Evaluation of Network Performance Based on Structured Geometric Topologies

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***Abstract*— At present, the research on computer network topologies rests mainly on typically unstructured networks such as mesh networks. 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. In addition, it can be shown that the planarised CP structure exhibits superior performance compared to the other three network designs examined. For instance, the end-to-end delay of Voice displays a value of approximately 0.15 seconds during periods of high load. The evaluation conducted in this paper holds vital importance for the configuration of topological networks in the context of constructing network infrastructure.**

Keywords*— *Network Performance Modelling, Structured geometric topology, Network Resilience, Network Configuration

I. Introduction

Data communications 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 civilisation. The efficacy of the network architecture employed in data communication is crucial for ensuring a reliable, efficient, and secure transmission of data between the sender and the recipient. At this point, it is crucial to have an evaluation of the network architecture design, which enables the network designer to select the most suitable network architecture for the circumstances and establish whether it can be implemented. Network performance behaviours refer to the criteria or parameters used to evaluate the performance of a network, including but not limited to traffic, response time and network delay.

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 [1]. Currently, network topology research mainly lies in unstructured network topologies, which include bus [2], mesh [3][4], star [5], ring [6], and tree [7] networks. In contrast to the prevalent network topologies, some researchers have identified less typically employed topologies that provide distinct advantages in the establishment of network architectures. Gang Sun et al. [8] 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. Albert Greenberg and other Microsoft technicians [9] proposed the VL2 architecture, a topology implementing a complete routing and forwarding suite on a triple fold (multi-root tree) but differing 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 unstructured 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 a physical network topology in a large-scale Internet of Things (IoT) system [10], supercomputers [11][12] and clusters as well as networks on a chip [13]. However, only a few structured network topologies have been applied to network infrastructures. Han Haibo [14] proposes 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)”.

This paper evaluates structured geometric topologies' suitability for application in network infrastructures and aims to promote network performance by developing knowledge of the relationship between structured geometric topologies and network configuration.

This study uses Riverbed Modeler to simulate CP, HC, and TP structured network topologies and mesh unstructured topology. It then compares them to find the structured network topologies with higher network performance. The software is specifically designed for researchers in network architecture and can essentially satisfy the needs of complicated large-scale network simulations. It is widely used for local and wide area network performance modelling and evaluation in the network industry [15]. Riverbed Modeler's suitability for this study includes an extensive model library, scalable design, high-quality modelling data, user-friendly interfaces and flexible display of simulation results [16]. With the help of these, we can simulate a realistic and detailed model for reference.

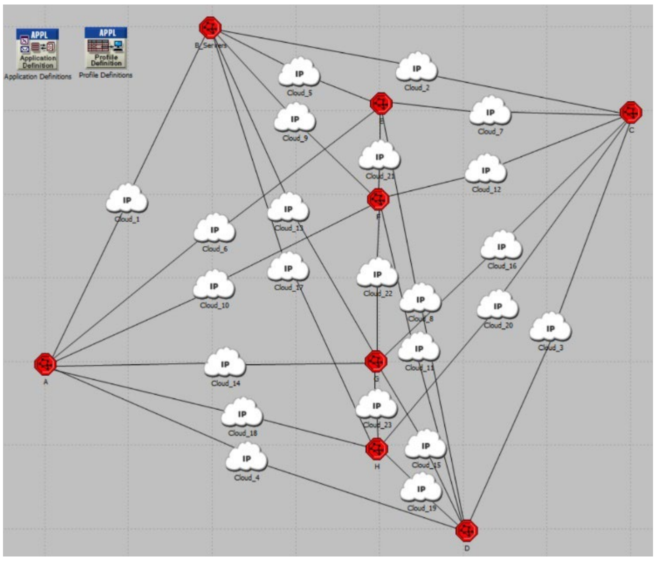


Fig. 1. Cross Polytope (CP) in the Simulation Scenario

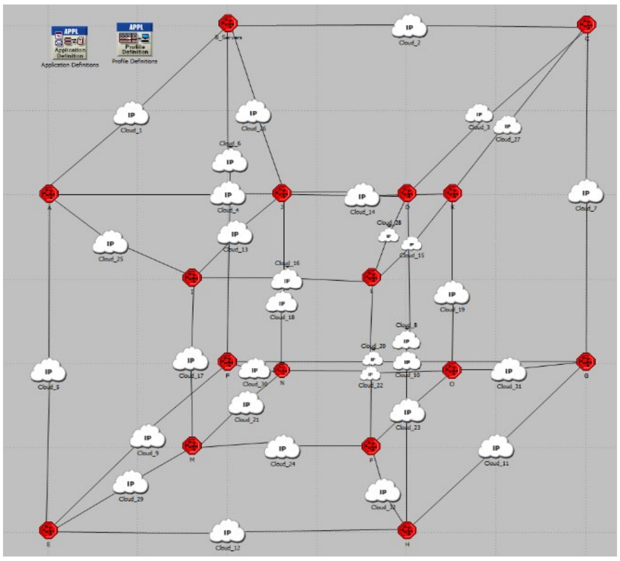


Fig. 3. Hypercube (HC) in the Simulation Scenario

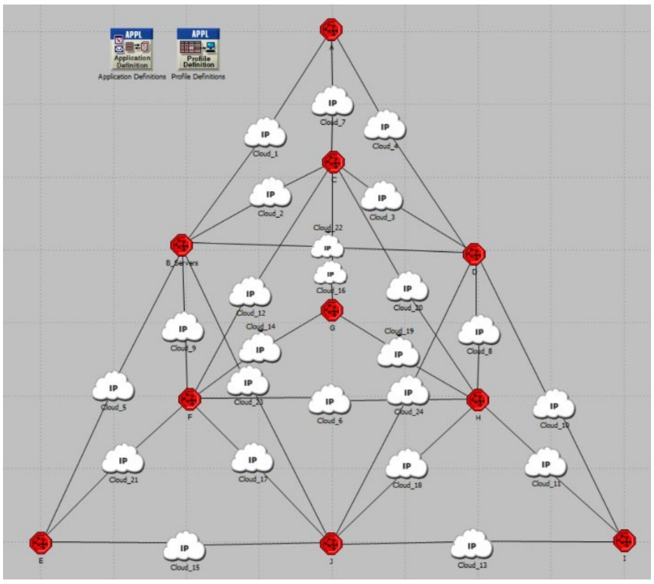


Fig. 2. Triangular Pyramid (TP) in the Simulation Scenario

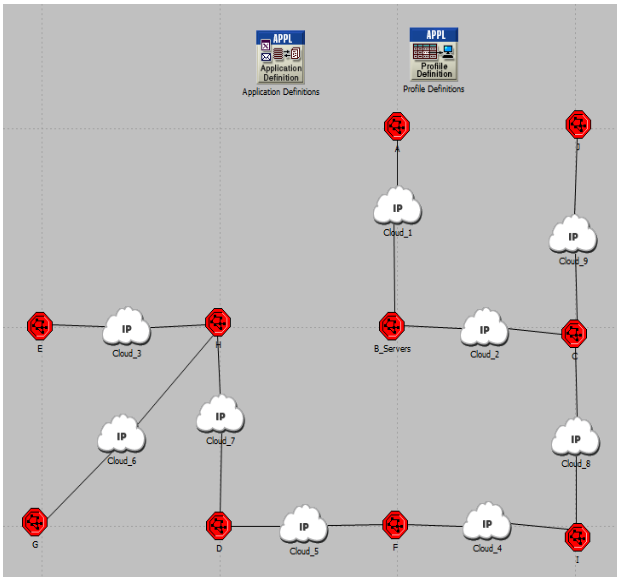


Fig. 4. Unstructured Mesh in the Simulation Scenario

II. STRUCTURED NETWORK TOPOLOGIES

In this paper, we explore the network performance behaviours of three types of structured planarised multi-dimensional topologies and one unstructured topology: cross polytope (CP), hypercube (HP), triangular pyramid (TP) and unstructured mesh topology.

A. Cross Polytope Topology

J.G. Lee et al. [17] 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. 1). 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. The CP structure possesses a high degree of symmetry and duality, hence facilitating the development and investigation of network structures. 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.

B. Triangular Pyramid Topology

Razivi and Sarbazi Azad propose a triangular pyramid (TP) network (see Fig. 2) based on the triangular grid [18]. 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.

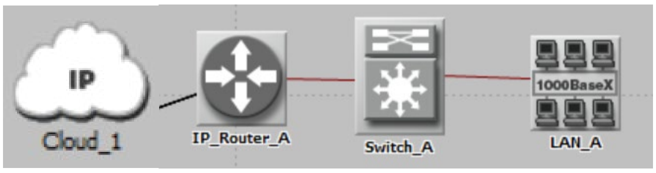


Fig. 5. Client Subnet

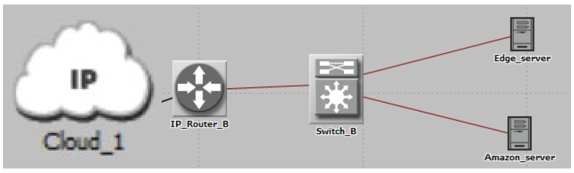


Fig. 6. Server Subnet

C. Hypercube Topology

The hypercube topology is a graph-like structure where the nodes are distributed according to the vertices of the shape of a multi-dimensional square, these 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 [19]. A hypercube is one of the most popular, shared and influential topological structures. It has the advantages of a small diameter, symmetrical structure, recursive structure and robust scalability [20]. A hypercube has 16 nodes, 32 sides and two cubes. (see Fig. 3).

D. Unstructured Mesh Topology

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.

III. SCENARIO CONFIGURATION

To study the network performance of two structured geometric topological networks, three discrete-event simulation models of LANs with client and server subnets were designed using the Riverbed Modeler (Optimised Network).The structured geometric topology structures are shown in Fig. 1, Fig. 2, Fig. 3 and the unstructured mesh network structure in (Fig. 4) which we use as a baseline for comparison.

A. Parent Subnets

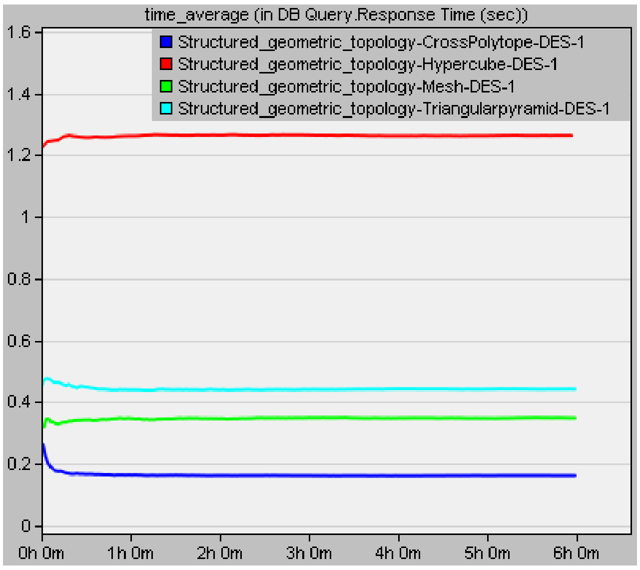
Each sub-network interface makes use of switched technology in conjunction with a direct connection to an IP-based network, which is used to describe the operation of an internet-based IP datagram processing (the Internet). Two "Definitions objects" have been selected: "Application Config", the application definition 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. In the parent subnets, PPP-DS3, whose data rate is 44.736 Mbps, is used as the link to connect the IP cloud and the Subnet. A choice of a low data rate (i.e. 44.736Mbps) has been deliberately made to understand the stress points on the networks presented.

B. Clients and Servers Subnets

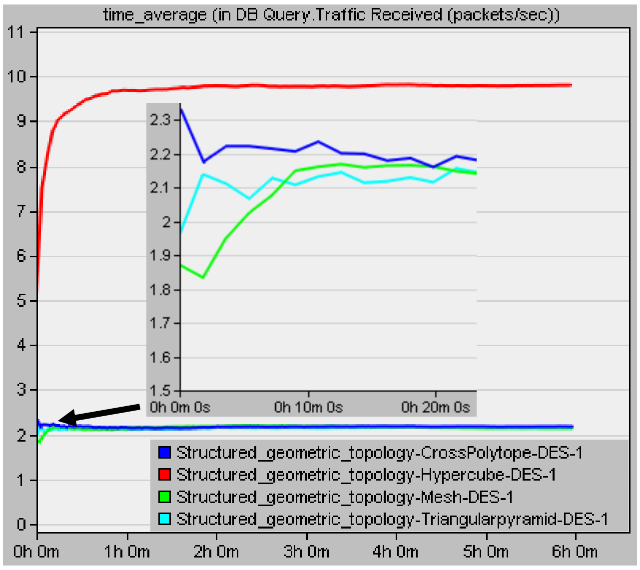
The client architecture (see Fig. 5) for applications consists of one LAN (with ten workstations), one Ethernet switch, and one IP router. The 100BaseT_LAN object represents a switched ethernet LAN, with a data rate consistent with other objects. In this paper, we set up ten workstation nodes on each LAN node to simulate an actual scenario and increase the traffic on the network, putting more pressure on the whole network to test its performance. The server structures, as seen in Fig. 6, are subnets containing the server (node B). These subnets are organised into four parent subnets, each of which includes two servers, one IP router, and one switch. The servers use the ethernet-server model describing server nodes with TCP/IP and UDP/IP.

TABLE I. APPLICATION CONFIGURATION

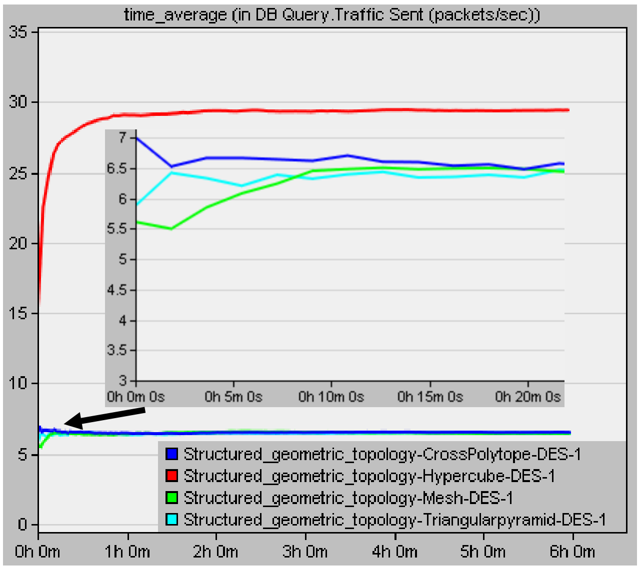
	Applications	Statistics	Traffic loads configuration
Time-independent Application	Database (Amazon)	Response Time (sec)	High load Transaction Inter-arrival Time (second): Exponential function (mean outcome is 12) Transaction Size: Constant (32768 bytes) Type of Service: Best Effort
		Traffic Received (packets/sec)	
		Traffic Sent (packets/sec)	
	HTTP (Edge)	Page Response Time (sec)	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)	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: Best Effort



(a) Database Query Response Time



(b) Database Query Traffic Received



(c) Database Query Traffic Sent

Fig. 7. Database Query Results

C. *Application Configuration*

All applications are set to high-load testing to test the capabilities of each topology network. High-load testing aims to ensure the network is resilient enough to withstand a large influx of traffic or users at any given time. This test also pushes networks beyond their standard operating capacity to find their breaking points. It aims to find their limits and observe their network performance as they approach these extremes. This paper sets all three applications to their corresponding high-load cases, e.g., Voice has a high load mode of "IP Telephony and Silence Suppressed".

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 I. No Quality-of-Service mechanisms have been incorporated explicitly into the simulation model. The applications outlined in Table 1 are subjected to IP Best Effort service to reveal the true character of each geometric topology under heavy traffic loads.

IV. SIMULATION RESULTS AND DISCUSSIONS

In this paper, all the figures are presented as time-average, allowing us to clearly see the trend of each network performance parameter as the passage of time ensues. All network statistics are presented in a six-hour simulation in superimposed mode for each graph to simplify analysis and understanding. In this study, the network performance of an unstructured mesh and three structured geometric structures is investigated, implementing two time-independent applications and one time-dependent application base on Ethernet.

A. *Database Query Results*

As shown in Fig.7 (a), 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 is risen. 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. Unfortunately, HP's query response time exceeds 1s due to the longer average path of sending a packet from the server side to the user side, resulting in a longer response time. 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, HC and mesh structures are less appropriate for usage in database applications.

The data presented in Fig. 7 (b) and Fig. 7 (c) indicate 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 low IP and Ethernet data rates imposed on part of our stress testing criteria. The user can send on average close to 6.5 packets per second through the CP and TP structures and approximately 30 packets through the HC. In contrast, the mesh structure has a limited capacity, allowing for the transmission of only approximately six packages. For database applications, the

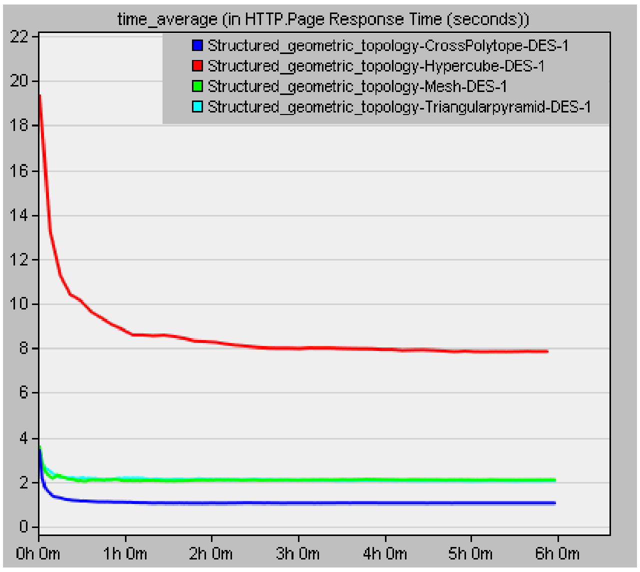


Fig. 8. HTTP Page Response Time

optimal architecture among the four topologies modelled in this paper is the CP structure, which improves response performance under higher traffic loads.

B. *HTTP Result*

Based on the data presented in Fig. 8, it is evident that the hypercube structure exhibits a notably poor response time, requiring around 8 seconds to attain stability. Conversely, the other three topologies demonstrate far faster stabilisation, with 2 seconds or less durations. Notably, the response time of the CP structure stabilised and remained at 1 second after approximately 15 minutes of simulation time. The extended duration of Hypercube's HTTP page response time can be attributed to the substantial quantity of nodes, specifically an excessive number of clients utilising the application, hence generating a significant volume of page requests that subsequently impact the response time. Moreover, the increased hops travelled by information packets within the hypercube result in higher utilisation, leading to a longer response time for the webpage.

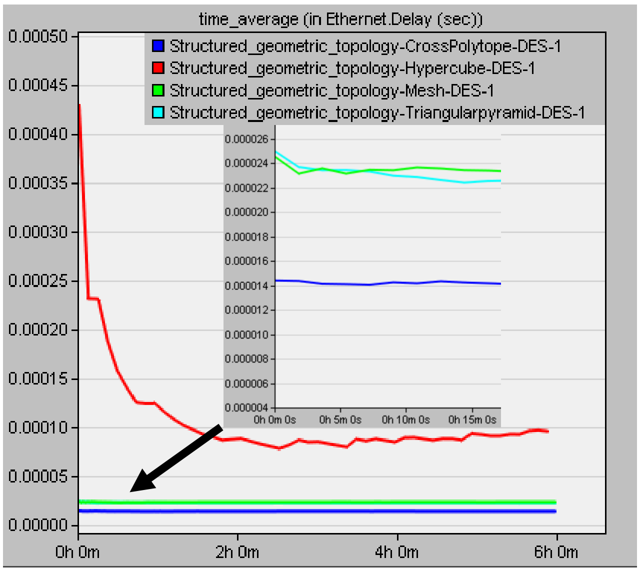


Fig. 9. Ethernet Delay

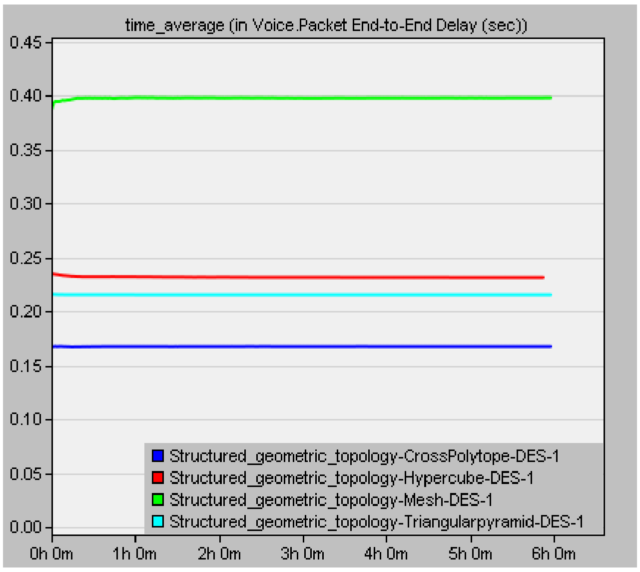


Fig. 10. Voice Packet End-to-end Delay

C. *Ethernet Result*

Ethernet delay is defined as the end-to-end delay of all packets received by all the stations. The data is transmitted through 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 low network delay. As shown in Fig. 9, the Ethernet delay of the four structures is relatively stable and not high except for the hypercube. The stability of the hypercube's ethernet delay is achieved after a simulation time of approximately two hours, with a corresponding decrease of 0.45 milliseconds. One of the contributing factors to the increased Ethernet delay seen in the hypercube geometric topology is the comparatively greater average distance covered by a packet during transmission from the server to the client. This extended distance necessitates a longer duration of time for the package to traverse the transmission medium. Another factor to consider is that the increased number of nodes leads to a longer duration for data to traverse through switches and routers. The delay of Ethernet in both mesh and TP topologies exhibits minimal differences, but the Ethernet delay in the CP topology is around 58% of that in mesh and TP topologies. The result indicates that the CP structured geometric topologies have higher performance and are the superior option for use in Ethernet.

D. *Voice Result*

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 as possible to 0.15s voice quality and less than 0.4s according to the ITU (International Telecommunication Union), which provides recommendations for VoIP performance in the G.114 standard [21]. According to. Fig. 10 demonstrates that the end-to-end delay of all four topologies falls within the acceptable range as specified above. However, it is worth noting that the unstructured mesh topology exhibits a significantly greater latency of 0.4 seconds compared to the other three structured geometric topologies. The hypercube topology, characterised by an increased number of nodes and longer average transmission lines, exhibits significant improvement in comparison to the structured topology. This improvement is seen in the substantial reduction of end-to-end delay by over 0.15 seconds compared to the mesh topology. The simulation results of CP continue to exhibit the most favourable performance in terms of end-to-end delay, with a value that closely approximates 0.15 seconds. The result serves as an exemplary illustration of how the end-to-end latency 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.

V. CONCLUSIONS AND FUTURE WORK

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-sensitive 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.

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.

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