Survey on Telesurgery Systems for Healthcare 4.0: A Comparative Analysis

Syeda Areesha Najam, Sana Fatima
CS 2023, Habib University

***Abstract*—Telesurgery is universally known as master-slave technology that has a great potential to provide healthcare surgical procedures in real-time to people living in distant or remote areas. It uses wireless channels and robots to carry out surgeries while there is no physical presence of surgeons in the operation theatre. The mentioned technology not only overcomes the shortage of surgeons or other healthcare experts, but it also eliminates any geographical barriers hence reducing the traveling costs and time. One of its key benefits is that it ensures the safety of the patient, as well as the surgeon, and performs remote surgeries with high accuracy and efficiency. This paper aims to provide a comparative analysis of four different telesurgery systems i.e. Tactile-Internet based, HaBiTs, AaYusH, and BATS.**

***Index Terms*—telesurgery, system models, LTE communication, blockchain, smart contract, healthcare 4.0, limitations, performance, Unmanned aerial vehicles, artificial intelligence**

I. Introduction

THe rapid technological advancements made in recent years are clearly a sign that soon robots will replace humans in almost all sectors. We can see how machines have bought ease into the life of humans, but the era where these robots will replace humans is not a far fetch idea. The use of robots does not only correspond to providing ease to humans but protecting them from hazardous task too. For instance, the Unimate which is the first industrially successful robot performed automated tasks dangerous to humans at a General Motors assembly plant in New Jersey [1]. Considering such advancements, people have recognized the importance of robots in recent COVID times, which have brought numerous risks, constraints to our society, and millions of life losses. More than 1,800 healthcare workers from 64 countries had died of COVID-19 as of July 2020, with the youngest being 20 and the oldest being 99 [2]. By the end of August 2020, in the United States, there were 1,079 fatal incidents of healthcare professionals [3]. Furthermore, during the 2003 outbreak of severe acute respiratory syndrome (SARS) in Canada, 51 % of the 438 cases, including three fatal cases, were healthcare personnel [4]. All of this emphasizes the importance of telesurgical robots on ground as they would be regulated by experts with practically no direct interaction between people, henceforth bringing down the risk of infection among the healthcare workers.

A. Motivation

The motivation behind this study is related to the problems faced during the COVID times. As mentioned above, the life of healthcare workers is at stake during such pandemics, where the bodily presence is very risky. One of the other key problems faced during the pandemic was the reachability. Since traveling was restricted, finding enough health experts (compared to the rapidly increasing number of patients) within a city was quite difficult. Telesurgical systems are the best solution to both problems as it provides accurate surgical methods while ensuring the safety of both, the healthcare expert as well as the patient. Alongside the benefits, telesurgical robots require advanced technologies and communication channels which we are lacking. Using the traditional systems for communication purposes does not allow a doctor to perform time-sensitive surgical procedures from a remote location, which ultimately means that the life of a patient is at stake. Therefore, we need an error-free, sensitive, and smart telesurgical system. According to the literature discussed in later sections, such systems do exist and thus we aim to come up with a detailed comparison of such systems which would not only provide with the work done in the mentioned field but will also give directions for future improvements and implementation in the said category.

B. Organization

The paper is organized such that Section I describes the importance of telesurgery systems and our motivation to work towards the mentioned domain. Section II briefly mentions the components of conventional telesurgical systems. Then, section III goes through related works in this domain, systematically. This section begins with a discussion of typical TS models and ends with highlights of modern TS systems. The urge and significance of system models have also been highlighted briefly here , directing the audience to the four latest TS systems focused in this survey paper. The following part (IV) provides a full description of each of the selected TS systems, with a focus on system modeling and proposed solutions to related issues. At next, Section V provides the comparative study for the chosen TS systems based on specific parameters. The paper is then concluded in section VI, alongside giving some points to be considered for future works.

II. Typical Telesurgery Systems

Telesurgery is a complex master-slave system, which is one of the most common modes of controlling surgeries.

This system consists of human-system interface (HSI) and robot or robotics arm. The HSI is controlled from master's end which is doctor/surgeon in our case and robot is placed at patient's end which is slave in our end. The robot listens to the patient and communicates it to the doctor through an efficiently integrated network channel. The robot then follows the commands given as input from doctor at the master end which comprises of haptic devices, a visual display, and audio devices (microphone and headphones). This is why this system is categorized as master-slave system.

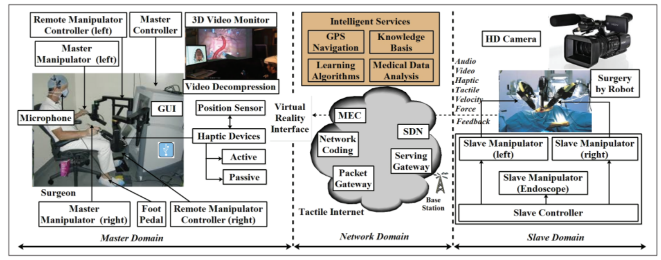

Fig. 1. System Model: TI (Tactile Internet) [9]

III. RELATED WORKS

Telesurgery systems are of great importance and so a lot of research has been done on developing advanced systems which are getting better with time. The first robotic surgery was carried out in the 1980s using the first surgical robot: PUMA 560 [5]. It was used for neurosurgical biopsies. Later, in 1988, a robot "PROBOT" [6] was used in order to make cuts in trans-urethral prostate surgery. During the 1990s, Integrated Surgical Solutions, along with IBM, developed another robot "ROBODOC" [7] using which they successfully prepared a certain cavity in the femur for hip replacement in humans. ROBODOC was the first surgical robot approved by the FDA [7]. The very first successful telesurgery was carried out in 2001 by Doctors Jacques Marescaux and Michel Gagner [8]. They removed the gallbladder while staying in New York City, whereas their patient was in France. Despite the successful surgery, the ROBODOC was not used later because of its high cost as well as the high latency time (155 ms) [8].

To overcome the problem of high latency, the Tactile-Internet-based telesurgery was introduced in 2019 [9]. It ensured ultra-low latency ($\leq$ 1ms) along with ultra-high reliability (99.9 percent). One of the major drawbacks of TI was that it wasn't found to be reliable in terms of data privacy while performing complex surgical procedures as security issues were not addressed. To overcome these limitations, another TS framework called HaBiTs [10] was introduced. It uses the concept of private blockchain in TS. It is more secure and thus has a high degree of confidentiality but using blockchain as storage medium is not found to be cost-effective.Beside this, it also has interoperability issues. Considering these aforementioned issues, Aayush [11] was proposed in 2020, which is a Ethereum smart contract (ESC) and IPFS-based TS system. This model overcame the issue of interoperability and also resulted in improved latency and reliability. Following the implementation of Aayush, the need of more transparent and self-manageable TS system was highlighted for more complex telesurgeries to be performed remotely on a collaborative level. The mentioned need led to the introduction of latest TS system, BATS in 2021 which is an AI and blockchain-enabled Unmanned Aerial Vehicle (UAV)-assisted tele surgery system. The fusion of AI in existed TS systems resulted in appreciable achievements. These intelligent systems are not only capable of assisting telesurgical procedures but also can predict the disease and treat the patients like wise,

In this survey paper, the later section will present the detailed discussion on modern telesurgical systems proposed in [9], [10], [11] and [12].

IV. FOCUSED TELESURGICAL SYSTEMS

This section focuses on the most recent TS systems proposed in [9], [10], [11], and [12]. Here, the detailed discussion on system models have been made, while considering performance evaluation and limitations also. This section provides some valuable insights into how improvements in conventional TS systems have been developed from 2019 to 2021.

A. Tactile-Internet-Based Telesurgery System for Healthcare 4.0

Telesurgery systems are a good way to overcome the shortage of surgeons, but at the same time risks the life of patients if there are communication delays. The traditional telesurgery systems had high communication delays and extra costs which limits the use of TS in a global environment. A good number of doctors have initiated TS from far-away locations, but the rate of success is unsatisfactory. This is because of the latency and reliability concerns namely 3G and 4G which have a latency of $\approx \leq$ 10 [9] and hence not suitable for surgeries in distant locations. From the year 2004 to 2019, telesurgical robots have led to approximately 144 deaths and 1391 injuries [9] in the US. The mentioned statistics highlight the importance of ultra-low latency and high reliability. A solution to the aforementioned problems was needed and so a new strategy was proposed in 2019 [9]

To overcome the key issues of telesurgery systems, that is low reliability and high latency, the authors [9] came up with the idea of incorporating 5G Tactile Internet into the existing TS. The Ultra-Reliable Low Latency Communications (URLCC) characteristics of Tactile-Internet (TI) provide low latency (¡ 1ms) as well as high reliability (99.999 percent) hence transmitting human skills over a wide range of networks [9]. It also ensures the realistic and flawless behavior of systems along with low battery consumption.

The basic layout of the proposed strategy consists of three key domains (Figure 1): master domain (controller), slave domain (controlled), and network domain (communication channel). The surgeon (or any other healthcare expert) is a part of the master domain that controls the robot (slave) via the human interface system (HSI). It passes certain instructions to the slave domain including how the task is to be performed, what position should be acquired, with how much force or velocity should the robotic arms move, etc. These commands are passed via the network domain which provides a communication path between the master and slave. The robot follows the commands and sends the feedback to the master in form of text, images, or audio-visual data. The mentioned steps keep on repeating until the surgery is completed. In this human-machine interaction, the robot carries out the surgery with the help of the commands given by the surgeon (master). The above-mentioned description gives a clear idea that the research focused more on optimizing the two main factors, i.e. high reliability and low latency. The aforementioned technique was implemented later and was found not to be reliable in terms of data privacy for complex surgical procedures.

B. HaBiTs: Blockchain-based Telesurgery Framework for Healthcare 4.0

As mentioned before, the TI was not authentic in terms of security and data privacy so a technique was needed which provides a solution to it. This framework was named HaBiTs [10]. It is based on private blockchain and a 4G/LTE communication pathway. It fulfills the need for providing a secure connection with the help of Smart Contracts (SCs). These SCs are basically a piece of code that is written in order to maintain trust between the connected parties and eliminates the need for a mediator for data sharing.

For telesurgery systems, the accuracy of data is crucial and so it should be stored in a way that makes it accessible only to the trusted participants. It should also be ensured that none of the participants could manipulate the data in any way. If we centralize the data in a cloud server, we cannot guarantee that the data is in its original form. This is because cloud server does not ensure security and is always at risk of privacy threats. Therefore, the data can easily be modified which would consequently lead to disruption in the surgical procedures. This is why there is a need for blockchain technology.

The blockchain consists of a chain of blocks that provides security while maintaining and transacting confidential data. It provides a great number of benefits over the traditional TS such as reducing maintenance costs, increase in data consistency, fast information sharing and timely access, disaster recovery, traceability, etc. It does not need any intermediary for data or contract sharing as the blockchain has SC as an agreement of trust. The blockchain framework only allows authorized users to access the data stored in it. This is done by using permissioned hyper-ledger fabric, which is basically an open-source blockchain model, where SC has different defined roles. The hyper-ledger fabric runs

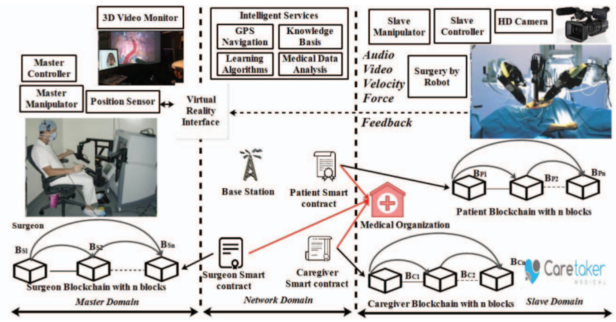

Fig. 2. System model for HaBiTs [10]

on an authentication mechanism that provides security to the TS system. Once the data is written in the block, no one can alter or manipulate it in any way. If anyone tries to make the slightest modifications, he/she can easily be tracked.

As shown in figure 2, the three basic components of HaBiTs are the same as TI, i.e. master, slave, and network domain. There is a slight change in the working of the components. The surgeon (which comes under the master domain) controls the robot (slave domain) by giving commands via the HSI. There is also a surgeon hyper-ledger fabric that can be heart, ortho, neuro, etc. The surgeon which is currently in control of the robot only has the access to his/her blockchain. The slave domain, that is the robot, executes the commands given by the surgeon. To protect the data, as well as the commands, given by either the caregiver or patients in response to the security attacks, Bc and Bp (blockchain structures), are used. The network domain works in the same way as it works in the TI, which is by providing a communication path between the master and the slave domain. Unlike TI, the data here is stored in the block and hence it is secure.

This means that the limitations of security have been overcome using the framework of HaBiTs. But, when this framework was implemented, it was found that although it offers a high degree of confidentiality, it is not a suitable framework as it has interoperability and latency issues. Moreover, the cost to use blockchain as a medium of storage is quite high.

C. AaYusH: A Smart Contract-based Telesurgery System for Healthcare 4.0

Later on, after the HabiTs telesurgery system, authors in [11] proposed another TS system in 2020 which leads to higher throughput and lower latency while ensuring secure, reliable, and efficient data storage. As mentioned above, Habits face interoperability issues too due to the usage of private BC. However, the TS systems mentioned above did not use distribute Interplanetary File System (IPFS) protocol to store the data in the blockchain environment. As per the authors in [11], till 2020, a more secure and distributed data storage–based TS system was required.

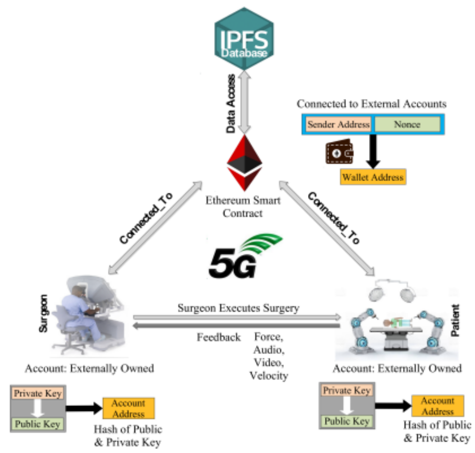

Fig. 3. System model for Aayush [11]

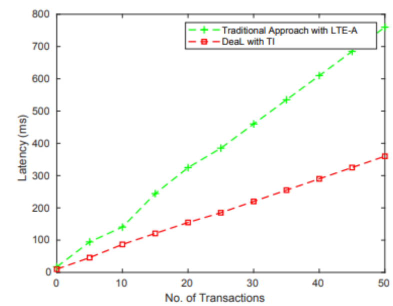

Fig. 4. Traditional Approach vs TI [11]

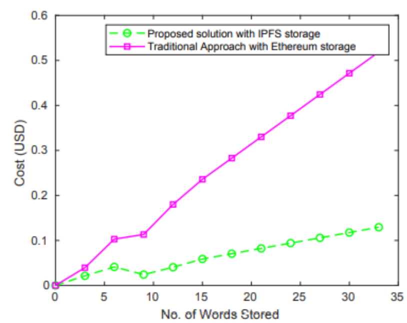

Fig. 5. Traditional Approach with Ethereum storage vs IPFS storage [11]

Considering the mentioned issues and lacks, in 2020, Aayush proposed the use of Ethereum smart contract (ESC) and IPFS-based TS system. In this proposed system, the security and privacy issues were resolved by making use of ESC, whereas the storage cost issue (due to the usage of BC as a storage medium in HabiTs) was solved by introducing distributed IPFS protocol. Unlike other TS systems, Aayush used a public blockchain i.e. Ethereum to overcome the interoperability issues between surgeon and patient. Note that as per this proposed system; patients and surgeons are connected through 5G enabled Tactile Internet that has enormous potential to deliver real-time ultra-responsive surgical services with high accuracy, remotely.

Fig.3 shows the model which consists of entities (surgeon and patient), IPFS protocol, wallets, and the potential communication links. The ESC (Ethereum smart contract) is responsible for building up a connection between mentioned entities. In this procedure, multiple surgeons across the world can collaborate in operating on a single patient which gives a sense of practicality and better results. The surgeons can initiate their TS procedure and pass on control commands to the robot through the human system interface over the 5G-enabled TI transmission channel. The commands coming from the surgeon end are stored in Ethereum BC, which is immutable. Coming to health records of patients which are critical, the IPFS database is used for storing them. These records can be used using the patient IPFS hash key. The reason behind introducing the use of IPFS is having high throughput and low latency in data access. Moreover, as mentioned before, the use of a 5G-enabled TI communication channel to connect the patients and surgeons achieves ¡1ms round trip latency which is ultra-low latency, and 99.999 % reliability which is ultra-high reliability. Besides this, interestingly, there is also a feedback system in Aayush that helps users to choose the doctor for surgeries as per scores (given by previous patients). The proposed model ensures security, privacy, and cost-effective data storage by using ESC with IPFS which allowed for the elimination of third-party organizations.

For the proposed system model, it is important to analyze the security vulnerabilities of ESC before its deployment. The proposed SC for Aayush and further security vulnerabilities were tested and analyzed using the MyThril open-source tool [13]. The mentioned tool detects security bugs using various analytical techniques such as console analysis, control flow checking, and taint analysis. It came out that no issues or bugs were detected as a result.

As per the discussion made above, we can see that mainly latency and data storage costs were focused. In [11], the performance evaluation based on mentioned parameters revealed that latency achieved by Aayush is quite low than traditional approaches due to use of 5G-enabled TI. Similarly, the use of distributed IPFS protocol in Aayush along ESC is free of cost, only cost for storing hash is involved. However, the cost for storing hash varies as per the method used for its storage in the blockchain. All of this can also be seen from the plots (Fig. 4 and Fig. 5). The reason behind achieving lower latency is the ultra-reliable low latency communications (URLLC) characteristic of Tactile Internet, which made optimization of latency and reliability possible but to a limited extent.

This model was able to overcome the issue of cost efficiency and interoperability but persisted with latency and reliability issues, resulting in difficulty in complex surgeries to be performed remotely. A team of doctors may face network issues for highly critical surgical procedures which cannot bear ever a millisecond of communication delay. Since there is no element of intelligence in this model, the patient and doctor are highly dependent on surgeons locally, which limits the sense of practicality.

D. BATS: A Blockchain and AI-empowered Drone-assisted Telesurgery System towards 6G

After the performance evaluation of Aayush in 2020, the need for more transparent, trustable, and self-manageable TS systems was highlighted for complex surgeries. The discussion made above for HabiTs and Aayush signifies that till 2020, the reliability and latency for modern TS systems were still an issue. Moreover, the emergency requirement of any medical equipment and medicine was another issue that was not considered till 2020. Note that, latest by the introduction of Aayush, the engineers were mainly working with blockchain and 5G communication channels.

Motivated by the mentioned issues, in 2021, an AI and blockchain-enabled Unmanned Aerial Vehicle (UAV)-assisted telesurgery system called BATS was proposed. Unlike HabiTs and Aayush, BATS used an ultra-responsive 6G communication channel that overcomes the latency and reliability issues of remote surgeries with the capability of high localization and sensing controls. The important characteristics of the 6G network are on-air latency i.e. less than 1 ms, higher reliability of 99.99999 %, and connection density of 10^7 devices/km^2. As per the authors in [12], the TS system using a 6G network channel allows health care professionals to collaborate over the wireless communication 6G channel by accessing the patient's data or past reports from the centralized cloud-based server. However, the use of centralized systems may result in the issue of conflicts between entities and may also require a third-party system to establish trust between entities involved in telesurgery.

The mentioned risk issue can partially be resolved with public blockchain technology i.e. Ethereum as per the proposed model (common in BATS and Aayush). It is to mention here that a blockchain is a chain of immutable blocks, which ensures that the data does not go under any modification once stored in the chain. The above-mentioned trust issue is also resolved via blockchain smart contract (ESC). The blockchain ESC maintains the trust between entities by self-enforcing and self-executing the agreement conditions and also maintains security. Thus, BC assists robots in interchanging services through network channels efficiently. As per the description mentioned above for BATS, besides the 6G network channel and blockchain, artificial intelligence is another major part of this model. The introduction of AI in telesurgical systems enabled these systems to predict the disease and the feasibility of the surgical procedure to be performed considering the patient's symptoms like blood pressure, heart rate, sugar level, etc. Also, the past medical records of patients stored in IPFS-based storage are used for predictions and analysis. As per this computation,

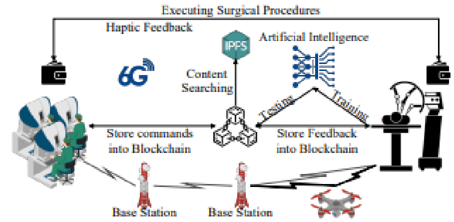

Fig. 6. System model for BATS [12]

the authors in [12] have claimed that the UAVs assist in getting the light-weight medical equipment and medicines in emergencies eliminate the road traffic circumstances and increase the survival rate, practically [14]. Interestingly, like Aayush, BATS also has a feedback module for both patients. This module helps patients in selecting surgeons based on feedback (ratings, scores, etc) from previous patients the surgeon has attended. This time, unlike Aayush, the feedback module in BATS also allows hospitals to select surgeons based on the predicted disease and connect them with patients.

Fig. 6 shows the system model for BATS which has already been discussed in detail above. However, we can see that BATS consists of four entities (surgeons, patients, hospitals, and UAV). The collaboration between these entities is possible via 6G network channels, IPFS, and intelligent robots. In order to classify the disease based on sensed symptoms, the model is trained using the XGBoost AI algorithm. In addition to the classification of diseases, a probability value is assigned which defines or indicates the criticality of the disease. In contrast, UAVs are used to assist in the provision of on-site medical equipment and medicines required during remote surgery. As per the system model in [12], the BATS is essentially based on five different layers that are a patient layer, analytics layer, analytics layer, blockchain layer, and surgeon layer.

Since AI is one of the major components of BATS, the accuracy matrix for the prediction and classification of disease is a limitation. Other than this security in data sensing was also not provided. We have discussed above that the public BC can only partially solve the issue of data insecurity and conflicts occurring due to the usage of a centralized cloud for storing data, thus this is also a limitation.

In [12], it is mentioned that the proposed system model for BATS was evaluated on predicted model comparison, network metric comparison, and blockchain performance evaluation. Despite the mentioned limitations, as per [12], it comes out that the BATS achieved extremely high throughput, low packet loss, and, low storage cost compared to other TS systems. Other than this, BATS achieved high prediction accuracy working on a disease symptoms database designed by Columbia University [15]. connector to table The description mentioned above for four TS systems, mainly focused on system model, performance evaluation

Year	Author	Objective	Latency	Reliability	Network Channel	Data storage technology	Limitations
2019	[9]	Proposed an ultra-reliable and low latency Tactile Internet-based telesurgery framework for healthcare 4.0	<1ms	High	5G enabled TI	Cloud server	• Security issues were not addressed. • Only for non-complex surgeries.
2019	[10]	HabiTs; a permissioned blockchain based TS system	<10ms	Low	4G enabled TI	A private BC	• High latency and low interoperability. • Not cost-effective.
2020	[11]	Aayush; A Smart Contract (SC) based Telesurgery	<1ms	High	5G enabled TI	A public blockchain i.e. Ethereum smart contract (ESC) and IPFS-based TS system (decentralized)	• Network issues for complex (collaborative) surgeries. • Not trustable for medical emergencies. • No intelligence
2021	[12]	BATS; AI and blockchain-enabled UAV assisted telesurgery system	<1ms	High	6G enabled TI	Same as Aayush TS system	• Security at data sensing is not provided • Limited intelligence accuracy

TABLE I
A COMPARATIVE STUDY

and limitations can be summarized in a table. Table 1 shows the comparative study on the aforementioned frameworks. Following parameters are considered for the comparative study,

1) Latency
2) Reliability
3) Blockchain
4) Intelligence
5) Implementation
6) Limitations

V. COMPARATIVE ANALYSIS

Now that we have discussed all four focused telesurgical systems, this section discusses the comparative analysis between HabiTs, Aayush, and BATS. One after another, we now have an idea that these TS systems have undergone different changes and introductions in terms of network channel and data storing techniques. The comparison between mentioned three TS systems will be based on network throughput, network latency, and simulated packet loss rate. This will assist us in identifying the need for suggested modifications in TS systems from 2019 to 2021, as well as determining the appreciable model features of the latest system proposed by 2021.

A. Network Throughput

The throughput value is an important indicator of network performance. It is the number of data packets that arrive at the destination IP per second. The comparison plot in [12], gives us some interesting and useful insights on deciding which model outflanks the others. From Fig. 7 it is clear that the proposed approach of using a 6G network channel in BATS beats other traditional models using 4G and 5G. It is to mention here that the network channel plays the main role in determining the throughput value. Other factors which affect network throughput are transmission medium, packet loss, and latency.

B. Network Latency

The discussion made above in sub-sections A, B, C, and D has made it clear that network latency is one of the most

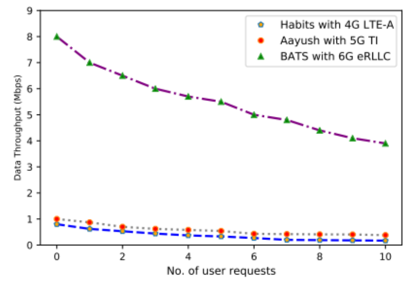

Fig. 7. Network throughput comparisons [12]

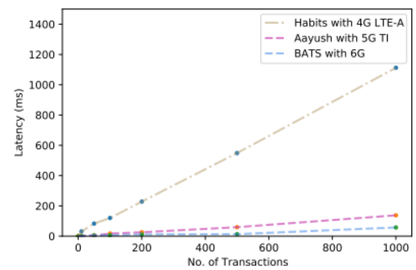

Fig. 8. Network latency comparisons [12]

critical parameters in communication that is responsible for the success or failure of remotely performed telesurgeries. The network latency shows how responsive the model is to the continuous data communication that takes place during telesurgery. Fig 8 summarizes that the BATS outperforms HabiTs and Aayush. We can see that the Aayush and BATS are very close to each other. It is because of the common data storing technique that is IPFS-based blockchain. However, the use of a 6G network channel in BATS over 5G in Aayush resulted in lower latency for BATS.

C. Simulated packet Loss rate

For telesurgical systems, other than latency and reliability, data loss is also one of the major concerns. By packet loss rate, we refer to the portion of data packets that couldn't be received by the destination. There can be multiple reasons behind this, like dropped packets, packets lost in transmission, and the wrong IP address of the destination. From Fig. 9, it can be determined that BATS has a low pace of data packet loss as compared to other TS systems. Note that the packet loss is examined with an increase in synchronous data traffic. The rising hype of 6G network channels in the industry is emphasizing the handling of voluminous data with a low rate of packet loss.

Following this comparative analysis, we can conclude that the BATS is a highly trustable system that outperforms other traditional TS systems in every aspect, including better throughput value, lowest latency, and low packet loss rate. We may determine from the description of focused telesurgical systems in section IV and the focused parameters in comparative analysis that the data storage technology and network channel were the main focus each year. The network

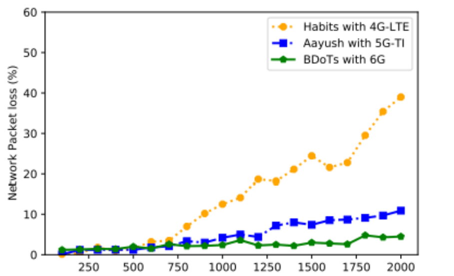

Fig. 9. Simulated packet loss rate comparisons [12]

channel determines the reliability percentage, latency, network packet loss, and transfer rate, whereas the data storage technique determines the security, transparency, and performance. These two domains must be further explored in order to achieve more robust explorations and practical implementations.

Despite appreciable and significant developments in the field of telesurgical robots, we do not have these around us. One of the key reasons for this is the social acceptability of robots, particularly in emergency medical situations. This topic is beyond the scope of this study.

VI. CONCLUSION

In this article, we have analyzed four different frameworks used in telesurgery systems based on different parameters like reliability, security, blockchain, and latency. Telesurgery systems are becoming a need in this era of exponential advancements in technology. As we have recently been through a pandemic, we do realize the importance of healthcare experts but at the same time treating patients with such contagious diseases is a threat to their lives. This is why we need robots to ensure the safety of patients as well as the experts. This will not only prepare us for future pandemics but would also overcome the problem of reachability of healthcare experts in rural areas. Successful and efficient telesurgery systems can also solve the problems of shortage of surgeons in developing and underdeveloped countries. Moreover, it will save time and cost of traveling from one location to another.

In the future, the above-mentioned telesurgery systems can be improved by further modifications as mentioned in [12] that TS smart contracts could be implemented with minimum latency and high efficiency which would result in telesurgery systems that has ideal characterstics.

REFERENCES

[1] Ranev, D. and Teixeira, J., 2020. History of Computer-Assisted Surgery. Surgical Clinics of North America, 100(2), pp.209-218.

[2] Medscape. 2020. In Memoriam: Healthcare Workers Who Have Died of COVID-19. [online] Available at: ¡https://www.medscape.com/viewarticle/927976¿ [Accessed 17 May 2022].

[3] the Guardian. 2022. Lost on the frontline: US healthcare workers who died fighting Covid-19. [online] Available at: ¡https://www.theguardian.com/us-news/ng-interactive/2020/aug/11/lost-on-the-frontline-covid-19-coronavirus-us-healthcare-workers-deaths-database¿ [Accessed 17 May 2022].

[4] MOORE, D., GAMAGE, B., BRYCE, E., COPES, R. and YASSI, A., 2005. Protecting health care workers from SARS and other respiratory pathogens: Organizational and individual factors that affect adherence to infection control guidelines. American Journal of Infection Control, 33(2), pp.88-96.

[5] Pdfs.semanticscholar.org. 2014. [online] Available at: ¡https://pdfs.semanticscholar.org/ccfb/a2ca41c316346f980e5eeed54bfaef 3b0c06.pdf¿ [Accessed 16 May 2022].

[6] Harris, S., Arambula-Cosio, F., Mei, Q., Hibberd, R., Davies, B., Wickham, J., Nathan, M. and Kundu, B., 1997. The Probot—an active robot for prostate resection. Proceedings of the Institution of Mechanical Engineers, Part H: Journal of Engineering in Medicine, 211(4), pp.317-325.

[7] Cross, M., Newman, J. and Carroll, K., 2014. Robotic-assisted total hip arthroplasty: a critical appraisal. Robotic Surgery: Research and Reviews, p.37.

[8] Clinic, T., The History of Robot-Assisted Surgery — The Surgical Clinic. [online] The Surgical Clinic. Available at: ¡https://thesurgicalclinics.com/history-of-robot-assisted-surgery/¿ [Accessed 16 May 2022].

[9] Gupta, R., Tanwar, S., Tyagi, S. and Kumar, N., 2019. Tactile-Internet-Based Telesurgery System for Healthcare 4.0: An Architecture, Research Challenges, and Future Directions. IEEE Network, 33(6), pp.22-29.

[10] Gupta, R., Tanwar, S., Tyagi, S., Kumar, N., Obaidat, M. and Sadoun, B., 2019. HaBiTs: Blockchain-based Telesurgery Framework for Healthcare 4.0. 2019 International Conference on Computer, Information and Telecommunication Systems (CITS),.

[11] Gupta, R., Shukla, A. and Tanwar, S., 2020. AaYusH: A Smart Contract-Based Telesurgery System for Healthcare 4.0. 2020 IEEE International Conference on Communications Workshops (ICC Workshops),.

[12] Gupta, R., Shukla, A. and Tanwar, S., 2021. BATS: A Blockchain and AI-Empowered Drone-Assisted Telesurgery System Towards 6G. IEEE Transactions on Network Science and Engineering, 8(4), pp.2958-2967.

[13] GitHub. 2022. GitHub - ConsenSys/mythril: Security analysis tool for EVM bytecode. Supports smart contracts built for Ethereum, Hedera, Quorum, Vechain, Roostock, Tron and other EVM-compatible blockchains.. [online] Available at: ¡https://github.com/ConsenSys/mythril¿ [Accessed 16 May 2022].

[14] Yang, B., Cao, X., Yuen, C. and Qian, L., 2021. Offloading Optimization in Edge Computing for Deep-Learning-Enabled Target Tracking by Internet of UAVs. IEEE Internet of Things Journal, 8(12), pp.9878-9893.

[15] People.dbmi.columbia.edu. 2022. Disease. [online] Available at: ¡https://people.dbmi.columbia.edu/ friedma/Projects/DiseaseSymptomKB /index.html¿ [Accessed 17 May 2022].