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Analyzing methods of network topologies based on chordal rings

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Abstract: This paper presents a methodology for the transmission properties research of networks patterned according to the third-degree chordal graphs. When designing and analyzing ICT systems, it is vital to consider the topology of network components. The telecommunication network structure can be described by a graph. Computing modes or specialized computers are the vertexes and the edges are bidirectional, independent transmission channels that represent the connected nodes. The algorithm is potentially useful for the determination of the impact of diameter and an average path length of the chordal rings on the properties of the transmission network. It is also useful for the indications of alternate paths in the event of node or link failure. Two types of tests were conducted. The first of them is realized by the HTTP protocol and the second by the SSIM method. The obtained results confirmed that these parameters are decisive in the flow capacity and delaying the transferred data.

Key words: Network, information systems, chordal rings, graph, topology

1. Introduction

An ICT system is a set of interlinked IT devices and software that ensures data processing, storing, and transmitting via the ICT network by means of an end user's device appropriate for each network. It consists of a number of intelligent nodes, the purpose of which is to provide the end system users a certain level of services of proper quality, speed, and reliability [1]. When designing and analyzing ICT systems, it is crucial to consider the topology of the network components (interconnection network), which is decisive for its effectiveness [2,3].

The utilized ICT networks are often characterized by an irregular topology, a result of "matching' their network to the operator and users' shifting needs [4]. As a consequence, such a network does not provide the optimal conditions for data transfer. During a period of increased traffic [5,6], in order to provide sufficient transmission quality, it is vital to increase the transmission speed and reduce the occurring delays, which is particularly important in cases of image transfer [7]. The application of optimized nodes of identical networking hardware considerably reduces investment costs such as assembly expenses (CAPEX), and also facilitates and reduces costs of utilization and maintenance of the aforementioned systems (OPEX). An additional advantage is the symmetric connectivity, routing simplicity, good scalability, ease of management, and, due to introduction of additional connections chords, the increase of efficiency [8,9].

Telecommunication network structures can be described by graphs. Computing modes or specialized

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computers are the vertexes (nodes) and the edges are bidirectional, independent transmission channels that represent the connection of the nodes. In the case of identical node degrees, such networks can be modeled by regular graphs.

The most frequently used transmission medium in a modern ICT network is an optical fiber cable and the ring network topology is the one most commonly applied. Standard ring network transmission parameters are not satisfactory, so they were modified by introducing additional internode connections named chords. The resulting topologies are called chordal rings [10]. Figure 1 depicts a diagram of an actual network using third-degree graphs. The topology presents a network project for Kuyavian-Pomeranian Province in Poland. The structure of the NDR was dictated by the need to improve its reliability.

Over the past several decades, an interdisciplinary field called complexity science has emerged. This field deals with issues of virtual system components and sets them to interact with each other in simulated worlds. The answer to the development of this field in this article is a network project for Kuyavian-Pomeranian Province in Poland, implemented within the framework of the regional operational plan. It is intended for communication between the state administration and the security, property, and health of citizens.

The problem of transmission properties, interconnection networks, and simple interaction is also used in many other areas, for example from crowd disasters to crime, terrorism, wars, and the epidemic spreading of diseases [11]. The focus of these works was the application of a scientific approach to understanding interpersonal relationships [12], behavior analysis in different models, behavior of social systems, and others. In this field, authors propose to use a number of various methods, i.e. information systems, computer science, and technology. Many publications [13–15] suggested that transmission properties of graph-patterned networks are influenced greatly by their diameter and average path length. The definitions of these basic parameters are given below.

Definition 1 *A D(G) graph's diameter equals the longest of minimal paths that connect any two graph nodes (Eq. (1)):*

$$D\left(G\right) = max_{v_i v_j}\left\{d\left(v_i,\, v_j\right)\right\} \tag{1}$$

where v_i, v_j are node numbers and $d(v_i, v_j)$ is the length of the path (number of edges) connecting v_i, v_j nodes.

Definition 2 *Average path length d_{av} in the graph is defined by Eq. (2):*

$$d_{av} = \frac{1}{p(p-1)}\sum_{i-0}^{p-1}\sum_{j=0}^{p-1} d_{min}(v_i, v_j) \tag{2}$$

where d_{min} is a minimal number of edges between nodes v_i, v_j, while $i \neq j$, p represents the number of nodes that constitute the graph.

This article presents the methodology and results of research on how the above mentioned parameters influence the transmission properties of ICT systems with third-degree chordal-ring topology.

2. Methodology

Simulation tests were carried out in order to evaluate and compare transmission properties of ICT networks delineated by various regular networks. Virtual devices connected via the virtual network of the tested chordal ring were used. Figure 2 depicts a general diagram of the tested network.

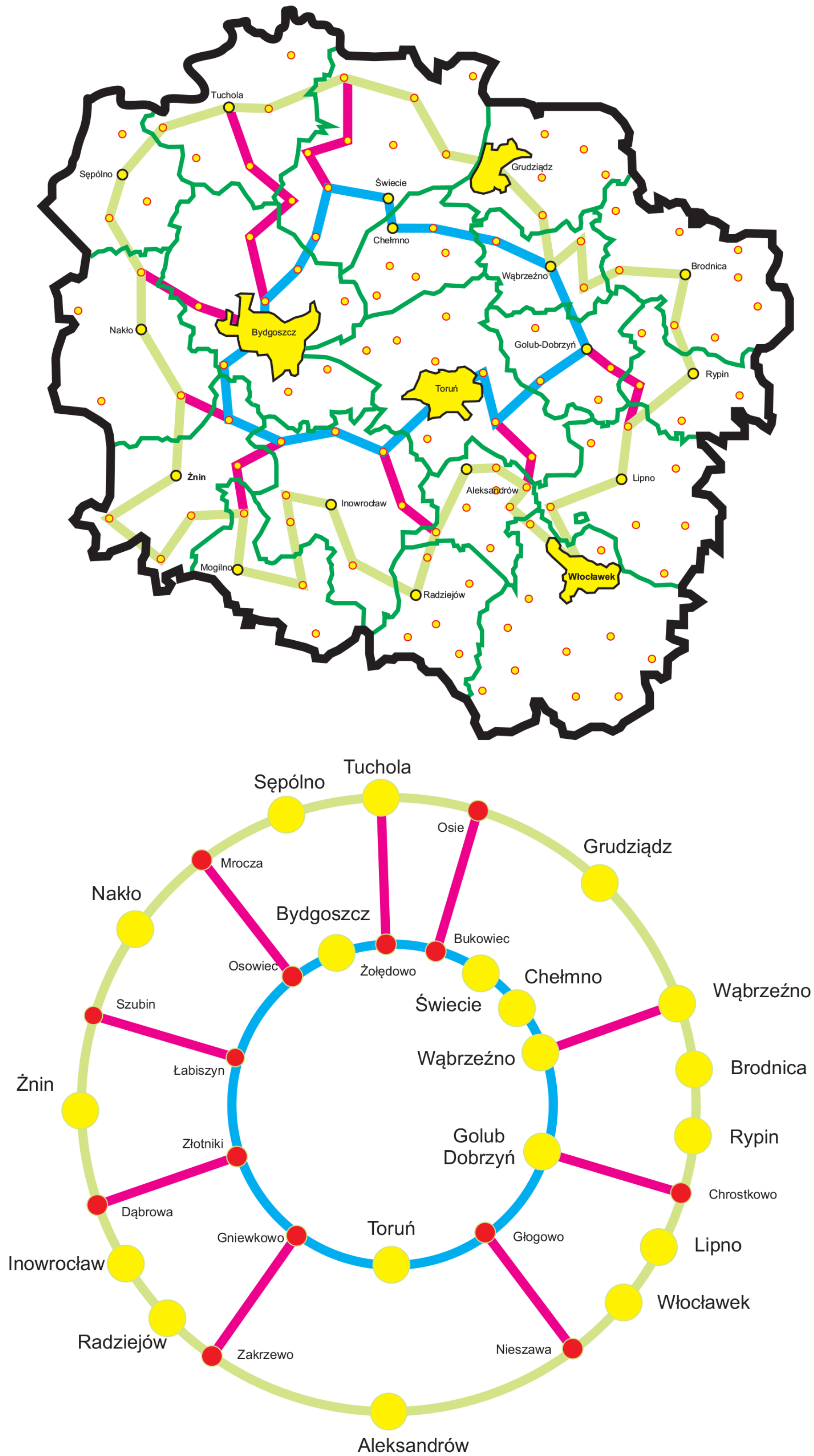


Figure 1. An example of a telecommunication network for Kuyavian-Pomeranian Province: a) simplified network diagram, b) network diagram using NDR structure.

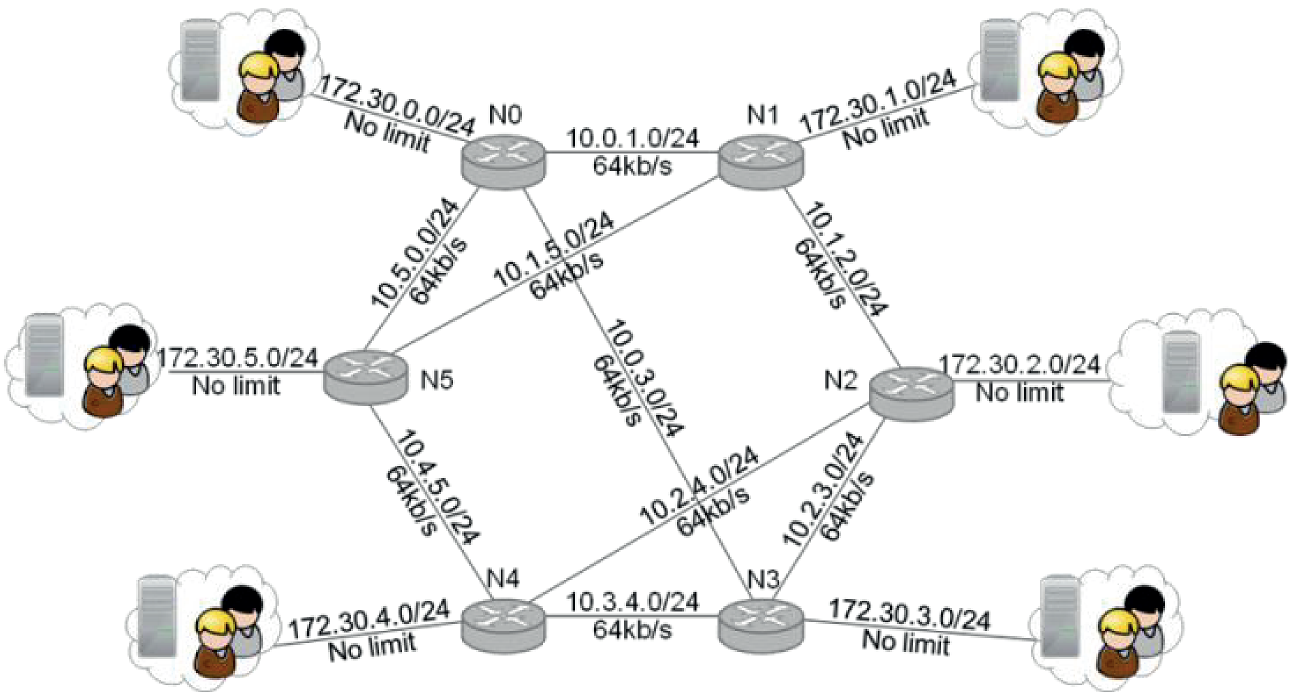


Figure 2. The diagram of the tested network.

The vertex of the graph consists of routers, which are the network's nodes. The nodes are interconnected by links, the edges of the graph. To ensure uniform traffic generated in the network, to each router a subnetwork was connected, consisting of a server and a fixed number of users. To achieve access to a dataset stored on other servers that are connected to different routers, each user has to send a request and the corresponding server sends back the desired data. Streaming was also applied, i.e. servers transmitting videos addressed to users of other subnetworks. In this way, ICT traffic was generated for the purpose of carrying out the tests.

The analyzed networks were constructed on the basis of programmable routers installed on virtual devices operating on Vyatta OS. It is a Linux distribution system used as a router or a firewall. VirtualBox was applied for the virtualization environment. It is equipped with rapid network interface configuration capabilities for virtual devices. An 'internal networking' mode was used to realize interrouter connectivity, due to its ability to connect virtual devices via the Ethernet. Configuration management of the network and the server and user's software was based on original programs implemented in the Java and Python languages.

To eliminate the influence of the processing power of computers on which the tests were applied, the bandwidth of the internode connections was experimentally reduced to 64 kb/s. The IP addresses of router interfaces were statically set and at the same time the dynamic open routing protocol OSPF was applied [16].

Two test scenarios were introduced to test networks in regards to their transmission properties. The first consisted of measuring the data volume transferred via various connective networks with the HTTP protocol, while the second realized video streaming in real-time, where the image quality was evaluated.

2.1. Scenario I - HTTP traffic

The HTTP protocol was used for testing chordal rings networks, as it is most often used both by clients machines and devices that perform network services. To determine what kind of Internet traffic is the most common, traffic on the seven most popular web servers (according to a ranking from 2012) was assessed. These included Google, Facebook, Badu, YouTube, Twitter, Yahoo!, and Wikipedia. Each of these portals had the most popular subsites determined or, in the case of search engines, the most frequent entries. Next, the average content size triggered by search engines' requests was measured. In the case of YouTube, only loading of the site was considered. Figure 3 depicts the results, which allowed to determine the network testing conditions.

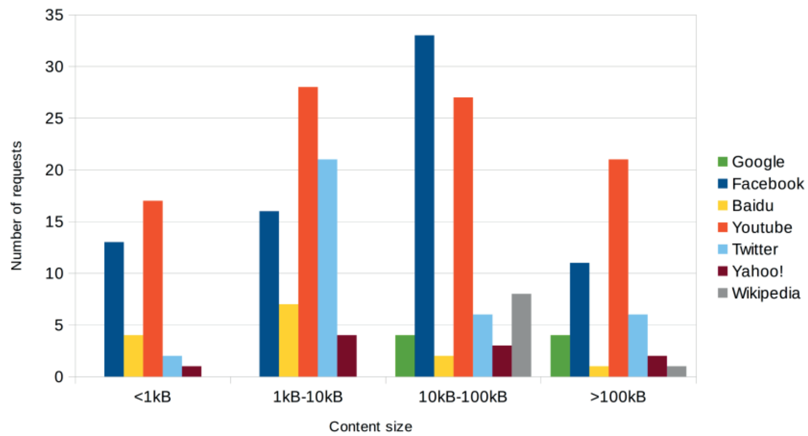


Figure 3. HTTP content size for particular subsites of the most popular web servers.

The charts show that the highest number of requests came from YouTube and Facebook, and to a lesser extent Twitter. Data size was correlated with the portal type. For YouTube, the distribution of transfer was balanced for the entire tested range of 1–100 kB. For Facebook, the majority of data ranged between 10 kB and 100 kB, while for Twitter it was between 1 kB and 10 kB. For the purpose of this analysis, taking into account computer capabilities and assumed bandwidth of the connections, it was decided that the test will consider data sizes ranging from 1 kB to 32 kB.

To determine the transfer properties of networks limited by chordal rings, the following conditions were set:

- Networks are described by third-degree regular graphs;
- Users send their requests to the web servers, and the measured data are contained in the replies loaded in time (the considered content size minus the HTTP headings);
- The HTTP requests are generated by 5 users connecting to every node, with the assumed equal probability of choosing the end server;
- The requests obtain responses ranging from 1 kB to 32 kB;
- The test is conducted for a response time limit ranging from 10,000 to 50,000 ms;
- The frequency of the sent requests is shifted within the range of 0.02–0.12 Hz, depending on the number of nodes;
- The test results are calculated as an arithmetic average of three repetitions of the same test.

The results are depicted on charts with the average transfer speed VTR from the user's perspective of the network represented by the tested graph. An average transmission speed was calculated according to Eq. (3):

$$V_{TR}\left[\frac{kB}{s}\right]=\frac{\sum_{i=0}^{n-1}\sum_{j=1}^{m}Dane_{ij}(T)}{(n-1)\cdot m\cdot T} \tag{3}$$

where the numerator defines the sum of transfer during the duration of the test, n is the number of servers, m is the number of users per node, and T is the duration of the test.

The graphs show the results of the study of third-level structures with different nodes as a function of the timeout waiting time for the received information. For the analysis of the influence of diameters and average path lengths of the graphs studied, the values of these parameters are given in the tables (Table 1) preceding the graphs.

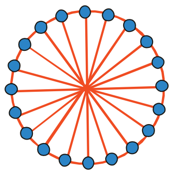
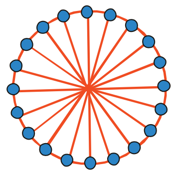
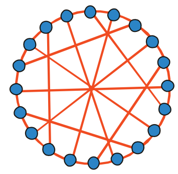
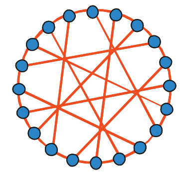
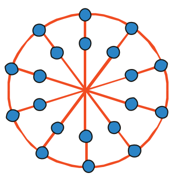
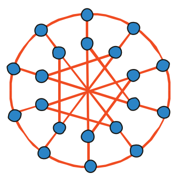
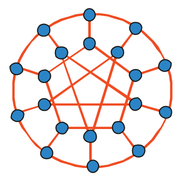
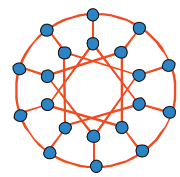
			
CHR3(20;10)	**CHR3(20;7)**	**CHR3n(20;6,10)**	**CHR3m(20;7,9)**
D(G)=5;dav =3,1	**D(G)=4;dav=2,53**	**D(G)=5;dav=2,47**	**D(G)=4;dav=2,53**
			
NdRa(20;5)	**NdRb(20;3,5)**	**NdRc(20;2,4)**	**NdRm(20;3)**
D(G)=5;dav=2,89	**D(G)=4;dav=2,53**	**D(G)=4;dav=2,53**	**D(G)=5;dav=2,63**

Table 1. Samples of tested networks.

Figure 4 depicts the results of tested networks consisting of 20 nodes within the response time limit to the received data with shifting intensity of requests generated by the users. By analyzing the results of the tests, it was found that the best transmission properties have networks described by the CHR3n and NDRm graphs. This group of networks has the shortest average path lengths. This observation confirms the thesis that the network bandwidth is closely related to the magnitude of this parameter.

The results indicate that transmission properties of the network (its capacity) are directly dependent on the diameter and the average path length of its graph. Furthermore, it was stated that together with the increase in the frequency of requests sent to the servers, initially an increase occurs in the transfer speed to a certain maximum which equals the full utilization of the link capacity. Then a decrease occurs in the transfer speed, which can be explained by the network overflow.

The transfer speed is also dependent on the response time: the longer it takes, the more efficient the transfer speed is. However, this dependency is not linear; the speed converges until a certain value as depicted in Figure 5, Thus, any further increase of the response time is baseless. This phenomenon can be explained by looping packets in the web that never reach their recipient, simultaneously making it harder for other packet bursts to reach their destinations.

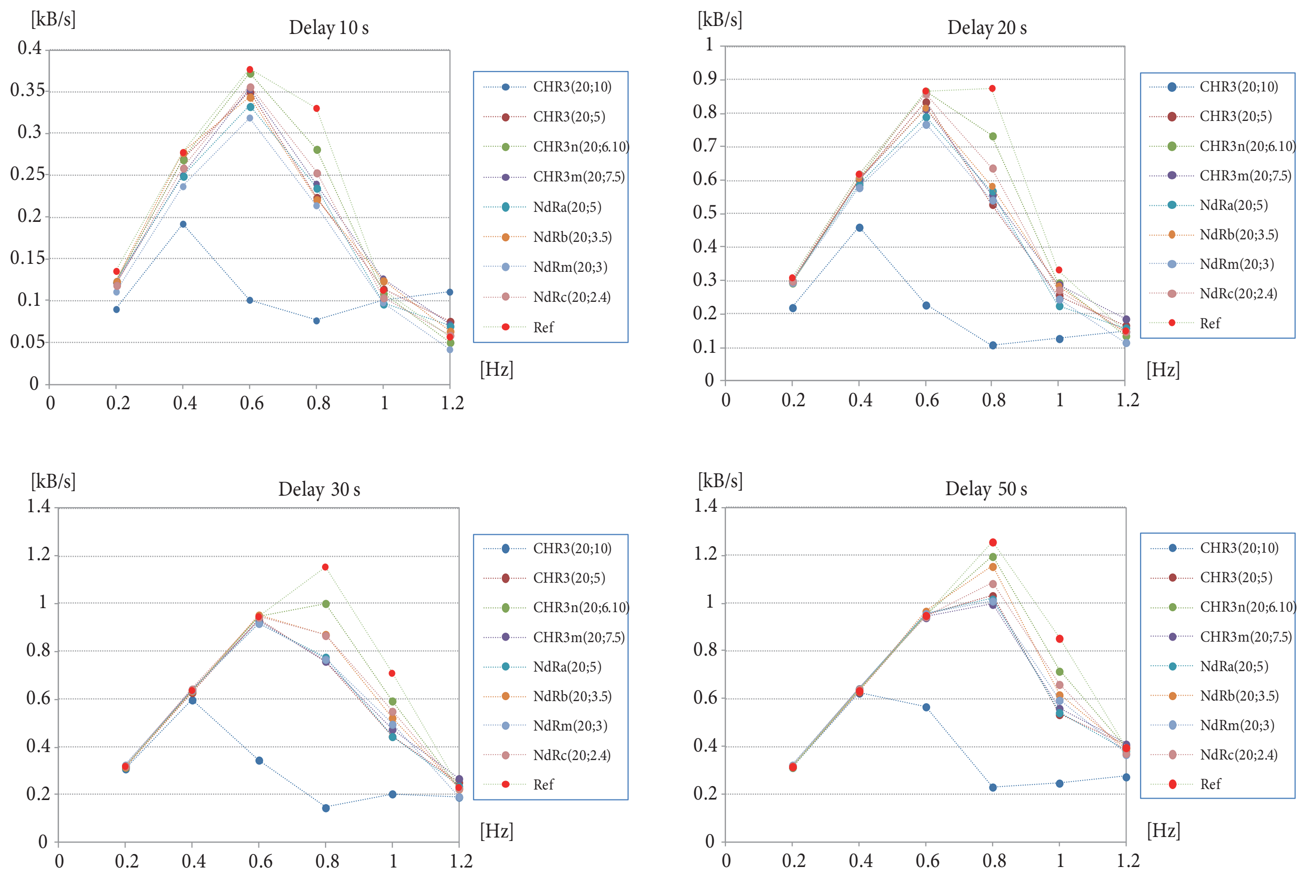


Figure 4. Results for the 20-node network within the response time function for the transferred data.

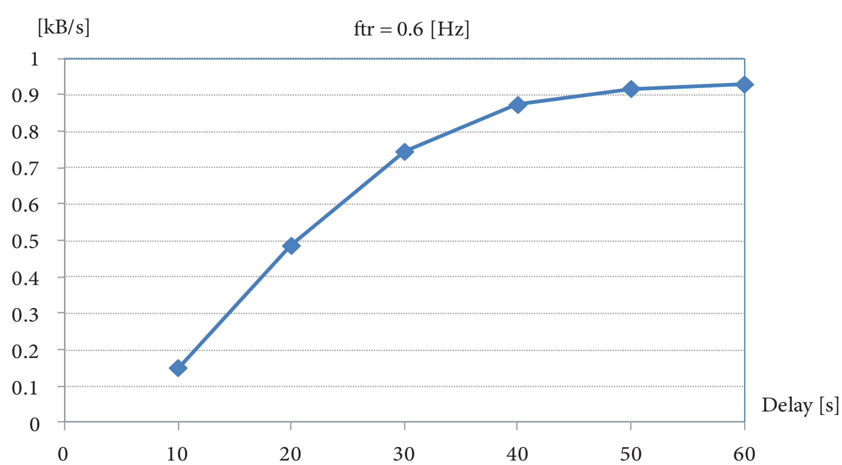


Figure 5. The influence of the response time on the transferred speed for an example graph of CHR3n (36;6,14).

The conclusion is that optimizing the network utility can be achieved by defining both the maximum amount for the received traffic and the response time.

2.2. Scenario II – streaming the video

The following conditions were applied during the testing of transmission properties. Videos were streamed from servers to users. The tests utilized videos from the LIVE [17,18] and the EPFL [19–21] databases with a total 15-s transmission duration of each stream. Those samples (30 frames per second) were saved in the YUV format.

To reflect the real-network conditions, the videos were converted into the H.264 format. The tools Mencoder and avconf were used for that purpose. The conversion reduced the video size; calculated Fps, i.e. determined the frequency with which the static image is transferred to the user; experimentally matched the CRF parameter (constant rate factor) responsible for the quality of converted images; and matched the defining parameter for the maximal interval between the full-image frames.

The tests were conducted by H.264-format streaming from servers to all users within the network, assuming balanced distribution between the source servers. The video streaming was organized within the NAL unit (network abstraction layer). The first byte of each one serves as a heading and defines the data type within the unit. The following bytes consist of data defined in the heading (Figure 6).

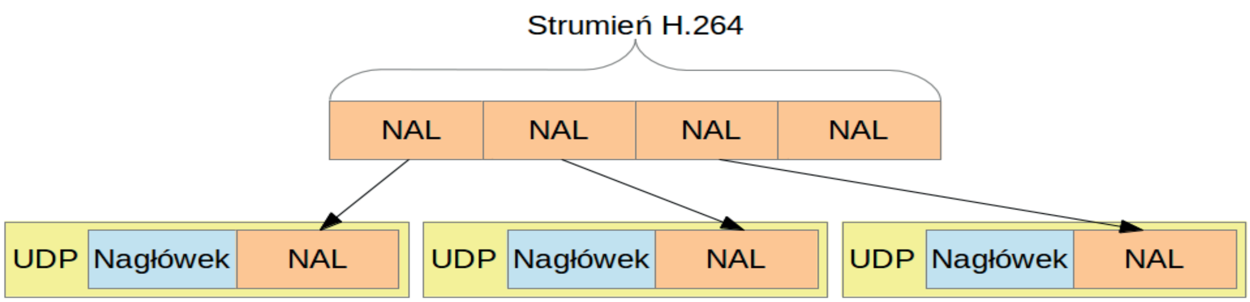


Figure 6. The H.264 streaming diagram.

The servers, based on the NAL unit analysis complemented with heading, transferred video data in the UDP packets burst to the users. The heading consisted of the stream and frame numbers and the transmission time. The transfer speed was equal to the streaming speed on the receiving end. After receiving the packet the user's application checked if there was no timeout. If not, the NAL utility content was matched to the stream received earlier, retaining the proper file sequence. Otherwise the burst was rejected, resulting in worsening of the video quality.

Each received stream was decoded, creating individual video frames. Reference streams underwent decoding as well and next the two streams were compared frame by frame using the SSIM (structural similarity index method) [22]. The SSIM aims to determine the image similarity rate. This numerical rate ranges from 0 to 1, where 1 stands for identical images and 0 represents no similarity. Each analyzed frame is split into three constitutive colors (red, blue, green). The rate is calculated for each constitutive color separately and returned as their arithmetic average, calculated for all frames of all streaming transmissions within a single test.

To represent the shifts in the image quality when the SSIM rates vary in relation to the original images, Figure 7 depicts some frames from videos received during the tests.

In order to verify the transmission properties of networks based on chordal ring topology, the following conditions were carried out for network tests:

- Servers connected to nodes send the stream video in the H.264 format via the 24-node network build of the third-degree chordal ring;

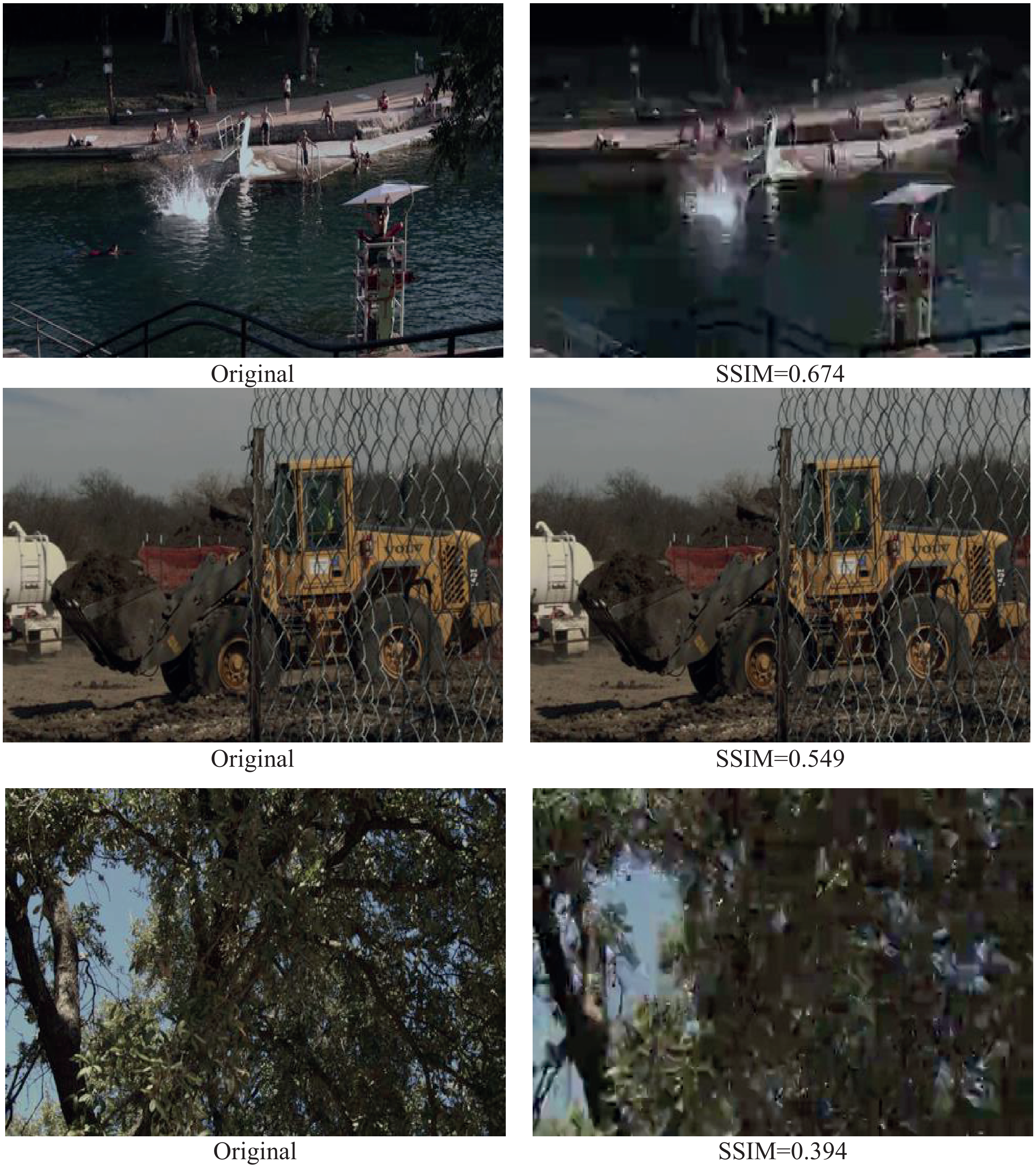


Figure 7. Comparison of images when the SSIM factor varies.

- The is unicast transmission, i.e. a single server sends a packet burst to a single user;
- Each subnetwork streamed independently to 5 users, with assumed equal probability of choosing the end user;

- The users received streams of varying frames per second with experimentally matched CRF parameters;
- The test was carried out for the response time limit ranging from 1000 to 50,000 ms;
- The test resulted in the quality SSIM parameter, determined from the comparison of sent and received streaming frames;
- The final result of the test was calculated as an arithmetic average of three repetitions of the same test.

The tests were realized for the coefficients of transmitted and received video streams. The networks that underwent the test were delineated by third-degree graphs, as displayed in Table 2.

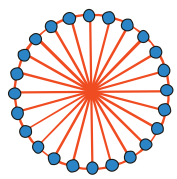
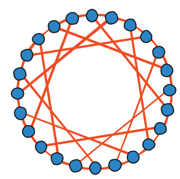
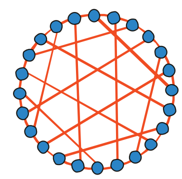
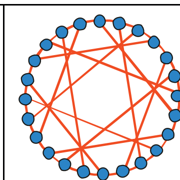
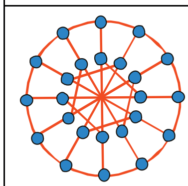
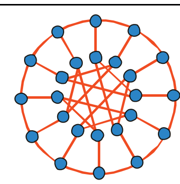
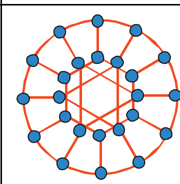
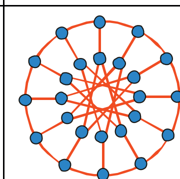
			
CHR3(24;12)	**CHR3(24;7)**	**CHR3n(20;6,10)**	**CHR3m(20;7,9)**
D(G)=6;dav=3,61	**D(G)=5;dav=2,78**	**D(G)=4;dav=2,65**	**D(G)=5;dav=2,78**
			
NdRa(24;3)	**NdRb(24;3,5)**	**NdRc(24;2,4)**	**NdRm(24;5)**
D(G)=4;dav=2,76	**D(G)=5;dav=2,87**	**D(G)=5;dav=2,83**	**D(G)=4;dav=2,69**

Table 2. Tested networks.

Measurement of stream similarities within the Fps parameter function was conducted for varying values of allowed batch response time after transmission via the networks.

The tests were carried out for an experimentally matched CRF parameter value equaling 38 within the Fps function, which had an impact on the content transferred from servers to users. By increasing the Fps parameter value it is possible to increase the transferred content; however, as the chart shows, this interrelation is nonlinear (Figure 8).

The following charts (Figure 9) display image similarity rate values within the Fps parameter function in distinct response times. To evaluate the quality of images transmitted across different network topologies, the results obtained are related to the results obtained for the reference graphs. Based on the presented results, the best results in terms of the quality of the received images were obtained (without reference graphs) for networks described by the CHR3n and NdRm topologies, in which the average path length compared to other structures is the shortest.

The SSIM rate was measured for the shifting Fps parameter within the assumed packet group response time function. The charts depict the obtained results (Figure 10).

The results suggest that the video quality improves together with the increase of the response time, and the increased value of the Fps parameter causes this quality to decrease. This is a consequence of an increased

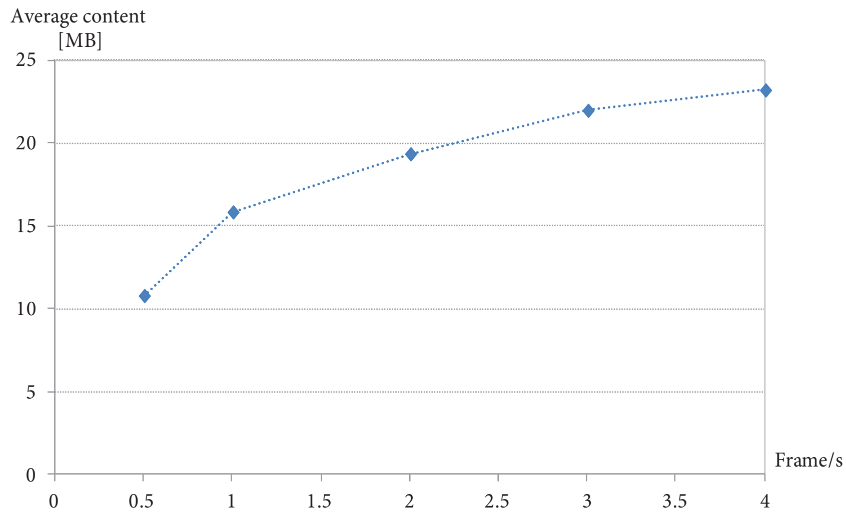


Figure 8. The impact of the Fps parameter on average data volume transferred via servers to the users.

amount of data transferred by the network, thus creating a need to match the transfer speed to the network transmission capabilities.

The results of the research confirm that the best image quality is obtained when all the networks are delineated by graphs of minimal diameter and average path length.

2.3. Methodology verification

Real-time devices run the tests for the third-degree network in order to verify the methodology for the HTTP traffic analysis. Due to limited technical capacities (number of routers), tests were conducted for the 8-node network.

Below is a diagram of the tested network and charts with results of networks tests on virtual devices (Figure 11).

Figure 12 depicts the results of the third-degree network flow capacity. The difference between results for virtual devices (Vyatta) and the real-time server-based network (Cisco) is minor. These validates the applied methodology, and consequently it can be applied to researching developed networks without the need to involve large amounts of resources.

3. Conclusions

This article presents a methodology for the transmission properties research of networks patterned according to third-degree chordal graphs. For that purpose, two types of tests were conducted. One consisted of measuring the transferred data within various networks by applying the HTTP protocol, while the other assessed the image quality in streamed videos by means of the SSIM (structural similarity).

The tests were made according to the author's concept based on a set of virtual devices interconnected via the virtual network of third-degree chordal ring topology.

The obtained results confirmed the previously untested theory that both the diameter and the average path length are decisive in ensuring the flow capacity and delaying the transferred data. It was confirmed that the best results are obtained when the topology is delineated by graphs of the aforementioned parameters' lowest values.

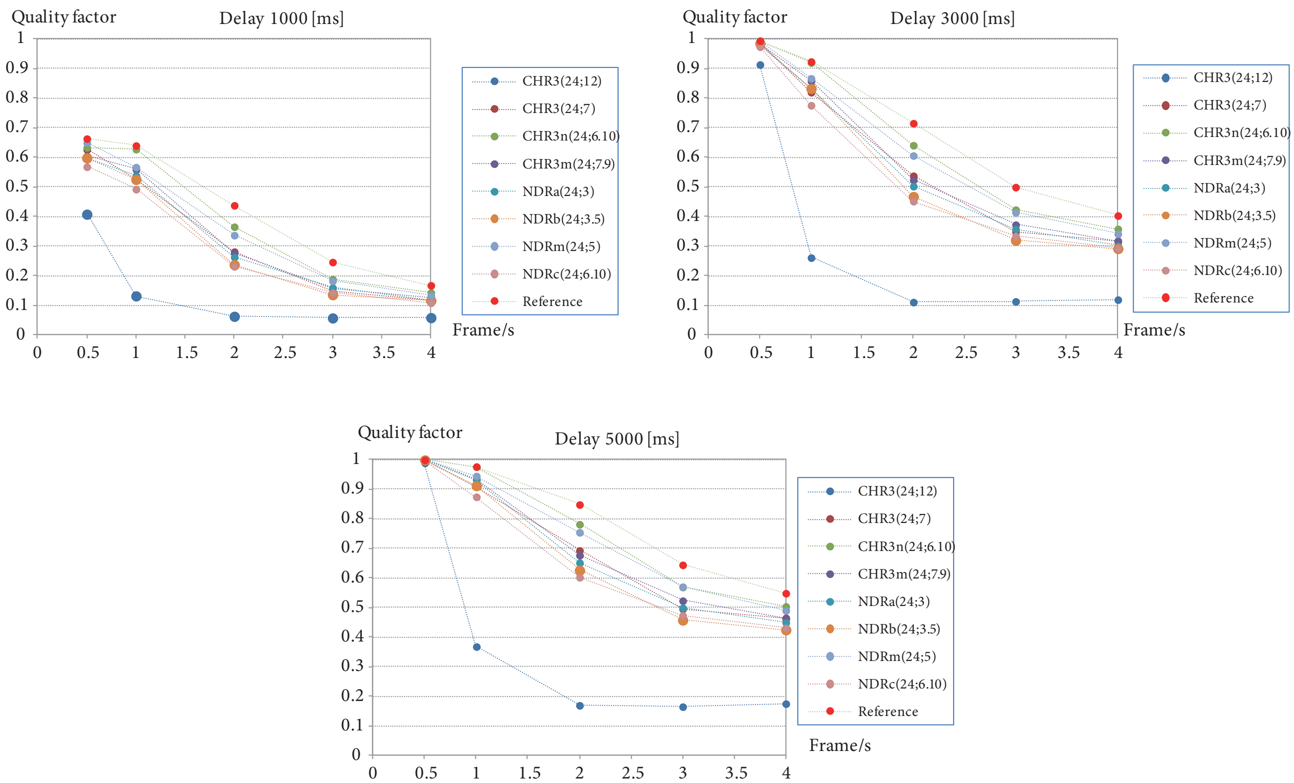


Figure 9. The results of image quality for a shifting Fps parameter function in distinct response times.

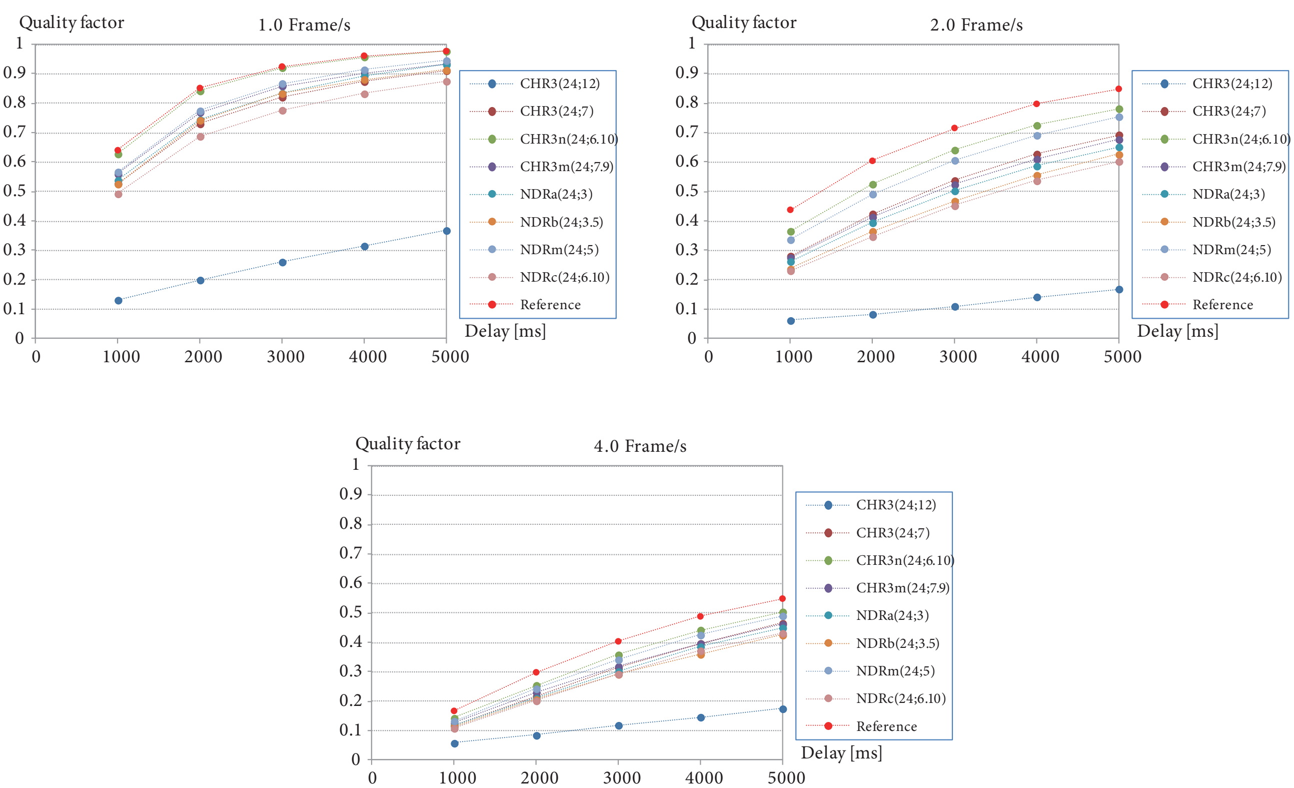


Figure 10. The results of video quality within the response time function and the third-degree graph Fps parameter.

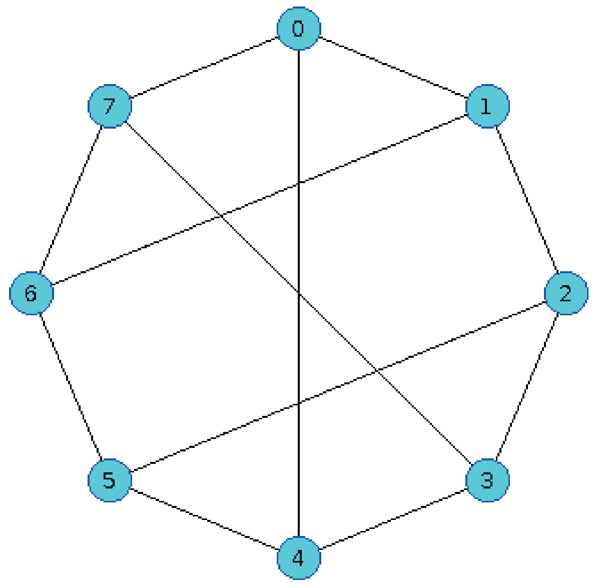


Figure 11. Diagram of the tested network for the third-degree graph.

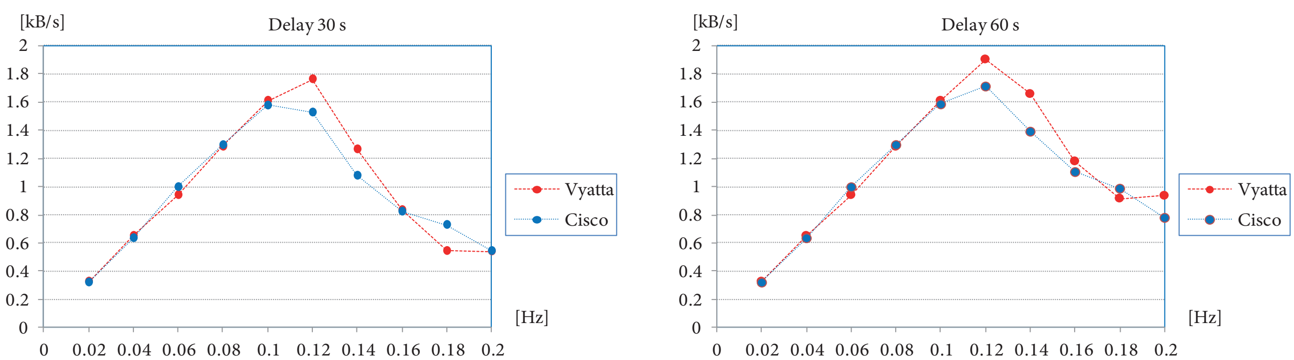


Figure 12. The results of the third-degree network flow capacity.

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