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TELEMETRY AS THE FOUNDATION OF PREDICTABLE QOS IN HYBRID CAMPUS NETWORKS

This paper addresses the problem of ensuring predictable Quality of Service (QoS) in hybrid campus networks that integrate wired Ethernet segments and wireless Wi-Fi segments into a unified infrastructure. It is shown that the fundamentally different nature of constrained resources — bandwidth and queueing in the wired environment versus airtime in the wireless medium — precludes the direct application of classical QoS mechanisms without adaptation. The necessity of a systematic end-to-end QoS approach is substantiated, based on policy alignment across heterogeneous segments and the use of telemetry as a means of verifiability and controlled adaptation. Classes of telemetry metrics are proposed that enable the assessment of resource state, access quality, and integral end-to-end quality indicators in

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hybrid campus networks. The role of telemetry as a foundation for building stable QoS policies and for the subsequent application of automation and machine learning methods is demonstrated.

Keywords: *hybrid campus network; Quality of Service; QoS; network telemetry; Wi-Fi; Ethernet; airtime; end-to-end QoS.*

Introduction

Modern campus networks integrate multiple networking technologies — such as the IEEE 802.3 family of standards—into a unified hybrid infrastructure in which the interaction between different transmission media is critically important. The defining characteristics of such networks include user mobility and traffic heterogeneity, which make Quality of Service (QoS) management an inherently end-to-end challenge. In Wi-Fi networks, the primary constrained resource is airtime, which is strongly influenced by radio environment conditions, whereas in wired and optical Ethernet networks the limiting factors are bandwidth and queueing resources.

Consequently, achieving predictable and stable QoS requires coordinated policies, systematic telemetry, and adaptive control mechanisms that enable effective coordination of resources across both segments and ensure service reliability for all traffic classes.

Problem Statement

The objective of the paper is to develop a systematic approach to ensuring predictable Quality of Service in hybrid campus networks that combine wired and wireless segments within a unified infrastructure. The study focuses on analyzing the fundamental differences in the nature of constrained resources in Ethernet and Wi-Fi networks and on identifying the implications of these differences for the organization of end-to-end QoS.

The primary task is to substantiate the role of telemetry as a key instrument for verifiable QoS, enabling a transition from declarative and static policies to controlled adaptation, based on the actual state of the network. Within this scope, the paper also addresses the task of classifying and systematizing telemetry metrics that are informative for assessing Quality of Service in both segments and that can be coherently aligned across the hybrid network.

Hybrid Campus Network: Definition and Key Characteristics

A hybrid campus network is a network of a single institution or a group of enterprises, geographically confined, that belongs to a specific branch of the regional provider Internet topology. Such a network integrates wired optical and copper Ethernet segments with wireless Wi-Fi segments into a single service domain with coordinated access, security, and Quality of Service policies. Unlike the traditional model, in which wireless access was treated as an auxiliary component, in a hybrid campus network both transmission media are considered equal and integral parts of a unified infrastructure.

A key characteristic of a hybrid campus network is **user mobility combined with traffic heterogeneity**. Users and devices can dynamically change their points of attachment and access types while simultaneously consuming services with diverse requirements in terms of latency, bandwidth, and reliability. This transforms Quality of Service provisioning from a set of local configuration tasks into a comprehensive end-to-end system-level challenge.

Hybrid campus networks are typical for **modern universities, healthcare institutions, corporate and industrial facilities**, where stationary systems, staff mobile devices and numerous Internet of Things devices coexist. In such environments Wi-Fi is used not only for user access but also to support mission-critical services, which significantly increases the requirements for QoS predictability and stability.

A fundamental distinction between hybrid campus networks and traditional architectures lies in **the different nature of their constituent resources**. In wired Ethernet segments, the primary resources are link bandwidth and service queues, whereas in Wi-Fi the limiting resource is airtime, which is allocated among stations in a competitive manner and is highly dependent on radio-environment conditions. This precludes the direct application of classical QoS mechanisms without appropriate adaptation.

An additional challenge arises from **the nondeterministic nature of wireless access** and the need to align priorities across heterogeneous traffic classification and scheduling mechanisms in Wi-Fi and Ethernet. A priority assigned in the wired portion of the network does not guarantee equivalent service quality in the wireless segment without proper mapping and control.

Therefore, a hybrid campus network must be treated as **a single managed system** in which QoS is shaped along the entire transmission path. This necessitates a systematic QoS approach based on coordinated policies, the use of telemetry and careful consideration of the physical and protocol-level characteristics of different access media.

Primary Approaches to QoS Organization in Wired and Wireless Campus Network Segments

Quality of Service in campus networks is defined as a set of mechanisms for managing constrained resources in order to provide specified performance characteristics for different traffic classes. In hybrid campus networks these mechanisms are implemented simultaneously in wired Ethernet environments and wireless Wi-Fi environments, which differ fundamentally in their physical and protocol-level characteristics.

QoS in the Wired Ethernet Segment. In the wired segment QoS is based on a relatively deterministic channel model in which the primary constrained resources are **link bandwidth and device buffer memory**. Classical approaches include traffic classification and marking (IEEE 802.1p, DSCP), the use of queues and schedulers, as well as traffic policing and shaping mechanisms. When properly configured, these mechanisms make it possible to achieve reproducible and predictable behavior for critical traffic classes, particularly real-time services.

QoS in the Wireless Wi-Fi Segment. In the wireless Wi-Fi segment, QoS is implemented under conditions of shared use of the radio medium, where the primary scarce resource is **airtime** and medium access is inherently competitive. The IEEE 802.11e standard defines MAC-layer enhancements, in particular the Enhanced Distributed Channel Access (EDCA) mechanism, which is implemented in practice through Wi-Fi Multimedia (WMM) [1]. These mechanisms allow different contention parameters to be assigned to traffic classes but do not provide strict resource guarantees.

The effectiveness of QoS in Wi-Fi is highly dependent on physical-layer factors, including radio environment conditions, modulation rates, the number of retransmissions and client density. Under such conditions, the traditional interpretation of QoS as a bandwidth guarantee is of limited applicability; a more appropriate metric becomes **fairness in airtime allocation**.

Comparison of QoS Approaches in Ethernet and Wi-Fi. The key differences between QoS approaches in wired and wireless segments are summarized in Table 1.

Implications for Hybrid Campus Networks. The comparison demonstrates that QoS in Ethernet and Wi-Fi relies on **fundamentally different resource and contention models**. In a hybrid campus network, this implies that identical traffic marking (e.g., DSCP—Differentiated Services Code Point) does not guarantee equivalent service quality across wired and wireless segments without additional policy alignment. Accordingly, QoS organization must be treated as an end-to-end system-level task that requires consideration of Wi-Fi physical constraints, the use of telemetry and controlled policy adaptation.

Table 1. **Differences between QoS approaches in wired and wireless segments**

Characteristic	Ethernet	Wi-Fi
Primary constrained resource	Bandwidth, queues	Airtime
Medium access type	Deterministic	Competitive
Main QoS mechanisms	Queues, schedulers, shaping	EDCA / WMM (IEEE 802.11e)
Impact of physical layer	Minimal	Critical
Base fairness metric	Bytes / throughput	Airtime
Predictability	High	Limited
Congestion response	Queuing, packet loss	Collisions, increased latency

At the same time, there is a need for rapid and flexible modification of policies. Software-defined networking (SDN) is well suited to this task [2]. In addition to improved flexibility, software-defined networks may also demonstrate superior latency characteristics [3].

Telemetry as the Foundation of Verifiable QoS in Hybrid Campus Networks

The Role of Telemetry in QoS. In hybrid campus networks, Quality of Service cannot be treated as a set of declarative policies or static configurations. Due to the differing physical nature of wired and wireless segments, as well as the dynamic behavior of Wi-Fi, actual service quality is formed over time and depends on the current state of the network. In this context, **telemetry becomes a necessary prerequisite for verifiable and controllable QoS**.

Telemetry enables the network operator to:

• observe actual resource consumption;

• detect discrepancies between configured policies and real network behavior;

• evaluate the impact of changes to QoS parameters;

• provide a foundation for adaptive control without sacrificing stability.

Without telemetry, QoS remains a local configuration artifact rather than a systemic property of the network.

Principles of Telemetry System Design. When applying telemetry to QoS tasks, not only the metrics themselves are important, but also the principles governing their selection and processing [4]:

• **End-to-end consistency** — metrics must be aligned across Wi-Fi and Ethernet segments.

• **Measurability** — each metric must have a well-defined method of collection and interpretation.

• **Sensitivity to degradation** — metrics should react to quality degradation before it becomes critical.

• **Compatibility with automation** — metrics must be suitable for aggregation and analysis in cloud-based systems.

This approach enables the application of machine learning (ML) techniques for monitoring hybrid campus networks [5].

Classes of QoS Telemetry Metrics. For a systematic analysis of QoS in a hybrid campus network, it is advisable to distinguish several complementary classes of metrics, as summarized in Table 2.

Telemetry Aggregation and Alignment. Individual metrics have limited value without alignment across segments. This is achieved through:

• normalization of indicators;

• aggregation by traffic classes and locations;

• correlation between Wi-Fi and Ethernet metrics.

Of particular importance is the transformation of Wi-Fi metrics (e.g., airtime, retries) into a form suitable for comparison with wired-network indicators.

Table 2. **Complementary classes of metrics for systematic QoS analysis**

Metric category	Key metrics	Interpretation	Collection methods
Traffic and queues (Ethernet & Wi-Fi)	Average/peak per-class throughput, queue occupancy, packet drops, queueing delay and variation	Reflect congestion and scheduler efficiency; in Wi-Fi, reveal systematic degradation	Switch/AP counters, SNMP, streaming telemetry, hardware queue counters
Airtime and access (Wi-Fi)	Airtime share per class/client, access attempts and retries, average wait time, collisions/backoff	Assess fairness of resource allocation; identify cases where high priority does not yield expected QoS	AP counters, Wi-Fi controller telemetry, vendor-specific streaming APIs
Physical layer (Wi-Fi)	RSSI, SNR, MCS in use, retransmissions, channel width, noise level	Separate physical issues from QoS policies; critical for correct control	AP telemetry, radio monitoring sensors, client driver data
End-to-end delay and quality	End-to-end latency, jitter, packet loss, service reachability	Reflect user-perceived quality; verify achievement of target QoS	Active probing, passive flow analysis, application-layer telemetry
Stability and dynamics	Rate of metric change, oscillation amplitude, duration of degraded states, hysteresis	Distinguish short-term bursts from persistent problems; prevent unstable control	Time-series aggregation, sliding windows, cloud analytics

Limitations of Telemetry. Telemetry has inherent limitations:

- delays in data collection and aggregation;
- incompleteness and vendor-specific implementations;
- limited accuracy of client-side data.

Therefore, telemetry cannot be used for instantaneous control; instead, it should serve as the foundation for **controlled adaptation** and for verifying the effectiveness of QoS policies.

Conclusions

Hybrid campus networks integrate Ethernet and Wi-Fi into a unified system in which user mobility and traffic heterogeneity transform QoS into an inherently end-to-end challenge. The principal difficulties arise from the different nature of constrained resources: Ethernet is limited by bandwidth and queueing resources, whereas Wi-Fi is constrained by airtime and radio-environment conditions. Directly transferring QoS policies between these segments without adaptation does not guarantee equivalent service quality.

Effective QoS provisioning requires coordinated policies, the use of telemetry and adaptive priority control. Telemetry makes it possible to monitor actual resource consumption, identify discrepancies between configured policies and the real network state, establish a foundation for controlled adaptation. Only a comprehensive system-level approach—based on end-to-end metrics, data aggregation, and alignment between Wi-Fi and Ethernet—can ensure predictable and stable Quality of Service.

The proposed telemetry-based approach enables not only the observation of the current network state but also the verification of target QoS attainment, the detection of latent degradation, and the evaluation of policy effectiveness. The systematization of metric classes provides a practical basis for their implementation in monitoring systems and for subsequent use in automated or intelligent control algorithms.

The results of this study can be applied to the design of hybrid campus networks, the optimization of their operation, the development of solutions based on Software-Defined Networking and cloud-based or on-premises analytics. From a practical perspective, the work lays the groundwork for improving the stability of mission-critical services, reducing the risk of quality degradation, and transitioning toward predictable QoS as a managed property of modern campus networks.

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ТЕЛЕМЕТРІЯ ЯК ОСНОВА ПЕРЕДБАЧУВАНОГО QOS У ЗМІШАНИХ КАМПУСНИХ МЕРЕЖАХ

Вступ. Сучасні кампусні мережі інтегрують численні мережеві технології в єдину гібридну інфраструктуру, в якій взаємодія між різними середовищами передачі є критично важливою. Визначальними характеристиками таких мереж є мобільність користувачів та неоднорідність трафіку, що робить управління якістю обслуговування QoS невід'ємною частиною проблеми. У мережах Wi-Fi основним обмеженим ресурсом є ефірний час, на який сильно впливають умови радіосередовища, тоді як у дротових та оптичних мережах Ethernet обмежувальними факторами є ресурси пропускної здатності та черги. Отже, досягнення передбачуваної та стабільної QoS вимагає скоординованих політик, систематичної телеметрії та адаптивних механізмів управління.

Метою цієї статті є розробка системного підходу до забезпечення передбачуваної якості обслуговування в гібридних кампусних мережах, які поєднують дротові та бездротові сегменти в рамках єдиної інфраструктури. Дослідження зосереджено на аналізі фундаментальних відмінностей у характері обмежених ресурсів у мережах Ethernet та Wi-Fi та на визначенні наслідків цих відмінностей для організації наскрізної QoS.

Методи. Запропоновано класи метрик телеметрії, що дозволяють оцінювати стан ресурсів, якість доступу та інтегральні показники end-to-end якості в змішаних кампусних мережах.

Результати. Показано, що різна природа обмежених ресурсів — пропускної здатності та черг у дротовому середовищі й ефірного часу в бездротовому — унеможливлює пряме перенесення класичних QoS-механізмів без адаптації. Обґрунтовано необхідність системного наскрізного підходу до QoS, заснованого на узгодженні політик між сегментами та використанні телеметрії як інструмента перевірюваності й контрольованої адаптації. Показано роль телеметрії як основи для побудови стабільних QoS-політик і подальшого застосування методів автоматизації та машинного навчання.

Висновки. Результати цього дослідження можуть бути застосовані для проектування гібридних кампусних мереж, оптимізації їхньої роботи та розробки рішень на основі програмно-визначених мереж та хмарної або локальної аналітики. З практичної точки зору, робота закладає основу для підвищення стабільності критично важливих послуг, зниження ризику погіршення якості та переходу до передбачуваної QoS як керованої властивості сучасних кампусних мереж.

Ключові слова: гібридна кампусна мережа; якість обслуговування; QoS; мережева телеметрія; Wi-Fi; Ethernet; ефірний час; наскрізна QoS.