



**Università degli Studi dell'Aquila**  
**Dipartimento di Ingegneria e Scienze dell'Informazione e Matematica**

**Seminario Professionalizzante**  
**“Advanced Internet Architecture, VHC Telco Networks, Services, Edge Cloud**  
**and Mathematical Models”**

**1<sup>a</sup> edizione**

**A.A. 2025-26**

**PROPOSTA**

**Gianfranco Ciccarella**

**Seminar Objective**

This seminar provides an advanced, integrated understanding of the Internet as a global communication system. The Internet interconnects packet networks via standard protocols and provides access to shared resources — such as servers, clouds, and client terminals — which deliver and manage services. The seminar analyzes:

- **Internet architecture principles:** the interconnection of packet networks, functions layering, and the complete distribution of all the functions that provide connectivity and services
- **Services:**
  - **Network Services** manage connectivity — the transport of individual packets within a network and the interconnection between networks. This is a basic connectivity service that does not manage packet flows. Network service protocols reside in IETF layers up to Layer 3 (Network).
  - **Application Services** manage the applications used by clients. These services are run on resources (servers/clouds and client terminals) connected to the networks and control both:
    - The end-to-end (e2e) connectivity, i.e., the bidirectional flow of packets across different networks between the client terminal and the server/cloud offering the service.
    - The e2e "state" of the networks between the server/cloud and the client terminal, via flow control and congestion avoidance mechanisms based on TCP and UDP protocols.
    - The "intelligence" for controlling e2e connectivity and network state resides in the devices connected to the networks, which are not

network components themselves. Application service protocols belong to IETF Layer 4 (Transport) and Layer 5 (Application).

- **Enabling Services** improve Application Services performance by distributing some application "components" (software and content) on cloud platforms located "closer" to client terminals. Application performance depends on "application transport protocols" (TCP and UDP) and is limited by the e2e network services' Key Performance Indicators (KPIs), such as available transmission capacity (Bit Rate bottlenecks), latency, packet loss and round-trip time (RTT). Distributing application components improves these network KPIs and, consequently, application performance. This approach represents the most effective and efficient solution for enhancing application performance. Enabling Service protocols operate at IETF Layers 4 (Transport of Applications) and 5 (Applications).

The principles of Internet architecture and its services provide the flexibility required for deploying new applications, as they do not necessitate changes to the network architecture. Performance improvements are achieved by deploying distributed cloud platforms, referred to as Edge Cloud platforms, when connected at the network edges.

The seminar also compares two distinct network architectures: Telecommunication Operators' networks (Telco networks) and Big Internet networks (OTT networks). Telco networks provide connectivity from user devices (terminals or servers/clouds) to the Big Internet networks. The servers/clouds of companies offering Application Services (OTTs) and Enabling Services are, usually, connected to the Big Internet networks.

The course begins with an analysis of Internet architecture and services, defining the main Network and Application Services KPIs, and covering the fundamentals of window-based flow and congestion control mechanisms. This includes TCP sliding-window mechanisms, ACK-clocking, Bandwidth-Delay Product (BDP), fairness, and Active Queue Management (AQM). These concepts are studied analytically using fluid-flow models that evaluate application Throughput (TH) for given protocols (e.g., Reno, Cubic) when network KPIs are measured. TH represents the actual application speed, which is lower — sometimes significantly lower — than the available Bit Rate (a network KPI measuring transmission capacity).

In the second part, queueing network models are introduced, along with the fundamentals of queueing network-based flow and congestion control mechanisms for protocols like BBR (Bottleneck Bandwidth and Round-trip Time). Queueing network models or simulations are used to evaluate network KPIs, while fluid-flow or queueing-network-based models provide application service KPIs.

This section also introduces the Edge Cloud Computing paradigm, analyzing how distributing Application Services components across Cloud and Edge Cloud improves application KPIs. It covers the principles of enabling technologies and services, such as content delivery via transparent caching, and presents:

- **Jackson's queueing-network-based models to evaluate the main network service KPIs** for networks with and without Edge Cloud. Comparing these two architectures provides a quantitative analysis of improvements in both network and application KPIs. Jackson's models offer simple solutions when their assumptions hold: communication links and nodes modeled as M/M/1 systems, independence of

interarrival times and packet lengths, Poisson arrivals at entry points, exponentially distributed packet lengths, and densely connected networks. The primary approximation is the independence of interarrival times and packet lengths, which is lost after the first transmission line. Kleinrock's "independence approximation" suggests that merging packet streams on a transmission line restores this independence. If independence holds, other approximations (e.g., packet length distribution) can be managed using the Pollaczek-Khinchin (P-K) formula. When Jackson's assumptions are not met, simulations and field measurements provide more accurate network KPI evaluations.

- **Fluid-flow-based models to evaluate application KPIs**, using network KPIs obtained from queueing-network-based models or simulations, for networks with and without Edge Cloud. This comparison demonstrates the performance improvement enabled by Edge Cloud and illustrates how distributing Application Services across Cloud and Edge Cloud enhances application KPIs. **Comments on queueing-network-based models for evaluating application KPIs** (e.g., for the BBR protocol) in both network scenarios are also provided.
- The **principles of key Enabling Technologies and Services**, such as transparent caching for content delivery, 360-degree augmented reality, and real-time interactive applications are also discussed.

The overarching goal is to provide students with a unified, end-to-end view of how network architectures, transport protocols, and Edge Cloud design jointly define network efficiency, Quality of Experience (QoE), and the economic sustainability of ultra-broadband and Very High Capacity (VHC) networks and services.

## Seminar Internal Organization

Recipients:

The seminar primarily targets:

- PhD students in ICT, Computer Engineering, and Information Engineering.
- Master's students in Telecommunications Engineering, Computer Engineering, Electronic Engineering, and Control Systems Engineering.
- Third-year Bachelor's students in related engineering programmes may also be admitted, subject to background assessment.

The course is suitable for both Italian and international students and is delivered entirely in English. External auditors may be admitted.

Duration: 28 hours, delivered as 7 sessions of 4 hours each.

Lecturer: Gianfranco Ciccarella, Senior ICT Consultant; former Corporate CTO and CIO (Telecom Italia Sparkle); Chairman and CEO of Telecom Italia group companies; former Adjunct Associate Professor of Telecommunications at Brooklyn Polytechnic, New York; former Professor of Automatic Control at the University of L'Aquila.

Schedule and Delivery:

The seminar is proposed to take place between the 4th of April and the 23rd of May 2026, in person.

Tentative dates: April 10th; April 17th; April 24th; April 28th; May 8th; May 15th; May 22nd.

Tentative schedule: 12:00–13:00 & 15:00–18:00; or 11:00–13:00 & 15:00–17:00.

## Seminar Program

### Part I. Internet Architecture, Services, Flow and Congestion Control Fundamentals (12 hours)

#### Day 1. Internet Architecture, Network and Application Services and Protocols (4 hours)

The seminar opens with an in-depth exploration of Internet Architecture. Students are guided through the layered architecture defined in classical RFCs, with particular attention to RFC 1622. This establishes the functions managed by network services (IETF layers up to 3, Network) and by application services (layers 4, Transport, and 5, Application), which manage packet flows via end-to-end connectivity control (flow control and congestion avoidance mechanisms). The session reconstructs the technical foundations of the end-to-end principle, examining how intelligence placed at the network edges has shaped scalability, robustness, and service innovation. Building on these concepts, the lecture explains the relationship between packet formats, MTU and MSS constraints, the mechanics of packet switching, and defines the main KPIs for network and application services. Special emphasis is placed on Layer 4 transport protocols: TCP, which provides reliable transport, and UDP, which does not. However, both TCP and UDP must manage the network "state" via flow and congestion control mechanisms. High-level comments on virtual circuits, dedicated networks, and the main differences between Telco Networks and Internet networks will be presented to highlight the related technical and economic issues.

#### Day 2. Window-Based Flow and Congestion Control: Transport Dynamics (4 hours)

This session examines the dynamics of TCP flow and congestion control. Students revisit the sliding-window mechanism and progressively reconstruct how slow start, congestion avoidance, additive increase, and multiplicative decrease interact to regulate traffic injection into the network. Through graphical timelines and control diagrams (e.g., the Slow-Start/Congestion-Avoidance cycle), the session clarifies how throughput emerges from the interplay between window size and connectivity KPIs such as RTT and packet loss. The discussion then analyzes the Bandwidth-Delay Product as a determinant of maximum achievable throughput, followed by an introduction to mathematical transport models. The lecture illustrates how fluid-flow abstractions — routing matrices, link prices, and distributed feedback loops — capture the behavior of multiple flows sharing a constrained bottleneck. *These models allow congestion control to be understood not only as a protocol mechanism but as a dynamic, fully distributed control system influenced by delay, fairness requirements, and stability conditions.* Comments on protocols such as BBR (Bottleneck Bandwidth and Round-trip Time) will be provided to compare the window-based approach with queueing-network-based flow and congestion control.

#### Day 3. Queueing Theory and Active Queue Management (4 hours)

The third day consolidates analytical foundations by introducing queueing-theoretic models for network components (nodes and links) and for packet networks. Through examples, students study deterministic and stochastic queueing systems such as D/D/1 and M/M/1, examining how utilization ( $\rho$ ) shapes the average packet time in the system, the average

number of packets waiting in the queue and in the system, and system stability. This theoretical introduction motivates the limitations of the traditional drop-tail discipline, including full-queue behavior and unfairness among flows. The lecture then introduces Active Queue Management techniques, focusing on RED and Adaptive RED, explaining how anticipatory packet drops can reduce delays, prevent queue build-up, and promote fairness. The session concludes with a discussion of the "under-utilization problem" in very high-speed networks, analyzing how modern TCP variants such as CUBIC attempt to overcome the slow growth of the congestion window in high-BDP environments.

## **Part II. Application KPIs, QoE, and Edge Cloud Computing (16 hours)**

### **Day 4. Application KPIs: Throughput and Quality of Experience (4 hours)**

Part II connects network service KPIs to application transport protocol behavior — that is, to the actual application performance experienced by end-users. The lecture begins by distinguishing the Application Throughput (TH) KPI from the available Bit Rate (BR), a network KPI, using fluid-flow models and measurements. TH is typically much lower than BR, even in broadband and ultra-broadband networks. TH and other key Application KPIs are limited by Network KPIs (such as available Bit Rate, RTT, and packet loss). Two approaches can improve application performance in any network: QoS (Quality of Service) and/or QoE (Quality of Experience). QoS improves network KPIs by increasing network capacity (higher transmission bandwidth and node service rates) and/or implementing traffic management (priority and dedicated Bit Rate). Today, with most packet payloads encrypted, QoS via traffic management is only applicable in limited cases, such as specific virtual circuits within a Telco network. QoE improves network KPIs by distributing some application components (processing power, software, and data/content) on servers/clouds closer to clients. The difference between QoS and QoE is significant, impacting both the degree of application performance improvement achievable and the cost of deployment. Real-world cases from fixed and mobile systems are analyzed to illustrate typical performance bottlenecks in streaming, web browsing, and interactive services. These examples provide a practical understanding of how connectivity impairments limit application transport layer performance.

### **Day 5. Edge Cloud Computing Architectures (4 hours)**

The fifth day introduces the architecture and principles of Edge Cloud Computing (ECC). The lecture explains how distributing applications and contents closer to end-users, within access POPs, reduces the utilized available Bit Rate, RTT, and packet loss and improves applications performance. The session clarifies the conceptual separation between connectivity services — responsible for single-packet transport within a network at IP (Layer 3) and Link (Layer 2) levels — and application services, managed by servers/clouds, which control both e2e connectivity and the applications themselves. Distribution 'closer' to clients significantly improves application performance and, in many cases, reduces network cost.

Jackson's queueing network model assumptions and equations to evaluate connectivity KPI will be presented. The network service KPIs for simple networks with and without an Edge Cloud platform will be compared. Comments on more complex architectures will also be provided. The results from Jackson's model are discussed to offer a high-level view of when this model is applicable and when simulations are necessary (e.g., for networks with G/G/1 node/link models).

Cloud platforms are crucial for OTTs, which have deployed Edge Cloud platforms near Telco networks and in some Telco Core POPs. For Telco networks, deploying Edge Cloud is often necessary because Telco networks can limit OTT application performance. To achieve the best application improvement and highest network savings, Edge Cloud platforms should be connected to Telco Access POPs. However, Edge Clouds connect via Layer 3, while traditional Telco networks use Layer 2 tunnel connectivity from the user terminal to the Core, with Layer 3 only from the Core to the Big Internet. Therefore, to install Edge Cloud in Telco Access POPs, some Core functions must be distributed to the access POPs (virtualized or managed via local breakout) to gain Layer 3 visibility and insert packets from the Edge Cloud into the Layer 2 tunnel to the user terminal or server/cloud.

#### **Day 6. ECC Impact on Performance, Network Cost, and Business Models (4 hours)**

This session completes the queueing network models analysis and expands into the broader system-level consequences of deploying ECC. Starting from performance benefits — improved throughput, reduced latency and loss — the lecture shows how ECC enables new revenue streams and supports advanced services like UHD streaming, low-latency communications, and interactive applications. Students then explore how network operators can reduce Total Cost of Ownership (TCO) through edge-based distribution, multi-operator sharing of ECC platforms, and optimized traffic flows in the access and metro networks. Several multi-operator case studies illustrate how ECC architectures reshape both performance engineering and economic models in modern telco environments.

#### **Day 7. Integrating TCP Dynamics with Edge-Native Architectures (4 hours)**

The final day synthesizes the entire seminar by linking connectivity dynamics to architectural choices in next-generation networks. Students analyze how congestion control constraints influence the feasibility and design of services requiring stringent QoE guarantees, such as 4K/8K video, cloud gaming, extended reality, and low-latency industrial applications. The session examines emerging trends — including Very High Capacity (VHC) networks, edge-native computing paradigms, Multi-access Edge Computing (MEC), and AI-assisted optimization — highlighting how the future evolution of network architectures depends on the coordinated tuning of transport protocols, edge infrastructures, and application service models. The goal is to provide a unified perspective on how end-to-end performance emerges from the interaction of architectures, protocols, and technical-economic constraints.

#### **Bibliography (to be completed)**

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