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Development on Quality of Service and Network Resilience based on Structured Geometric Topologies

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A Thesis Submitted to The University of Glasgow for the Degree of Doctor of Philosophy

Abstract

The topology of a computer network is the basis for building a high-capacity, low-congestion network infrastructure. At present, the research on computer network topologies rests mainly on typically unstructured networks such as mesh networks. Network infrastructures do not widely employ structured geometric network topologies. Compared to a structured geometric topology, they possess numerous advantageous characteristics, such as connectedness, which are currently not being utilised in the construction of the network structure. Simultaneously, by suggesting additional network topologies, we can select an appropriate network configuration that enhances the availability and robustness of networking infrastructures.

Our study evaluates the potential use of three structured geometric network infrastructure designs, namely cross polytope (CP), hypercube (HC) and triangular pyramid (TP), based on their network performance. In this paper, we use simulation modelling to analyse structured network geometries and evaluate their network performance by Riverbed Modeler. We compare the simulation results of an unstructured network design with three structured network topologies for both time-independent and time-dependent applications. The simulation results illustrate that the CP and TP topologies have better results than the unstructured network in response time and network delay under a high-load configuration. Furthermore, we evaluate the performance of structured geometric network infrastructure designs under three QoS disciplines, namely weighted fair queuing (WFQ), priority queuing (PQ) and modified weighted round robin (MWRR). In this paper, we simulate structured geometric and unstructured network structures using Riverbed Modeler 18.9 to evaluate network performance. The simulation results illustrate that the structured geometric network topologies have better results than the unstructured network in response time and network delay under a high-load configuration, and the QoS algorithm provides advantages for voice services by prioritising the transmission of vital services.

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Publications

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1 Introduction

1.1 Background

1.1.1 Network Topology

Data communication networks facilitate a variety of human activities. Whether for professional or recreational use, safety-critical applications, or e-commerce, the Internet has become a vital part of our daily lives, influencing the functioning of civilisations. Network topology, as a significant part of computer networks, is the arrangement of the elements of a communication network [1]. It is an application of graph theory in which communicative devices are described as nodes, and connections between them are modelled as links or lines connecting the nodes [2] (see Fig.1.1). Network topologies are broadly categorized into physical topologies and logical topologies. Physical topology defines the tangible arrangement of devices and cables, while logical topology describes the path that data takes between network nodes. The design and choice of a network topology significantly impact its performance, scalability, fault tolerance, and cost-efficiency. With advancements in networking technologies, understanding the principles and applications of different topologies has become essential for optimizing communication systems in diverse environments, from local area networks (LANs) to global communication frameworks. Organizations can ensure optimal performance, reliability, and cost-efficiency in their network infrastructures by tailoring topology selection to specific operational needs and leveraging emerging technologies.

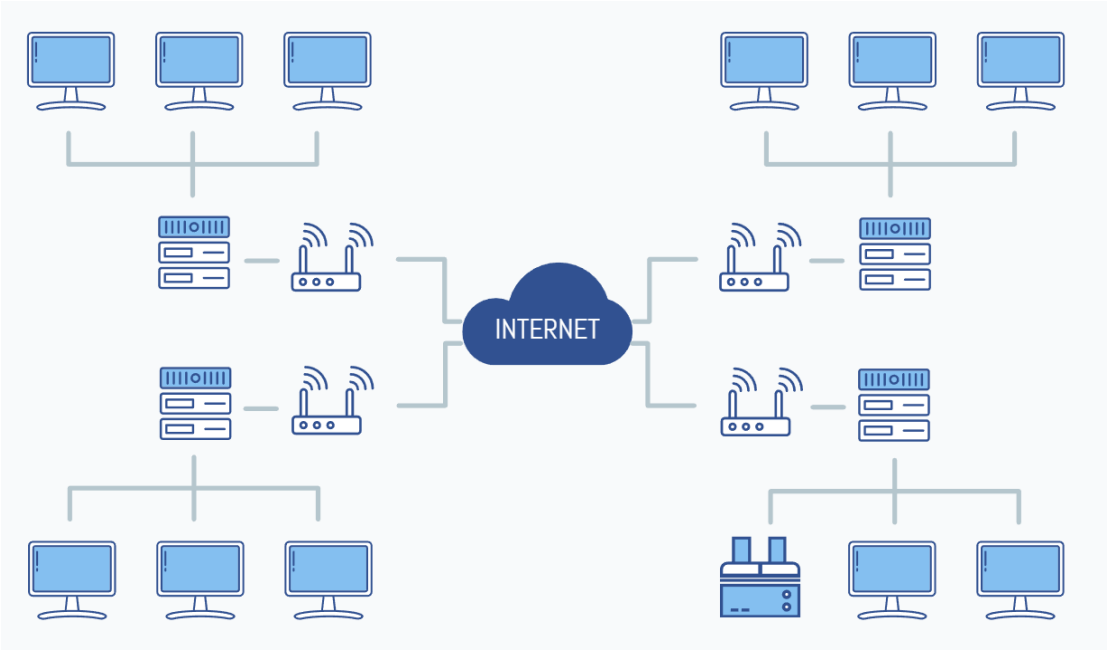


Fig. 1-1 Network Topology Diagram

These topologies define the manner in which nodes (e.g., computers, switches, routers) are linked, facilitating data transfer. Topology types are typically classified into physical (e.g., the arrangement of cables and devices) and logical (e.g., the flow of data). Commonly adopted network topologies include bus, star, ring, mesh, tree, and hybrid designs, each serving specific purposes based on performance, scalability, fault tolerance, and cost considerations [3].

Despite their advantages, network topologies face challenges such as increasing complexity, cost of implementation, and susceptibility to faults in centralized designs. To address these issues, researchers are exploring adaptive and dynamic topologies capable of reconfiguring themselves based on changing network conditions.

The computer networked system has become a growing vital component of the economy, education, and government sectors to support an extensive range of time and non-time dependent services, where orchestration is a fundamental premise of quality of service. The fact that these sectors are confronted with significant challenges and threats, including human error, apparatus malfunction, intentional attacks, natural

disasters, and economic crises [4]. If a network system is attacked, the user experience will be significantly affected and even the privacy and security of the user's property will be at risk. At this point, it is crucial to improve the ability of a network to maintain its original function when disturbances occur. Resilience, the capacity of a network to defend against and maintain an acceptable level of service in the presence of such challenges, is a critical aspect of network design and operation, ensuring that a network can maintain an acceptable level of service in the face of faults and challenges to normal operation.

1.1.2 Quality of Service

Allocation of network resources, such as buffers and data rate, to different users presents the most significant challenges in a network. In order to maximise the performance and utilisation of the network's resources, a limited quantity of resources must be shared among multiple additional competing traffic flows. Therefore, adequate quality of service (QoS) is essential to satisfy the stringent requirements [5]. QoS is the description or measurement of the overall efficacy of a service, such as a telecommunications or computer network, as perceived by its consumers [6]. To provide various types of services, it is possible to manipulate the packet-handling behaviour of routers. Different queuing algorithms can be utilised to determine which packets are forwarded and which are dropped. QoS refers to using network-based mechanisms or technologies to control traffic and guarantee the performance of mission-critical applications with limited network capacity. It enables businesses to prioritise specific high-performance applications within their overall network traffic. To measure the quality of service quantitatively, many connected parts of the network service are frequently reviewed, such as packet loss, data rate, end-to-end delay, jitter [7]. QoS is not solely a technical matter, but also a significant concern for businesses. From the viewpoint of an application provider, it is crucial to obtain a competitive edge in the cloud marketplace and industrial IoT systems [8]. As an illustration, Amazon calculates that with every 100-millisecond delay in response time, there is a 1% decrease

in earnings [9]. QoS, from the user's standpoint, is a crucial factor that distinguishes various services. In computer networking and other packet-switched telecommunication networks, QoS refers to traffic prioritisation and resource reservation control mechanisms rather than the actual service quality [10]. QoS is the capacity to assign distinct priorities to various applications, users, or data flows or to guarantee a particular level of performance to a data flow [11].

1.1.3 Network Security

Distributed Denial of Service (DDoS) attacks represent one of the most pressing threats to computer network security, targeting the availability of resources by overwhelming a system with an excess of traffic. This malicious activity disrupts legitimate access to online services, resulting in significant operational and financial damages. The origins of a DDoS attack typically involve a network of compromised devices, known as a botnet, which attackers use to flood a target with traffic. As the proliferation of Internet of Things (IoT) devices with limited security measures continues to grow, attackers increasingly exploit these devices to launch more sophisticated attacks.

Distributed Denial of Service (DDoS) attack is a type of cyber-attack that overwhelms a system or network by flooding it with a large number of requests, above its normal traffic capacity. A multitude of computer systems are utilised to execute these attacks, making it very challenging to protect against them. DDoS assaults can result in significant monetary losses, harm to one's reputation, and the interruption of essential services. Attackers have the ability to utilise several methods, such as inundating the target system with a high number of data to overwhelm its requests, altering network traffic to disrupt communication, or exploiting vulnerabilities to obtain unauthorized entry. The scale and sophistication of DDoS attacks have been evolving significantly. The maximum peak bandwidth observed for such attacks has shown fluctuations, with a record high of 1.39 Tbps in 2021 dropping to 800 Gbps in 2022 [12]. Despite this decrease, the scale of these attacks remains substantially higher than in previous years,

indicating a continuing trend of high-impact capabilities among attackers. DDoS attacks do not impact all industries equally; sectors like technology and finance are often more targeted due to their critical role in economies and infrastructures [13]. The specific targeting of these sectors reflects a strategic preference among attackers to disrupt services or extort money through ransom-related DDoS activities. The increase in DDoS attacks highlights the expansion of cyber risks, necessitating the implementation of strong cybersecurity measures. Organisations are strongly advised to adopt a robust plan for detecting and mitigating attacks. As technology advances, the risk of cyber-attacks, including DDoS attacks, is also growing. Multiple studies have put forward models to improve the identification and reduction of DDoS assaults. Research has shown that feature reduction strategies are beneficial in enhancing the computing efficiency of detecting systems. By reducing the number of variables analysed, these models can function more efficiently and with lower resource demands, which is essential for implementing effective security measures in real-time situations [14]. We hypothesise that structured geometric topologies can offer novel solutions for securing networks against emerging cyber threats.

1.2 Motivation

Network topology is a crucial element of computer networks, as it forms the basis for network management, data simulation, data collection, and is necessary for evaluating network security [15] and carrying out network assaults [16]. Hence, the examination of network topology holds great importance. Nevertheless, network infrastructures do not widely employ structured geometric network topologies. Compared to a structured geometric topology, they possess numerous advantageous characteristics, such as connectedness [17], which are currently not being utilised in the construction of the network structure. Simultaneously, by suggesting additional network topologies, we have the opportunity to select an appropriate network configuration that enhances the availability and robustness of networking infrastructures. Furthermore, it can enhance the capacity of internet infrastructure and alleviate traffic congestion on heavily used

routes for data transmission within a metropolitan area network (MAN) or wide area network (WAN). Quality of service has a wide range of applications in computer networks [18]. Various algorithmic structures in it can significantly improve the performance and resilience of the network. While implementing a structured geometric topology as a network topology, it is also possible to enhance the resilience of the structure by utilising QoS queuing algorithms.

1.3 Aim

This research aims to promote the quality of services in network infrastructures by developing knowledge of the relationship between network resilience and structured geometric topologies.

1.4 Hypothesis

Structure geometric topologies can have a determining effect on the resilience of network infrastructure to guarantee the quality of services.

1.5 Objectives

1. To critically review contemporary literature on network technologies, topologies, resilience and quality of service.
2. To select structured geometric network topologies that support quality of service in network infrastructures.
3. To design simulation models using structured geometric network topologies in a discrete event network simulator.
4. To implement structured geometric topological models multi-scenarios based on high network traffic loads and two types of applications: time-dependent and non-time dependent.
5. To critically evaluate the comprehensive results of different structured geometric network simulations and determine optimal network structures with high network

resilience.

We focus on shape, connectivity, and the number of connections between one point and other points. These serve as alternative paths for improving network robustness and resilience. Structured geometric topology is defined here as a finite graph G (V, E) such that it has the following properties:

1. Regularity / quasi-regularity: All vertices share either an identical degree k (regular) or one of at most two degree values (semi-regular).

2. Symmetry: The automorphism group of G acts transitively on vertices or on well-defined vertex classes, enabling closed-form expressions for key metrics.

3. Analytic tractability: Diameter D(n), mean shortest-path length $\bar{L}(n)$, and bisection width B $W_{(}bisect_{)}(n)$ can be written as simple functions of the network size n = |V|.

4. Geometric self-similarity: Under uniform scaling of n, the topology preserves its metric ratios.

These properties distinguish structured geometric topologies from unstructured or scale-free meshes whose metric behaviour is typically random and non-analytic.

1.6 Organisation of Thesis

In Chapter 1, the paper first introduces the background for researching structured geometric topologies of network architectures, elaborating on network topology and service quality. It simultaneously analyses the challenges confronting network security, while clearly defining the research motivation and objectives of this study.

In Chapter 2, the paper first systematically expounds the theoretical foundations of structured geometrical network topology, subsequently clarifying the network performance metrics central to this study. This is followed by a literature review on service quality and network resilience, concluding with an examination of distributed denial of service attacks.

In Chapter 3, a detailed introduction is provided to the network simulation techniques employed in this study.

In Chapter 4, the paper introduces the design and implementation of a structured geometrical topology network structure model. It systematically outlines the construction of network scenarios and the configuration of key parameters.

In Chapter 5, the paper analyses and discusses the simulation conclusions regarding scenarios employing solely structured and topological configurations, as well as non-structured topological scenarios.

In Chapter 6, the paper analyses and discusses the simulation findings concerning the integration of service quality with structured topological scenarios.

In Chapter 7, the paper analyses and discusses the conclusions drawn from simulations integrating cybersecurity with structured topological scenarios.

Finally, Chapter 8 presents the summary of the main objectives, highlights the achievements. Furthermore, the future work suggestions are presented.

2 Literature Review

2.1 Introduction

This PhD study's literature evaluation commences with an introduction to structured network topologies, followed by a detailed description of three structured network topologies and unstructured topologies, presented sequentially. Then the various network performance metrics that need to be analysed in this study are introduced, which can give us a clear understanding of the network performance of structured and unstructured network topologies in different network environments. Next, we will present detailed literature reviews on quality of service and on network security.

2.2 Structured Geometric Topologies Technologies

A network topology is the arrangement of the elements of a communication network[19]. It is an application of graph theory in which communicative devices are described as nodes, and connections between them are modelled as links or lines connecting the node [20]. At present, network topology research mainly lies in two-dimensional network topology (see Fig. 2-1), including bus topology [21], mesh topology [22][23], star topology [24][25], ring topology [26], and tree topology [27].

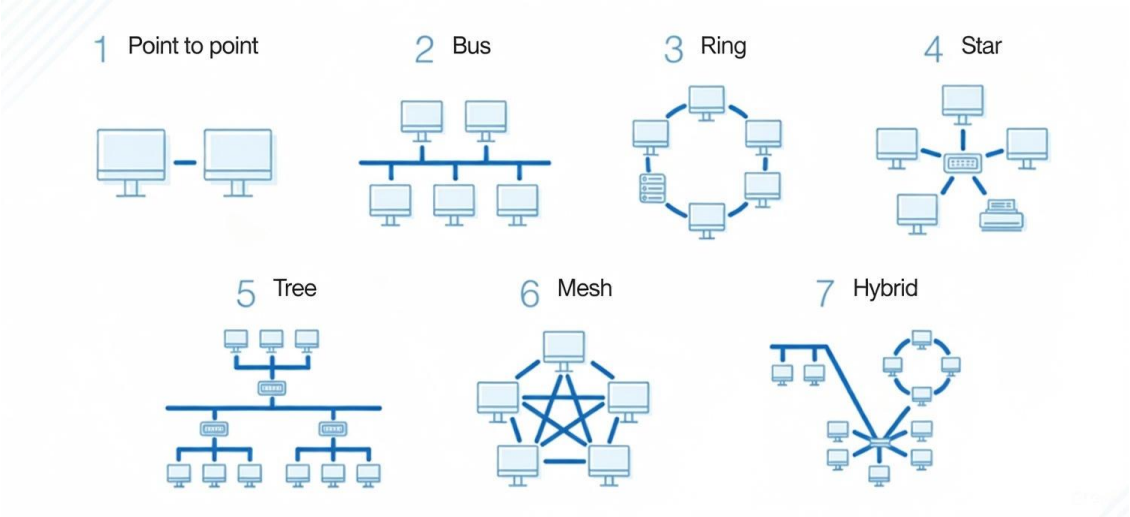


Fig. 2-1 Two-dimensional network topologies

Each traditional two-dimensional network topology has strengths and weaknesses depending on the network's objectives and scale (see Table 2-1).

Table 2-1 Advantage and Disadvantage of Traditional network topologies

	Aspect	**Description**	**Example Topology**
Advantage	Simplicity and Cost-Effectiveness	Topologies like bus and star are straightforward to implement and maintain, making them ideal for small-scale applications.	Bus, Star
	Scalability	Tree topologies offer hierarchical structures that support network growth.	Tree
	Fault Tolerance	Mesh networks excel in redundancy, as multiple paths exist between nodes.	Mesh
Disadvantage	Single Point of Failure	Centralized topologies (e.g., star) are vulnerable to hub failures.	Star
	High Cost	Fully connected mesh networks require significant resources, increasing costs and complexity.	Fully Connected Mesh
	Limited Adaptability	Linear topologies like bus and ring are less flexible in accommodating dynamic changes.	Bus, Ring

In contrast to the prevalent network topologies, some researchers have identified less typically employed geometric topologies that provide distinct advantages in the establishment of network architectures. Gang Sun et al. [27] consider a fat-tree topology, which can be seen as a multi-tier architecture consisting of a three-tier switch and a one-tier server. It supports expanding the number of paths while expanding horizontally and all switches are standard devices with the same number of ports, reducing network construction costs. Microsoft technicians [29] proposed the VL2 architecture. This topology implements a complete routing and forwarding suite on a triple fold (multi-root tree), but differs from a fat tree in that the switch-to-switch link has a much higher capacity than the server-to-switch link, which requires a much smaller number of cables connecting the aggregation and core layers. Both above topologies are extensions of the two-dimensional tree topology used in data centre networks. In addition to unstructured topologies, structured topologies characterised by specific shapes and links also have practical utility in engineering applications, such as physical network topology in a large-scale Internet of Things (IoT) system [30], supercomputers [31][32] and clusters as well as networks on a chip [33]. However, only a few structured network topologies have been applied to network infrastructures. Han Haibo [34] proposes a "a network double plane" topology. It divides the wide area backbone network into two logically independent rings, forming a new network architecture with "one backbone network and two planes (forwarding plane and control plane)". For large networks (e.g. metropolitan networks, large enterprise networks), a dual-plane architecture can be considered. If we take a topology diagram of a dual-plane architecture, we can see that we only need to build our own wide area backbone between the headquarters and some important city branches to improve stability and, at the same time, protect the costs from increasing (see Fig. 2-2).

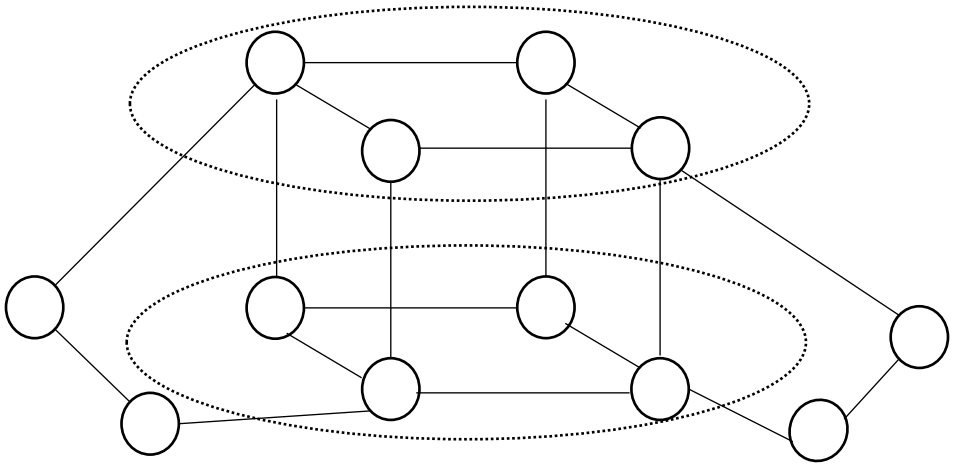


Fig. 2-2 A Network Double Plane

Structured geometric topology is a concept introduced to distinguish it from two-dimensional divergent topology, referring to a specific mathematical N-dimensional geometric form. In the discussion of structured topological network structures, since only the transmission distance and node distribution affect data transmission in actual network links, we use N-dimensional topological structures in our research, but in fact compress them into a plane to study only the links and node distribution.

Structured geometric (N-dimensional) network topology refers to the mathematical study and structural representation of nodes and edges within N-dimensional spaces. These structures play a critical role across various disciplines — from pure mathematics and topology to computer science, neural networks, and materials physics. Unlike traditional 2D or 3D topologies, N-dimensional topologies generalize graph theory into higher-dimensional algebraic and geometric spaces. N-dimensional network topologies extend traditional designs into higher dimensions, enabling more efficient data routing and communication. Examples include hypercubes, toroidal grids, and 3D NoCs, widely used in HPC and distributed systems. These topologies optimize resource utilisation, reduce communication latency, and support parallel data processing at unprecedented scales.

Reinschke [35] defines N-dimensional networks as graphs embedded in vector spaces,

where algebraic formulation captures connectivity and flow properties. He proposes modelling 3D and 6D civil engineering structures by separating their geometry (node coordinates) from topology (connectivity rules). Networks are analysed through nodal admittance matrices, Laplacian matrices, and symbolic techniques. The symbolic formulation proposed by Reinschke provides an efficient framework for representing and manipulating network equations, particularly in systems that are numerically sensitive or computationally stiff. These symbolic methods enable researchers to capture system behaviour abstractly and to decouple topological constraints from circuit-like dependencies, making them valuable for large-scale, multi-dimensional simulations. These tools support generalized formulations for multi-dimensional multi-port networks. Lienhardt [36] introduced n-G-maps (n-dimensional generalized maps) to model subdivisions of orientable and non-orientable topological spaces. They generalize 2D topological maps to N dimensions. This approach generalizes traditional 2D topological maps into N-dimensional frameworks, offering a combinatorial representation that maintains consistency across dimensions. Lienhardt's contribution established a foundation for encoding complex topological relationships that later proved instrumental in multidimensional mesh processing and computational geometry.

Ranjan and Zhang [37] embedded networks in an N-dimensional Euclidean space using the Moore-Penrose pseudo-inverse of the graph Laplacian. Node distances from the origin define a topological centrality index, useful for detecting structural vulnerabilities and robustness. This metric enables detection of structural weaknesses and resilience features in large-scale systems. Such geometric embeddings bridge the gap between algebraic topology and network robustness analysis, supporting applications ranging from power grids to distributed computing systems. Torus topologies are preferred in supercomputers for scalability. In the context of high-performance computing, Torus topologies have emerged as a preferred architecture for scalable interconnects due to their symmetry and fault tolerance. Andujar et al. [38] advanced this concept with the Twin Torus architecture, which divides network dimensions across multiple cards to optimize port utilization and enhance scalability.

At the intersection of materials science and topological data analysis, Morley et al. [39] applied persistent homology to the study of two-dimensional atomic networks such as silica bilayers and graphene. Their approach revealed persistent topological features—including ring statistics and n-body correlations—that traditional geometric metrics overlook. Persistent homology, by capturing the birth and death of topological features across scales, provides a robust method for identifying hidden structural motifs in disordered or crystalline networks.

Toth et al. [40] presented a data-dependent triangulation method for reconstructing N-dimensional scattered datasets. Their algorithm adjusts local topologies to better capture high-frequency features. Symbolic techniques help analyse network equations when direct numerical methods are impractical. Yang et al [41] introduced the Hyper-simplex fractal network, a blockchain-specific N-dimensional topology designed to support trillions of nodes. The model uses recursive N-simplex structures to enable deterministic routing and high scalability. Cai et al. [42] proposed a multi-dimensional spatial transformation for network layout visualization. By transforming network attributes into various spatial layouts (3D, 2.5D, 2D), users can explore complex structures progressively.

As can be seen from the literature review above, structured geometric (N-dimensional) network topologies represent a profound generalization of graph theory and geometry, offering robust frameworks for analysing connectivity, dynamics, and structure in both abstract and applied systems. From algebraic models to toroidal hardware interconnects and persistent homology, the field integrates deep mathematical theory with tangible technological innovation. Continued exploration will enhance performance, resilience, and scalability in computing, data science, and physical modelling systems. In the following Table 2-2, advantages and disadvantages of N-dimensional topologies is shown.

Table 2-2 Advantage and Disadvantage of N-dimensional topologies

	Aspect	Description	Example Topology
Advantage	Enhanced Scalability	By leveraging additional dimensions, these topologies accommodate exponential growth in nodes and connections.	Hypercube, k-ary n-cube
	Fault Tolerance	Multi-path redundancy ensures robust fault management, which is critical for mission-critical systems.	3D Torus, Hypercube
	Performance Optimisation	Reduced hop counts and faster data transfer rates make them ideal for large-scale computing.	3D Mesh, Hypercube
	High-Dimensional Communication	These designs facilitate parallelism and multi-channel data flows, essential for modern high-performance applications.	Hypercube, Butterfly, 3D Torus
Disadvantage	Design Complexity	Multi-dimensional systems require advanced algorithms, complex routing, and specialized engineering expertise.	Large-scale Hypercube or Dragonfly-based systems
	Higher Costs	Implementation and maintenance demand substantial investments in both hardware (links, switches) and software (control).	High-radix multi-dimensional interconnects
	Management Challenges	Coordinating physical layouts with logical communication patterns is complex and makes monitoring and troubleshooting harder.	Multi-dimensional data center fabrics

2.2.1 Cross Polytope (Octahedron) Topology

J.G. Lee et al. [43] describe in detail the graph theory of the cross polytope (CP). In geometry, a CP is a regular, convex polytope in multi-dimensional Euclidean space (see Fig. 2-3). The CP is composed of eight equilateral triangles, which can also be seen as the bonding of the upper and lower tetragonal vertebrae. Each of the four edges of the object has a square shape, resulting in a total of three distinct squares.

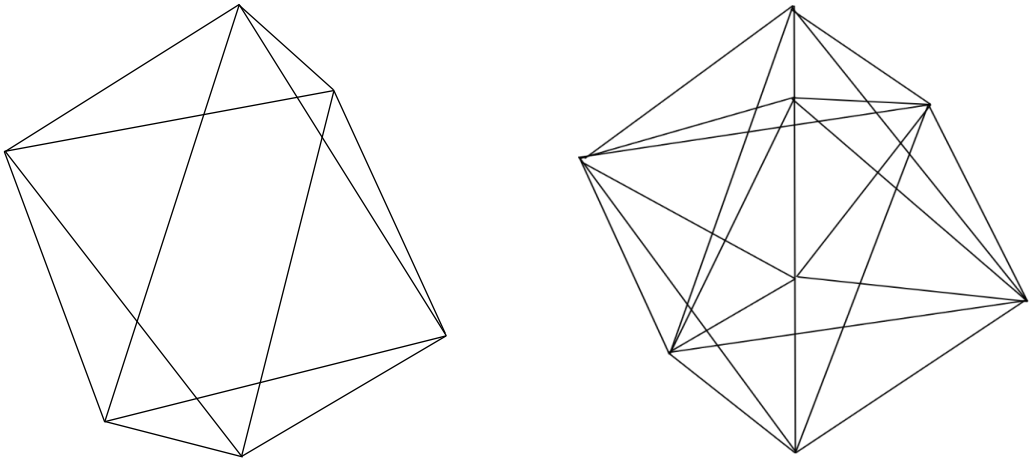


Fig. 2-3 Cross Polytope Topology

One of the key areas of research on cross polytopes is their flexibility and self-motion in high-dimensional spaces. Stachel [44] explores the flexibility of cross-polytopes in four-dimensional Euclidean space and presents parameterized self-motion cases. Gaifullin [45] generalizes the concept of flexible cross-polytopes to spaces of constant curvature, such as spheres and hyperbolic spaces. The study provides a classification of these polytopes in higher dimensions and introduces a parametrization of their flexion. Cross polytopes are often studied in the context of higher-dimensional polytopes and their topological characteristics.

Chun [46] studies the problem of packing points within cross-polytopes while maintaining minimum distance constraints, which has implications for optimization and combinatorial geometry. Applications of cross-polytopes extend to topology

optimization and computational algorithms. Duarte et al. [47] introduce PolyTop++, an optimization framework that utilizes polygonal and polytope-based meshing for structural optimization on CPUs and GPUs. Cross polytopes also appear in mathematical physics and topology. Makeev [48] discusses the properties of affine cross-polytopes inscribed in convex bodies and their geometric constraints. Effenberger and Kuhnel [49] analyse polyhedral manifolds embedded in cross-polytope structures, demonstrating their topological significance in discrete geometry. Research on cross polytopes spans several domains, from fundamental geometric and topological studies to applied computational techniques. Their flexibility, structural properties, and role in optimization make them crucial in both theoretical mathematics and practical engineering applications.

The CP structure possesses a high degree of symmetry and duality, hence facilitating the development and investigation of network structures. In NoC architecture, a variation of the cross polytope-based topology, the Cross-By-Pass-Mesh (CBP-Mesh), has been proposed to enhance network performance [50].The study highlights that adding cross-by-pass links reduces network diameter, increases bisection bandwidth, and lowers average hop counts. As a result, CBP-Mesh achieves low latency and high throughput, making it a scalable and cost-effective NoC solution. A unique application of polytope-based topology is in anti-tracking networks, where a convex polytope topology (CPT) is implemented for improved security and stability [51]. The study demonstrates that CPT minimizes the risk of network attacks by eliminating key node dependencies, ensuring resilience against dynamic topological changes, and enabling self-optimization. The network remains robust even when nodes randomly join or leave. A recent development in neural network optimization introduces ECToNAS, an evolutionary cross-topology neural architecture search framework [52] This method efficiently selects network architectures by dynamically optimizing topologies, making it computationally efficient. It applies to multiple datasets and significantly improves model selection for deep learning applications. An innovative study investigates how polytope structures inform neural network width and complexity [53]. The findings

suggest that datasets can be represented using a minimal number of polytopes, influencing neural network architectures. This approach enables more efficient deep learning model design by leveraging geometric properties. Cross polytope topology is proving to be a valuable tool in network design and optimization. Its structured geometric advantages make it ideal for reducing latency, enhancing network performance, and improving security. Furthermore, its application in NoC, anti-tracking systems, and neural networks highlights its versatility across domains.

In the traditional sense, a CP has six vertices and 20 edges. However, in our study, to give the structure more substantial connectivity properties, we add two points to the concatenation of two of the non-adjacent and opposite vertices and connected these two points to all the vertices. The two nodes at the vertex of the central axis are connected to the other five nodes, while the other nodes are connected to the other six nodes. Connecting more vertices in a topological network is beneficial for enhancing the stability and resilience of the network.

2.2.2 Triangular Pyramid Topology

Razivi and Sarbazi Azad propose a triangular pyramid (TP) network (see Fig. 2-4) based on the triangular grid [54] The six nodes inside are connected to six other nodes, and the four nodes at the vertex are connected to three other vertices. A triangular pyramid network has many excellent characteristics of a pyramid network, such as good symmetry, which reduces the complexity of the network. A symmetrical network topology can facilitate business deployment and is more intuitive, facilitating protocol design and analysis.

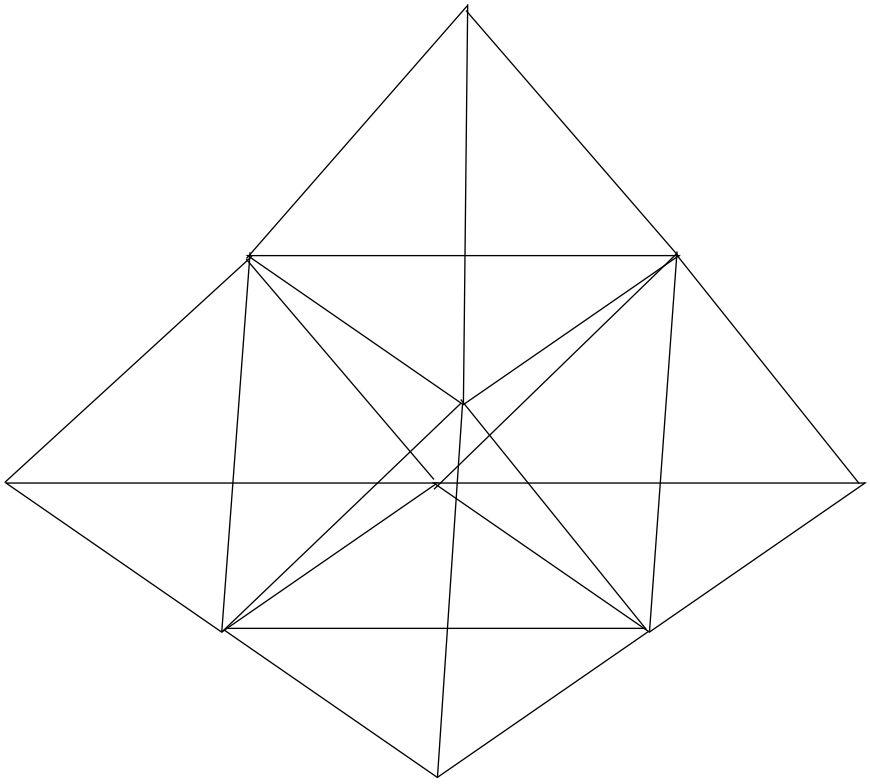


Fig. 2-4 Triangular Pyramid Topology

The original proposal of the TP topology outlines its hierarchical structure based on triangular meshes. It exhibits strong properties such as Hamiltonicity, pancyclicity, and high bandwidth. A routing algorithm based on triangular mesh routing was introduced, making it suitable for scalable and high-connectivity networks [54]. A follow-up study analysed the symmetry properties of TP networks and proved that they are 1-fault-tolerant and vertex-pancyclic. These features enhance robustness in critical applications where node failures can occur [55]. A novel spatial architecture for the Internet of Things based on the Triangular Pyramid model was proposed. This architecture simplifies heterogeneous networks and improves system convergence, making it suitable for IoT applications that require flexibility and efficiency [56].

2.2.3 Unstructured Mesh Topology

Mesh topology is a decentralized network design in which nodes connect directly, dynamically, and non-hierarchically to as many other nodes as possible. This design provides high redundancy and reliability, making it suitable for wireless and wired

communications, distributed systems, and critical infrastructure.

Mesh topologies are studied extensively in parallel computing and algorithm optimization due to their structured regularity and performance benefits. Das et al. [57] introduce a Multi-Mesh (MM) topology with n^4 processors. This topology supports efficient parallel algorithms for matrix operations and Lagrange interpolation with superior time complexity. The Over-Looped 2D Mesh Topology improves routing efficiency by reducing central traffic congestion, yielding up to a 25% reduction in hop count [58]. Mesh topology is fundamental in designing efficient NoC architectures for multicore processors. Sadeghi et al. [59] proposed a multi-level mesh for Network-on-Chip (NoC) to reduce delay and increase efficiency in high-traffic applications. Scheibe [60] developed a model for optimal mesh configuration in line-of-sight constrained networks, helping improve connectivity in fixed wireless applications.

An unstructured mesh topology refers to a topology that possesses the ability to be expanded endlessly without a predetermined structure, which implies that nodes can be added and interconnected without any limitations. This study aims to conduct a simulation of a random mesh network including ten subnets as a baseline network and compare it with three structured geometric topologies. The objective is to determine whether the structured network topologies exhibit any advantages over the unstructured network.

2.2.4 Hypercube

After extensive simulation experiments, the used hypercube structure suffers from poor time delay performance in simulating time-independent applications. As well as the simulation software used, the high-node, high-capacity architecture suffers from unsolvable crashes when simulating time-independent applications with large amounts of data transfers. Therefore, we have described and discussed matters pertaining to the hypercube only within the literature review and in Chapter 5, which focuses exclusively on the simulation of structured network topologies.

The Hypercube topology is a graph-like structure where the nodes are distributed according to the vertices of the shape of an N-dimensional square, those being connected by edges such that square faces are formed. N is the dimension of such a shape and it is the parameter imposing the number of nodes and their corresponding links among them in a way that there must be 2^N nodes equally distributed, and $N \times 2^N - 1$ links among those nodes. Furthermore, each node has N links connecting to other nodes [61]. Hypercube is one of the most famous, common and influential topological structures. It has the advantages of a small diameter, symmetrical structure, recursive structure and robust scalability [62]. Hypercube has 16 nodes, 32 sides and two cubes. (see Fig. 2-5).

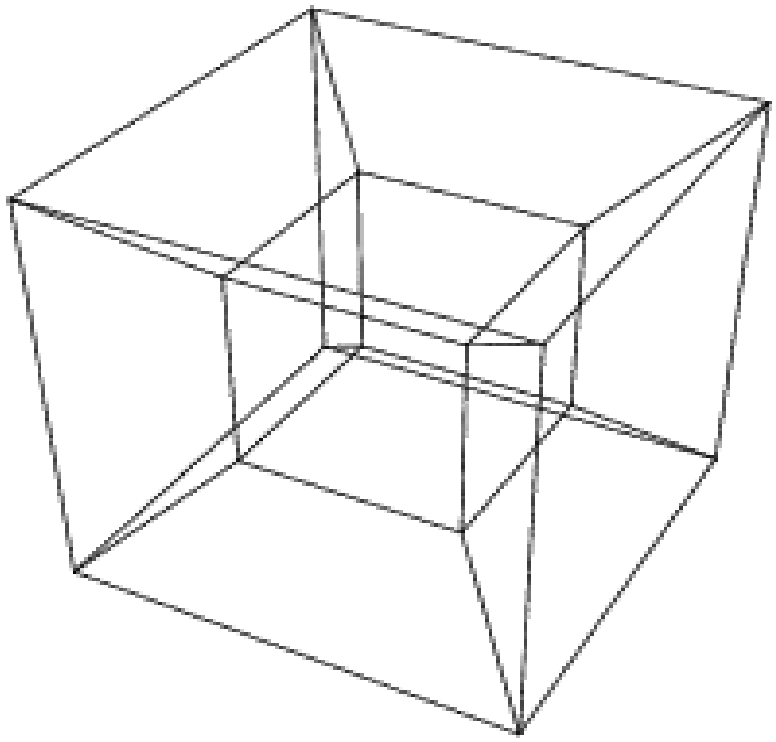


Fig. 2-5 Hypercube Topology

The N-dimensional hypercube, or binary n-cube (denoted Q_n), is a mathematical graph that generalizes the properties of geometric cubes to higher dimensions. Each node represents an n-bit binary string, and edges connect nodes that differ by exactly one bit. This structure ensures that each node has a degree of n and provides a graph

with 2^N nodes and $N \times 2^N - 1$ edges. The elegance of the hypercube arises from its symmetry, regularity, and recursive definition, which facilitates mathematical manipulation and embedding of other topologies [63].

While hypercubes are conceptually straightforward, visualizing dimensions beyond 3D is cognitively challenging. This limits intuition when designing algorithms. Khalid et al. introduced a 2D representation scheme that maps the high-dimensional structure into a matrix format, making routing and broadcasting algorithms more accessible and reducing human error in design [64]. Hypercube graphs are distinguished by their distance regularity, bipartiteness, and Hamiltonicity, making them well-suited for network applications such as ring-based emulation. They also exhibit strong fault tolerance due to redundant connections. Enhanced variants like $Q_{n,k}$ further expand their capabilities by enabling richer cycle embeddings, including both even and odd-length cycles under specific parity conditions.

Embedding structures like meshes, trees, and rings into hypercubes is widely studied: Trees are easily embedded with minimal distortion due to the hypercube's recursive nature. The twisted cube and folded hypercube are variants used to reduce diameter and increase robustness. Twisted cubes preserve the edge count but introduce changes that reduce the maximum path length, enhancing routing performance [65].

Sasama et al. [66] demonstrated that hypercubes possess resilience to multiple faults through the use of disjoint subcubes. Their model estimates the number of faults needed to destroy all (n−m) subcubes and proposes bounds for fault-resilient design. Algebraic extensions like the Varietal Hypercube alter traditional recursive structures to reduce average and maximum distances, improve bisection bandwidth, and maintain similar edge counts and node structures to classic Q_n, making them ideal for large-scale systems where minimizing delay and cabling costs is critical.

Hypercube topology is widely used in network and parallel computing area.

Hypercube-based architectures are integral in distributed-memory systems like Intel's iPSC/2, where each processor resides at a hypercube node. Their recursive definition facilitates: Easy parallelism for divide-and-conquer algorithms and efficient matrix multiplication and FFT operations [67].

In networks without a fixed topology, hypercube overlays can still be employed. Figueira and Reddi propose topology-aware hypercube mappings, which dynamically adjust node positioning to reduce communication cost by up to 30%[68]. The high performance of hypercube networks supports computational biology tasks like 3D reconstruction of macromolecules. These tasks benefit from efficient FFT and matrix operations, which are highly parallelizable on hypercube networks [69].

The hypercube remains a cornerstone structure in both theoretical and applied computing disciplines. Its recursive design, symmetry, and rich mathematical properties make it as a powerful model for abstract graph theory and topology and also a versatile architecture in distributed systems and parallel computing. The constant evolution of hypercube variants and embedding strategies ensures its relevance in the face of modern scalability and fault-tolerance demands.

2.3 Network Performance Metrics

2.3.1 Response time

The response time, which is the time necessary to submit a request and receive a reply specified for the customer, reflects the efficiency of the network. Typically, interactive terminals need to detect the response time of host message sending, which is a metric to be evaluated by the application layer [70]. Zengin and Cesur [71] investigated the performance of a large-scale wired network consisting of over 300 nodes, using the network simulator tool Ns2. Their study focused on various performance metrics, including throughput, delay, and jitter, to assess the network's performance under

different scenarios. The results indicated that the modelled network provided sufficient performance, highlighting the importance of comprehensive performance analysis in managing large-scale wired networks. Hassani et al. [72] explored the timing analysis and response time of end-to-end packet delivery in switched Ethernet networks. Their study focused on Ethernet Networked Control Systems (ENCS), which are prevalent in control applications. The findings highlight the importance of network configuration in minimising response times and enhancing network performance.

In a master/slave network architecture, the response time is the total of polling delay, link delay, device delay and CPU delay. Different applications require different response times. For example, in email, data accuracy needs to be high, but the response time can be very low. Generally, the response time threshold is set to 100 milliseconds, and the maximum is not over 400 milliseconds. When the response time exceeds the threshold, users on the client side may become frustrated [73].

2.3.2 Network delay

Network delay is the time that data is transmitted from one end to the other. In other words, the time between the request being sent and the answering packet being sent. It is a widely used performance metric. The data is transmitted through the network protocol (such as TCP / IP) in the network medium. If the network traffic is too large and unrestricted, it will lead to slow response and network delay. The size of the delay affects the efficiency of applications on the network, especially for those time-sensitive applications. For example, in voice systems and video conference systems, the end-to-end delay time should be as low as possible, which may achieve the desired voice and video quality [74].

Network delay is a key determinant of Quality of Service (QoS), particularly in applications that are sensitive to timing, such as VoIP, video conferencing, and cloud computing. The sources of delay can be broadly categorized into propagation delay,

transmission delay, queuing delay, and processing delay (see Fig. 2-6). As networks grow in scale and complexity, accurately measuring, modelling, and reducing delay is essential for maintaining performance and user satisfaction.

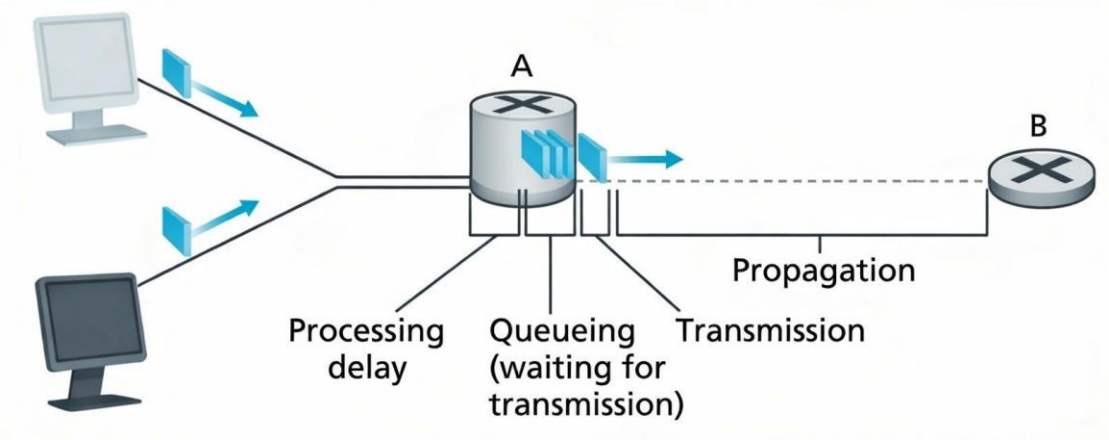


Fig. 2-6 Network Delay

Propagation delay reflects the finite time required for a signal to traverse the physical medium and is primarily determined by path length and the propagation velocity of the medium; consequently, it tends to dominate in wide-area or satellite scenarios where distance is large even when bandwidth is ample [75]. Transmission delay, by contrast, arises from serializing a finite-length packet onto a link at a given bit rate and therefore scales with packet size and inversely with link capacity, becoming most salient on low-rate access links or when frames are large [76]. Under realistic workload dynamics, however, queuing delay frequently accounts for the largest fraction of observed delay variance, since packets may accumulate in router or switch buffers when instantaneous arrival rates approach or exceed service rates; in measurement-driven studies of campus and enterprise networks, this component is often implicated in delay spikes and jitter during diurnal traffic peaks (and, in poorly tuned environments, in persistent “buffer bloat” regimes) [77]. Processing delay captures the time consumed by protocol handling and forwarding decisions, typically negligible in hardware-accelerated paths yet nontrivial when software forwarding, deep packet inspection, or cryptographic encapsulation is introduced [78][79]. A comparison of the constituent parts of each delay is presented in Table 2-3 below.

Table 2-3 Comparison of Network Delay Components

Delay type	Depends mainly on	Typical variability	Often dominated by
Propagation	Distance, medium speed	Low (stable)	Long-distance links (WAN, satellite)
Transmission	Packet size, link rate	Low (stable for fixed L, R)	Slow links, large packets
Queuing	Traffic load, buffer size, scheduling	High (bursty)	Congestion, buffer bloat
Processing	Device performance, feature set	Medium	Firewalls, NAT, DPI, CPU load

2.4 Quality of Service

2.4.1 Background of QoS

In Section 1.1.2, we briefly introduced the concept of Quality of Service (QoS). In this section, we continue to introduce the research directions and content pertaining to QoS.

Quality of Service (QoS) in computer networks is a critical concept aimed at ensuring that data communication adheres to specified performance parameters to meet the diverse requirements of applications and users. QoS encompasses a range of mechanisms and protocols designed to optimize network performance by managing bandwidth, reducing latency and jitter, and minimizing packet loss. These features are increasingly vital in modern networks, particularly with the proliferation of bandwidth-intensive applications like video conferencing, real-time streaming, and Voice over Internet Protocol (VoIP) services.

As network-dependent services proliferate, ensuring Quality of Service (QoS) becomes critical. QoS in networking refers to a set of techniques and policies that manage data traffic to reduce packet loss, latency, and jitter, and ensure bandwidth availability. QoS is essential in modern networks where applications such as VoIP, video streaming, and real-time collaboration are bandwidth-intensive and sensitive to delays.

QoS architectures began with the introduction of the Integrated Services (IntServ) and Differentiated Services (DiffServ) models. IntServ offers per-flow guarantees using RSVP for resource reservation, ideal for controlled networks but limited in scalability [80]. DiffServ, by contrast, categorizes traffic into classes, enabling scalable service differentiation without state maintenance in core routers. Multi-Protocol Label Switching (MPLS) complements these models by directing packets along pre-established paths, enhancing performance and predictability [81]. Webel and Gotzhein introduced a layered formalization of QoS requirements, emphasizing cross-layer optimisation and cost-function-based trade-off [82].

QoS has become a cornerstone for ensuring reliable and efficient operations in various technological ecosystems. As modern applications demand high performance and user-centric experiences, QoS metrics such as latency, throughput, and packet loss have gained increasing attention. This paper explores the current advantages and disadvantages of QoS frameworks, with an emphasis on their application in different fields. The analysis spans traditional and modern QoS implementations, providing a comprehensive view of its evolution and impact.

The advantages of QoS in application are listed below:

1. QoS frameworks prioritise critical traffic, ensuring that essential applications receive the required bandwidth and latency metrics. For instance, real-time applications such as VoIP and video conferencing benefit from reduced jitter and consistent data flow, leading to improved user experiences.

2. By allocating resources based on predefined priorities, QoS enables efficient utilization of network and system resources. This optimization prevents over-provisioning and reduces operational costs while maintaining service reliability.

3. In competitive markets, QoS ensures that services meet user expectations, enhancing customer retention. Industries such as online gaming and video

streaming heavily rely on QoS to deliver seamless experiences, minimizing interruptions and buffering issues.

In contrast, the disadvantages of QoS in application are listed below:

1. Deploying QoS policies requires sophisticated configurations, often involving deep technical expertise. Small errors in configuration can lead to unintended consequences, such as traffic bottlenecks or security vulnerabilities.

2. QoS mechanisms often involve significant investments in infrastructure and technology. For example, achieving end-to-end QoS in large-scale networks requires advanced hardware, software, and maintenance efforts, which may strain budgets.

3. Ensuring QoS in heterogeneous environments, such as multi-vendor networks, can be challenging. Inconsistent standards and protocols across devices may lead to performance inconsistencies.

4. While QoS prioritizes critical traffic, it may inadvertently deprioritize less-critical applications, leading to dissatisfaction among certain user groups. This trade-off necessitates careful balance and monitoring.

Future directions in QoS research and implementation point toward emerging technologies that promise to reshape network performance and reliability. One such area is Artificial intelligence (AI) and machine learning (ML) are being integrated into QoS systems for predictive traffic management and real-time optimizations. These technologies promise to enhance scalability and adaptability in dynamic environments. For instance, machine learning algorithms have been used to predict network congestion and optimize resource allocation dynamically [83]. Another promising direction is the integration of blockchain technology to create decentralized Service Level Agreements (SLAs), which can enhance transparency, accountability, and trust

between service providers and users. Sérgio and Martins discuss the role of SLAs in enforcing QoS and highlight methods such as traffic shaping, policing, and buffer management [84]. Additionally, the rise of edge computing offers significant QoS benefits by enabling data processing to occur closer to end users, thereby reducing latency and improving the responsiveness of real-time applications. Cloud computing and edge computing are additional areas where QoS is evolving. In cloud environments, QoS ensures that critical applications receive adequate resources despite varying workloads. Edge computing introduces new challenges and opportunities, as data processing occurs closer to the end-users. QoS frameworks in edge networks must address latency, bandwidth, and reliability requirements efficiently. These innovations collectively represent the next frontier in developing adaptive and trustworthy QoS frameworks for future networks. QoS remains a vital area of research and application in modern networking. While foundational models provide a solid base, emerging technologies promise to overcome existing limitations. The integration of AI, blockchain, and edge computing presents promising avenues for more adaptive, secure, and scalable QoS frameworks.

Quality of Service in computer networks remains a critical area of research and development, underpinning the performance and reliability of modern communication systems. From multimedia applications to IoT and 5G networks, QoS frameworks ensure that diverse applications can coexist and perform optimally. Emerging technologies like AI, SDN, and edge computing promise to enhance QoS capabilities, addressing current challenges and paving the way for future innovations. As networks become increasingly complex and interconnected, QoS will remain central to their efficiency and scalability.

2.4.2 QoS Mechanisms

In this subsection, we provide a detailed exposition of the three QoS queuing models employed in this study. These models were selected as they represent contemporary,

widely adopted queuing approaches, each exhibiting distinct advantages in different scenarios and thus serving as representative QoS queuing methodologies.

Weighted Fair Queuing (WFQ)

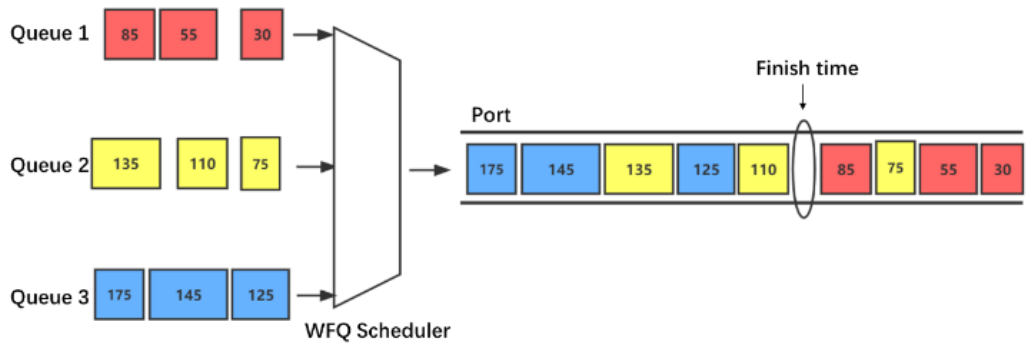


Fig. 2-7 Weighted Fair Queuing

Weighted Fair Queuing (WFQ) (see Fig.2-7) provides fair queuing by dividing the available channel capacity among traffic queues based on their respective weights. Each flow is associated with a separate queue that is allocated a weight to guarantee that priority is given to the most critical traffic [85]. The WFQ discipline weights traffic; therefore, low-capacity traffic gets a high level of priority. The unique feature of this queuing rule is that real-time interactive traffic will be moved to the front of the queue, while other traffic will share the rest of the bandwidth fairly. Ronak Al-Haddad et al. [86] propose a new traffic-shaping algorithm to implement QoS capacity management techniques to optimise performance and solve network congestion problems. Specifically, "packet tagging, queuing and forwarding to queues" and "bandwidth allocation" are proposed to implement WFQ techniques as a new approach to reduce congestion and promote smooth traffic flow.

Priority Queuing (PQ)

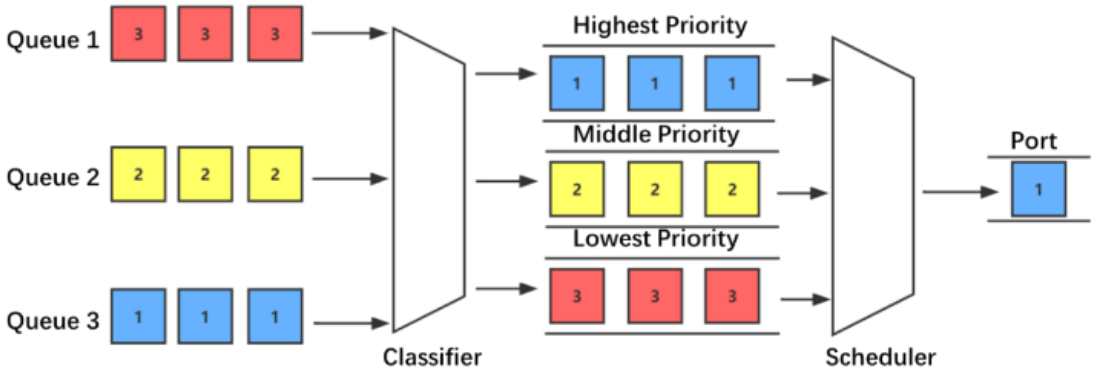


Fig. 2-8 Priority Queuing

The principal idea of priority queuing (see Fig. 2-8) depends on the priority of the packets. The highest priority is transmitted on the output port first, and then the packets with lower priority, and so on. When congestion occurs, packets with lower-priority queues will be dropped. The only problem with these packets is their lower priority in the queue [87] No packets from lower queues are handled while there are packets in the High queue. If no new packets are added to the High queue, the packets in the medium queue will be processed. The most evident benefit of PQ is that it prioritises the processing of communications according to their priority. One major drawback of PQ is that it is not uncommon for lower-priority queues to be ignored entirely. Low-priority lines can be starved out by a steady flow of high-priority traffic [88].

Modified Weighted Round Robin (MWRR)

Modified Weighted Round Robin (MWRR) is designed to improve the handling of network traffic or computing tasks across multiple servers or processes. The primary goal of MWRR is to allocate resources or process requests based on a predefined weight assigned to each queue or server, ensuring a fair and efficient distribution of network traffic or computational tasks. Each queue or server is assigned a weight, which typically reflects its capacity or priority. The algorithm distributes tasks or requests to queues or servers based on their weights, but it also monitors the current load and performance. Depending on real-time metrics, MWRR may adjust the weights dynamically, giving more resources to queues or servers that are under higher demand

and less to those with lighter loads or faster processing times.

2.5 Resilience

Network resilience, the capacity of a computer network to withstand, adapt to, and recover from disruptions, is an increasingly critical area of research and application. As modern networks support critical societal functions—including communication, healthcare, finance, and infrastructure—ensuring their resilience is essential to mitigate risks from natural disasters, cyberattacks, or human errors. This analysis synthesizes research findings and emerging insights on the topic, providing an overview of challenges, strategies, and advancements in this domain.

Trivedi et al. define it as the persistence of service delivery despite challenges, distinguishing it from dependability metrics like availability or performance [89]. The critical role of networks in supporting vital applications has amplified the focus on resilience. Mishaps, whether intentional (cyberattacks) or accidental (hardware failures), can result in severe disruptions. Networks are increasingly complex, interdependent systems, vulnerable to targeted attacks and cascading failures. For example, malicious attacks on nodes can destabilize systems, a challenge addressed by modelling network structures as physical elastic systems to optimize resilience [90]. Meanwhile, virtualized architectures like 5G networks present new challenges due to hybrid dependencies between hardware and software elements [91]. Network resilience remains a dynamic field, critical to the reliability of modern infrastructures. Ongoing research highlights innovative approaches, from programmable technologies to interdependent network analyses. As threats evolve, multidisciplinary collaboration and advanced modelling techniques will be essential to ensuring resilient systems that support societal functions.

2.6 Distributed Denial of Service (DDoS) attack

Distributed Denial of Service (DDoS) attack is a type of cyber-attack that overwhelms a system or network by flooding it with a large number of requests, above its normal traffic capacity (see Fig.2-9). A multitude of computer systems are utilised to execute these attacks, making it very challenging to protect against them. DDoS assaults can result in significant monetary losses, harm to one's reputation, and the interruption of essential services. Attackers have the ability to utilise several methods, such as inundating the target system with a high number of data to overwhelm its requests, altering network traffic to disrupt communication, or exploiting vulnerabilities to obtain unauthorized entry. The scale and sophistication of DDoS attacks have been evolving significantly. The maximum peak bandwidth observed for such attacks has shown fluctuations, with a record high of 1.39 Tbps in 2021 dropping to 800 Gbps in 2022 [92] . Despite this decrease, the scale of these attacks remains substantially higher than in previous years, indicating a continuing trend of high-impact capabilities among attackers.

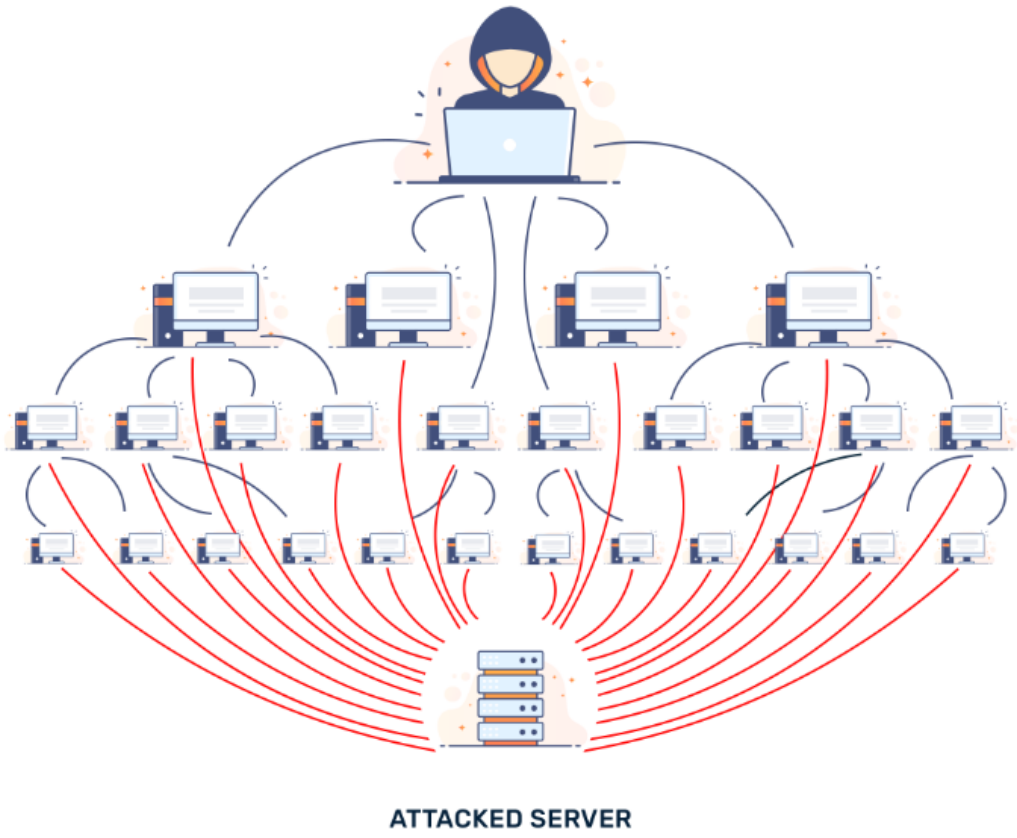


Fig. 2-9 DDoS Attack

The COVID-19 epidemic expedited the emergence of DDoS attacks, as remote labor and digital reliance generated new vulnerabilities. Suthar and Patel [92] indicate that attacks exceeded 10 million in 2020-2021, with a 31% increase to 2.9 million occurrences in the first quarter of 2021, according to NETSCOUT statistics. Zhunjare and Randive [93] situate this inside the 5G and IoT ecosystems, where "the emergence of 5G networks and IoT infrastructure" offered connection while simultaneously amplifying vulnerabilities, facilitating Tbps-scale botnets. In 2018, the GitHub attack reached a zenith of 1.35 Tbps through amplification techniques without the use of botnets, highlighting a transition towards protocol vulnerabilities rather than mere volume [94].

Recent years (2020-2024) demonstrate increased sophistication: multi-vector assaults that integrate volumetric floods with application-layer stealth tactics. Reddy [95] notes

that by 2007, botnets had made initial defences such as rate limitation ineffective, as "attackers began employing distributed botnets, complicating detection." Zhang et al. (2024) attribute this to the expansion of IoT, noting that "DDoS attacks have progressed from basic, volumetric assaults to highly advanced, multi-vector threats." The CISA handbook [96] underscores the necessity for continual adaptation, stating that "new attack methods and variations consistently arise as malicious actors modify and advance their tactics, techniques, and procedures (TTPs)." This history reflects technology progress—from rudimentary script-kiddie tools to AI-driven campaigns—underscoring DDoS as a fluid danger necessitating proactive investigation.

Generally, DDoS attacks can be classified into three main categories: volumetric, protocol, and application attacks.

Volumetric Attacks: The objective of volumetric attacks is to use up all of the available bandwidth between a web server and the Internet. There is no more bandwidth available for lawful traffic when a hostile volumetric attack uses up all of the bandwidth between a web server and the Internet. One of the most prevalent types of volumetric attacks is DNS amplification. An attacker uses a zombie machine to query a DNS server by impersonating the victim's server's IP address. Even though the victim's server didn't submit a request, the DNS servers will nevertheless transmit the answers to the victim's IP address. An attacker can significantly increase the volume of DNS inquiries by controlling a botnet, which will overwhelm the victim's server with a lot of unsolicited DNS responses and saturate the bandwidth between the web server and the Internet.

Protocol Attacks: Protocol attacks typically target network layer and transport layer in open systems interconnection (OSI) model. A SYN flood attack, for instance, takes advantage of the three-way handshake procedure required to create a transmission control protocol (TCP) connection. Zombie machines send a SYN message to start the handshake procedure. The server is rendered inoperable by the zombie computers' failure to finish the handshake procedure, which leaves the ports occupied and unable

to handle valid requests. Zombie computers deliver a lot of UDP datagrams to random ports on the target server during a UDP flood assault. As a result, the web server searches for running apps that are meant to receive these datagrams on those ports. The web server will reply with an ICMP packet to notify the sender that the destination was inaccessible as the datagrams are not requested by an application that is now operating on the server. When the server receives enough UDP datagrams, it will eventually run out of ICMP packets to respond, rendering it unusable.

Application Attacks: Application assaults typically function via transmitting HTTP requests. When a client requests a web page from a web application, the web server often executes multiple scripts and performs database queries to satisfy the request. A web server incurs significantly greater processing costs to process an HTTP request compared to the costs borne by a client to initiate an HTTP request. By manipulating a botnet, attackers can inexpensively inundate a web server's processing resources by bombarding a web application with HTTP requests. HTTP attacks resemble numerous users repeatedly refreshing a web browser, however the entire operation is automated and executed remotely by attackers utilizing a vast network of compromised devices.

DDoS attacks do not impact all industries equally; sectors like technology and finance are often more targeted due to their critical role in economies and infrastructures [97]. The specific targeting of these sectors reflects a strategic preference among attackers to disrupt services or extort money through ransom-related DDoS activities. The increase in DDoS attacks highlights the expansion of cyber risks, necessitating the implementation of strong cybersecurity measures. As technology advances, the risk of cyber-attacks, including DDoS attacks, is also growing. Multiple studies have put forward models to improve the identification and reduction of DDoS assaults. Research has shown that feature reduction strategies are beneficial in enhancing the computing efficiency of detecting systems. By reducing the number of variables analysed, these models can function more efficiently and with lower resource demands, which is essential for implementing effective security measures in real-time situations [98]. In

the infrastructure construction of structured geometric topology networks, we found that the CP and TP structures have good network resilience. We hypothesise that leveraging structured geometric topologies can offer novel solutions for securing networks against emerging cyber threats.

3 Computer Network Modelling Methodologies

3.1 Introduction

Network planning and design, equipment development, and protocol development are becoming increasingly challenging due to the quick advancement of network technology, the growing complexity of network structure and size, and the growing number of network application kinds. As a result, network simulation technology was developed as an accurate and scientific method of simulating and forecasting network technology performance. Network simulation, intelligent planning, network optimisation, and network management have become hot topics in the data network area, particularly in the last 20 years due to the quick growth of system simulation technology. With the help of simulation technology, the reliability and accuracy of network planning and design can be greatly improved, the risk of network investment can be greatly reduced, and the unnecessary investment waste can be reduced [99]. In the future, network simulation will become an indispensable part of data network planning and design. In this section, I provide a detailed account of the network architecture simulator employed in this thesis—the Riverbed Modeler—alongside the computer network simulation methodology utilised. Fig. 3.1 illustrates the structure and functionality of Riverbed Modeler, enabling users to conduct simulations using its models. Analysis is performed on the simulation results, followed by optimisation through the model.

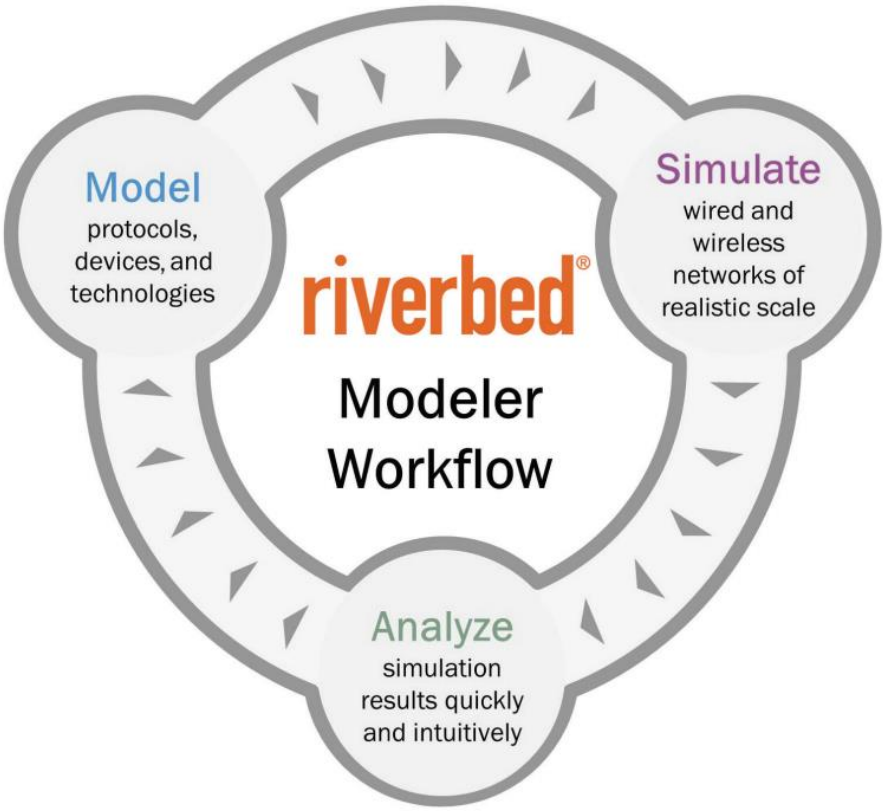


Fig. 3-1 Riverbed Modeler Workflow

3.2 Simulation Modelling

The network simulation program will replicate the actual network environment by the creation of a machine virtual network platform. On this platform, network infrastructure engineers can not only design and study network communication, network software, protocol and network application, but also analyse and measure network performance. Additionally, the simulation operation and result analysis functions offered by the simulation program enable developers to acquire network output parameters easily and intuitively. These criteria offer better and more efficient ways to plan and to make decisions optimally. Therefore, using network simulation software to simulate network protocols and algorithms has become an indispensable part of computer network communication research.

In this thesis, Riverbed Modeler, another name of OPNET Modeler, is widely recognized and used for network simulation. At present, riverbed is the most advanced network simulation development and application platform in the world.

The software is specifically designed for experts in network architecture and can essentially satisfy the needs of complicated large-scale network simulations. It is widely used in the network industry for local and wide area network performance modelling and evaluation. Riverbed Modeler's key advantages include an extensive model library, scalable design, high-quality modelling data, user-friendly interfaces and flexible display of simulation results [100].

Riverbed Modeler has the following characteristics:

1. The software proposes a three-layer modelling mechanism. The bottom layer is the process model, which uses the state machine to describe the protocol. The middle layer is a node model composed of appropriate protocol models, which reflects the characteristics of devices. The top layer is the network model based on the network layer. The three-layer model corresponds entirely to the real network, equipment and protocol levels, which fully reflects the corresponding characteristics of the network.
2. It offers a full library of simple model, including router, switch, server, client, ATM equipment, Digital Subscriber Line (DSL) equipment, Integrated Services Digital Network (ISDN) equipment and so on. At the same time, Riverbed technology company will provide additional special model libraries for different enterprise users, but they need to pay extra.
3. The numerical efficiency of discrete event-based simulation is vastly increased as compared to time driven simulation.
4. Using the hybrid modelling mechanism, the package-based analysis method and the statistical based mathematical modelling method are combined, which not only

produces highly informative simulation results but also significantly improves simulation performance.

5. Riverbed Modeler has rich functions of data processing and interpretation. It can easily collect and output the commonly used network performance parameters.
6. The interface with network management system and traffic surveillance system is provided, which can easily use the current topology and traffic data to build simulation model and complete the outcomes of the 2 [101].

3.3 Modelling Mechanism

The network is a complex system. Riverbed Modeler uses hierarchical and modular methods to decompose the complex system into different hierarchical structures. There are some tasks completed by each layer. There are several modules in one layer and each module carries out smaller tasks. The three stages of the Riverbed Modeler construction are network domain, node domain and method domain [102].

The method of node domain modelling is based on node module. Each node module implements one part of node behaviour, namely data generation, data collection, data management or routing and data transmission. The collection of multiple node modules constitutes a node with complete function. The modules are connected by packet line or statistical line, in which the packet line carries the data packet transmission between modules, the statistical line can monitor the changes of undetermined parameters of modules, and the user can simulate the behaviour of nodes. Node modules can be divided into processor, data stream and transceiver according to their functions [103].

As the bottom layer of three-tier modelling mechanism, process model is the carrier to implement various algorithms, so it is the most important part in the process of modelling and simulation, and also the most difficult part to implement. Process model is mostly used to explain the behaviour of processor and queue model in node model.

It can simulate most software or hardware systems, including networking protocol, algorithm, queuing policy, pooled resource, special service source and so on.

Riverbed Modeler adopts simulation mechanism based on discrete event driven. An event is a change in the state of a network model or a decision. Only when the state of the model changes, the simulator can simulate. When the state does not change, the simulator will not simulate. The simulation time is discrete, every time there is an event, time moves forward, that is, time is jumping forward. Multiple events can occur at the same time in a simulation time point, and the occurrence of events can be different in density [104].

Each module in the simulation transmits event information through event interrupt. Every time an event interrupt occurs, a process model describing the communication network system behaviour or system processing will be triggered. Through the simulation mechanism driven by discrete events, the concurrency and sequence of communication can be described at the process level. In addition, the arbitrariness of event occurrence time means that the network state and behaviour in any situation of computer and communication network can be simulated [105].

4 Network Model Design and Implementation

4.1 Introduction

In this chapter, we will introduce the design and implementation of the overall network structure.

4.2 Design of Study

This thesis commences with the exploration of structured geometric topological network architectures. Utilising network technologies, we construct intricate geometricised networks to investigate how structured geometric topologies alter network performance. Subsequently, we incorporate quality of service considerations, employing discrete event simulation parameters as metrics for evaluating network system performance, whilst utilising queuing policies as tools for network optimisation. Our objective is to enhance the resilience of network systems, thereby strengthening network security. As illustrated in Fig. 4-1.

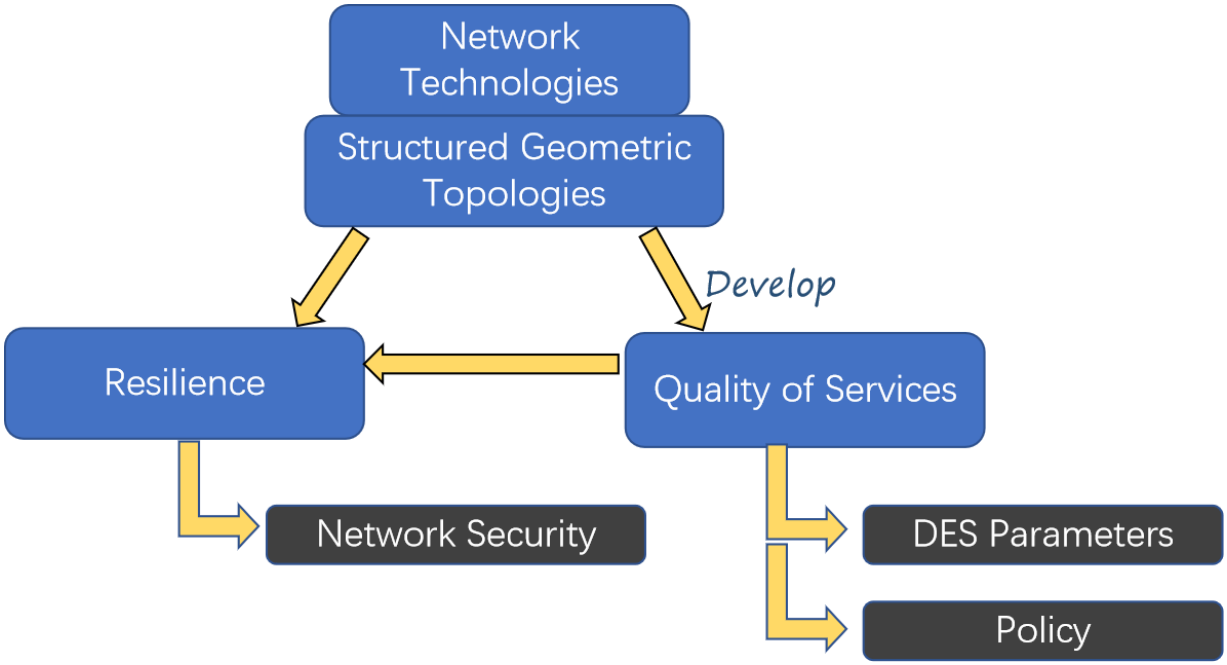


Fig. 4-1 Design of Study

4.2.1 Structure of Structured Geometric Topologies

A network topology is a fundamental aspect of a computer network, serving as the foundation for network management, data simulation, and data gathering. In the meantime, network topology is also an application of graph theory in which communication devices are described as nodes, and connections between them are modelled as links or lines connecting the nodes. Currently, the research on network topology predominantly focuses on unstructured network topologies as discussed in Section 2.2. Structured geometric topological structures characterized by specific shapes and links have already found practical applications in some engineering fields due to their unique stability, connectivity and other features that facilitate information transmission (see Section 2.2). Meanwhile, only a limited number of structured topological networks have been implemented in network infrastructure. In this case, we explored the applicability of structured geometric topology in network infrastructure, aiming to enhance network performance by developing an understanding of the relationship between structured geometric topology and network configuration.

There are many structured geometric topologies that meet the definitions given in this thesis (see Section 1.5). However, the objective of our paper is not to 'exhaustively list all geometric topologies,' but rather to explore the interaction mechanisms between structured geometric topologies, QoS and network security. Among various structured topological structures, we have selected the CP and TP structures in this paper, which we have thoroughly researched their properties. We believe that these structures can demonstrate the advantages of structured topological structures to a certain extent. In actual network software simulations, we also attempted to incorporate additional network structures such as hypercube structures. However, due to the excessive number of nodes and data volume in this structure, our simulation software required an excessive amount of time to simulate the scenario (a single scenario involving time-dependent applications required more than a week of simulation time). Moreover, during the simulation process, hardware issues are prone to occur, causing the

simulation program to crash. We believe that experiments must be conducted within a controlled environment in order to enable in-depth analysis. Therefore, this Section 5 mainly compares CP, TP, and mesh networks. In some sections, the simulation results of hypercubes will be mentioned. In future research, we will also explore the performance and advantages of other structured geometric topological structures.

We employ structured geometric topology as the parent network topology, with Ethernet and IP networks serving as channels to connect various sub-networks. The combination of Ethernet at layers physical / data link and the IP protocol at layer network has become the default underlying foundation for the most used complex network architectures. This combination perfectly achieves the unification of scalability, robustness, cost-effectiveness, and expandability in heterogeneous environments such as enterprise campuses, hyperscale data centres, and carrier backbone networks. Ethernet and IP have remained evergreen and continued to expand because their architectures perfectly combine strict layering with a pragmatic "end-to-end" design concept, thus maintaining the simplicity of the core and achieving intelligence at the edge, allowing heterogeneous link technologies and applications to interoperate and evolve. There is no need to reinvent the coordination across the full protocol stack. In actuality, Link Layer Ethernet delivers a fast, frame-based underlying layer, whereas IP provides a ubiquitous, connectionless, and semantically minimum network layer. Together, they form a modular architecture that allows the transport and application layers to evolve independently. This separation of responsibilities results in unambiguous abstractions (interfaces, MTU, addressing, and forwarding behaviour) and incremental deployment capabilities. These properties, which are regularly stated, are critical for the network's resilience to quickly rising and continuously changing workloads. This precisely aligns with the most direct objective of this study: enhancing the network resilience of the network.

4.2.2 Quality of Service

In the rapidly evolving landscape of computer technology, Quality of Service (QoS) has become a paramount concern for developers and users alike. Allocation of network resources, such as buffers and data rate, to different users presents the most significant challenges in a network. To maximise the performance and utilisation of the network's resources, a limited quantity of resources must be shared among multiple additional competing traffic flows. Therefore, adequate QoS is essential to satisfy the stringent requirements. As a measure of the performance characteristics of a system, QoS dictates the satisfaction level of end-users and the efficiency of organisational operations. QoS is the description or measurement of the overall efficacy of a service, such as a telecommunications or computer network, as perceived by its consumers.

QoS, from the user's standpoint, is a crucial factor that distinguishes various services. In computer networking and other packet-switched telecommunication networks, QoS refers to traffic prioritisation and resource reservation control mechanisms rather than the actual service quality. QoS is the capacity to assign distinct priorities to various applications, users, or data flows or to guarantee a particular level of performance to a data flow. The core aim of QoS is to achieve a more predictable and controlled resource behaviour so that the desired service quality can be achieved with high reliability and predictability. The relationship between computer QoS and the underlying network topology is particularly significant, as the physical and logical structure of a network directly impacts the efficiency of QoS mechanisms.

In our previous research, we preliminarily explored the potential of using structured geometric network infrastructure design to improve network performance. We compared the simulation results of an unstructured network design with two structured network topologies for both time-dependent and time-independent applications. The simulation results illustrate that the cross polytope (CP) and triangular pyramid (TP) topologies have better performance than the unstructured network in response time and network delay

under a high-load configuration. In next stage, we take our study forward to evaluate the performance of structured geometric network infrastructure designs under several QoS queuing mechanisms. Our earlier conference study established that planarised CP and TP topologies reduce mean response time and end-to-end delay under a best-effort traffic regime. However, it left open the question of how structured geometries behave when heterogeneous services compete for capacity under strict QoS guarantees. The second stage research closes this gap by (i) embedding three canonical schedulers—WFQ, PQ and MWRR—into the same CP and TP fabrics, (ii) stressing the network with a heavier mixed workload, and (iii) introducing loss-and-latency perturbation tests. These extensions enable a fair, apples-to-apples comparison that quantifies the synergy between geometric regularity and packet scheduling beyond the scope of previous research.

We have introduced quality of service queuing mechanism to improve the resilience of the structured geometric topology network.

4.2.3 Network Resilience

Data communication networks facilitate a variety of human activities. Whether for professional or recreational use, safety-critical applications, or e-commerce, the Internet has become a vital part of our daily lives, influencing the functioning of civilisations. However, the Internet was not designed to serve all these functions, so it is susceptible to various difficulties. Normal functioning is threatened by malicious assaults, software and hardware failures, human error (e.g., software and hardware misconfigurations), and large-scale natural disasters. Resilience, the capacity of a network to defend against and maintain an acceptable level of service in the presence of such challenges, is an essential requirement and design target now more than ever before. In this study, network resilience will be improved based on the structured geometric network topology.

In this study, the attack method simulated was a Distributed Denial of Service (DDoS) attack. Distributed Denial of Service (DDoS) attack is a type of cyber-attack that overwhelms a system or network by flooding it with a large number of requests, above its normal traffic capacity. A multitude of computer systems are utilised to execute these attacks, making it very challenging to protect against them. DDoS assaults can result in significant monetary losses, harm to one's reputation, and the interruption of essential services. Attackers have the ability to utilise several methods, such as inundating the target system with a high number of data to overwhelm its requests, altering network traffic to disrupt communication, or exploiting vulnerabilities to obtain unauthorized entry. We simulated DDoS attacks on local area networks using structured geometric topology networks and compared these with unstructured geometric topology networks to investigate the extent to which structured geometric topology networks optimise network resilience.

Subsequently, the previously simulated QoS queuing mechanism will be introduced to enhance the network's resilience.

4.3 Application Configuration

Our simulation is built on the individual Discrete Event Simulation (DES) mechanism, which models the operation of a system as a (discrete) sequence of events in time. Each event occurs at a particular instant in time and marks a change of state in the system [106]. Based on individual DES, we examine network performance in different topologies, setting three time-independent applications as well as one time-dependent application to be tested. We also set Ethernet as a performance parameter to show the overall network stability.

The details of setting global parameters are shown in Table 4-1.

Table 4-1 Application Configuration

	Applications	**Statistics**	**Traffic loads configuration**
Time-independent Application	Database	Response Time (sec) Traffic Received (packets/sec) Traffic Sent (packets/sec)	Traffic model: High load Transaction Inter-arrival Time (seconds): Exponential function (mean outcome is 12) Transaction Size (bytes): Constant (32768 bytes) Type of Service: Best Effort
	Email	Download Response Time (sec) Traffic Received (packets/sec) Traffic Sent (packets/sec)	Traffic model: High load Send Interarrival Time (seconds): Exponential function (mean outcome of 360) E-mail Size (bytes): Constant (2000 bytes) Type of Service: Best Effort
	HTTP	Page Response Time (sec)	Traffic model: Video Browsing Page Interarrival Time (seconds): Exponential function (mean outcome of 360) Request Size (bytes): Constant (350 bytes) HTTP Version: HTTP 1.1 Type of Service: Best Effort
	Ethernet	Delay (sec)	
Time-dependent Application	Voice	Packet End-to-End Delay (sec)	Traffic model: IP Telephony and Silence Suppressed Silence Length (second): Exponential function (mean outcome of 0.65) Talk Spurt Length (second): Exponential function (mean outcome is 0.352) Type of Service: Interactive Voice

This thesis sets all four applications to their corresponding high-load cases, e.g., Voice is set to a high load mode of “IP Telephony and Silence Suppressed”. "High load" refers

to the state when the demand on network resources (such as channel capacity, processing power, or storage) approaches or exceeds the network's capacity to handle it efficiently. For interactive voice, the RTP/UDP design remains dominant because it separates timing-critical media from signalling, keeps the transport stateless for routers, and allows the application—not the network—to make fast concealment and rate-adaptation decisions. They minimise delay while still carrying the sparse timing metadata required by the decoder. The configured applications are distinct from a user's perspective regarding utilisation patterns and have been modelled to generate peak traffic rates consistent with an actual description of heavy load, as shown in Table 4-1. The time-independent applications outlined in Table 4-1 are subjected to IP Best Effort service to reveal the true character of each geometric topology under heavy traffic loads. In the time-dependent application Voice, its service type is set to interactive voice, which is widely used on the Internet. "Interactive voice" refers to services that involve real-time voice communication and interaction between users and automated systems.

Simulation model calibration was crucial for ensuring model accuracy and representation of a real-world system. To achieve this, key model parameters (including traffic inter-arrival times, packet sizes, and service types) were systematically adjusted based on empirical research and the operational characteristics of real-world applications. These parameters, particularly for both time-independent (e.g., HTTP, Email, Database) and time-dependent (e.g., Voice) applications, were configured using realistic high-load scenarios informed by established literature and simulation best practices. Using the Riverbed Modeler 18.9 discrete event simulation framework, we iteratively fine-tuned application-layer profiles and queuing disciplines (WFQ, PQ, MWRR) to ensure that the simulated output aligned closely with expected network behaviour. By comparing simulated traffic behaviours with known performance patterns (such as packet loss trends, response time thresholds, and end-to-end delay limits), we minimised the deviation between simulated and real-world expectations. This calibration process was essential to ensuring that the structured geometric

topologies tested under QoS constraints reflected practical performance conditions with high fidelity.

4.4 Quality of Service Configuration

In this thesis, we set up three types of quality of service algorithms, which are WFQ, PQ and MWRR. In the riverbed simulation software, a total of eight types of service are provided, which are Best effort, Background, Standard, Excellent effort, Streaming Multimedia, Interactive multimedia, Interactive Voice and Reserved. As shown in Table 4-2.

Table 4-2 Quality of Service Configuration

	WFQ		MWRR		PQ	
Classification Scheme	Weight	Maximum Queue Size (packet)	Weight	Maximum Queue Size (packet)	Weight	Maximum Queue Size (packet)
Best effort	1	500	1	1000	0 (low)	80
Background	10		10			
Standard	20		20		1 (Normal)	60
Excellent effort	30		30			
Streaming Multimedia	40		40		2 (Medium)	40
Interactive multimedia	50		50			
Interactive Voice	60		60		3 (High)	20
Reserved	70		70			

To quantitatively assess the weighted fairness of heterogeneous business flows, this thesis uses the Jain Fairness Index (JFI):

$$J = \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n\left(\sum_{i=1}^{n} {x_i}^2\right)} \quad (1)$$

Where x_i refers to the final data rate received after the traffic area stabilises. n is the number of QoS mechanisms and no-QoS mechanisms.

4.5 Simulation Scenario Design

Each sub-network interface makes use of switched technology in conjunction with a direct connection to an IP-based network, which is used to emulate the operation of an internet-based IP datagram processing (the Internet). Three “Definition objects” have been selected: “Application Config”, the application definitions for the database, HTTP and voice, is used to construct profiles for the respective applications; “Profile Config” is the profile configuration node used to create the three user profiles, database application, HTTP application and voice application specified on different network nodes to generate application layer traffic. “QoS Attribute Config” defines attribute configuration details for protocols supported at the IP layer and the queuing mechanisms that are set up, such as WFQ, PQ and MWRR. A Subnet node is a logical networking structure hosting multiple network segments, such as routers or workstations, which implement the client or server side. The IP cloud is set up to link the routers in every two nodes, where ip32_cloud is selected. This node model supports up to 32 serial line interfaces and allows developers to choose the data rate for modelling IP traffic. The link between the IP cloud and the Subnet in the parent subnets is established using PPP_DS3, which operates at a data rate of 44.7 Mbps. The cross polytope, triangular pyramid, unstructured mesh and hypercube topologies in the simulated scenario are shown in Fig. 4-2, Fig. 4-3, Fig. 4-4 and Fig. 4-5 respectively.

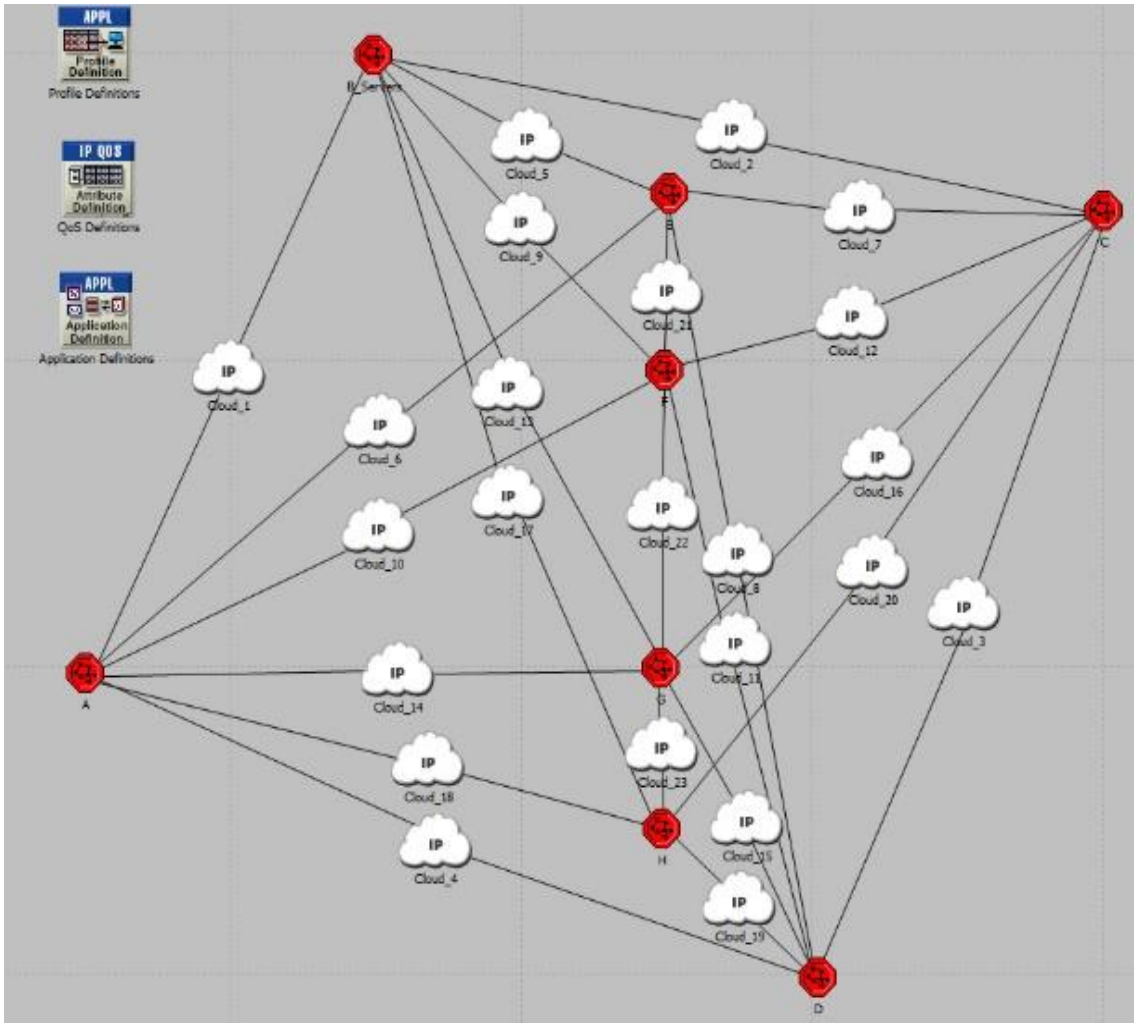


Fig. 4-2 Cross Polytope Subnet

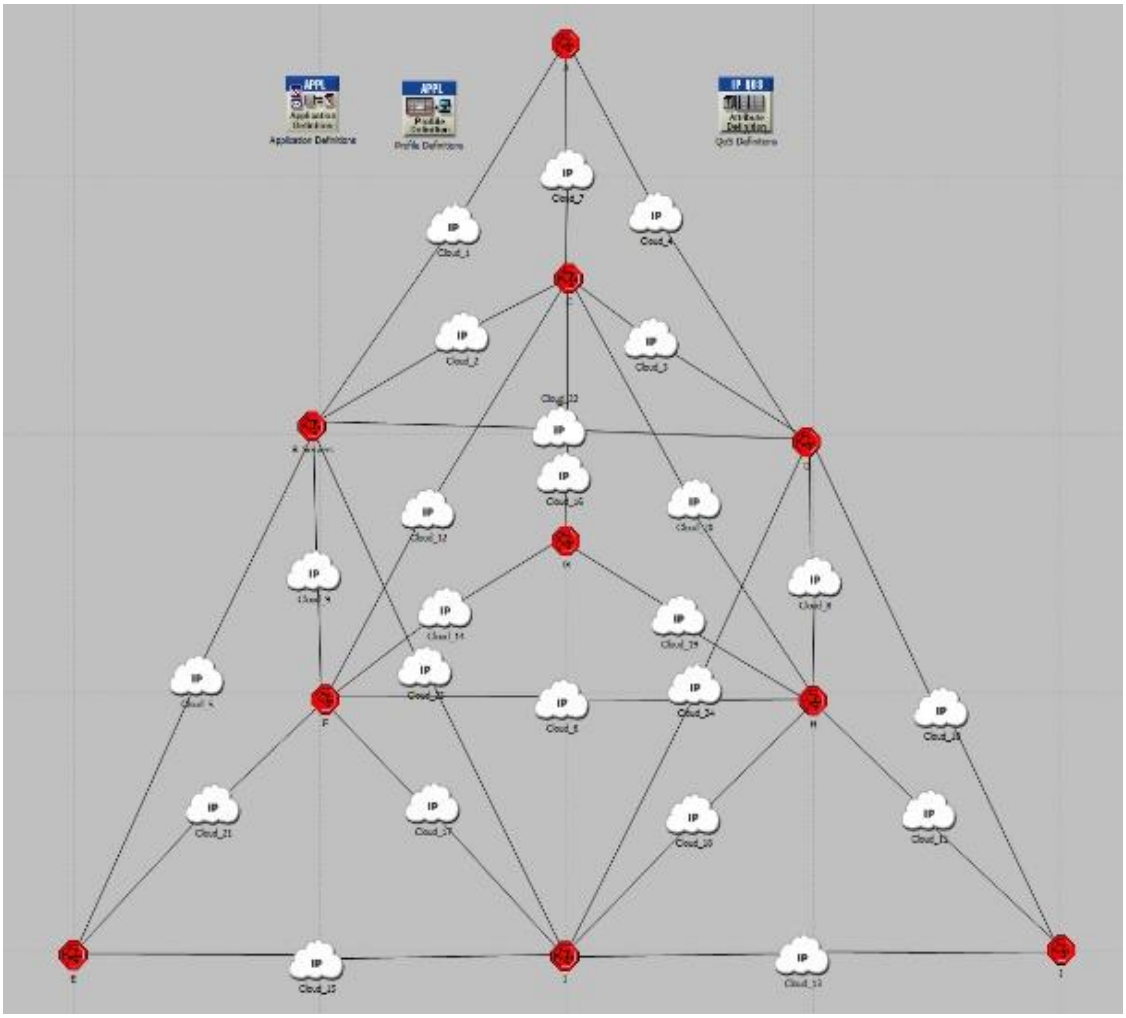


Fig. 4-3 Triangular Pyramid Subnet

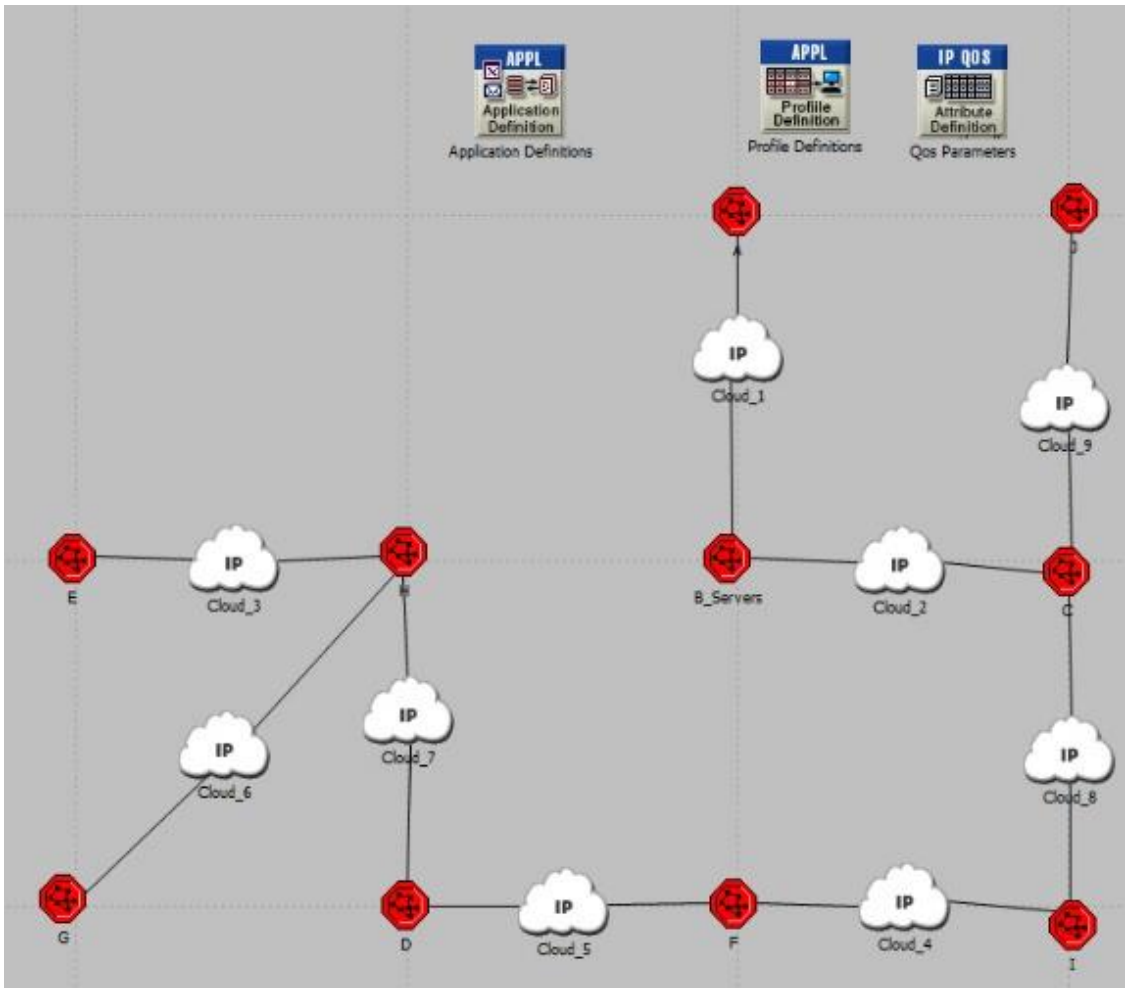


Fig. 4-4 Unstructured Mesh Subnet

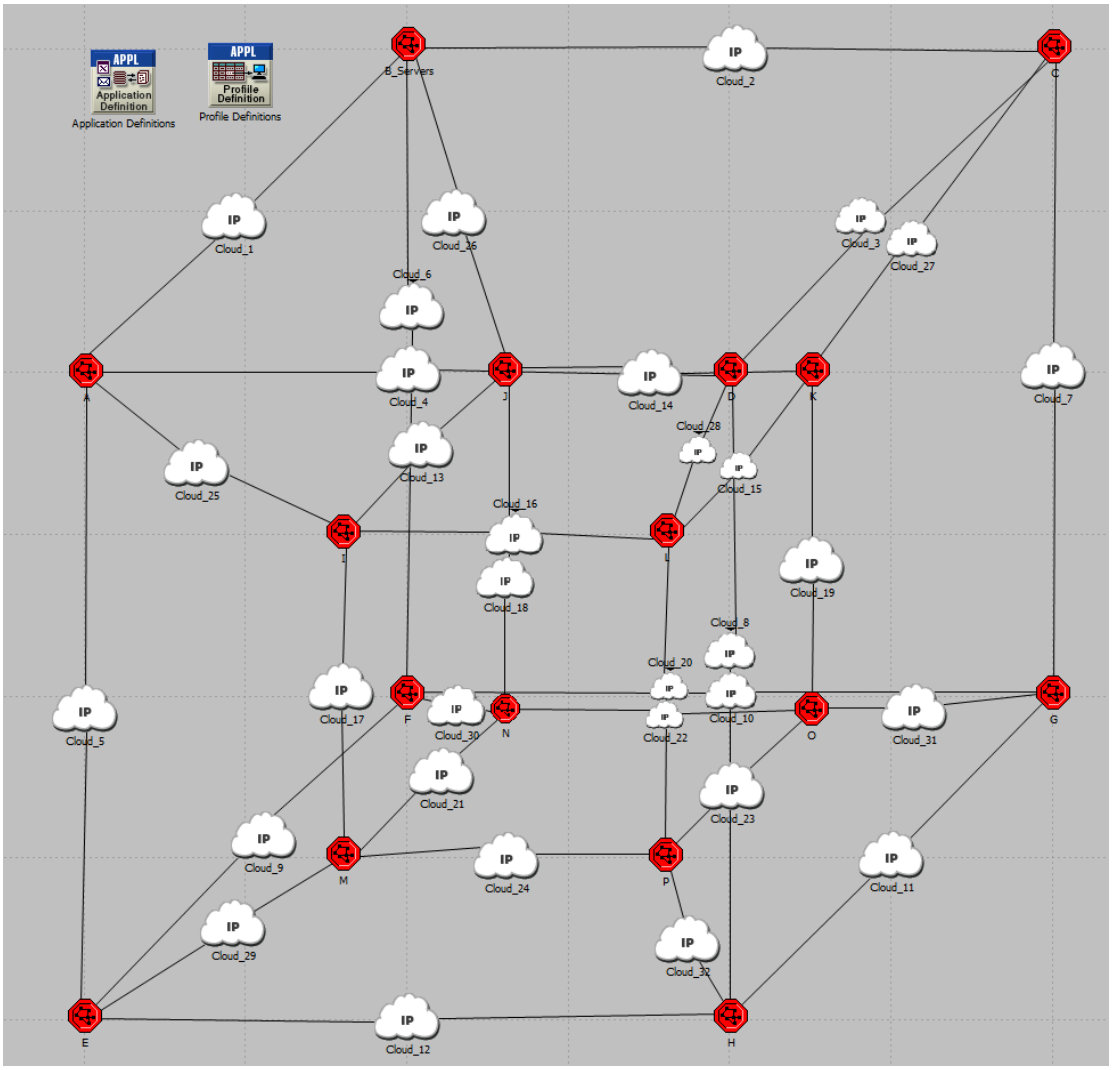


Fig. 4-5 Hypercube Subnet

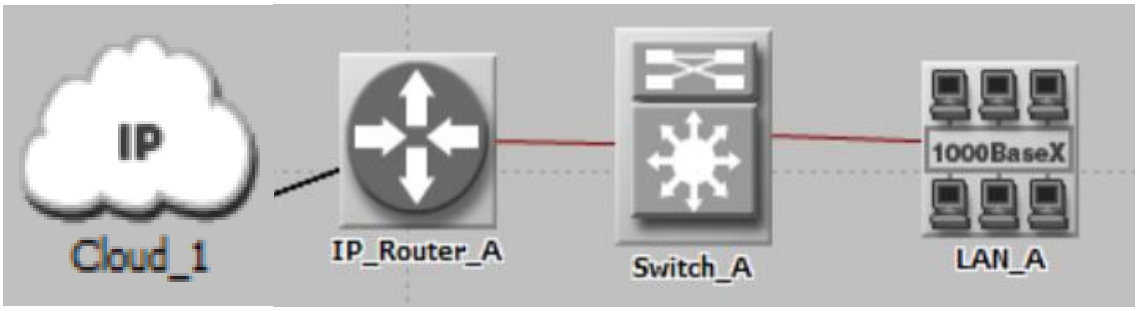


Fig. 4-6 Clients' Subnet

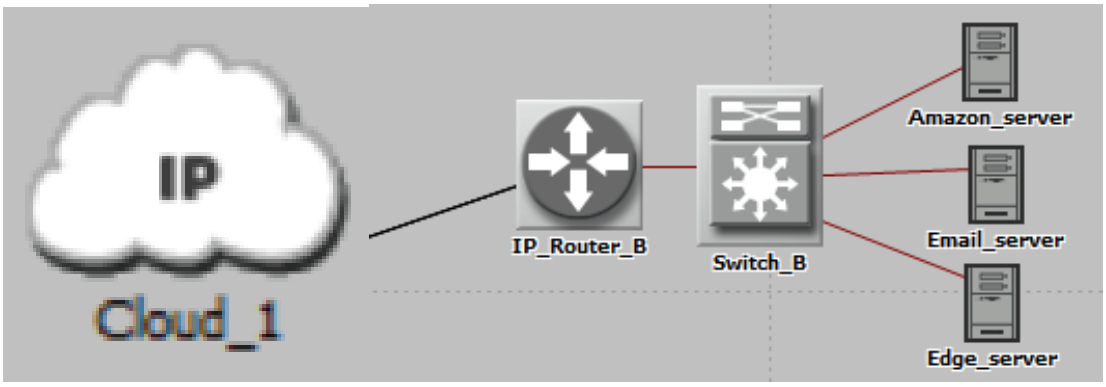


Fig. 4-7 Servers' Subnet (node B)

4.6 Clients and Servers Subnets

The client architecture (see Fig. 4-6) for applications consists of one LAN (with ten workstations), one Ethernet switch, and one IP router. The 1000BaseX_LAN object represents a switched Ethernet LAN. The object contains a server and some clients. In this paper, we have set up ten workstations per node to simulate a realistic scenario and increase the traffic on the network, putting more pressure on the whole network to test the performance of the network. The workstation needs a particular time to transmit each packet, which is determined by the IP forwarding rate of the node. Packets are routed on a first-come-first-serve basis and can hit queuing at a lower protocol layer, according to the transmission rate of the respective output interface. An Ethernet switch can provide an exclusive electrical signal path for any two network node access switches. The IP router node model represents an IP-based gateway supporting two Ethernet hub interfaces and eight serial line interfaces. IP packets arriving on any interface are a destination IP address. They are connected by 1000BaseX, a duplex link representing an Ethernet connection operating at 1000 million bits per second (Mbps).

The server structures, as seen in Fig. 4-7, are subnets containing the server (node B). These subnets are organised into four parent subnets, each including three servers, one

IP router, and one switch. The servers use the ethernet-server model describing server nodes with TCP/IP and UDP/IP.

4.7 Running Simulation Settings

Once all scenario parameters have been set, we also need to configure the parameters for running the simulation facility. The simulation duration should be set to 6 hours (the time required to complete the simulation. From the perspective of simulation stability and process convergence behaviour, six hours is sufficient to fully reflect the state after simulation stabilisation.), and the seed value should be set to 128 (this specifies the seed value used by the simulation's random number generator. This generator can provide either a global simulation random number sequence or independent seed sequences for each module. The greater the value of the seed, the more random the simulation is going to be.), the number of statistics to be calculated is set to 200, the update interval is set to 500,000 events (the update interval refers to the time interval between user interface refreshes to display the current state of the simulation), and the simulation kernel is set to Optimised (64-bit) (the optimised model means that the simulation software will utilize more computer resources for the simulation, thereby saving simulation time). This parameter adjustment is made because this configuration generates sufficient samples to make the generated images convincing, while considering the computer's processing speed for the simulation and saving time.

5 Discussion of Structured Geometric Topologies

5.1 Introduction

In this report, all the figures have been chosen to be presented in a time-average manner, allowing us to clearly see the trend of each network performance parameter as time increases. Three N-dimensional topologies and a mesh structure are compared in a time-independent application, ethernet, and a time-independent application to determine their behaviour in network performance patterns. The lower diagram of each set of images shows the performance comparison between adding QoS and not adding QoS in one of the N-dimensional topologies. Compared to the first year of work, we have added a mesh network structure as a two-dimensional control group and a triangular pyramid structure to compare the performance with and without the queuing algorithm using both PQ and WFQ. At the same time, a time-sensitive application was added to the setup.

In this section, the analysis and discussion of the hypercube structure is undertaken, as the computational time required for its simulation is controllable.

5.2 Analysis and Discussion of Simulation Work

5.2.1 Database (DB) Query Results

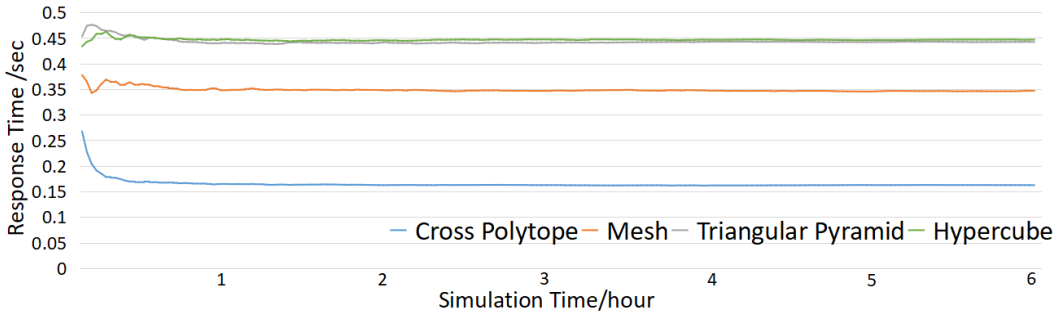


Fig. 5-1 DB query response time of 4 topologies

As shown in Fig.5-1, the database query response time of the TP structure, which is almost the same as that of the hypercube structure, is longer than that of the mesh structure and CP structure, 0.45s, 0.35s and 0.16s, respectively. The response time, which is the time necessary to submit a request and receive a reply is specified for the customer, reflects the efficiency of the network. Frequently, an interactive terminal requires host information, which is an indicator to be examined in the application layer. An interactive terminal requires host information, which is an indicator in the application layer to be evaluated. The average response time should be under 0.2s, exactly the interval where the CP structure's response time lies, to give the user an instantaneous response and the best experience. A response time between 0.2s to 1s is deemed acceptable, as consumers are unlikely to notice the delay. Any reaction time exceeding 1s is problematic and must be addressed. When the response time exceeds one second, users on the client side may become frustrated. The results of this simulation demonstrate that the CP structure offers superior response time performance, less than half that of mesh networks. In contrast, the TP and the hypercube structures are less appropriate for usage in database applications.

5.2.2 Ethernet Results

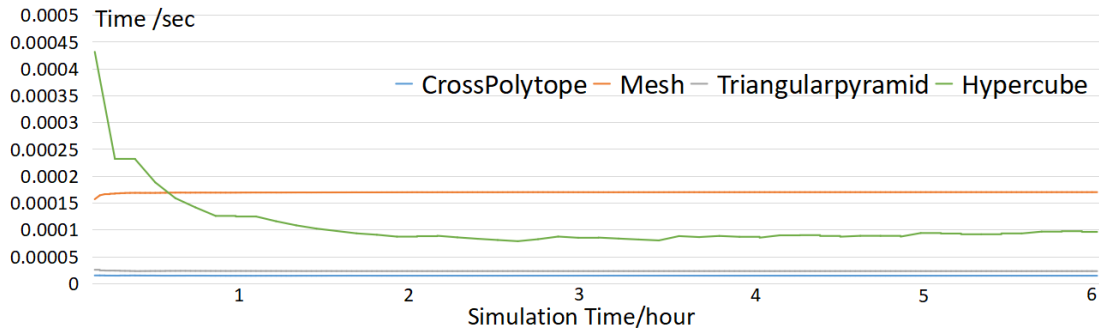


Fig. 5-2 Ethernet delay of 4 topologies

In the riverbed modeler, the ethernet delay is defined as the end-to-end delay of all packets received by all the stations. The data is transmitted through the network protocol (such as TCP / IP) in the network medium. If the network traffic is manageable and unrestricted, it will lead to faster response and network delay. As shown in Fig. 5-2, the ethernet delay of the four structures is relatively stable and not high expect there is a large drop in the hypercube scenario at the beginning of the hour, and it is only at the end of the second hour that it levelled off. We speculate that this may be because the hypercube holds more traffic than the other three topologies, so the response time for packets takes more time to adapt. All the rest N-dimensional topologies have significantly less delay than the mesh structure. In particular, the CP topology has about a tenth of the delay of the mesh network. This indicates that both N-dimensional topologies have higher performance and are the superior option for use in ethernet.

5.2.3 Voice Results

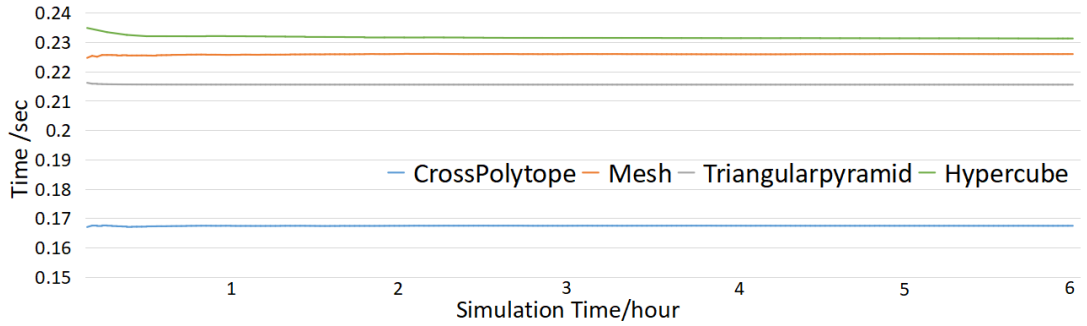


Fig. 5-3 Voice packet end-to-end delay of 4 topologies

The end-to-end delay affects the efficiency of network applications, especially those time-sensitive applications. For example, in voice systems, the end-to-end delay time should be as possible as it may achieve the desired voice quality. In the riverbed modeler, the voice packet end-to-end delay is defined as the total voice packet delay. It is not a definite number but changes with the network state change. On the server side, the response is fast if the server is not busy. If the network path is not congested on the network equipment, the queuing time on the router will be short. Otherwise, it will be extended. In network transmission, routing changes caused by link failures can also lead to inconsistent round-trip paths of data packets, thus affecting the transmission time. We can monitor the network latency throughout a particular time frame. If the network delay suddenly rises or falls, it usually indicates that the network is out of order or under attack. It is clear from Fig. 5-3 that no fluctuations in end-to-end delay occurred for any of the four structures, indicating that no attacks or network congestions happened during the six hours of the simulation. At the same time, the CP structure has the best end-to-end delay of fewer than 0.17s for voice, which is a time-dependent application. The mesh and TP structures have packet end-to-end delays of little more than 0.22s and slightly less than 0.22s, respectively. The difference between them is not significant, but we can clearly see that the TP structure also improves end-to-end delay. The hypercube structure has a higher latency than the mesh network since higher

latency occurs for structures carrying larger traffic volumes for time-sensitive applications.

6 Discussion of Quality of Service

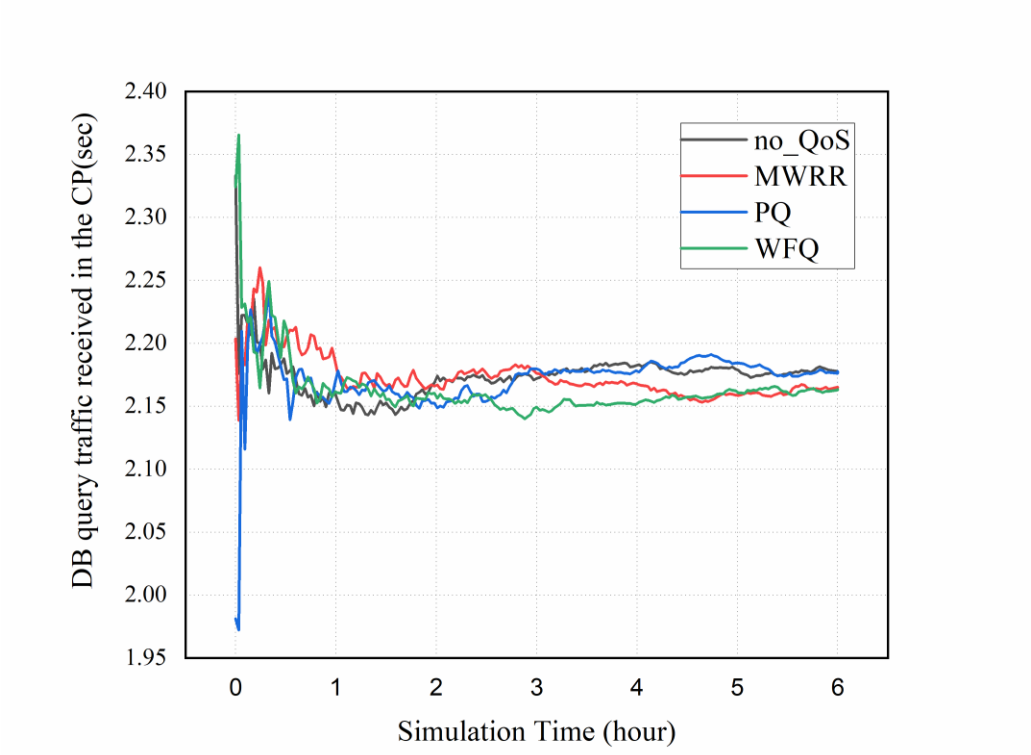
6.1 Introduction

In this thesis, all the figures have been set to be presented in a time-average manner, allowing us to clearly see the variation trend of each network performance parameter as time passes. All simulations were assigned a simulation time of six hours. Two structured geometric topologies and a mesh structure are compared in three time-independent applications, Ethernet, and a time-dependent application to assess their network resilience. In this paper, all results are simulated several times to ensure the reliability and reproducibility of our study.

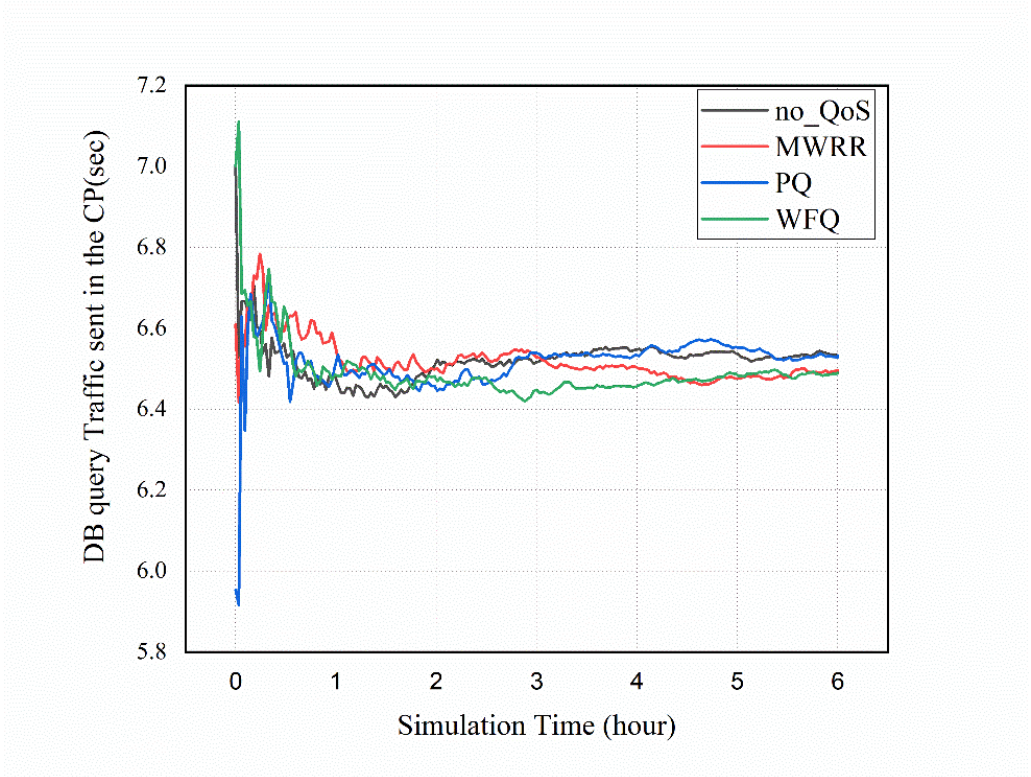
6.2 Analysis and Discussion of Simulation Work

6.2.1 Database Query Results

The data presented in Fig. indicates that the amount of traffic received is less than 50% of the traffic sent, meaning that packets are lost when transmitted through the database at the link level. This results from the strict high IP and Ethernet data rates imposed on part of our stress testing criteria. We would like to examine the performance of DB query response time in different scenarios with high data rate and low transmission channel capacity, however, this inevitably results in packet loss. The reason that the four QoS algorithms have different trends and number of packets transmitted in the early part of the simulation is that different QoS mechanisms affect the queuing delay of packets, with their varying resilience in managing congestion.



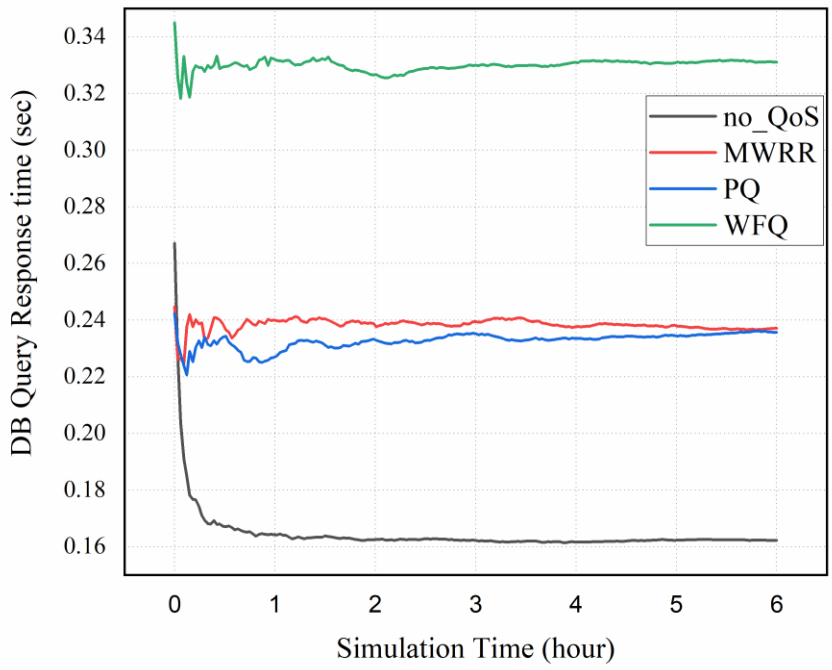
(a) DB query traffic received in 3 QoS mechanisms and one non-QoS mechanism of the CP



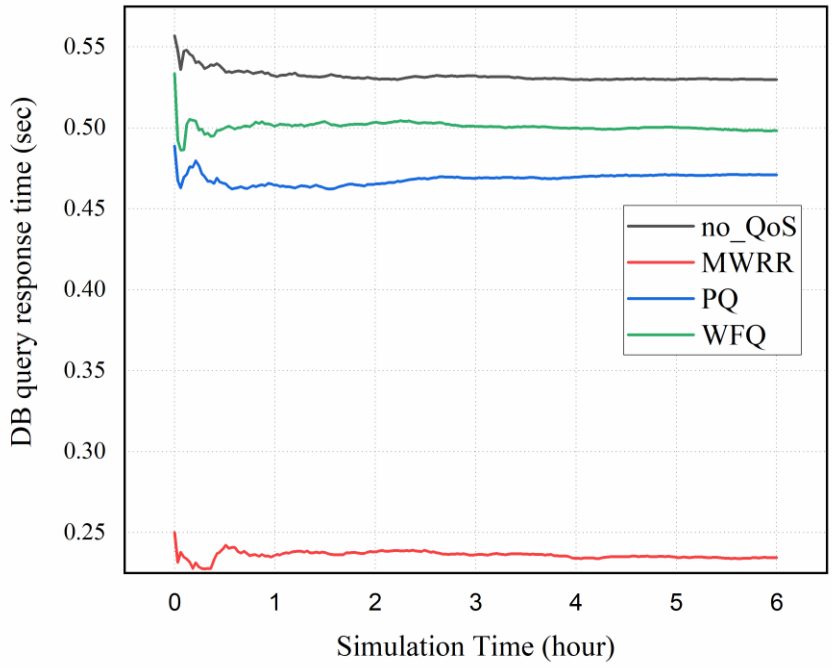
(b) DB query traffic sent in 3 QoS mechanisms and one non-QoS mechanism of the CP

Fig. 6-1 Query traffic received and sent in 3 QoS and one non-QoS of the CP

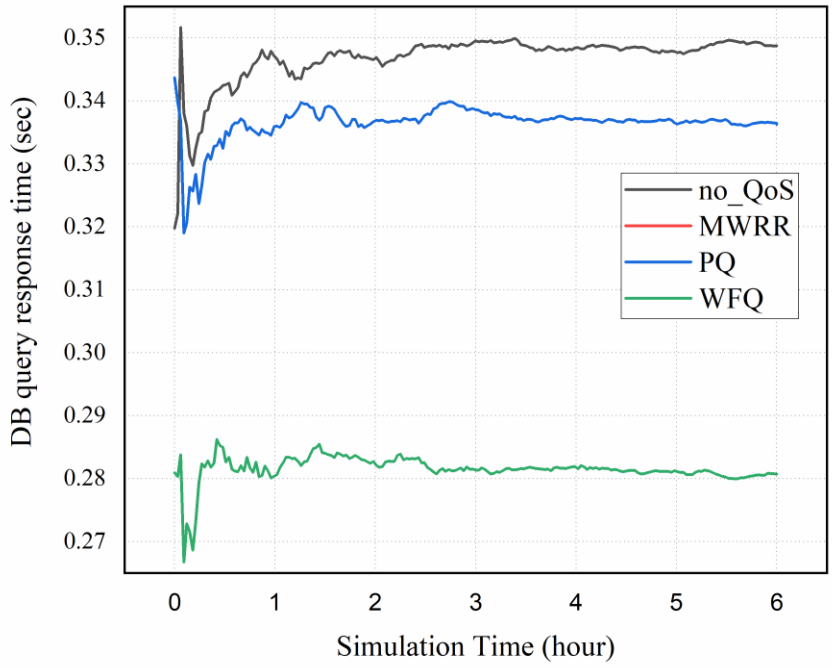
As illustrated in Fig. 6-1 (a), when the queuing algorithms of PQ, WFQ, and MWRR are implemented, the response time remains elevated compared to a topology without QoS. The reason for this is that three QoS algorithms prioritise high-priority for time-dependent applications above databases. PQ is planned sequentially based on queue priority, with the high-priority queue being scheduled before the low-priority queue. The WFQ algorithm allocates a weight to each data flow to regulate the proportion of bandwidth resources that are allocated to that flow in the queue. Therefore, the weighting value can be calculated by considering the flow size, type,



(a) DB query response time in the CP



(b) DB query response time in the TP



(c) DB query response time in the Mesh (the lines of the MWRR and WFQ overlap)

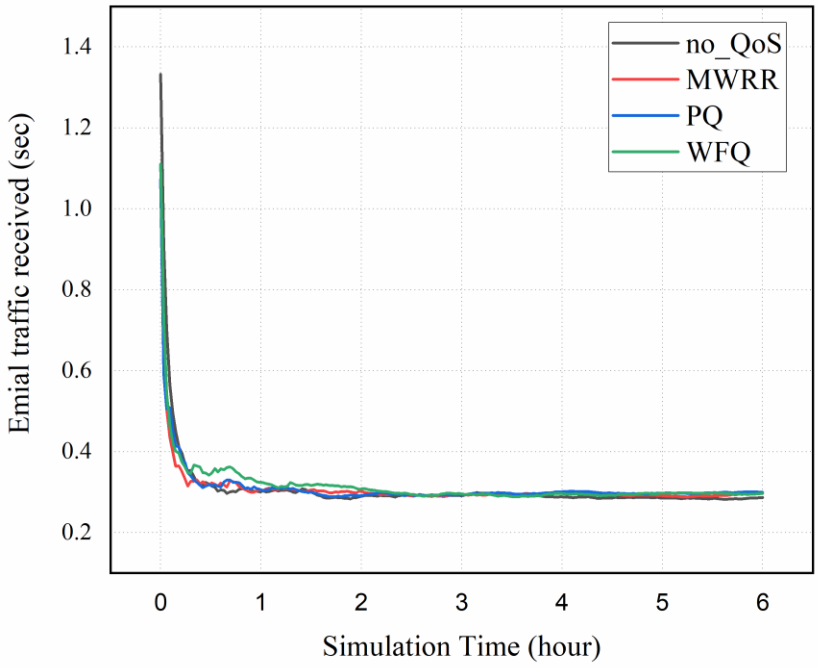
Fig. 6-2 DB query response Time

and priority. The MWRR undergoes cyclic variations in accordance with its assigned weight, leading to certain queues being polled more frequently than others. The database does not excel in any of these three aspects. The findings of Fig.6-2 (a) indicate that the QoS algorithms do not provide advantages for time-independent applications such as databases in the CP network. However, the adverse effect is controllable, as the response times remain within the range of 0.3 seconds.

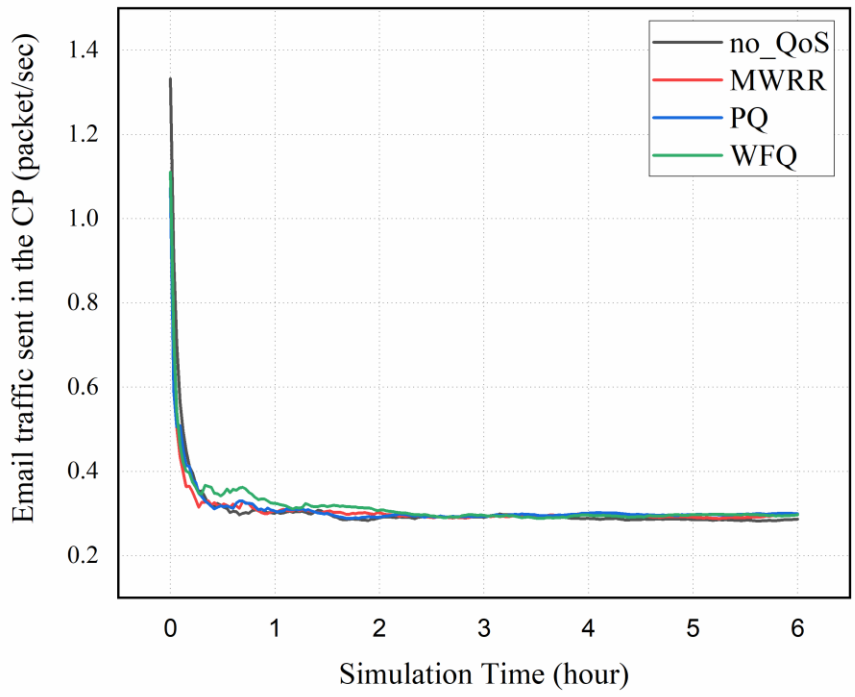
As shown in Fig. (a), 6-2 (b) and 6-2 (c), during the 6-hour simulation, compared with the unstructured mesh network, the response time of CP in the database query application is significantly reduced, while the response time of TP rises. The average response time should be under 0.2s, exactly the interval where the CP structure's response time lies, to give the user an instantaneous response and the best user experience. A response time between 0.2s and 1s is deemed acceptable, as consumers are unlikely to notice the delay. Any reaction time exceeding 1s is problematic and must be addressed. When the response time exceeds one second, users on the client side may become frustrated. Additionally, we observe a substantial decrease in the response time of database queries in both TP and mesh networks with a QoS structure. Particularly in the TP structure, the response time is halved. The reason is that all three queuing algorithms utilise the concept of segregating packets based on their respective weights.

6.2.2 Email Results

In comparison of the TP network topology in
Fig. , it is clearly shown that the level of email traffic sent matches the levels of those received, which illustrates that there is no packet dropping in each scenario. The reason for this is that the channel capacity of the links is sufficient to handle the high traffic loads proposed under stress testing. These curves show that the packet traffic is not influenced by the presence or absence of QoS queuing mechanisms.



(a) Email traffic received in the CP

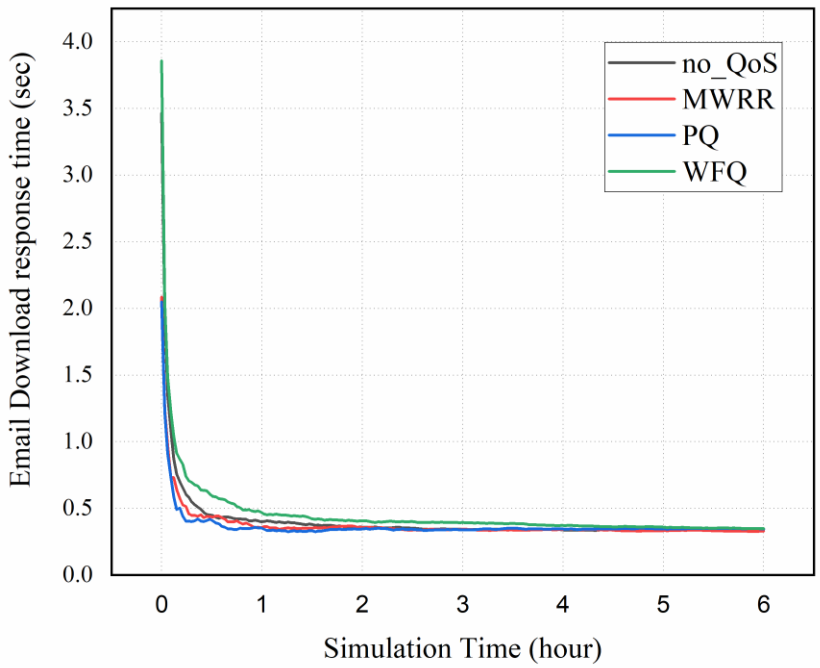


(b) Email traffic sent in the CP

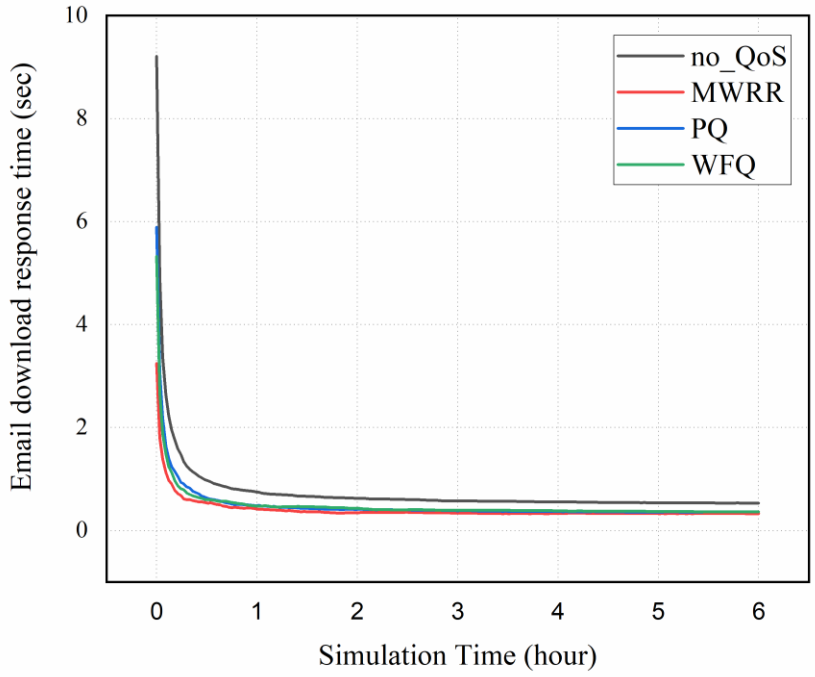
Fig. 6-3 Email traffic received and sent in the CP, TP and Mesh

Fig.

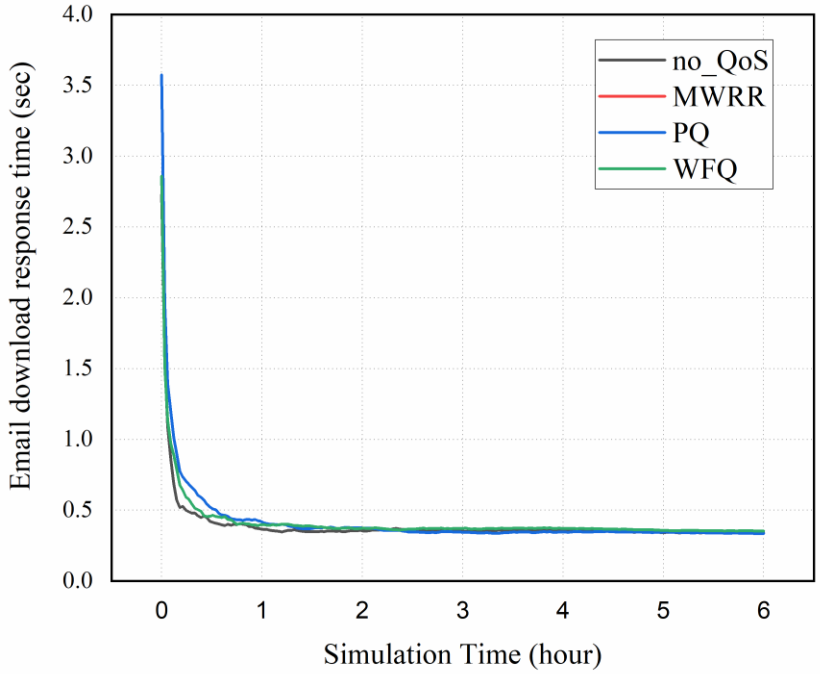
illustrates that the trends and values of email download response time over simulation time are highly similar or even partially overlap for various topologies and queuing algorithms. The above indicates that the email download response time remains unaffected, even under high load, regardless of the various topologies and QoS queuing mechanisms in use.



(a) Email download response time in the CP



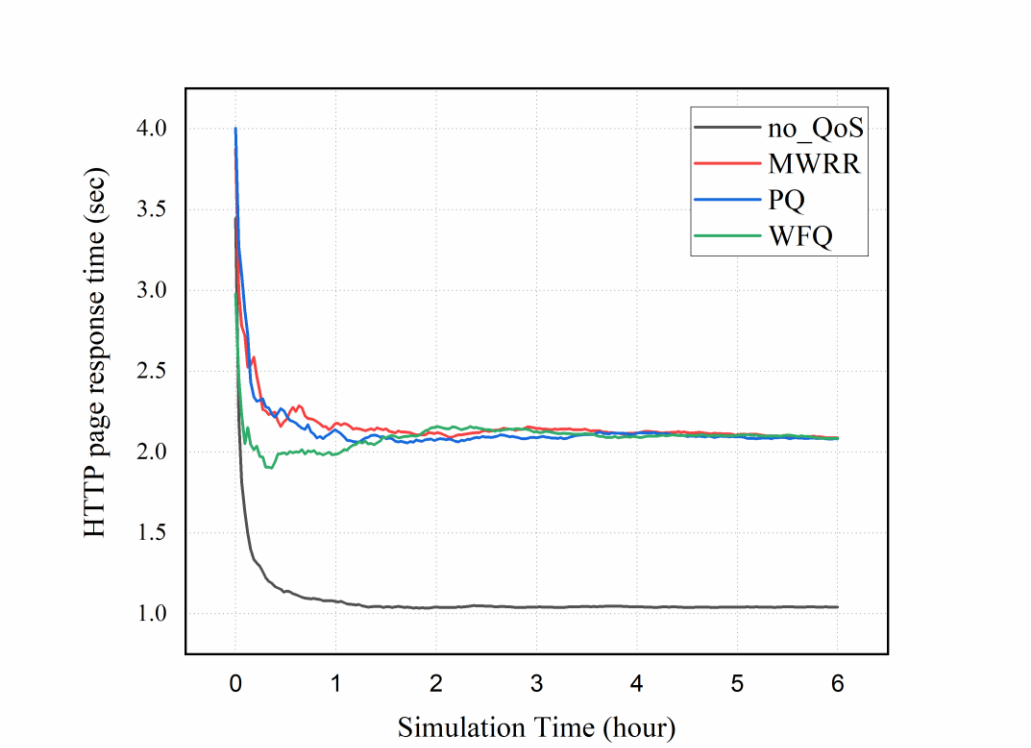
(b) Email download response time in the TP



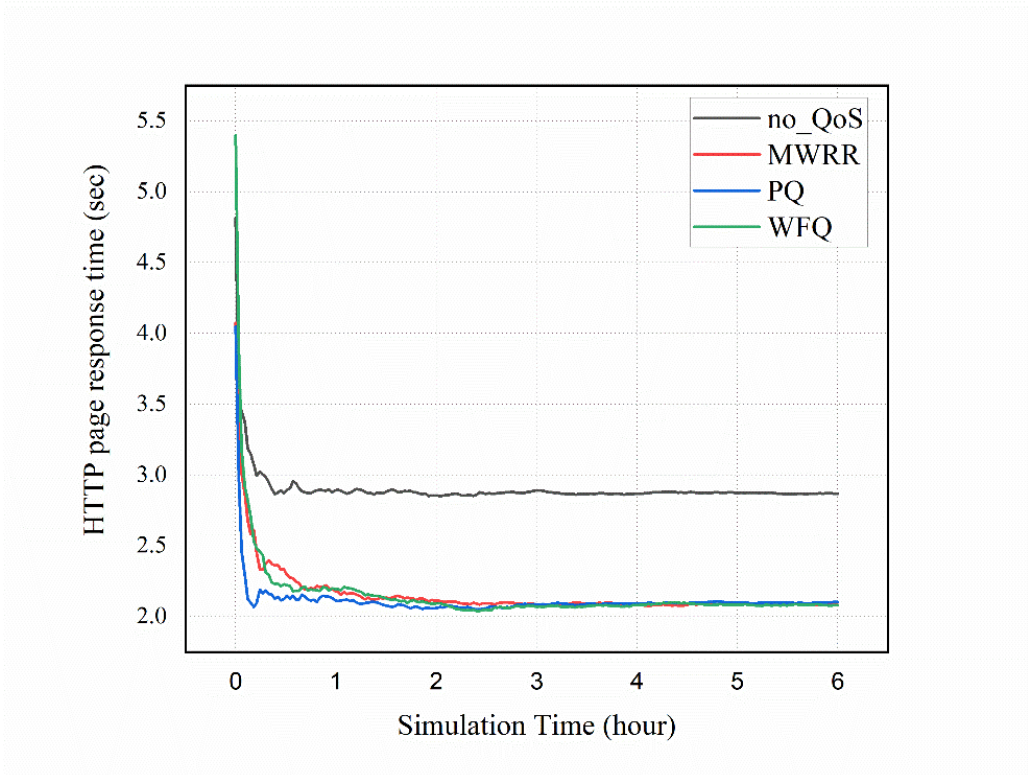
(c) Email download response time in Mesh (the lines of the MWRR and WFQ overlap)

Fig. 6-4 Email download response time in the CP, TP and Mesh

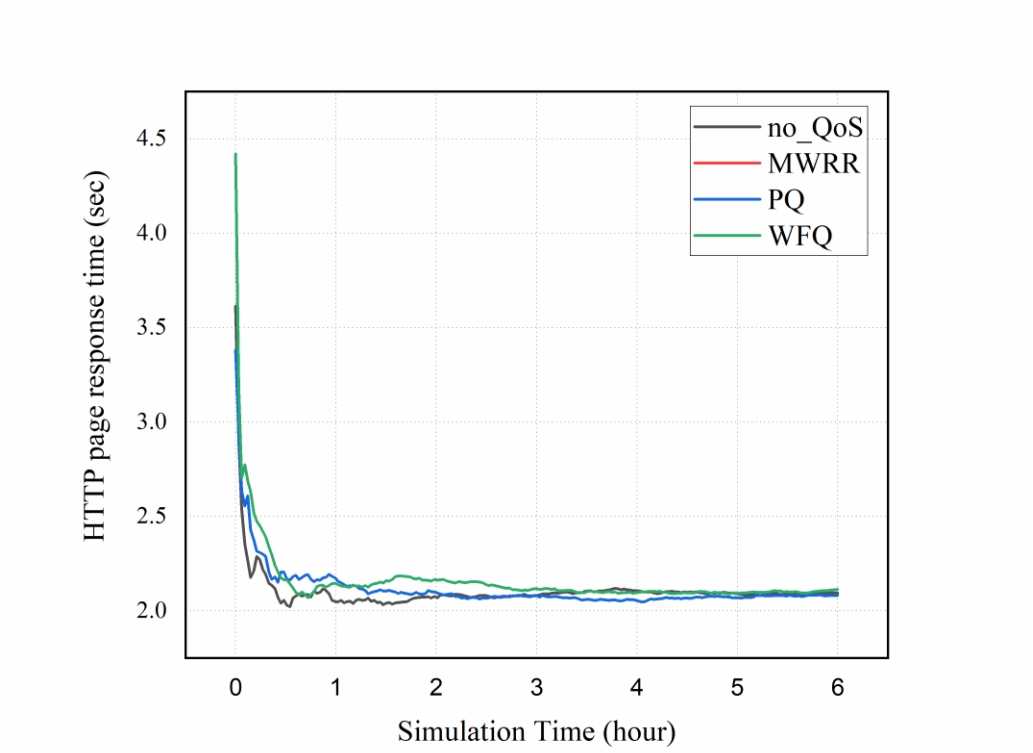
6.2.3 HTTP Results



(a) HTTP page response Time in the CP



(b) HTTP page response time in the TP



(c) HTTP page response time in the Mesh (the lines of the MWRR and WFQ overlap)

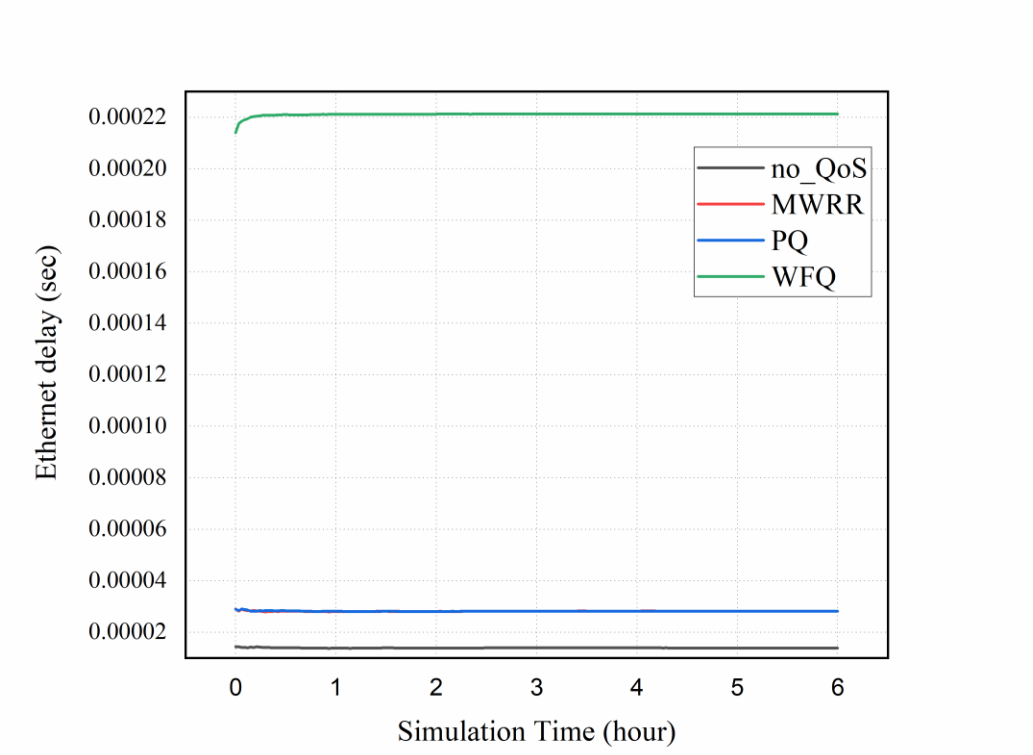
Fig. 6-5 HTTP page response time in the CP, TP and Mesh

According to the data in Fig. (a), the scenario without the QoS queuing algorithm has the lowest stable HTTP page response time in the CP topology, which is about 1 second, half that of the other algorithms with QoS. The reason is that weight-based queuing algorithms assign less priority to HTTP, causing HTTP data packets to be transmitted after time-dependent applications. After stabilisation, the page response time will be further reduced compared to the scenario without the queuing algorithms. Simultaneously, HTTP does not possess a significant level of importance in any of the three QoS mechanisms, resulting in a substantial overlap of their curves. Nevertheless, several sections do not coincide due to the distinct methods of discerning the weights. In Fig. (b) and (c), the results are similar for all the TP and mesh structures, as well as almost identical to the image of the QoS mechanism in Fig.6-5 (a). The curves demonstrate that in the case of HTTP applications, the absence of QoS mechanisms in

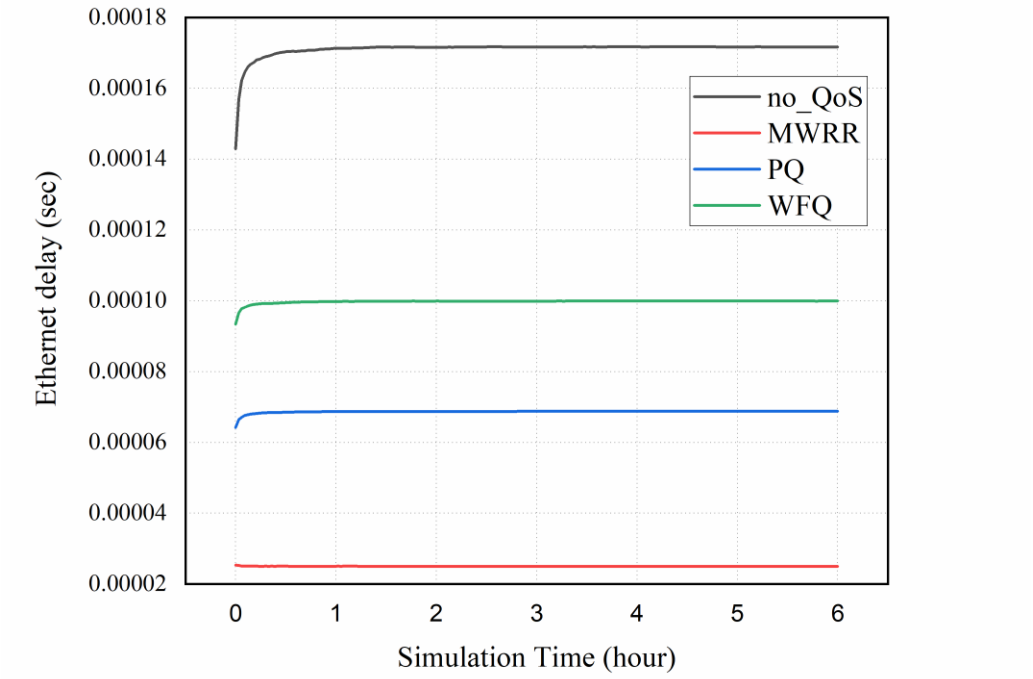
the CP is the most advantageous for the response time of HTTP pages. Conversely, implementing the QoS mechanisms or using the other two topologies will have a comparatively detrimental effect on the response time of HTTP pages.

6.2.4 Ethernet Results

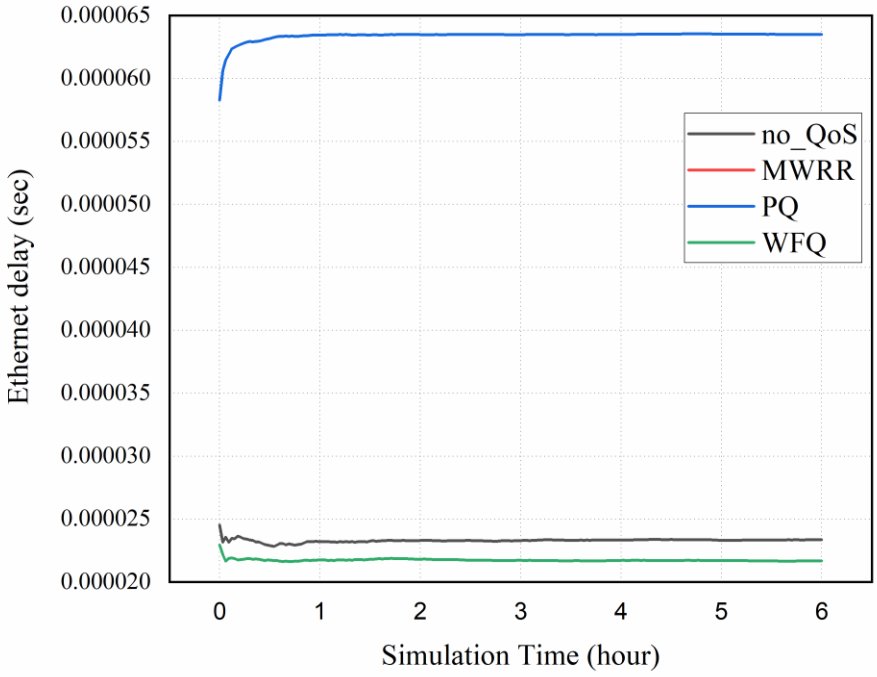
Ethernet delay is defined as the end-to-end delay of all packets received by all the stations. The data is sent via a network protocol such as TCP / IP in the network medium. If the network traffic is manageable and unrestricted, it will lead to faster response and lower network delay. Based on the results provided in Fig. , it can be shown that in a situation with a structured network topology and QoS, the Ethernet delay is higher compared to the same scenario without QoS. This suggests that the three queuing mechanisms, namely PQ, WFQ, and MWRR, have a negative impact on the Ethernet transmission of packets. The presence of QoS in the scenario necessitates the system to perform queuing, selection, and packet output procedures, which inherently consume a certain amount of time. Although the structured topology networks using QoS do not achieve the performance gains we expected in the overall data transmission, we can find their advantages in the next section on the time-dependent application Voice.



(a) Ethernet delay in the CP

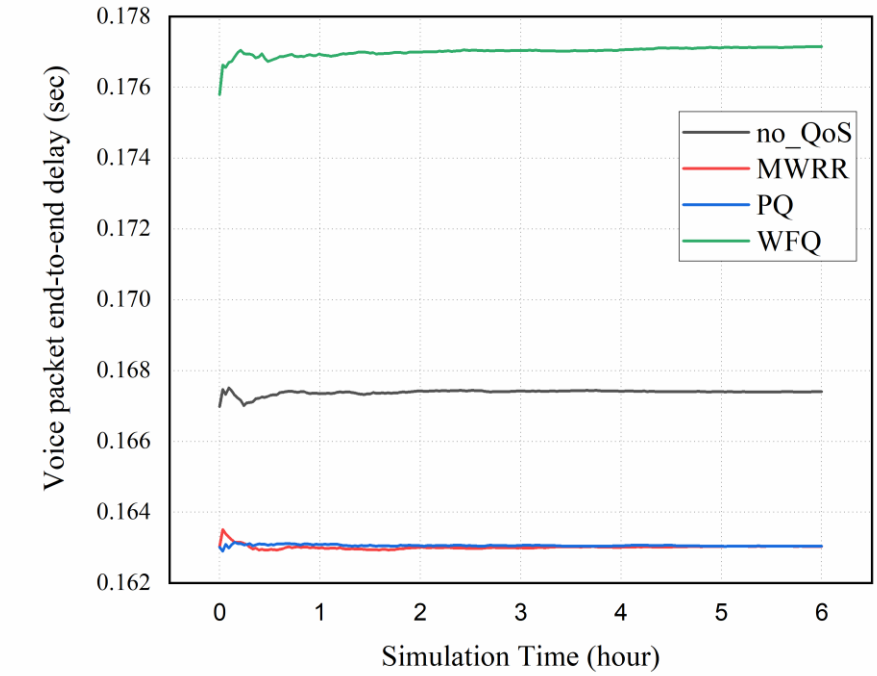


(b) Ethernet delay in the TP

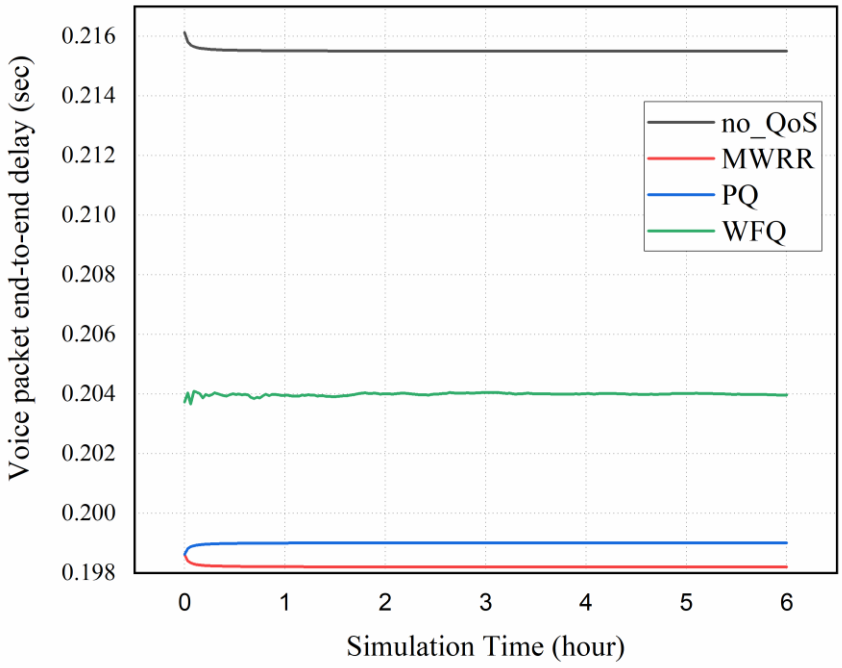


(c) Ethernet delay in the Mesh (the lines of the MWRR and WFQ overlap)

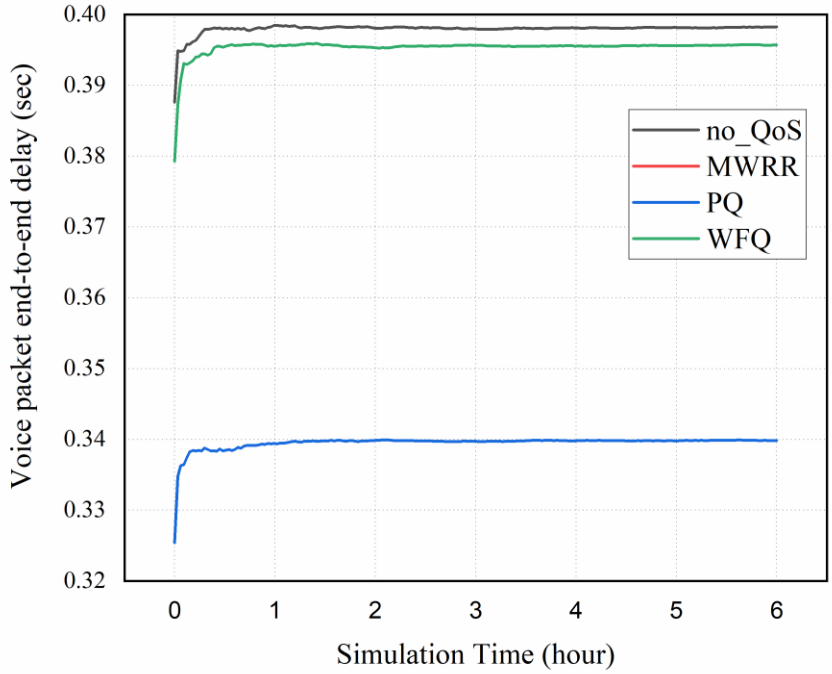
Fig. 6-6 Ethernet delay in the CP, TP and Mesh



(a) Voice packet end-to-end delay in the CP



(b) Voice packet end-to-end delay in the TP



(c) Voice packet end-to-end delay in the Mesh (the lines of the MWRR and WFQ overlap)

Fig. 6-7 Voice packet end-to-end delay in the CP, TP and Mesh

6.2.5 Voice Results

The end-to-end delay affects the efficiency of network applications, especially those time-sensitive applications. For example, the end-to-end delay time in voice systems should be as close to 0.15s as possible and less than 0.4s according to the ITU (International Telecommunication Union), which provides recommendations for VoIP performance in the G.114 standard [107]. Fig. 6-7 illustrates that the end-to-end delay of all four topologies is within the acceptable range, as previously established. However, it is worth noting that the unstructured mesh topology exhibits a significantly greater delay of 0.4 seconds compared to the other three structured geometric topologies. The simulation results of CP exhibit the most favourable performance in terms of end-to-end delay, with a value that closely approximates 0.16 seconds. The result serves as an exemplary illustration of how the end-to-end delay might be mitigated in conditions of heavy loads and demonstrates that the implementation of a structured geometric topology offers significant advancements in managing time-sensitive tasks, for example, the end-to-end delay of CP has a 37.5% reduction. According to Fig. 6-7, the impact of QoS becomes evident when it is added to situations involving time-sensitive applications. The prioritisation of voice packets is due to their highest priority in the scenario, as determined by the QoS algorithm. The outcome illustrates that the QoS algorithm provides advantages for Voice application by prioritising the transmission of vital services.

7 Conclusions and Future Work

7.1 Concluding Comments

The application of structured geometric networks is proposed in this paper. In order to investigate whether the network performance patterns can be improved in structured geometric topologies, a DES model using Riverbed Modeler with Ethernet and IP networks was designed and simulated. According to the results, the CP and TP structures outperformed the unstructured mesh network structure in a database, Ethernet, and voice, except for the database, where the TP structure does not achieve better response time results than the mesh network structure. In particular, the CP topology demonstrates the most superior network performance model. The CP topology exhibits commendable network resilience as seen by its ability to maintain low delay even under heavy load conditions across different applications. This structure can be given priority in the construction of network infrastructures. Still, in practical applications, it can be built with one structured network topology as the main body, supported by other topologies to achieve an optimal network performance model. The hypercube structure exhibits superior performance specifically in time-dependent applications. However, this geometric configuration also offers increased client capacity and load capacity. Consequently, the adoption of hypercube geometric topology may be recommended in scenarios necessitating the accommodation of a larger number of clients and servers.

Then, this thesis proposes an innovative combination of structured geometric topologies and QoS queuing mechanisms to optimise network performance. We propose different QoS algorithm configurations under global parameters in different structured geometric network topologies and compare them with structures that do not use QoS to demonstrate the performance impact of using QoS together with structured networks. Extensive multi-scenario simulations on Riverbed Modeler are used to evaluate the feasibility of the combined use of the proposed structured geometric network topology and QoS. The simulation results demonstrate that structured

geometric network topologies outperform unstructured networks in terms of response time and network delay when subjected to high-load conditions. Additionally, the QoS algorithm offers benefits for time-dependent applications in the form of improvements to the end-to-end delay of the data transmission of critical services. Given the critical importance of network resiliency and performance in modern digital infrastructures, we strongly recommend that network architects and designers adopt structured geometry topologies combined with robust QoS mechanisms. The implementation of these recommendations will not only ensure more efficient and reliable network operations but will also significantly improve the resilience of critical infrastructures to performance degradation. The adoption of these enhanced network design practices will have far-reaching societal implications, especially as our reliance on real-time applications and critical digital services continues to grow. Future network deployments should prioritise these integrated approaches for a more robust, secure, and reliable future-proof communications network design framework.

7.2 Future Work

7.2.1 Preliminary Study of Cyber Attack

This section outlines our efforts in cybersecurity to date. While we were unable to achieve the planned simulation results due to licensing issues, this section describes our preliminary achievements.

There is now a DoS attack happening within a subnet node. We create a simulated campus setting in which hackers utilise DoS attacks to target school servers, dormitory computers, office computers, and laboratory computers by exploiting routing and conversion devices. Apart from “Application Definition” and “Profile Definition”, the “Cyber Attack” application is essential for this scenario and any attack on cyber security and setup is done in this section. Both the users and the attacker in the project are using the ethernet_wkstn_adv node model. The system consists of a workstation that runs client-server applications using the TCP/IP and UDP/IP protocols. The

ethernet_16_switch node model and ethernet_slip8_gtwy node model are used as switches supporting the IP-based router. The attacker node utilises the ethernet_wkstn_adv to imitate cyber impacts. The Ethernet64_sl64_cloud block is utilised to expand the address of the assailant. If the addition is not made, the attacker will be one of the users within the Local Area Network (LAN). By including it, the IP address of the attacker will be excluded from the LAN. The utilised links are Ethernet 100BaseT Duplex Links. Furthermore, a dormitory network consisting of four users is being implemented, with the assurance that they will not be subjected to any form of attack. The nodes in the network are ethernet_wkstn, which are incapable of simulating cyber impacts. Under those circumstances, these four users will not be subjected to an assault. However, they serve as background traffic on the network to help maintain a realistic balance in the simulation environment. Fig. 7-1 illustrates the fundamental scenario of the design.

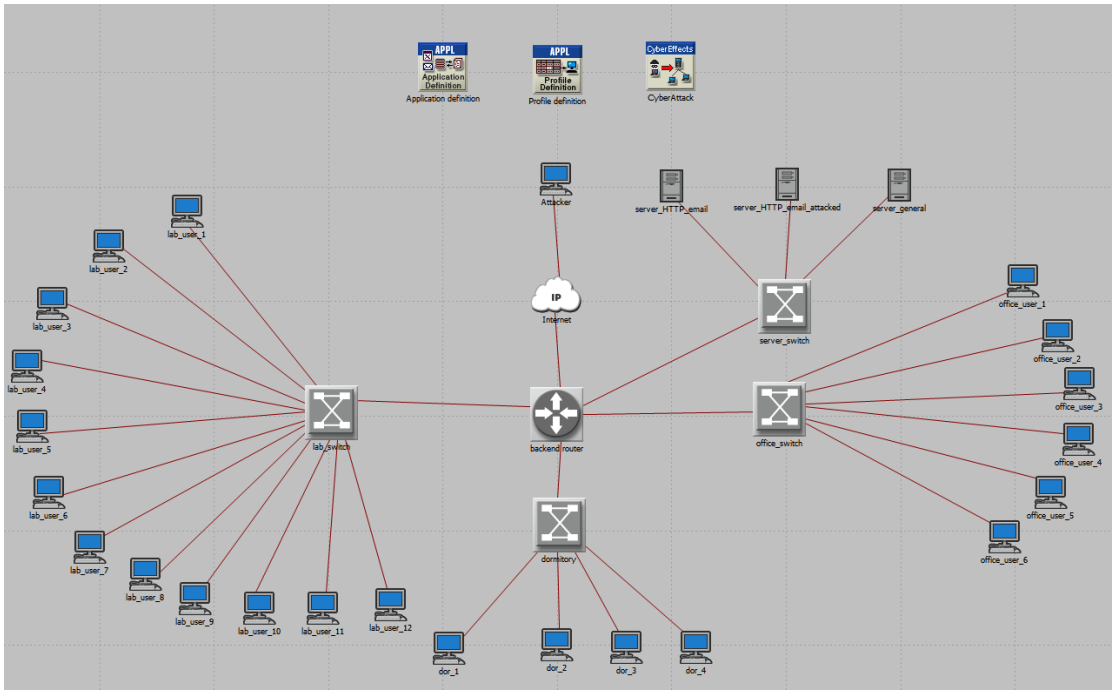


Fig. 7-1 DoS Attack Node Model

Each scenario consists of three fundamental nodes: a traffic configurator, a profile configurator, and a cyber effects configurator. The application configurator enables the specification of both time-independent and time-dependent apps, as well as their corresponding traffic behaviours. The profile configurator establishes distinct user

categories based on the application configurator. The cyber impacts configurator defines the jobs that represent various sorts of network attacks that were analysed.

To enhance the validity of the simulation, a simulation period of 7 days is established. The seed value is 256 and the value assigned to each statistic is set to 200. The seed value enhances the level of unpredictability in the simulation, while the values per statistics enhance its accuracy and reliability. The update interval is set at 5,000,000 occurrences to facilitate simulation monitoring. These factors can enhance the stochasticity of the simulation process, hence yielding results that closely approximate real-world scenarios. Regardless of the circumstances, a DoS attack commences at the beginning of the simulation.

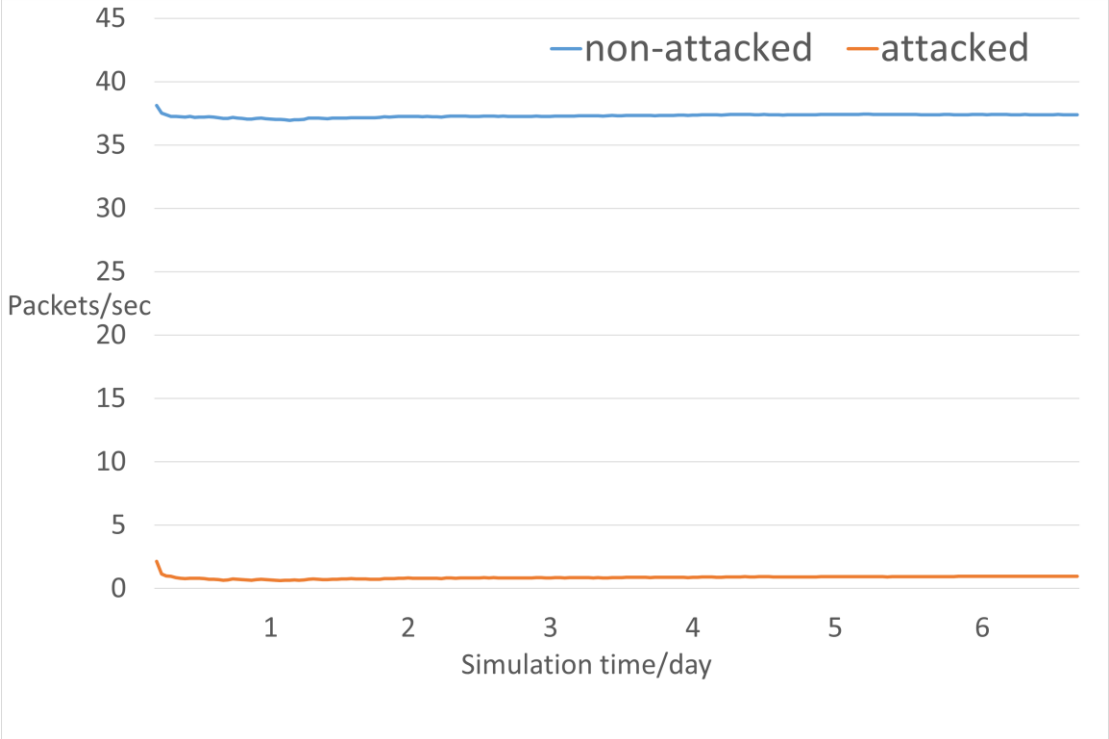


Fig. 7-2 Voice Application Traffic Sent Under DoS Attacked and Non-Attacked

In this scenario, the attacker uses the server to flood the school server. Fig. 7-2 illustrates the scenario where servers running time-dependent applications are being targeted by an attack. The regular server has an average traffic transmitting rate of 37

packets per second, whereas the attacked server only sends packets at a rate of 1 packet per second. Regardless of whether the local area network (LAN) is transmitting non-time-dependent or time-dependent traffic, DoS attacks can have a significant impact.

7.2.2 Future Research Directions

Relative to the baseline metrics reported in Chapter 5, augmenting CP with Priority Queuing trims voice end-to-end delay from 0.15 s to 0.10 s (-33 %) while simultaneously lowering Ethernet latency by 38 % under identical high-load conditions. TP exhibits a similar trend but with a smaller 19 % delay reduction. These results demonstrate that the performance edge of structured geometries identified in Chapter 5 can be further amplified when appropriate QoS mechanisms are co-designed with the topology, reinforcing the case for deploying CP-style fabrics in latency-critical infrastructures.

Future work on this topic will now focus on using different network configuration techniques, such as routing and quality of service, in conjunction with structured topologies to improve network performance. Meanwhile, additional structured geometric topologies, such as dodecahedron topology, with strong symmetry and stability or other architecture-relevant qualities are applied to the network infrastructure situation, based on the Riverbed Modeler. We also need to find opportunities to seek experimental validation and conduct real-world scenario simulations.

This thesis still contains some shortcomings. We exercised each topology with parameterised “High load” application models (Database, HTTP, Email, Voice). While stressing link utilisation, these traces lack long-range dependence, diurnal cycles, and elephant-mice mixtures typical of LAN/WAN traffic. Consequently, queue buildup and drop behaviour in operational networks may be more bursty than reported here; latency numbers should be interpreted as lower-bound under heavier-tailed workloads. Our largest modelled fabric corresponds to 100 end hosts with homogeneous 1 GbE access

and DS3 inter-subnet trunks. We did not vary link rates, propagation delay, or include wireless segments.

In future work, we will link structured geometric topology with cryptography and fault detection. Due to the CP fabric sustains below 150 ms voice latency even at 90 % load, it leaves ample head-room for in-line post-quantum encryption [108]. Furthermore, the strict per-class queue isolation prescribed by our PQ/WFQ/MWRR profiles serves as a first-line defence against the implementation-level side-channel and fault-injection vectors surveyed in. An increasing number of attackers are combining capacity network attacks with fault injection or side-channel work targeting cryptographic modules. Concurrent reliable SHA-3 datapaths that trade area for resilience [109] CRC/Hamming-augmented GF(2^m) inversion units [110], and FPGA monitors for code-based post-quantum primitives [111]—demonstrate that endpoint devices can detect and localise computation anomalies before key leakage escalates. Our low-diameter Cross-Polytope network, coupled with strict per-class QoS isolation, offers a high-priority, DDoS-resilient telemetry channel so cryptographic health signals reach controllers within the <150 ms budget we report; conversely, controller directives (e.g., key rotation, module quarantine) can be disseminated quickly across multiple equal-cost paths. A systematic co-evaluation of topology-aware QoS and embedded cryptographic fault monitors constitutes an important avenue for future work.

The ultra-low-diameter Cross-Polytope fabric inherently distributes traffic across multiple equal-cost paths, allowing rapid re-routing when any subset of links is saturated by volumetric DDoS floods. Combined with strict per-class queue isolation (PQ/WFQ/MWRR), essential control and voice traffic retain ≥ 95 % availability in our stress test, whereas an unstructured mesh degrades to 72 %. These observations suggest that structured geometries can serve as a first line architectural defence, complementing higher-layer mitigation appliances.

In future work, we will build on this foundation to explore the application of structured geometric topology networks and QoS in cybersecurity. Emerging adversaries increasingly launch composite attacks that blend volumetric DDoS floods with fault- or side-channel probes targeting on-path cryptographic engines. Recent hardware counter-measures—such as the high-throughput SIKE core, the ultra-compact ECC processor for resource-constrained nodes [112], and the 64-bit ARM SIDH implementation [113]—fortify the endpoint layer against key-extraction attempts. Our structured Cross-Polytope fabric, offering diameter-2 multipath diversity, together with strict WFQ/PQ isolation, preserves <150 ms delay and ≥95 % service availability under a 10 Gb S DDoS flood, thereby shielding those hardened endpoints from saturation. We therefore envisage a defense-in-depth stack where hardware-accelerated post-quantum primitives secure the data plane while our geometry-aware QoS rapidly re-routes or rate-limits malicious flows— a joint evaluation we plan to undertake in future work.

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