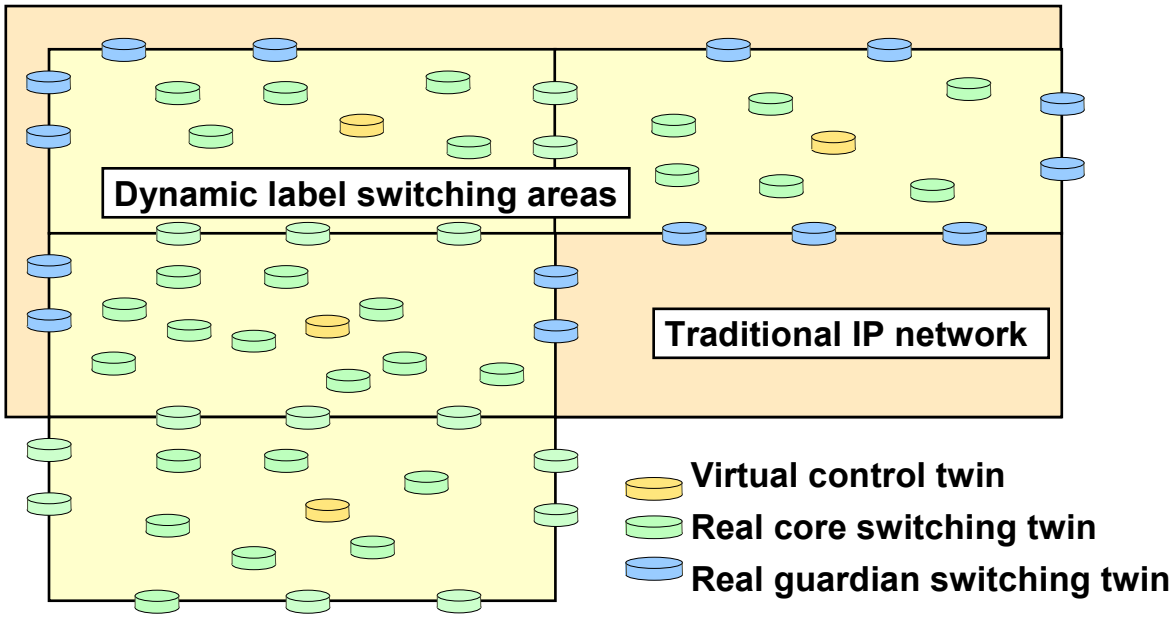
Fast parallel matrix processing with GPU

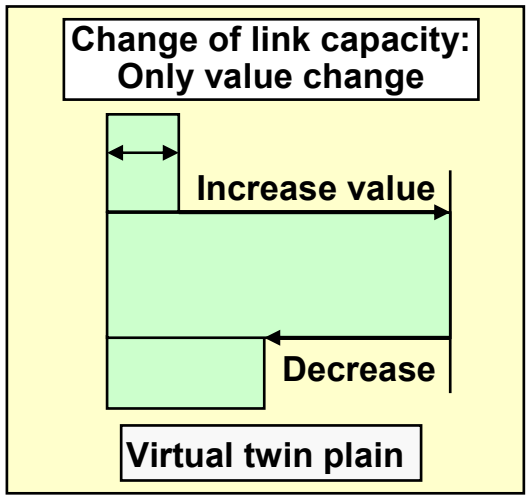
Flow operation in real (physical) twin network switches

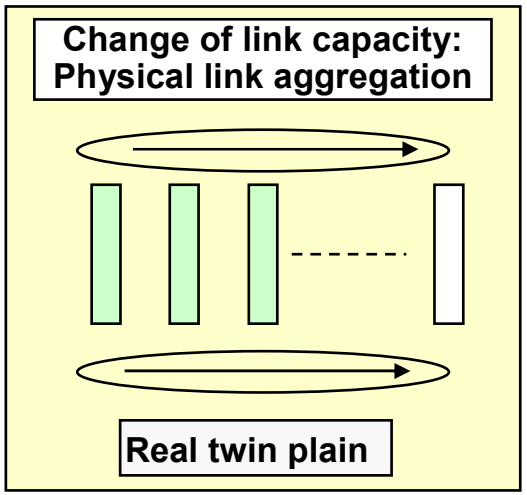


Packet routing:	Dynamic label switching (intrinsic availability)
Packet scheduling:	Priority plus destination time management
Control traffic:	Highest priority with Ethernet frame preemption
Control security:	QUIC with TLSv3 [public key + block-stream + hash]

SDN-Twin networking



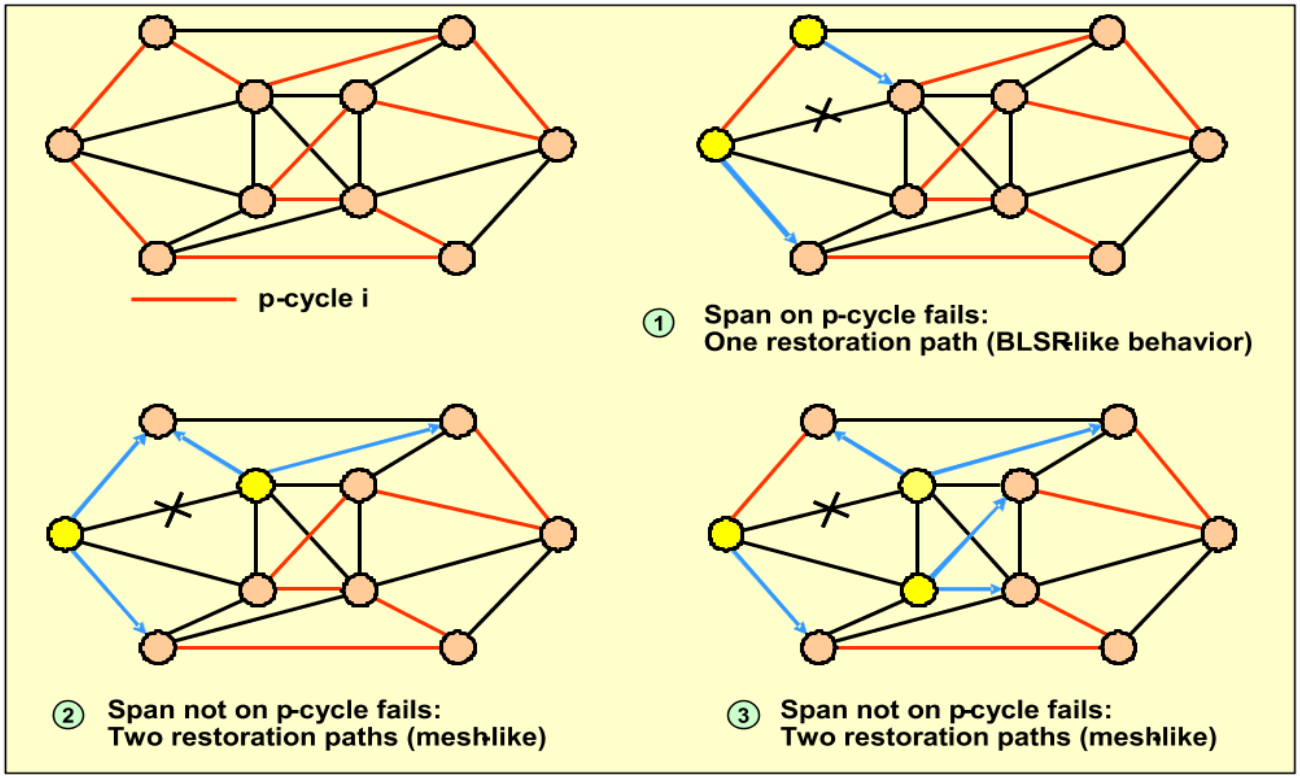


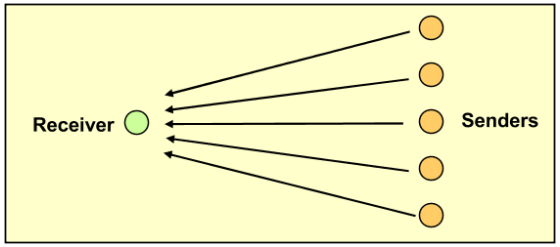


Science meets business

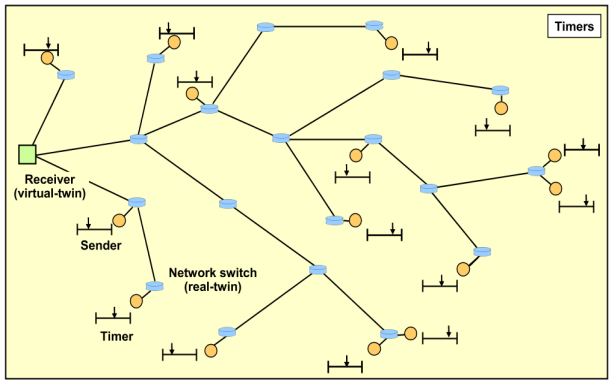
- Teletraffic theory
- Congestion theory
- Queueing theory
- Network calculation
- Reliability theory
- Graph theory
- Optimization
- Artificial intelligence
- Deep learning

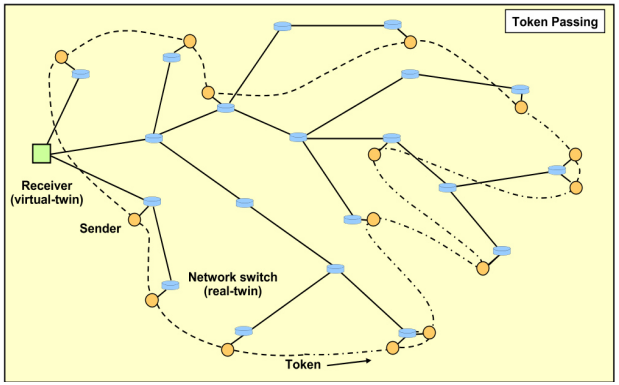
p-cycles (predefined protection) and m-cycles (monitoring)

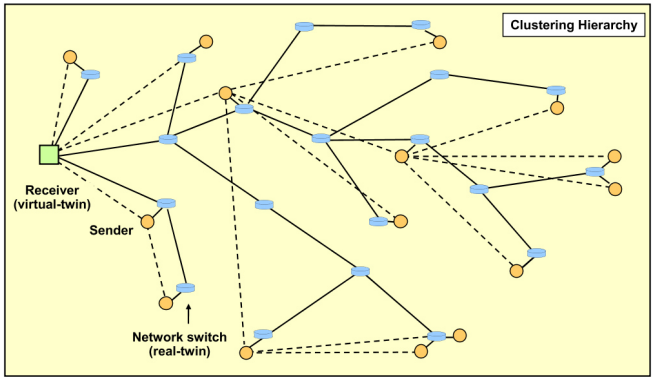




- Timing
- Token passing
- Clustering hierarchy





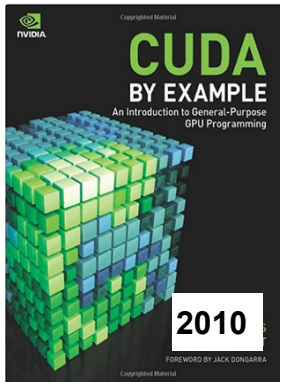


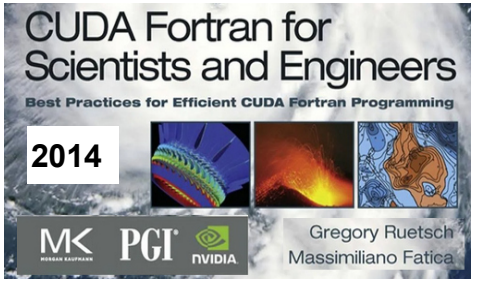
SDN-Twin uses well-established mechanisms and technologies

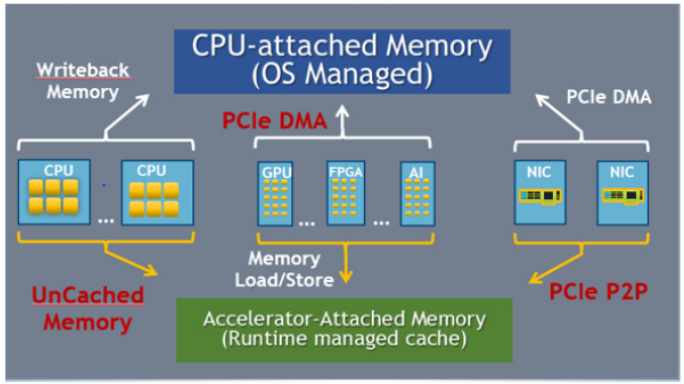
SDN-Twin resources: CPU/GPU/DPU, memory hierarchy, transmission technologies

- Digital twins (used in all business sectors)
- PCIe (peripheral component interconnect express)
- CXL (compute express link)
- NVMe (non-volatile memory express)
- CUDA (compute unified device architecture)
- RoCE (RDMA over converged Ethernet)
- CPU/GPU/DPU chips (universal, paralleling, routing included)
- Memory: DRAM, DDR2……. DDR6, persistent, non-volatile, …
- Transmission: Ethernet, WLAN, WiMax, G5/6, LoRaWAN,….

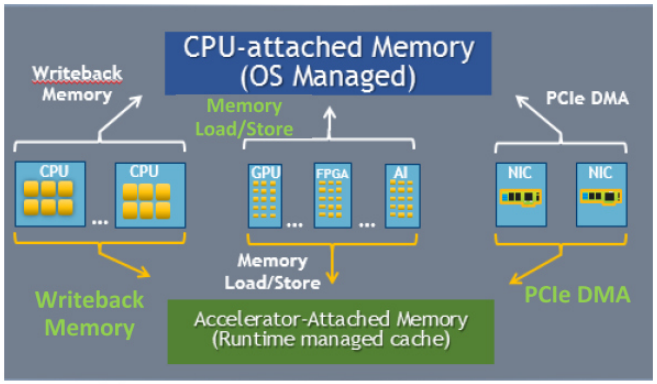
- Cockpit
- Radar
- Cameras
- Sensors
- TETRA
- GSM/GPRS
- LTE-static
- LTE-dynamic
- LTE-NOMA
- Wimax
- WLAN
- WPAN
- 6LoWPAN
- LLN



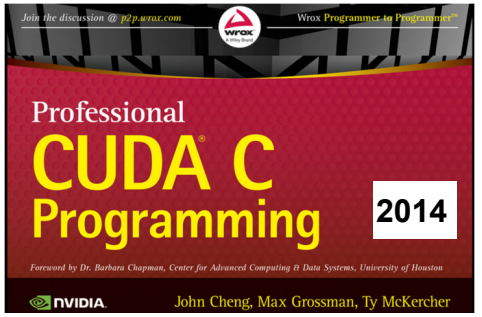




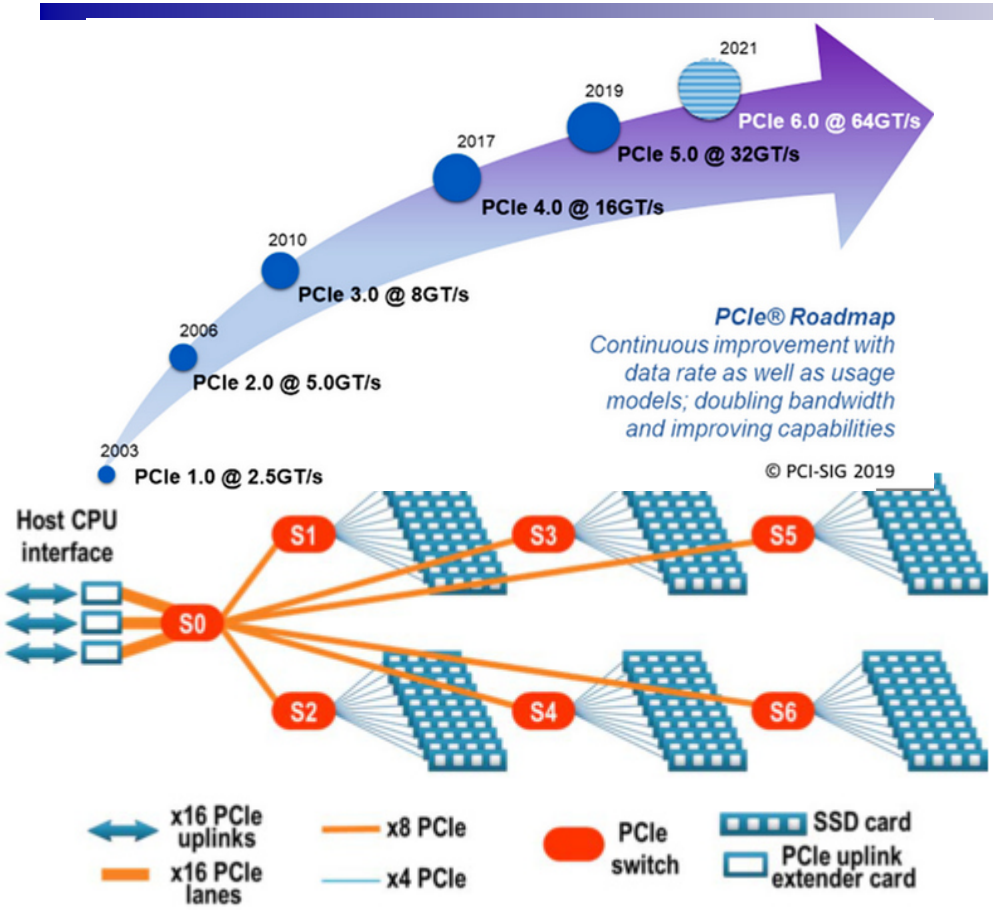
Today's Environment

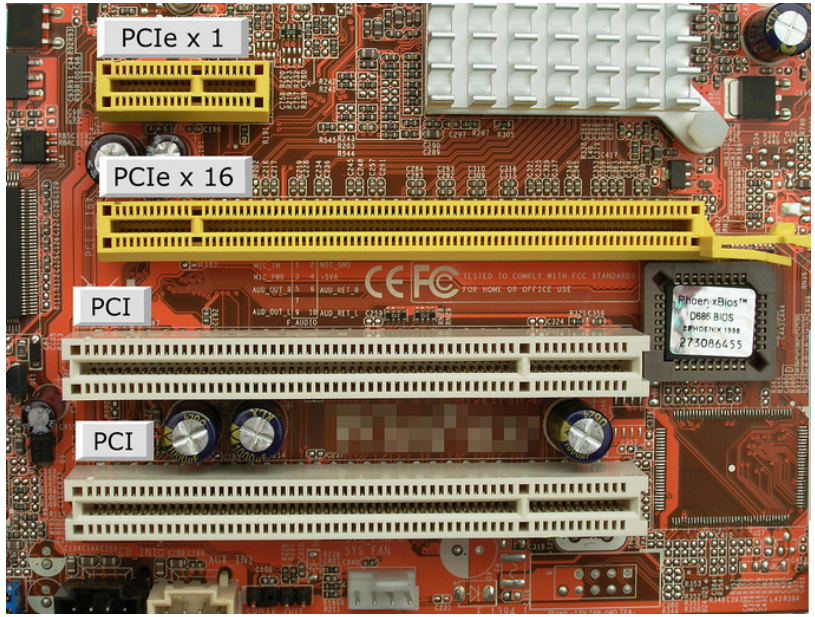


CXL-Enabled Environment



Software Systemtechnik: PCIe, CXL ,NVMe, RoCE, CUDA, FCUDA (F: FPGA)

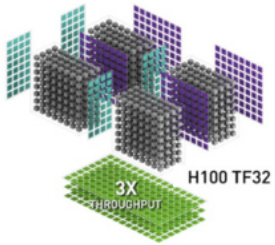


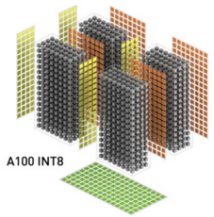


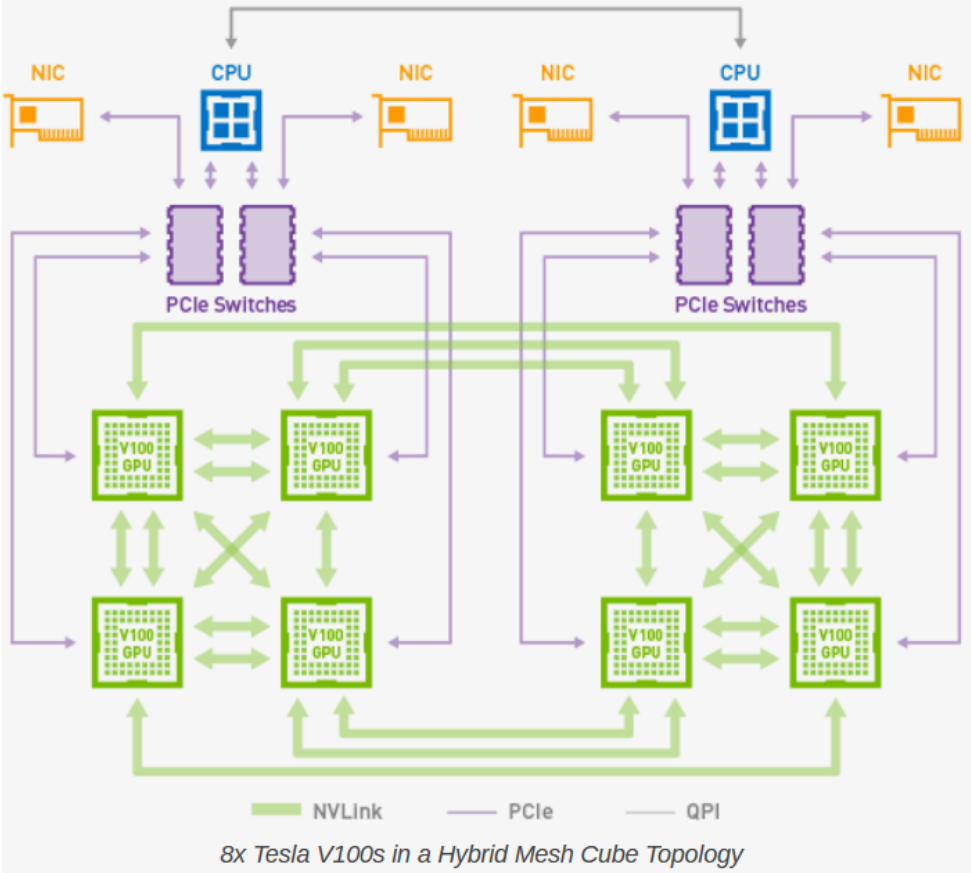
PCI Express 1.0 (×1 link)2.5 Gbit/s
PCI Express 1.0 (×16 link)40 Gbit/s
PCI Express 2.0 (×1 link)5 Gbit/s
PCI Express 2.0 (×8 link) 40 Gbit/s
PCI Express 2.0 (×16 link)80 Gbit/s
PCI Express 3.0 (×1 link)8 Gbit/s
PCI Express 3.0 (×4 link)32 Gbit/s
PCI Express 3.0 (×8 link)64 Gbit/s
PCI Express 3.0 (×8 link)64 Gbit/s
PCI Express 3.0 (×16 link)128 Gbit/s
PCI Express 4.0 (×16 link)256 Gbit/s
PCI Express 5.0 (×4 link) 128 Gbit/s
PCI Express 5.0 (×16 link)512 Gbit/s
PCI Express 6.0 (×16 link)968 Gbit/s

Software Systemtechnik: PCIe, CXL ,NVMe, RoCE, CUDA, FCUDA (F: FPGA), NVlink

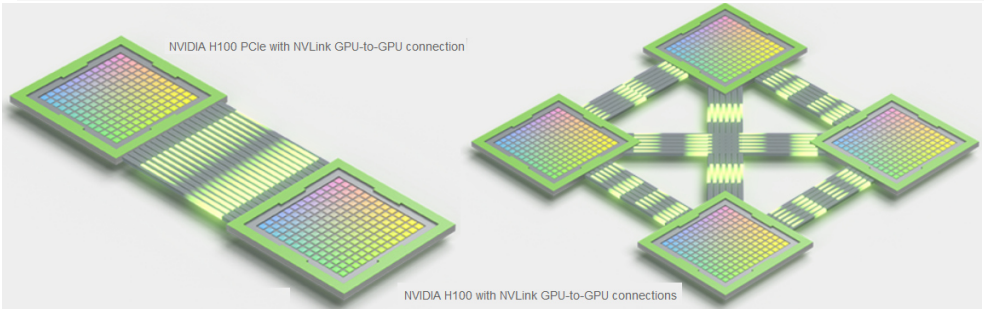
GPU	**8x NVIDIA H100 Tensor Core GPUs**
GPU memory	**640GB total**
Performance	**32 petaFLOPS FP8**
NVIDIA® NVSwitch™	**4x**
System power usage	**~10.2kW max**
CPU	**Dual x86**
System memory	**2TB**
Networking	**4x OSFP ports serving 8x single-port NVIDIA ConnectX-7 VPI** **400 Gb/s InfiniBand or** **200 Gb/s Ethernet**



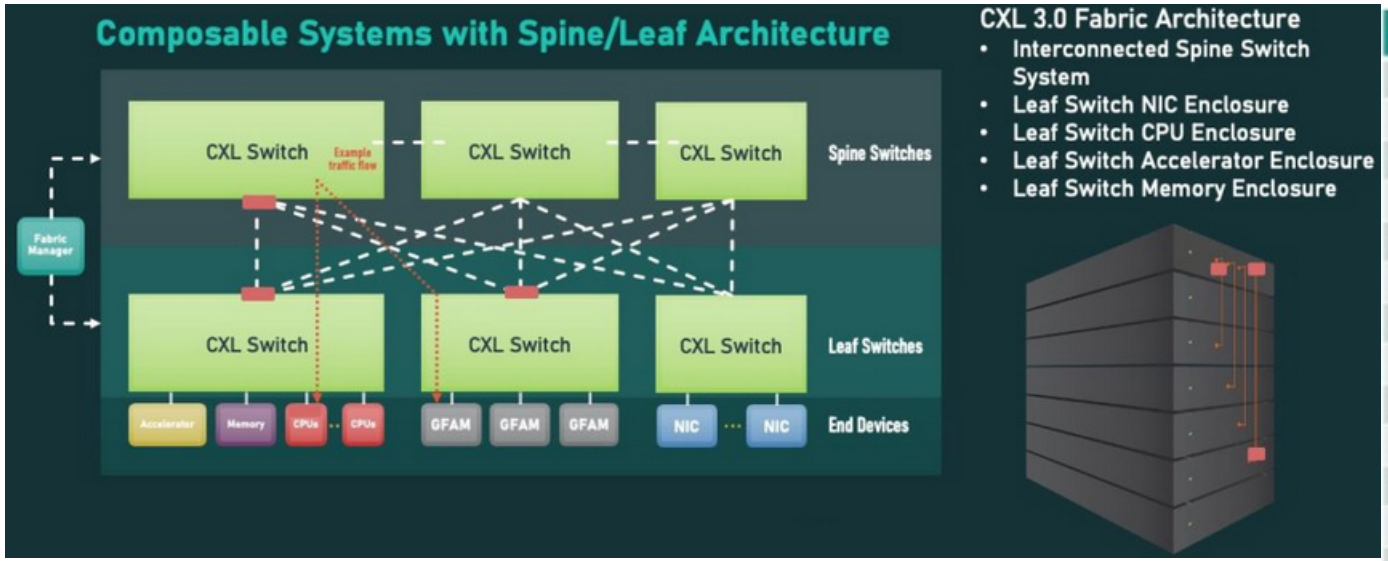




8x Tesla V100s in a Hybrid Mesh Cube Topology



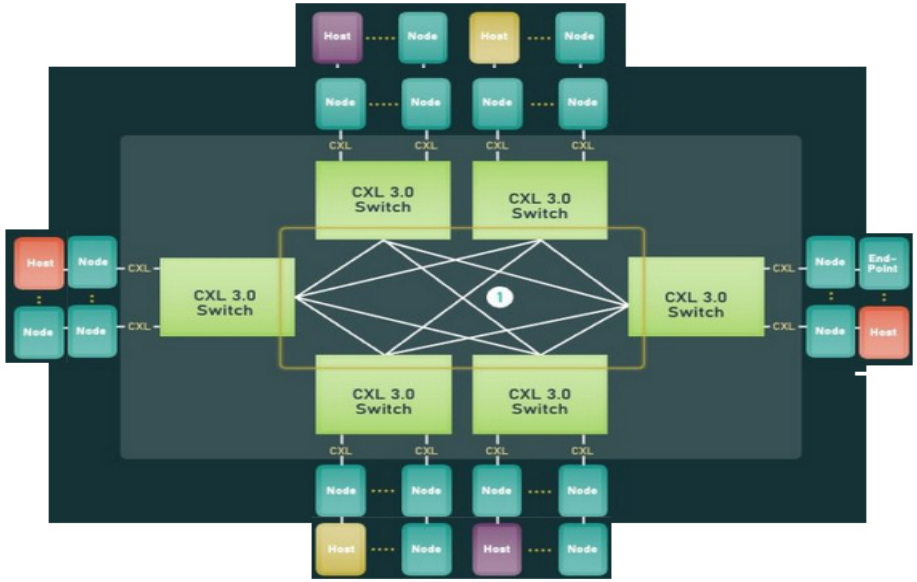
Software Systemtechnik: PCIe, CXL ,NVMe, RoCE, CUDA, FCUDA (F: FPGA)



CXL 3.0 Fabric Architecture

- Interconnected Spine Switch System
- Leaf Switch NIC Enclosure
- Leaf Switch CPU Enclosure
- Leaf Switch Accelerator Enclosure
- Leaf Switch Memory Enclosure

Features	CXL 3.0
Release date	1H 2022
Max link rate	64GTs
Flit 68 byte (up to 32 GTs)	
Flit 256 byte (up to 64 GTs)	
Type 1, Type 2 and Type 3 Devices	
Memory Pooling w/ MLDs	
Global Persistent Flush	
CXL IDE	
Switching (Single-level)	
Switching (Multi-level)	
Direct memory access for peer-to-peer	
Enhanced coherency (256 byte flit)	
Memory sharing (256 byte flit)	
Multiple Type 1/Type 2 devices per root port	
Fabric capabilities (256 byte flit)	



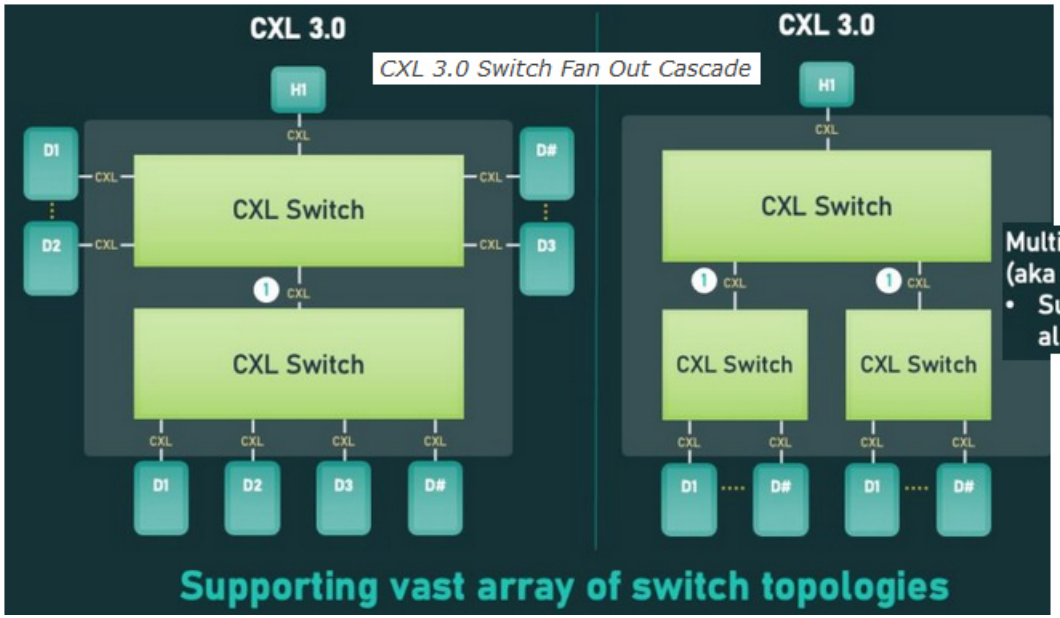
CXL 3.0 enables non-tree architectures

- Each node can be a CXL Host, CXL device or PCIe device

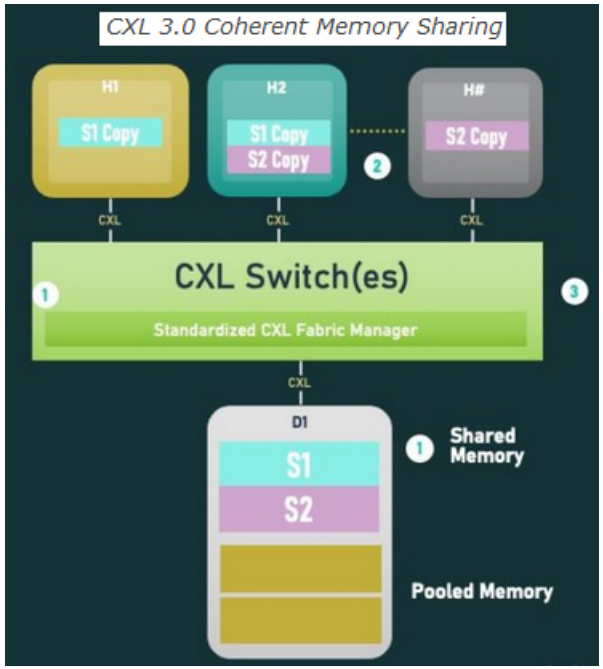
Nodes can be any combination:

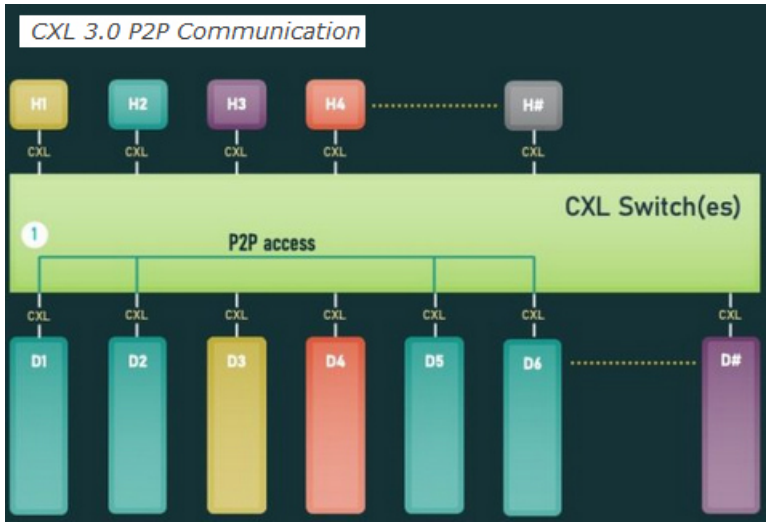
- Hosts
- Type 1 – Device with cache
  - Example: Smart NIC
- Type 2 – Device with cache and memory
  - Example: AI Accelerator
- Type 3 – Device with memory
  - Example: memory expander

11. Software Systemtechnik: PCIe, CXL ,NVMe, RoCE, CUDA, FCUDA (F: FPGA)



Multiple switch levels (aka cascade)
- Supports fanout of all device types





CXL 3.0 enables **peer-to-peer communication (P2P)** within a virtual hierarchy of devices
- Virtual hierarchies are associations of devices that maintains a coherency domain

1. Device memory can be **shared by all hosts** to increase data flow efficiency and improve memory utilization
2. Host can have a **coherent copy of the shared region** or portions of shared region in host cache
3. **CXL 3.0 defined mechanisms to enforce hardware cache coherency** between copies

Real speech produces virtual speech to become real again

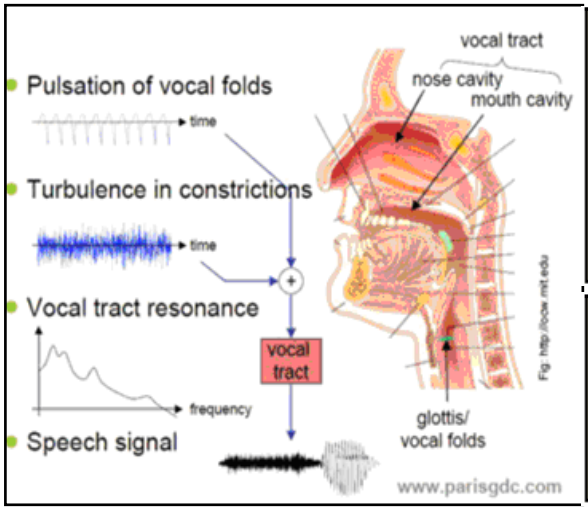
Real speech signal → real speech analysis ⇩⇧ → Real speech reconstruction → Real speech signal

Electronic noise source

- Speech parameters
- Speech frames
- Additional information

Transmission of virtual speech signal → Playout buffer → Virtual speech signal including reconstruction of missing speech parts and reparations

Transmitter: Speech parameter characterization ⇨ **Receiver: Optional speech frequency band extension**

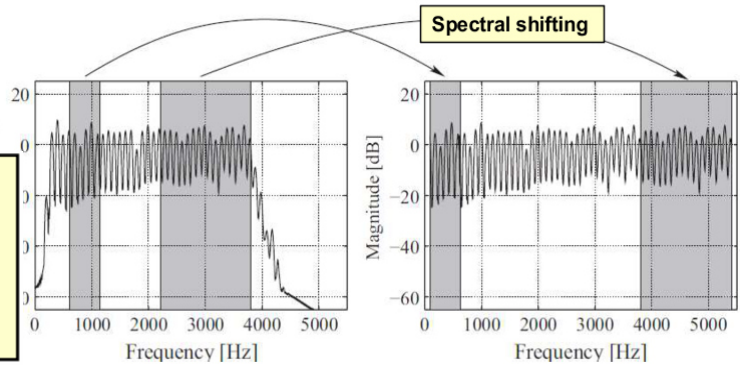


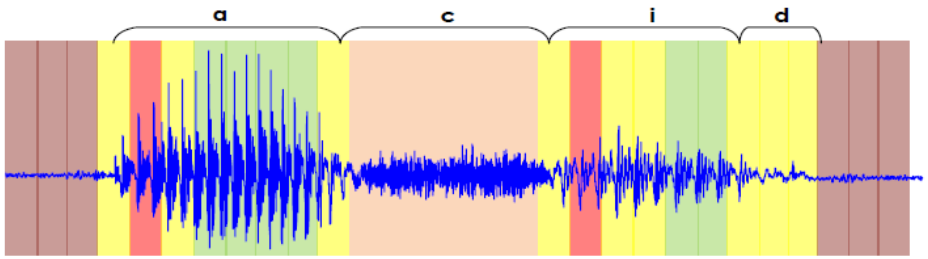
- breathy
- whispering
- creaky
- softer voice
- trembling
- dull and eager speech
- drunk

Signaltransformation Original sound

- negative surprise
- extrovert sadness

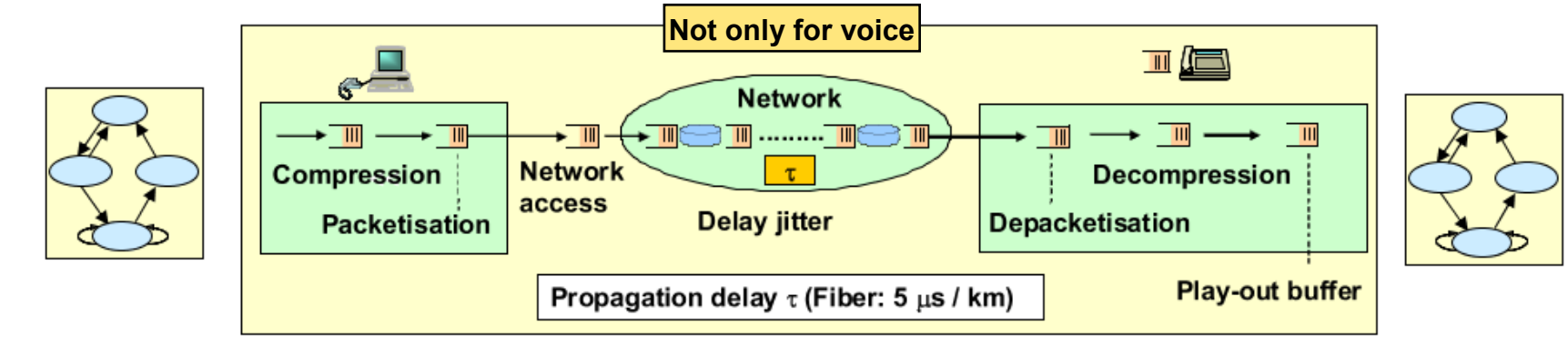
- pitch: lower and higher
- vocal tract: timbre 1 and timbre 2
- voiced contents
- noise contents
- glottal source

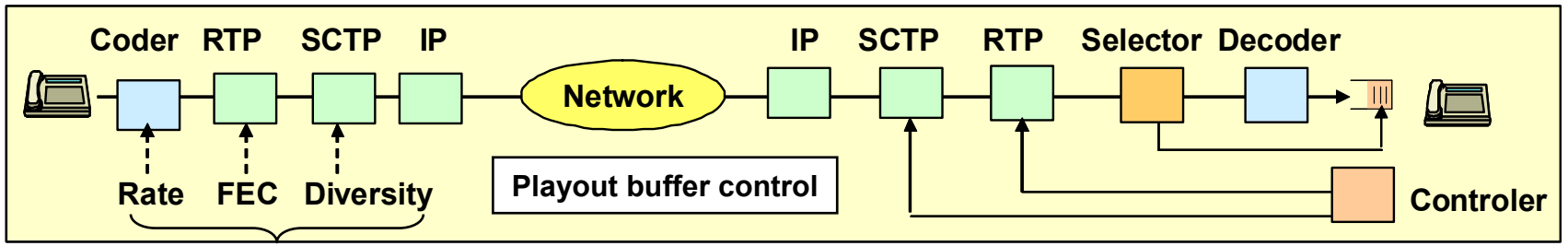




Inactive	– speech or audio activity not detected
Unvoiced	– unvoiced speech frames
Voiced	– quasi-periodic stable active segments
Transition	– improve robustness and encode strong onsets
Generic	– all other speech frames

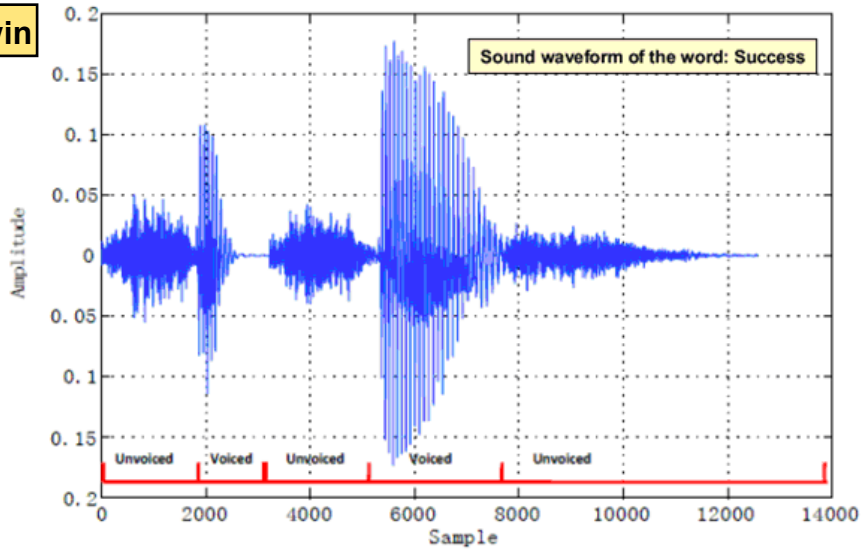
SDN-Twin to enhance IP real-time communications





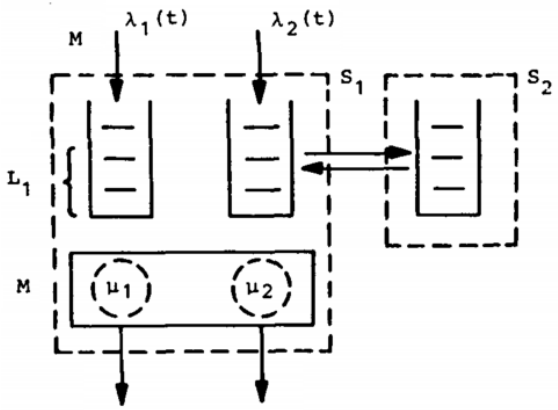
TX: Real twin

RX: Virtual twin

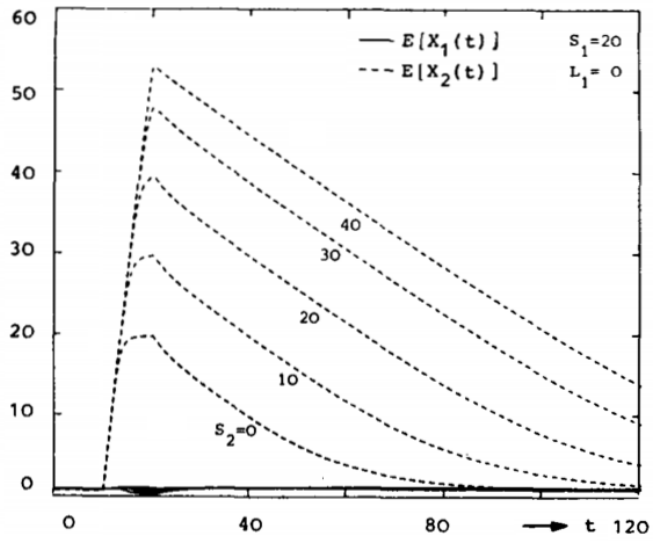


18. Echtzeitsimulation von mathematischen Modellen wie Warteschlangensysteme

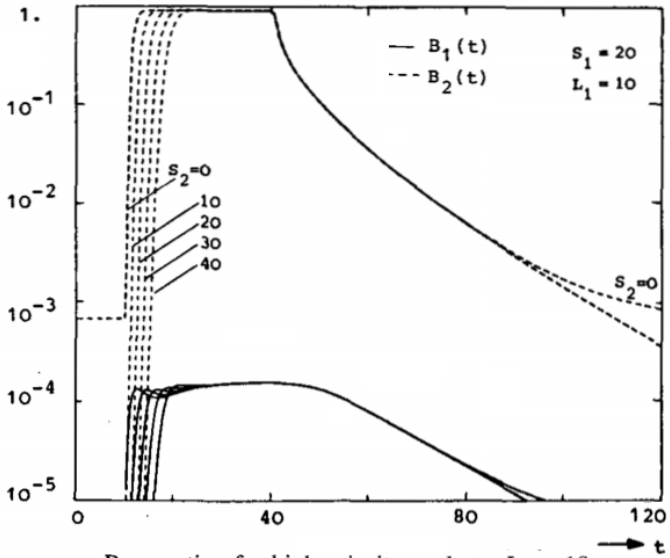
Transient analysis of Markovian queueing systems and its application to congestion-control modeling



FG-BG congestion-control mechanism
Short overload peak of low-priority traffic
Duration $T = 10$, starting at t

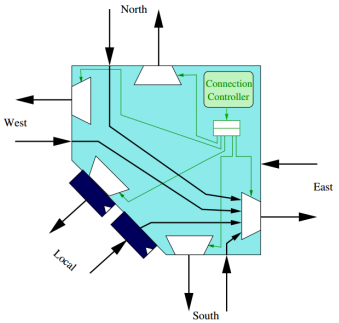


Mean system occupancies $E[X_1(t)]$ and $E[X_2(t)]$



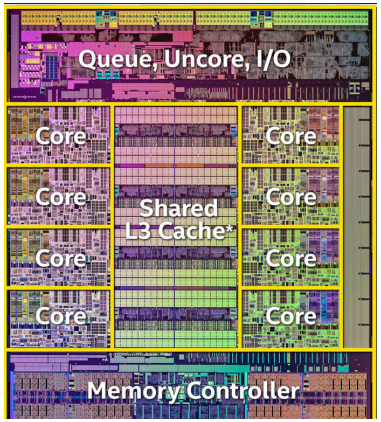
Reservation for high-priority packets, $L_1 = 10$

IEEE Journal on Selected Areas in Communications, Vol. SAC-4, No. 6, 1986, pp. 891- 904

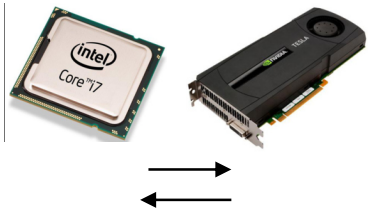


NoC: Network-on-Chip

DPU: Data processing unit



CPU **GPU**



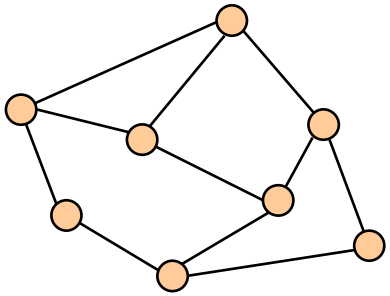
Modellierung von Systemen and Netzen

Modeling of Systems and Networks

Operations Research models

Optimization Methods for

- Routing
- Wavelength assignment
- Resource allocation
- Multicast trees
- Control functions
- Cost determination



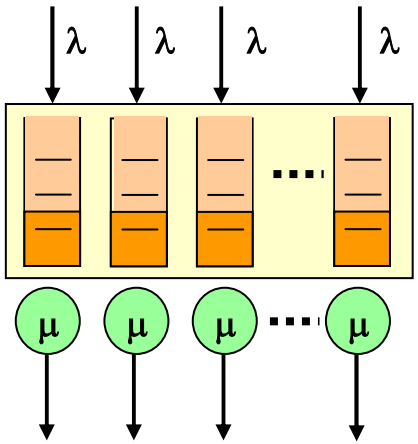
Network graphs, traffic matrix, object function, conditions

Analytical models

Performance evaluation

- Throughput, delay, loss
- Buffer size, occupancy
- Distributions

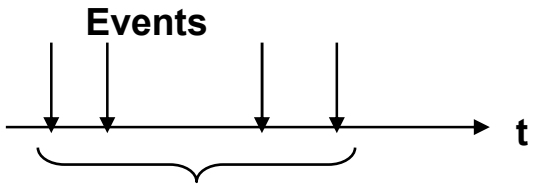
Thousands of models (Theories since 1915)



Simulation models

Performance simulations

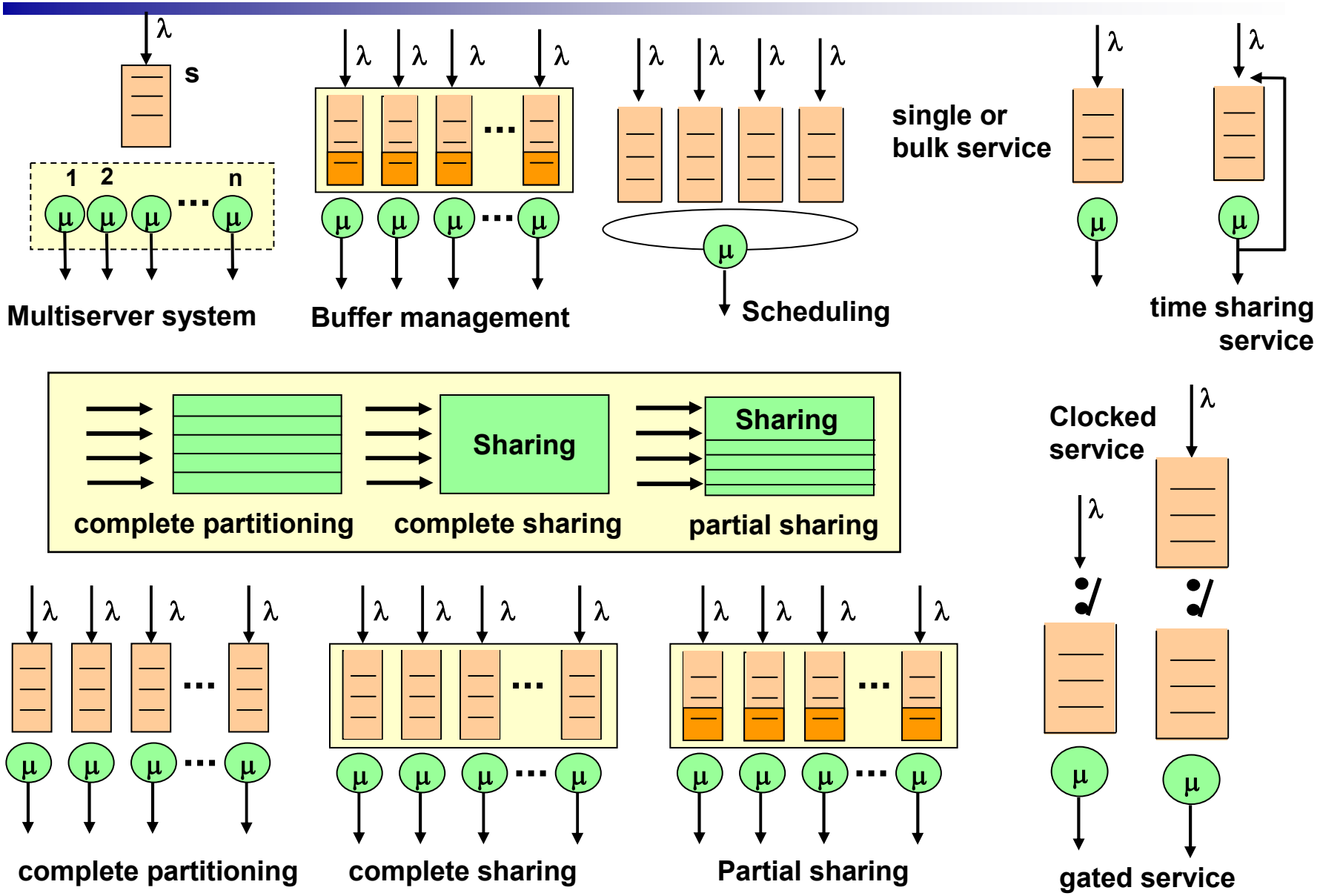
- Event-based
- Statistical Measurements
- Hybrid combinations of analytical models, simulation models and live-systems



Execution of individual Actions of the model

Events: Arrivals, service ends, time-outs, periodic time-marks, …

Zeitplanung und Bandbreitenverwaltung



Lectures on SDN-Twin networking

Vienna University of Technology

389.209 SDN-Twin: Software-defined-networking with digital twins
389.226 SDN-Twin automated software and hardware design, extensions, tests and installation logistics

389.213 SDN-Twin CPU/GPU/DPU processing with memory hierarchy and transmission technologies
389.217 SDN-Twin clouds, edge-computing and access networks

389.211 SDN-Twin optimization based on mathematics and metaheuristics
389.214 SDN-Twin path search, p-cycles, m-cycles, resource allocation and scheduling
389.215 SDN-Twin performance modeling and data traffic flow theory
389.216 SDN-Twin anomaly detection in customer flow protocols and security protection
389.219 SDN-Twin processing of addressing, signalling, mobility and multicast trees

389.220 SDN-Twin performance management of real-time packetized flows of voice, video and control
389.221 SDN-Twin real-time analysis and visualization of interconnections between cyber-physical worlds
389.222 SDN-Twin deep learning and analytics for physical network control and machine-to-machine flows

389.212 SDN-Twin: Digital-twin applications and services in all business sectors
389.208 SDN-Twin in metropolitan cities, towns, villages and rural plus sparsely populated areas
389.210 SDN-Twin in buildings, industries, farming, transportation and mission-critical infrastructures
389.218 SDN-Twin for twin-based moving networks like cars, trains, ships and airplanes

389.223 Real-time simulation of mathematical models, algorithms and methods with all their dynamics
389.224 Real-time communication over packet-oriented networks
389.225 Design of distributed computing systems with physical network and clouds inside
389.227 Modelling of cyber-physical digital twin systems and their technical realization

What makes SDN-Twin networking so attractive?

(1) Open source networking that will be driven by the newest results of the scientific community,
(2) Simplicity due to separation of network infrastructure and customer data flows,
(3) Universal network design method with purpose-tailored optimization,
(4) Perfect dynamic optimized logistic system that is operated adaptively by digital twins,
(5) Distributed computer system with an inside integrated network including diverse cloud elements,
(6) Networking paths become controlled transmissions within chips/devices and between devices,
(7) The best of two industrial worlds, computing/memory, transmission and networking principles
(8) Network programming as application with well-known languages,
(9) Automated pipe-lined generation from design up to installation lists,
(10) Complete analysis of all available routes and properties before realization,
(11) Using traditional teletraffic flow optimization for the coordination twin,
(12) Using queueing theory models for adaptive scheduling of forwarding in switching twins,
(13) Using twin control to continuously, but asynchronously, adapt the virtual model to physical reality,
(14) Zero-touch installation,
(15) Sustainable because stable lifetime with increased quality and growth,
(16) QKD (quantum key distribution) internal network security of infrastructure and customer flows,
(17) Complete operational transparency due to the intrinsic live simulating digital twin system,
(18) On-demand simulative Analysis of detected anomaly events in the original network design versions.
(19) Fast and automated (re)configuration of traffic and security requirements of customer flows.
(20) Early congestion detection with fast load capacity changes and delay timing control,

(21) Fast reaction to link and node failures,
(22) Optimal green network operation by closing and opening routing paths (standby or switched off),
(23) Combination of pacing and credit flow control,
(24) MTM (memory transfer mode) switching in virtual coordination twin and all real twin switching units,
(25) Continuously stable TCP flows with delivery guarantee and feedback notification and resequencing,
(26) Full link capacity flows without losses by using this TCP protocol in a special way,
(27) Lossless operation due to temporary FG-BG (foreground-background storage),
(28) Controlled network feedback as structured RDMA flow of m-cycles (monitoring) on screens,
(29) Structured RDMA flows allows physical network status data immediately to be plugged in,
(30) Minimal required protection capacity requirements by p-cycles (predefined),
(31) Simplified network management by detailed visualization and optical guidance what to repair,
(32) Routing through the physical network by dynamic label switching,
(33) Access load distribution for sudden unpredictable traffic load distribution changes,
(34) Computing system on a bounded switching area to be plugged easily into a existing network,
(35) When internal IP addressing should be maintained, freely chosen private IP addressing,
(36) Virtualization of addressing, signalling, mobility and multicast trees executed in real network,
(37) Visual location identification support for faulty equipment repair,
(38) Full operational transparency exhibiting best operational overall performance expressed by
minimum {Capex (capital expenditures), Opex (operating expenses), Lean} and
maximum {Availability, Performance, Quality features, Security, Green}.

aTinaTwin©

CREATING SDN-TWIN NETWORKS

The next revolution in IP networking:

A fresh new perspective on building software-defined computer and telecom networks using digital twins.

aTinaTwin is a private task force to make the concept and technology of SDN-Twin available to the public.
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