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Systematic Comparative Study of Circuit Switching, Packet Switching, and Hybrid Switching In Modern Communication Networks

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Abstract

The diversity of the traffic in the communication networks underscores the inadequacy of either circuit switching or packet switching. Packet switching is good at statistical multiplexing, and may prove difficult to provide bounded delay and low jitter without excessively provisioning it. Circuit switching on the other hand provides certain delay and bandwidth. In this paper, a

literature search and synthesis of circuit switching, packet switching, and hybrid modes is presented based on the principle, current advances, and performance analysis. We discuss such important hybrid paradigms as Asynchronous Transfer Mode (ATM), Multiprotocol Label Switching (MPLS), optical circuit/packet data-center architectures, and 5G-Time-Sensitive Networking (TSN) integration, as well as dynamic circuit allocation algorithms. We find through our synthesis that selective hybrid switching, which dynamically allocates circuit-like resources to URLLC flows or long-lived elephant flows and uses packet switching to serve best-effort traffic, is better in the performance metrics of latency (example, 10 milliseconds of latency in loads where best-effort traffic is provided by the use of a pure paradigm) and throughput, energy consumption, and QoS as the reviewed studies propose. Nanosecond-scale optical circuit switches and programmable data planes have nanosecond optical configurability, enabling historical scalability problems to reduce. Subsequently, hybrid switching creates an effective grid of 6G mobile networks, future data network interconnects, industrial automation, and deterministic network.

Introduction

1.1 Background to the study

Communication networks have been historically developed by two basic switching paradigms, namely: circuit switching and packet switching [1]-[4]. Circuit switching provides a specific end-to-end path over the period of the session, which guarantees bandwidth and predictable delay [6]. Packet switching as an alternative on the other hand, breaks down data into separately routed packets, sharing resources through statistical multiplexing to achieve high utilization and resilience [2], [15]. These models supported the global public switched telephone network (PSTN) and the Internet respectively [16], [21].

Modern networks have to accommodate the varied needs, such as ultra-reliable low-latency communication (URLLC), augmented mobile broadband (eMBB), massive machine-type communications (mMTC), real-time industrial control, and high-volume data transfers [11]. The pure paradigms are inadequate and this has led to the development of hybrid architectures which integrate circuit determinism and packet flexibility [5]-[14].

1.2 Statement of the Problem

Modern communication infrastructures require time-sensitive traffic to have a small latency and low jitter as well as efficiency in resource utilization to support bursty and elastic traffic [18], [19]. Pure packet-switched networks are characterized by varying queuing delays and packet loss at load (like a Fifth Generation (5G) ultra-reliable low-latency communication (URLLC) aims at an end-to-end latency of 1 millisecond with a 99.99% reliability [45], [46], conventional Internet Protocol (IP) networks may accept latencies in the (10-50) ms range at peak load [47], [48]. Pure, circuit switched networks waste bandwidth during idle modes and scaling characteristics are inferior to varying rate traffic [24]-[28].

Aim and Objectives

This paper aims to conduct a systematic comparative analysis of the circuit switching, packet switching and hybrid switching and their applicability to the current as well as future network through a literature synthesis.

The specific objectives are to:

i. Compare the functionality, performance metrics, strengths and weaknesses of circuit and packet switching.
ii. Examine how major hybrid technologies have evolved in history, operation and objectives and how successful they were.
iii. Determine major challenges, tradeoffs and situations in which hybrid switching proves to be better than the others and

suggest a new framework in terms of classifications.

Significance of the Study

Integrating theory and current trends, this paper offers a definitive source to researchers and designers that consider the revival of circuit-switching principles and integrating them with the packet switching to address the strict quality-of-service (QoS) requires in the Fifth Generation (5G)/sixth-generation (6G) networks, data-centers networks, and Internet of Things automation [29], [32], [34]-[36].

Related Works

Switching paradigm development is widely recorded. Pre-emptive circuit switching focused more on deterministic performance and bandwidth guarantees, the basis of the public switched telephone network (PSTN) [37], [38]. It was later enhanced by efficiency and resilience with the invention of packet switching in Advanced Research Projects Agency Network (ARPANET) and Internet Protocol (IP) architectures [39].

Mixed methods addressed gaps of reliability and efficiency. Virtual circuits in the packet networks were introduced with Asynchronous Transfer Mode (ATM) and Multiprotocol Label Switching (MPLS) to provide predictable performance with preservation of statistical multiplexing [13], [17]. Such has been succeeded by recent stress on optical circuit/packet integration, Fifth Generation (5G)-Time-Sensitive Networking (TSN), and programmable data planes [40], [49]-[51]. They bring to the fore hybrid possibilities of ultra-reliable low-latency communication (URLLC), industrial automation, and scalable data centers [41], [52]. This indicates that literature always uses the hybrid switching as a paradigm in the best balance between efficiency, scalability and determinism [42].

Gap Analysis

Available surveys give a general overview but tend to be shallow on integrations of Fifth Generation (5G)-Time-Sensitive Networking (TSN) after 2023 or programmable data planes such as Programming Protocol-independent Packet Processors (P4) on hybrid control [40], [41], [53], [54].

This review summarizes recent work post-2020, such as hybrid traffic scheduling in Fifth Generation (5G)-Time-Sensitive Networking (TSN) [49], [50], and presents innovative classification of hybrids in terms of the level of integration, the necessity of the systematic assessment in new 6G settings.

Study Methodology

This paper utilizes a literature review and a methodical comparison. It is theoretical, implying no original data gathering, experiments, and modeling. This was done in three steps:

i. Thorough collection and synthesis of concepts, architectures, performance measurement, strengths and weaknesses of operational characteristics of circuit and packet switching, in the form of comparing tables and graphs.

ii. Recent algorithms, hybrid models design, implementation, and analysis of important hybrid models, such as: Asynchronous Transfer Mode (ATM), Integrated Services (IntServ)/Resource Reservation Protocol (RSVP), Multiprotocol Label Switching (MPLS) traffic engineering, optical circuit/packet integration, Fifth Generation (5G)-Time-Sensitive

Networking (TSN) hybrid scheduling [49]-[51], and analysis and evaluation of design, implementation, and performance.

iii. Cross-source synthesis in order to discover constraints, trade-offs usage situations and open research questions in hybrid switching.

To guarantee rigor, searches were conducted in databases such as Institute of Electrical and Electronics Engineers (IEEE) Xplore, Association for computing machines (ACM) Digital Library, Scopus, and Google scholar databases using searches by terms such as circuit switching, packet switching, hybrid switching, Multiprotocol Label Switching (MPLS) and Asynchronous Transfer Mode (ATM), and Fifth Generation (5G) Time-Sensitive Networking (TSN) integration, optical hybrid networks, and programmable data planes hybrid (1990-2025).

- Inclusion criteria: peer-reviewed articles/conferences having comparisons of performance or architectures.
- Exclusion: non-English and non-technical reports.
- Articles were filtered to extract data related to measurement of parameters such as latency, throughput, utilization and reliability of approximately 100 articles and reviewed 55 of these articles in depth.
- Some of the analysis tools were performance matrices, evolutionary timelines and taxonomic diagrams.

Evolution of Communication Networks

Table 1.0: Evolution of Communication Networks

Period	**Technology**	**Key Concept**	**Core Applications**
Legacy Period (1900s-1970s)	Circuit Switching	Dedicated physical path established for the duration of a call	Public Switched Telephone Network (PSTN) (Landline phones), early Fax.
Internet Period (1970s-1990s)	Packet Switching (TCP/IP)	Best-effort delivery; data broken into packets and routed independently	Advanced Research Projects Agency Network (ARPANET), Email and World Wide Web
Quality of Service (QoS) and Cell Period (1990s-2000s)	Asynchronous Transfer Mode (ATM), Frame Relay, Resource Reservation Protocol (RSVP)	Cell Switching & Reservation; attempts to give packet networks “circuit-like” guarantees	Early Voice over Internet Protocol (VoIP), Integrated Services Digital Network (ISDN) and WANs
Hybrid/Label Period (2000s-2010s)	Internet Protocol/Multiprotocol Label Switching	Virtual Circuits; uses labels to create deterministic paths through packet	VPNs, ISP Backbones and IPTV

	(IP/MPLS) and Synchronous Optical Networking/Synchronous Digital Hierarchy (SONET/SDH)	networks	
Next-Generation Period (2010s-Present)	Software-Defined Networking (SDN), 5G	Programmable Networks; separation of the Control Plane from the Data Plane	Cloud Computing, 5G Slicing, IoT, Edge Computing

Comparative Analysis

Circuit, Packet, and Hybrid Switching Comparison

As established by the development of public switched telephone network (PSTN) to Next Generation Network (NGN), Voice over Internet Protocol (VoIP) blossoming and Multiprotocol Label Switching (MPLS)/Fifth Generation (5G) advances, circuit switching is reliable and guaranteed performance, packet switching flexible and efficient, and hybrids integrated between the two on different needs.

Table 2.0: Comparison of Circuit/Packet/Hybrid Switching

Category	**Circuit Switching**	**Packet Switching**	**Hybrid Switching**
Foundations	It is a dedicated private path for session	It splits data into packets and shares resources	It combines circuit reliability, and packet efficiency
Performance	There is guaranteed bandwidth, low latency, and ineffective capacity use	There is high resource utilization, with variable delay/jitter.	Differentiated Services (DiffServ) and Resource Reservation Protocol (RSVP) ensure efficient and low delay through QoS mechanisms
Protocols	Public Switched Telephone Network (PSTN) and Integrated Services Digital Network (ISDN)	It is made of Transmission Control Protocol/Internet Protocol (TCP/IP) and Internet Protocol/Multiprotocol Label Switching (IP/MPLS)	Multiprotocol Label Switching (MPLS), Asynchronous Transfer Mode (ATM), and Software Defined Networking (SDN)
Uses	Legacy phone networks	Voice over Internet Protocol (VoIP, Fifth Generation (5G), and Data centers	Applicable in network migration and streaming multimedia

Proposed Classification Framework for Hybrid Switching

To move beyond general comparisons, we propose a novel three-level classification framework for hybrid switching that is based on integration depth. This framework enables weighted comparisons. For instance, Level 3 offers the lowest latency but has higher complexity.

- Level 1 (QoS) emulation is achieved using overlay mechanisms on packet networks (such as Differentiated Services (DiffServ) to prioritize packets and emulate circuit-like behavior with no dedicated paths.
- Level 2 (Virtual Circuits) involves logical circuits through packet infrastructure (like Multiprotocol Label Switching (MPLS) and Label Switched Paths (LSPs).
- Level 3 (Dynamic Physical Circuits) involves the reconfiguration of physical resources at runtime, such as optical hybrids with sub-millisecond switching. [43], [44]

In-Depth Hybrid Mechanisms

Label Switched Paths (LSPs) are created as virtual circuits by MPLS, where ingress routers assign labels and intermediate nodes switch based on labels for deterministic forwarding, which combines packet multiplexing with circuit predictability [17].

In Fifth Generation (5G)-Time-Sensitive Networking (TSN), deterministic slots/cycles are dynamically managed within Fifth Generation (5G)'s statistical multiplexing: Time-Sensitive Networking (TSN) gates control packet release, integrated with Fifth Generation (5G) semi-persistent scheduling for hybrid traffic, ensuring <1 ms latency for critical flows [49], [50].

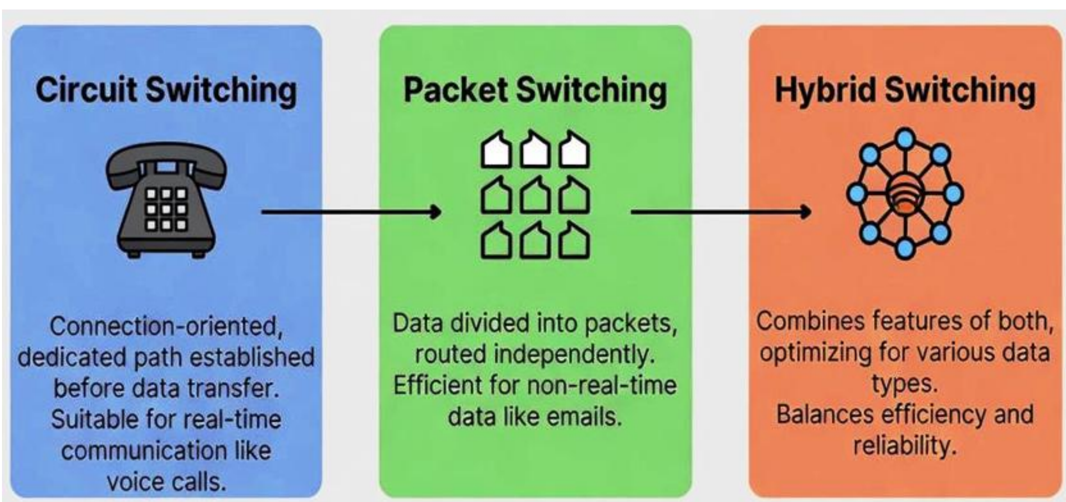

Figure 1.o: Switching Diagram for Circuit/Packet/Hybrid

Figure 1.0 above shows the Evolution of Network Switching since the analogue based system to the current software-defined systems. It divides technological changes into historical periods, depending on the way they treat data and the type of problems they address.

Outcomes and Discussions

Packet switching and circuit switching

Circuit switching offers zero jitter at the cost of low utilization; and packet switching is the most efficient in multiplexing but variable delay entails over-provisioning.

Hybrid Solution Development and Performance

Switches such as Multiprotocol Label Switching (MPLS) and Fifth Generation (5G)-Time-Sensitive Networking (TSN) save complexity and energy; programmable planes (Programming Protocol-independent Packet Processors (P4)) offer less than the us controlling bandwidth [53], [54].

6.3 Problems, Trade-offs and Application Scenarios

Signaling and prediction are among the outstanding concerns; hybrids are best in data centers and sixth-generation (6G) tactile applications, at the expense of determinism.

Recommendations

Selective hybrid switching on heterogeneous traffic with flows larger than 100 MB or jitter less than 100 ms should be adopted and allocate circuits [55]. The sub-ms hardware research, Programming Protocol-independent Packet Processors (P4) classification, and lightweight protocols are in the focus of the sixth-generation (6G) research.

Conclusions

Existing paradigms are not the future of the needs of next-generation; hybrids that are selective, with fast fabrics and programmable scheduling, are the best architecture to sixth-generation (6G) data-center and the Internet of Things (

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