Preliminary Analysis of LTE Systems with Edge Cloud Computing for Video Streaming Applications

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1. Introduction

With the introduction of packet-switched networks, it became possible to distribute multimedia content that combines data with audio and video information. In fact, once digitized, audio and video information is transferred in byte format. The initial difficulties encountered, however, involved the need for increasingly performant connections between network nodes in terms of bandwidth and throughput for real-time applications such as internet telephony (VoIP) and streaming, the latter having become predominant in internet traffic.

The main transport protocol for these applications is the Real-Time Protocol (RTP), which operates over lower-level protocols like UDP [1, 2, 3]. With the constant increase in IP traffic, a significant rise in video traffic is expected, which will constitute a large part of global internet traffic.

The growth of the sector involves various players, from Telcos, telecommunications operators overseeing technological infrastructures, to "Over The Top" (OTT) entities, which come from the digital services and technology sector and need an infrastructure to provide their services [4, 5] and energy systms [6, 7, 8]. The transition from a "voice-centric" to a "data-centric" communication model has required new interconnection models and services such as Content Delivery Networks (CDNs) to improve the Quality of Experience (QoE) for users.

This work focuses on improving QoE through Transparent Caching platforms, analyzing technologies and mathematical models, with the aim of optimizing access to multimedia content on modern networks such as LTE. The work is structured into various chapters that address technical and practical aspects related to these topics.

2. Services

2.1. Codec Video

In recent years, image and video encoding has become crucial for many digital applications, thanks to advanced technologies such as affordable processors, fast internet access, and standardization. This development has been driven by the need to bridge the gap between high user demands and limited network and storage capacities. For example, a digital video signal of "television quality" requires 216 Mbit of storage transmission capacity for one second of video, while a movie with a duration of about two hours requires over 194 GB of space, values that exceed the current capacities of networks. Video CODECs are essential as they allow data compression, facilitating transmission and storage.

Most video CODECs currently in use conform to one of the international standards for video encoding. Among the most influential, JPEG has become the standard for storing still images, while MPEG-2 and its evolutions, such as MPEG-4, are essential for digital television and DVDs [9, 10, 11, 12, 13, 14, 15, 16, 17]. Other video CODECs on the market include Divx, Xvid, VP8, VP9, and VP10.

2.2. Cloud Computing

The term Internet of Things (IoT), coined by Kevin Ashton, refers to a set of devices connected to the Internet, such as mobile phones, coffee machines, and many other objects [18, 19, 20, 21].

In 2003, there were about 6.3 billion people living on the planet and 500 million devices connected to the Internet, well below the threshold to consider the IoT as such.

The explosive growth of smartphones, tablets, and PCs brought the number of devices connected to the Internet to 12.5 billion in 2010, while the world population increased to 6.8 billion. It is precisely from this moment that the expansion of the IoT, according to Cisco IBSG's definition, begins [22].

The efficient and stable use of IoT technologies is linked to the data management and processing capabilities, significantly improved with cloud computing platforms such as fog computing or edge computing.

The main advantages of using cloud computing are:

- cost reduction;
- faster access;;
- economies of scale;
- improvement of overall performance;
- greater security.

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3. Content Distribution Platforms

3.1. Content Distribution: "The Bottleneck Theory"

The concept of content distribution arises from the simple necessity of having content closer to the customers who request it. Content distribution technologies have become pioneers in addressing some of the issues generated by the rapid growth of the Web, such as slow content download times and WAN link congestion.

The objective of this work is to measure the quality of certain connections to solve the problem of the "distant" location of some servers, which should instead be "replicated" near the client (requester) to optimize the user experience and resource utilization.

A data flow can traverse a network only at the speed allowed by the slowest link in its path. In theory, every route through a network has a potential "bottleneck. The necessity to improve the throughput is crucial for Non-Terrestrial Networks (NTNs) [23].

These critical points, often located at the "edge" of the Internet, are primarily influenced by bandwidth. In the past, corporate networks followed the 80/20 rule (80% of traffic on the LAN and 20% on the WAN), but with the expansion of the Internet, this balance has reversed, leading to an overload on the WAN. Companies, due to economic constraints, cannot increase the bandwidth of WAN links, making these critical points the main sources of congestion.

3.2. Content Delivery Network (CDN)

Content Delivery Network or Content Distribution Network is represented by a group of network servers located in specific data centers around the world with the purpose of facilitating the faster retrieval of content for Internet users. These servers cache all the information requested by a content provider.

CDNs improve the distribution of various types of content, including high-definition videos, audio streams, and software downloads. The use of CDNs offers significant advantages such as:

- improvement of Quality of Experience and download times;
- protection of servers from overloads and interruptions;
- flexibility in managing static content;
- ease in handling access spikes and increased security against attacks.

In summary, CDNs represent a fundamental infrastructure for the efficient distribution of content on the Internet, making the user experience smoother and more secure.

3.3. Transparent caching

The function of a Transparent Caching platform is similar to that of traditional CDNs, which is to ensure that content is placed near the end users, thereby reducing both the round trip time (RTT) and packet loss, thus improving throughput performance and Quality of Experience. The main difference from traditional CDNs is that Transparent Caching platforms use self-learning functionalities, meaning they dynamically learn the most important content (generally the most requested) and then classify them in order of importance, i.e., based on the most viewed. The content is then stored on a platform and made available only on demand. In addition to the traditional functions of a CDN, Transparent Caching platforms are often used for IP traffic that carries content not considered stable (such as web content) or for traffic for which there is no agreement with the Content Provider. The use of Transparent Caching platforms offers multiple advantages:

- no client configuration required, reducing administrative activities;
- increased application throughput;
- decreased necessary bandwidth;
- greater reliability.

In summary, Transparent Caching platforms offer a flexible and effective solution for improving network performance, optimizing content access for end users.

4. Performance Evaluation

4.1. Definition

Network performance is evaluated through the measurement of appropriate indicators, of which throughput (data flow) and latency are the main ones. It is then useful, if not essential, to consider the quantities derived from these.

4.1.1. Bandwidth

Bandwidth is the capacity of the physical channel available to transfer a certain amount of information (in bits) relative to the considered time interval.

4.1.2. Throughput (TH or THR)

Throughput refers to the amount of data traffic and information that actually reaches its destination within a unit of time, net of network losses and protocol operations. Thus, throughput is linked to the Quality of Experience perceived by the end user.

4.1.3. Latency

Latency is the time required for a message to reach the destination node and is measured in units of time, usually seconds.

4.1.4. Round Trip Time (RTT)

In this work, latency is considered as a performance indicator, defined as the time required for a message to travel from a source node to a destination node and then back to the source node. This time interval is called the Round Trip Time (RTT) of the network.

4.1.5. Packet loss (PL o PLR)

Packet loss is a good measure of the quality of the connection (in terms of packet loss rate) for many TCP-based applications. It is generally caused by congestion, which in turn causes queuing of messages waiting to be transferred (e.g., in routers).

4.1.6. Bit Rate (BR)

The bit rate (or transmission rate) is the number of bits per second; that is, the amount of digital information (bits) transferred per unit of time (second). Generally, it determines the size and quality of video and audio files: the higher the bit rate, the better the quality of the video and the larger the file size.

4.2. Mathis Model

The Mathis model explains the relationship between throughput and packet loss through the following formula:

$$TH = \frac{MSS}{RTT} * \frac{C}{\sqrt{p}}$$

where:

- MSS (Maximum Segment Size) is the maximum segment size;
- TH is the throughput;
- RTT is the round trip time;
- p is the probability of packet loss;
- C is a constant with a value equal to $\sqrt{\frac{3}{2}}$.

For simplicity, the values of p and the maximum segment size (MSS = 1460 bytes) are assumed to be constant. The Mathis formula, therefore, highlights how the value of throughput is inversely proportional to the probability of packet loss and latency, but directly proportional to the segment length, as summarized in the following figure.

$p \uparrow (\downarrow) \Rightarrow TH \downarrow (\uparrow)$	As the packet loss probability increases (decreases), the throughput value decreases (increases).
$RTT \uparrow (\downarrow) \Rightarrow TH \downarrow (\uparrow)$	As the data transfer time (RTT) increases (decreases), the throughput value decreases (increases).
$MSS \uparrow (\downarrow) \Rightarrow TH \uparrow (\downarrow)$	As the segment length increases (decreases), the throughput value increases (decreases).

Figure 1: Relations between the variables in the Mathis formula

5. Enabling Technologies

5.1. LTE

A study conducted by Cisco on global Internet traffic forecasts and trends for the period 2017-2022 has shown that mobile data traffic during this period will increase exponentially, reaching approximately 77.5 Exabytes per month by 2022 [24]. This volume will represent 20% of total IP traffic. To cope with this sudden increase in data traffic, new technologies have been introduced to enhance data transmission speeds and make frequency spectrum usage more efficient. Additionally, new frequencies for mobile radiocommunication have been introduced through an increase in the number of radio cells. This new technological approach has resulted in an increase in spectrum efficiency of about three times that of its predecessors, with significantly lower network costs.

LTE stands for Long Term Evolution; the telecommunications body known as the Third Generation Partnership Project (3GPP) initiated the project in 2004, although this new technology first entered the market starting in 2010.

LTE represents a broadband wireless technology designed within the telecommunications market. According to 3GPP, a series of advanced requirements have been identified for using this new technology:

- Reduction of cost per bit
- Increased service provisioning: more services at lower costs with improved user experience
- Flexibility in using existing and new frequency bands
- Simplified architecture, open interfaces
- Allowing reasonable terminal power consumption

The primary goal of LTE is to provide high data transmission speeds and increase capacity, improve coverage, achieve low latency, and optimize packet access technology to support flexible bandwidth implementation. At the same time, its network architecture has been designed to support packet-switched traffic, seamlessly and with high quality of service.

The LTE standard, therefore, supports only packet-switched communication with its all-IP network. The reason LTE is designed exclusively for packet switching is that it aims to provide uninterrupted IP connectivity between user equipment and the packet data network, without interrupting end-user applications during mobility [25].

		Villa Mondragone	Ingegneria dell'informazione	Netflix Pop Roma	Netflix Pop Milano	Iperf Public server Ile-de-France
Villa Mondragone	Distanza (Km)	0	10	30	600	1450
	ECC	SI	SI	SI	SI	NO
	IP	160.80.242.2	160.80.81.125	193.201.28.94	217.29.66.187	62.210.18.40

Figure 2: Scenario 1

6. Project

6.1. Introduction

The experimental activity presented describes the use of a drone equipped with a camera payload and a link to a ground station for transmitting a video made in accordance with the assigned mission, in 4K resolution, followed by uploading it to a transparent caching system.

The drone's function is simulated; the drone sends video to the server, which processes the received data. The server then sends the data to the client upon request.

Specifically, this work focuses on the activity described, for which a campaign was conducted to measure the quality of the link established between a client located at the University of Tor Vergata or at Villa Mondragone in Frascati, who wishes to view or download the video from a server located in Paris, Île-de-France.

6.2. Objective

The measured data will lead to a series of results representing a significant sample for evaluating the benefits derived from using a transparent caching function and estimating how this position affects final performance. In particular, simulations of transparent caching located at progressively decreasing distances from the client will be used in two different scenarios (e.g., in the first scenario, the client is located at Villa Mondragone, the server at Île-de-France, and the transparent caching servers in Milan, Rome, and Tor Vergata).

In terms of latency, it is expected that approaching the server will result in a reduction of this metric, leading to an increase in throughput.

6.3. Theoretical Preparation and Application of the Mathis Law

6.3.1. Ping

The ping function allows measuring the response time (round-trip time in milliseconds (ms)), packet loss percentages, variability in response time both in the short term (seconds scale) and long term, and the lack of reachability, i.e., no response for a series of pings.

6.3.2. Performance Measurements

Network processing efficiency largely depends on the network's ability to ensure an adequate level of performance, which must be measurable. Specifically, as previously illustrated, throughput is preferred, as it reflects actual measured performance rather than the maximum bandwidth available on the line. The second measurable value characterizing performance is latency, which corresponds to the time required for a message to traverse the network from the source node to the destination node and back to the source node. It is measured exclusively in terms of time.

6.3.3. Constraints and Limits of Measurements

A single physical line connecting the same two computers continuously has a constant RTT value, while TCP connections are likely to exhibit very different RTT values. For example, a TCP connection between two cities thousands of kilometers apart might have an RTT of 100 ms, whereas a TCP connection between two computers in the same room, only a few meters apart, might have an RTT of 1 ms, and the same TCP protocol must accommodate both connections. Additionally, to complete the scenario, the connection between the two cities might vary significantly within the same day, and even variations in RTT values are possible during a TCP connection lasting only a few minutes.

6.4. Tools

For conducting the experimental campaign, the following tools, data processing devices, and network equipment were used:

- iperf3;
- smartphone with Android operating system;
- PC with Windows 10 operating system.

6.5. Scenario 1

The experimental activity was based on measuring the RTT (Round Trip Time) using the PING functionality for decreasing distances, following the schema represented below and assuming that the service requester (client) was always located at the Villa Mondragone site.

The distance between the fixed client station and the servers simulating the transparent caching functionality at increasing distances also serves to hypothesize the theoretical value of RTT, which can be confirmed by the ping measurement. Some measurement samples confirm the validity of this reasoning.

6.5.1. Case 1 - Tratta Villa Mondragone-Ile-de-France

In the first scenario, Villa Mondragone was considered the access site (client) from which requests were made to the server at decreasing distances. In the initial phase, measurements were conducted using the IPERF3 tool, and these measurements were found to be consistent with those of the subsequent phase. A PING request was then sent to simulate access to the server located in Île-de-France, approximately 1450 km away. RTT measurements were taken with the PC (Villa Mondragone-Île-de-France) for different packet lengths, expressed in bytes. Subsequently, using the Mathis law, the throughput values for various PLR (0.1% and 0.37%) were derived, as shown in the following figure:

Byte	PLR	RTT[ms]	THR [Mbps]
8	0,0010	130	337,390701
8	0,0037	130	175,401073
16	0,0010	115	381,398184
16	0,0037	115	198,279474
32	0,0010	123	356,591798
32	0,0037	123	185,383248
64	0,0010	111	395,142263
64	0,0037	111	205,424681
128	0,0010	168	261,076138
128	0,0037	168	135,727021
256	0,0010	242	181,242939
256	0,0037	242	94,2237171
512	0,0010	80	548,259889
512	0,0037	80	285,026744
1024	0,0010	137	320,15176
1024	0,0037	137	166,438975

Figure 3: Measured and Derived Values for the Villa Mondragone-Île-de-France Route

6.5.2. Case 2 - Villa Mondragone-Milan Route

As in the previous case, this simulation considers the client located at Villa Mondragone, while the server being queried is positioned in Milan. In this scenario, it is as if a "transparent caching server" were used, placed in locations closer to the client compared to the server where the videos are stored. For this connection, RTT measurements were taken with the PC for the distance of approximately 600 km (Villa Mondragone-Milan) with various packet sizes, expressed in bytes. Subsequently, applying the Mathis formula, the throughput values were derived for different Packet Loss Rates (PLR) of 0.1% and 0.37%, as shown in the following figure:

Byte	PLR	RTT [ms]	THR [Mbps]
8	0,0010	92	476,74773
8	0,0037	92	247,849343
16	0,0010	141	311,069441
16	0,0037	141	161,717302
32	0,0010	128	342,662431
32	0,0037	128	178,141715
64	0,0010	153	286,671838
64	0,0037	153	149,033592
128	0,0010	152	288,557836
128	0,0037	152	150,014076
256	0,0010	67	654,638674
256	0,0037	67	340,330441
512	0,0010	76	577,115673
512	0,0037	76	300,028152
1024	0,0010	97	452,173105
1024	0,0037	97	235,073603

Figure 4: Measured and Derived Values for the Villa Mondragone-Milan Route

6.5.3. Case 3 - Villa Mondragone-Rome Route

Similar to Case 2, in this simulation, the client is at Villa Mondragone, while the server is located in Rome. For this connection, RTT was measured with the PC for the distance of approximately 30 km (Villa Mondragone-Rome) with different packet sizes, expressed in bytes. Using the Mathis formula, the throughput values were derived for various PLR values of 0.1% and 0.37%, as illustrated in the following figure:

6.5.4. Case 4 - Villa Mondragone-Tor Vergata University Route

In this case, as in the previous ones, the client is at Villa Mondragone, and the server is positioned at the University of Tor Vergata, Department of Information Engineering. RTT measurements were taken with the PC for the distance of approximately 10 km (Villa Mondragone-Tor Vergata) with various packet sizes, expressed in bytes. The Mathis formula was then used to derive the throughput values for different PLR values of 0.1% and 0.37%, as shown in the following figure:

6.5.5. Case 5 - Villa Mondragone-Villa Mondragone Route

In this final case, both the client and server are located at Villa Mondragone. For this connection, RTT was mea-

Byte	PLR	RTT [ms]	THR [Mbps]
8	0,0010	92	476,7477
8	0,0037	92	247,8493
16	0,0010	141	311,0694
16	0,0037	141	161,7173
32	0,0010	128	342,6624
32	0,0037	128	178,1417
64	0,0010	153	286,6718
64	0,0037	153	149,0336
128	0,0010	152	288,5578
128	0,0037	152	150,0141
256	0,0010	67	654,6387
256	0,0037	67	340,3304
512	0,0010	76	577,1157
512	0,0037	76	300,0282
1024	0,0010	97	452,1731
1024	0,0037	97	235,0736

Figure 5: Measured and Derived Values for the Villa Mondragone-Rome Route

Byte	PLR	RTT [ms]	THR [Mbps]
8	0,0010	48	913,7665
8	0,0037	48	475,0446
16	0,0010	55	797,4689
16	0,0037	55	414,5844
32	0,0010	57	769,4876
32	0,0037	57	400,0375
64	0,0010	44	996,8362
64	0,0037	44	518,2304
128	0,0010	56	783,2284
128	0,0037	56	407,1811
256	0,0010	93	471,6214
256	0,0037	93	245,1843
512	0,0010	57	769,4876
512	0,0037	57	400,0375
1024	0,0010	90	487,3421
1024	0,0037	90	253,3571

Figure 6: Measured and Derived Values for the Villa Mondragone-Tor Vergata University Route

sured with the PC for the distance of approximately 0 km (Villa Mondragone-Villa Mondragone) with various packet sizes, expressed in bytes. The throughput values were then derived using the Mathis formula for different PLR values of 0.1% and 0.37%, as depicted in the following figure:

6.6. Scenario 2

The experimental activity was based on measuring RTT using the PING functionality for decreasing distances, following the schema represented below, assuming that the service requester (client) was always located at the University of Tor Vergata, Department of Information Engineering.

Byte	PLR	RTT [ms]	THR [Mbps]
8	0,0010	44	996,8362
8	0,0037	44	518,2304
16	0,0010	57	769,4876
16	0,0037	57	400,0375
32	0,0010	51	860,0155
32	0,0037	51	447,1008
64	0,0010	62	707,4321
64	0,0037	62	367,7764
128	0,0010	57	769,4876
128	0,0037	57	400,0375
256	0,0010	132	332,2787
256	0,0037	132	172,7435
512	0,0010	57	769,4876
512	0,0037	57	400,0375
1024	0,0010	56	783,2284
1024	0,0037	56	407,1811

Figure 7: Measured and Derived Values for the Villa Mondragone-Villa Mondragone Route

The distance between the fixed client station and the servers, which simulate the behavior of transparent caching at increasing distances, also helps to hypothesize the theoretical value of RTT, which can be confirmed by the ping measurements. Some sample measurements confirm the validity of this reasoning.

		Ingegneria dell'informazione	Netflix pop Roma	Netflix pop Milano	Iperf Public server Ile-de-France
Ingegneria dell'informazione	Distanza (Km)	0	13	595	1440
	ECC	SI	SI	SI	NO
	IP	160.80.81.125	193.201.28.94	217.29.66.187	62.210.18.40

Figure 8: Scenario 2

6.6.1. Case 1 - University of Tor Vergata-Ile-de-France Route

In the first scenario, the University of Tor Vergata (Department of Information Engineering) was considered the access site (client) from which to request data from the server at decreasing distances. Initially, measurements were conducted using the IPERF3 tool, and results were consistent with those obtained in the subsequent phase. A PING request was then sent simulating access to the server located in Ile-de-France, approximately 1440 km away. For this connection, RTT measurements were taken with the PC (University of Tor Vergata-Ile de France) with various packet sizes, expressed in bytes. Subsequently, applying the Mathis formula, the throughput value was derived for different PLR values (0.1% and 0.37%), as shown in the following figure:

Byte	PL	RTT [ms]	THR [Mbps]
8	0,0010	130	337,3907
8	0,0037	130	175,4011
16	0,0010	132	332,2787
16	0,0037	132	172,7435
32	0,0010	167	262,6395
32	0,0037	167	136,5398
64	0,0010	152	288,5578
64	0,0037	152	150,0141
128	0,0010	166	264,2216
128	0,0037	166	137,3623
256	0,0010	214	204,957
256	0,0037	214	106,5521
512	0,0010	151	290,4688
512	0,0037	151	151,0075
1024	0,0010	146	300,4164
1024	0,0037	146	156,179

Figure 9: Measured and Derived Values for the University of Tor Vergata-Ile-de-France Route

6.6.2. Case 2 - University of Tor Vergata-Milan Route

As in the previous case, in this simulation, the client is located at the University of Tor Vergata (Department of Information Engineering), while the queried server is positioned in Milan. In this scenario, it is as if a "transparent caching server" were used, placed in locations closer to the client compared to the server where the videos are stored. For this connection, RTT was measured with the PC for a distance of approximately 595 km (University of Tor Vergata-Milan) with various packet sizes, expressed in bytes. Applying the Mathis formula, the throughput value was derived for different PLR values (0.1% and 0.37%), as illustrated in the following figure:

Byte	PL	RTT [ms]	THR [Mbps]
8	0,0010	100	438,6079
8	0,0037	100	228,0214
16	0,0010	103	425,8329
16	0,0037	103	221,38
32	0,0010	145	302,4882
32	0,0037	145	157,2561
64	0,0010	139	315,5453
64	0,0037	139	164,0442
128	0,0010	163	269,0846
128	0,0037	163	139,8904
256	0,0010	131	334,8152
256	0,0037	131	174,0621
512	0,0010	122	359,5147
512	0,0037	122	186,9028
1024	0,0010	191	229,6376
1024	0,0037	191	119,3829

Figure 10: Measured and Derived Values for the University of Tor Vergata-Milan Route

6.6.3. Case 3 - University of Tor Vergata-Rome Route

In this third case, the client remains at the University of Tor Vergata (Department of Information Engineering), while the server is located in Rome. For this connection, RTT was measured with the PC for the distance of approximately 13 km (University of Tor Vergata-Rome) with various packet sizes, expressed in bytes. Applying the Mathis formula, the throughput value was derived for different PLR values (0.1% and 0.37%), as shown in the following figure:

Byte	PL	RTT [ms]	THR [Mbps]
8	0,0010	137	320,1518
8	0,0037	137	166,439
16	0,0010	182	240,9934
16	0,0037	182	125,2865
32	0,0010	185	237,0854
32	0,0037	185	123,2548
64	0,0010	171	256,4959
64	0,0037	171	133,3458
128	0,0010	174	252,0735
128	0,0037	174	131,0468
256	0,0010	149	294,3677
256	0,0037	149	153,0345
512	0,0010	173	253,5306
512	0,0037	173	131,8043
1024	0,0010	166	264,2216
1024	0,0037	166	137,3623

Figure 11: Measured and Derived Values for the University of Tor Vergata-Rome Route

6.6.4. Case 4 - University of Tor Vergata-University of Tor Vergata Route

In this final case, both the client and server are located at the University of Tor Vergata (Department of Information Engineering). For this connection, RTT was measured with the PC for the distance of approximately 0 km (University of Tor Vergata-University of Tor Vergata) with various packet sizes, expressed in bytes. Applying the Mathis formula, the throughput value was derived for different PLR values (0.1% and 0.37%), as depicted in the following figure:

7. Conclusions

7.1. Scenario 1 - Considerations on the Behavior of the Function THR=f(RTT)

From a theoretical standpoint, applying the Mathis law and experimental laws linking distance to RTT yields

Byte	PL	RTT [ms]	THR [Mbps]
8	0,0010	127	345,3606
8	0,0037	127	179,5444
16	0,0010	152	288,5578
16	0,0037	152	150,0141
32	0,0010	144	304,5888
32	0,0037	144	158,3482
64	0,0010	194	226,0866
64	0,0037	194	117,5368
128	0,0010	150	292,4053
128	0,0037	150	152,0143
256	0,0010	129	340,0061
256	0,0037	129	176,7608
512	0,0010	131	334,8152
512	0,0037	131	174,0621
1024	0,0010	136	322,5058
1024	0,0037	136	167,6628

Figure 12: Measured and Derived Values for the University of Tor Vergata-University of Tor Vergata Route

results consistent with those measured. Specifically, the following aggregated values reflect a decreasing trend of THR as a function of RTT.

7.1.1. PLR=0,1%

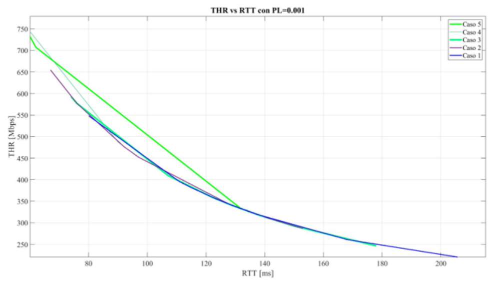

Figure 13: THR=f(RTT) scenario 1 and PLR=0,1%

Comparing the various curves for the different cases in Scenario 1, with PLR = 0.1%, the following observations are made:

- $RTT < 82ms$: THR decreases as RTT increases. In particular, the curve representing the simulation without Transparent Caching (Case 1) lies below all other curves, indicating that the result aligns well with expectations;
- $82ms < RTT < 86ms$: THR for the case without Transparent Caching (Case 1) is above the curve representing Milan (Case 2). In this interval, the Transparent Caching locations that still ensure efficient performance are Rome (Case 3), Tor Vergata (Case 4), and Villa Mondragone (Case 5);
- $86ms < RTT < 99ms$: THR for Case 1 is above Cases 2 and 4, so the Transparent Caching locations that still maintain efficient performance are Rome (Case 3) and Villa Mondragone (Case 5);
- $99ms < RTT < 105ms$: THR for Case 1 is above Cases 2, 3, and 4, meaning that the only Transparent Caching location still providing efficiency is Villa Mondragone (Case 5);
- $105ms < RTT < 127ms$: THR for Case 1 is above Cases 3 and 4. Therefore, the Transparent Caching locations that still ensure efficiency are Milan (Case 2) and Villa Mondragone (Case 5);
- $RTT > 127ms$: THR for Case 1 is above all other cases, indicating that none of the other Transparent Caching locations ensure efficient performance.

In summary, the final situation of Scenario 1 with PLR = 0.1% is represented in the following figure:

RTT [ms]	Caso 1	Caso 2	Caso 3	Caso 4	Caso 5
RTT<82					
82<RTT<86					
86<RTT<99					
99<RTT<105					
105<RTT<127					
RTT>127					

Figure 14: Summary of the THR=f(RTT) Function Behavior with PLR=0.1%

7.1.2. PLR=0,37%

With similar considerations applied for a different PLR (=0.37%), the following result is obtained:

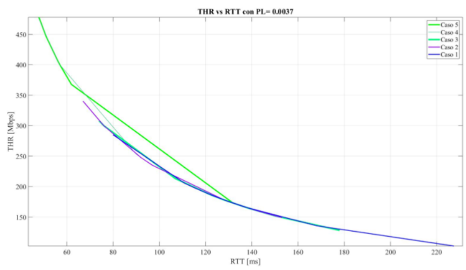

Figure 15: THR=f(RTT) scenario 1 and PLR=0,37%

In this case, the behavior of the functions is identical to the case with PLR = 0.1%, while at the same RTT, the THR value is approximately 90% higher than in the previous case. Therefore, it is observed that this second case validates the results already obtained.

RTT [ms]	Caso 1	Caso 2	Caso 3	Caso 4	Caso 5
RTT<82					
82<RTT<86					
86<RTT<99					
99<RTT<105					
105<RTT<127					
RTT>127					

Figure 16: Summary of the THR=f(RTT) Function Behavior with PLR=0,37%

7.2. Scenario 2 - Considerations on the Behavior of the Function THR=f(RTT)

From a theoretical perspective, applying the Mathis equation and experimental laws linking distance to RTT values leads to results similar to those measured. In particular, the following aggregated values reflect a decreasing trend of THR as a function of RTT.

7.2.1. PLR=0,1%

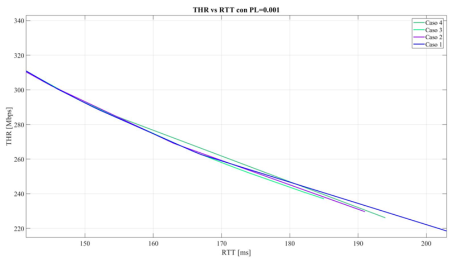

Figure 17: THR=f(RTT) scenario 2 and PLR=0,1%

From the comparison of the various curves for the different cases in Scenario 2 with a PLR of 0.1%, the following observations are made:

- $RTT < 167ms$: THR decreases as RTT increases, and in particular, the curve representing the simulation without ECC (case 1) is below all others, indicating that the result is largely as expected;
- $167ms < RTT < 172ms$: THR for the case without ECC (case 1) is above that for Milan (case 2), so in this range, the ECCs that ensure efficient performance are Rome (case 3) and Tor Vergata (case 4);
- $172ms < RTT < 180ms$: THR for case 1 is above that for cases 2 and 3, so the ECC that still ensures efficient performance is only Tor Vergata (case 4), which is the same site where the client is located;
- $RTT > 180ms$: The ECC no longer has any effect, and it is better for the client to query the main server directly.

In summary, the final situation for Scenario 2 with PLR = 0.1% is represented in the following figure:

RTT [ms]	Caso 1	Caso 2	Caso 3	Caso 4
RTT<167				
167<RTT<172				
172<RTT<180				
RTT>180				

Figure 18: Summary of the THR=f(RTT) Function Behavior with PLR=0,1%

7.2.2. PLR=0,37%

With similar considerations applied for a different PLR (=0.37%), the following observations are made:

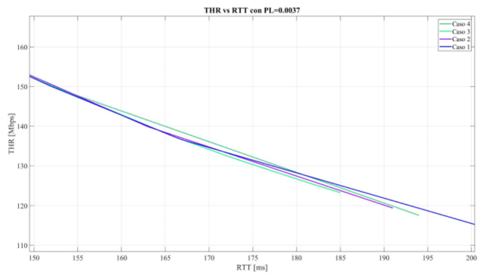

Figure 19: THR=f(RTT) scenario 2 and PLR=0,37%

The behavior of the functions is identical to the case with PLR = 0.1%, while at the same RTT, the THR value is approximately 90% higher than in the previous case. Therefore, this second case also validates the results previously obtained.

RTT [ms]	Caso 1	Caso 2	Caso 3	Caso 4
RTT<167				
167<RTT<172				
172<RTT<180				
RTT>180				

Figure 20: Summary of the THR=f(RTT) Function Behavior with PLR=0,37%

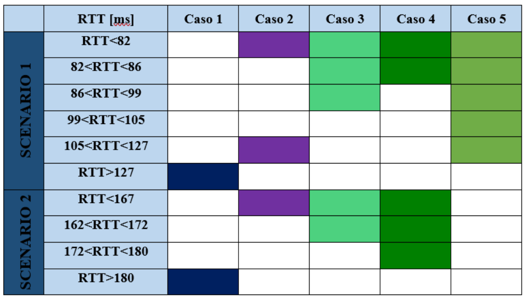

Figure 21: Summary of Scenarios

7.2.3. Comparison Between Scenarios 1 and 2

In summary, the behavior between the two scenarios is consistent. Indeed, for lower extreme values of RTT within the defined ranges for both scenarios, a server without ECC does not appear advantageous, whereas all other sites simulating the ECC function (Milan, Rome, Tor Vergata, and Villa Mondragone) are beneficial. Conversely, for higher extreme values of RTT, the site can be directly accessed by the client, as the values observed on other servers do not justify the use of ECC. In intermediate positions, however, as RTT increases, it becomes increasingly advantageous to use the server closest to the client.

Therefore, in conclusion, the experimental activity measuring RTT in different cases confirms and validates the results from the simulation activity based on the Mathis equation.

7.3. Percentage Variations in RTT

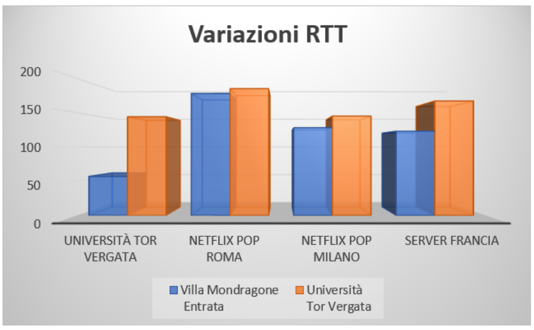

Figure 22: Variations RTT

Considering the percentage variations in RTT across different cases differentiated by server location, the results shown in the following figure are obtained. It is observed that the RTT variation is around 20%, except for the Tor Vergata site, where the variation is approximately 150%. The significant difference noted is certainly attributable to the quality of the LTE connection during the measurements. Given that the average value of the measurements is notably lower and consistent with theoretical predictions, it can be considered that the "anomalous" value might be regarded as a statistically insignificant outlier.

References

[1] L. Peterson, Computer Networks: A Systems Approach, Larry Peterson and Bruce Davie, 2019. (book).

[2] D. Połap, M. Woźniak, C. Napoli, E. Tramontana, Real-time cloud-based game management system via cuckoo search algorithm, International Journal of Electronics and Telecommunications 61 (2015) 333 – 338. doi:10.1515/eletel-2015-0043.

[3] C. Napoli, G. Pappalardo, E. Tramontana, Improving files availability for bittorrent using a diffusion model, in: Proceedings of the Workshop on Enabling Technologies: Infrastructure for Collaborative Enterprises, WETICE, 2014, p. 191 – 196. doi:10.1109/WETICE.2014.65.

[4] G. Ciccarella, F. Vatalaro, A. Vizzarri, Content delivery on ip network: Service providers and tv broadcasters business repositioning, in: 2019 3rd International Conference on Recent Advances in Signal Processing, Telecommunications & Computing (SigTelCom), IEEE, 2019, pp. 149–154.

[5] G. De Magistris, S. Russo, P. Roma, J. T. Starczewski, C. Napoli, An explainable fake news detector based on named entity recognition and stance classification applied to covid-19, Information (Switzerland) 13 (2022). doi:10.3390/info13030137.

[6] G. Capizzi, G. Lo Sciuto, C. Napoli, E. Tramontana, An advanced neural network based solution to enforce dispatch continuity in smart grids, Applied Soft Computing 62 (2018) 768–775.

[7] G. Lo Sciuto, G. Capizzi, R. Shikler, C. Napoli, Organic solar cells defects classification by using a new feature extraction algorithm and an ebnn with an innovative pruning algorithm, International Journal of Intelligent Systems 36 (2021) 2443–2464.

[8] G. Lo Sciuto, G. Susi, G. Cammarata, G. Capizzi, A spiking neural network-based model for anaerobic digestion process, in: 2016 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), IEEE, 2016, pp. 996–1003.

[9] I. E. Richardson, Video codec design: developing image and video compression systems, John Wiley & Sons, 2002.

[10] F. Fiani, S. Russo, C. Napoli, An advanced solution based on machine learning for remote emdr therapy, Technologies 11 (2023). doi:10.3390/technologies11060172.

[11] R. Giuliano, F. Mazzenga, E. Innocenti, A. Vizzarri, Integration of video and radio technologies for social distancing, IEEE Communications Magazine 59 (2021) 30–35.

[12] N. Brandizzi, A. Fanti, R. Gallotta, S. Russo, L. Iocchi, D. Nardi, C. Napoli, Unsupervised pose estimation by means of an innovative vision transformer, in: Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics), volume 13589 LNAI, 2023, p. 3 – 20. doi:10.1007/978-3-031-23480-4_1.

[13] F. Fiani, S. Russo, C. Napoli, A fully automatic visual attention estimation support system for a safer driving experience, in: CEUR Workshop Proceedings, volume 3695, 2023, p. 40 – 50.

[14] E. Iacobelli, S. Russo, C. Napoli, A machine learning based real-time application for engagement detection, in: CEUR Workshop Proceedings, volume 3695, 2023, p. 75 – 84.

[15] F. Fiani, V. Ponzi, S. Russo, Keeping eyes on the road: Understanding driver attention and its role in safe driving, in: CEUR Workshop Proceedings, volume 3695, 2023, p. 85 – 95.

[16] I. E. Tibermacine, A. Tibermacine, W. Guettala, C. Napoli, S. Russo, Enhancing sentiment analysis on seed-iv dataset with vision transformers: A comparative study, in: ACM International Conference Proceeding Series, 2023, p. 238 – 246. doi:10.1145/3638985.3639024.

[17] E. Iacobelli, V. Ponzi, S. Russo, C. Napoli, Eye-tracking system with low-end hardware: Development and evaluation, Information (Switzerland) 14 (2023). doi:10.3390/info14120644.

[18] J. Morgan, A simple explanation of'the internet of things', Retrieved November 20 (2014) 2015.

[19] G. Lo Sciuto, S. Russo, C. Napoli, A cloud-based flexible solution for psychometric tests validation, administration and evaluation, in: CEUR Workshop Proceedings, volume 2468, 2019, p. 16 – 21.

[20] S. I. Illari, S. Russo, R. Avanzato, C. Napoli, A cloud-oriented architecture for the remote assessment and follow-up of hospitalized patients, in: CEUR Workshop Proceedings, volume 2694, 2020, p. 29 – 35.

[21] F. Bonanno, G. Capizzi, G. L. Sciuto, C. Napoli, G. Pappalardo, E. Tramontana, A novel cloud-distributed toolbox for optimal energy dispatch management from renewables in igss by using wrnn predictors and gpu parallel solutions, in: 2014 International Symposium on Power Electronics, Electrical Drives, Automation and Motion, SPEEDAM 2014, 2014, p. 1077 – 1084. doi:10.1109/SPEEDAM.2014.6872127.

[22] D. Evans, The internet of things, How the Next Evolution of the Internet is Changing Everything, Whitepaper, Cisco Internet Business Solutions Group (IBSG) 1 (2011) 1–12.

[23] R. Giuliano, E. Innocenti, F. Mazzenga, A. Vizzarri, L. Di Nunzio, P. B. Divakarachari, I. Habib, Transformer neural network for throughput improvement in non-terrestrial networks, in: 2023 International Conference on Network, Multimedia and Information Technology (NMITCON), IEEE, 2023, pp. 1–6.

[24] V. Cisco, Cisco visual networking index: Forecast and trends, 2017–2022 white paper, Cisco Internet Report 17 (2019) 13.

[25] T. Ali-Yahiya, Understanding LTE and its Performance, Springer Science & Business Media, 2011.