Optimisation of a Virtual Clinic System for Use in Austere Environments With Limited Internet Access

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***Abstract*—Remote, rural, and underserved areas, also known as austere environments, lack access to medical doctors. This reduces the quality of care available to patients in these areas. Virtual clinics are a telemedicine tool which can connect doctors in well-resourced areas to nurses and community health workers in austere areas to provide clinical support and medical advice. However, virtual clinics implemented in austere environments must overcome the challenge of limited internet availability, as these areas often have limited telecommunication infrastructure. Previously, an initial prototype of a virtual clinic system was developed to address some of the contextual concerns of austere environments within the South African context. The system consisted of a web application and integrated medical devices. The initial design of this system did not optimise the quality of service provided to the end user. This paper aims to provide an optimised virtual clinic prototype that improves quality of service during virtual clinic consultations through implementing a new system architecture. Additionally, the paper will validate this optimised system on 3G, 4G, and 5G mobile networks during mock virtual clinic consultations.**

The results show that the optimised virtual clinic system improved the quality of service compared to the initial prototype. Additionally, the measured parameters were agreeable with reported values in literature for telemedicine applications. These results indicate that the virtual clinic system may have been improved for austere environments where internet access may be limited, however, further testing within rural environments must be conducted to further validate these preliminary results.

***Index Terms*—telemedicine, virtual clinic, quality of service, web development, rural healthcare**

I. Introduction

Austere environments are defined as environments where resources, particularly health resources, are limited or unavailable [1]. Patients typically do not have access to doctors, leaving them to rely on nurses or community health workers. While these medical staff can provide many aspects of primary care, there are some limitations regarding medications and diagnoses which can only be made by a licensed medical doctor [2]. Lesser experienced medical staff may also require additional support from doctors regarding medical decision-making [3]. Ultimately, the lack of doctors in austere environments can lead to a decrease in quality of primary health care. Virtual clinics are a form of telemedicine that can be implemented to allow these clinical staff to connect to doctors in better-resourced areas [4]. The clinical staff can then receive assistance in diagnosing, prescribing, treating, and referring patients. The use of virtual clinics to provide care has shown to have a multitude of benefits for patients, medical staff, and healthcare systems. These include reduced wait times and cost of care, as well as improved quality of care and health autonomy for patients [5].

While the evidence supports implementation of virtual clinics, austere environments in Southern Africa often present challenges that existing virtual clinics do not address. These include access to power, digital literacy of users, language barriers, and access to stable telecommunication networks [6]. Virtual clinics which aim to be implemented in these environments must take into consideration and design for these challenges in order to be successful.

Internet access is a particular challenge for austere environments, as real-time communication is vital to providing medical assistance virtually. However, austere environments in Southern Africa often rely on mobile networks, and some only have access to 3G mobile networks [7]. With these limited bandwidth networks, applications must consider how data can be transmitted efficiently.

To address these challenges, a virtual clinic system was designed and developed using the user-centred design method. While similar work was conducted previously to understand the quality of service (QoS) provided by the virtual clinic system, the system did not have any design features which optimised data transmission efficiency. Rather, the virtual clinic application was developed and a baseline assessment was conducted on its performance on rural networks. The aim of this paper is to demonstrate how the previously developed initial prototype of a virtual clinic system was redesigned to optimise for performance on limited bandwidth telecommunication networks. The paper is structured as follows. The related works section discusses the developed virtual clinic system and how telemedicine systems can be evaluated for QoS. The methodology section discusses how the virtual clinic system prototype was designed to optimise for bandwidth limitations in austere environments. It then outlines the methods used to evaluate the performance of the optimised system on various telecommunication networks. The results section presents the measured QoS parameters collected during mock virtual clinic consultations and compares these results to the initial prototype performance and values outlined from literature. The discussion and conclusion section then provides commentary on what these results indicate for the system and how they will be taken forward.

II. Related Works

A. Virtual Clinic System

The developed virtual clinic system is targeted toward connecting doctors to primary health nurses and community health workers in austere environments. One side of the system is stationed at an existing clinic in an austere environment. The other side is stationed in a well-resourced area where the doctor is located. The nurse or community healthcare worker in the rural clinic uses the system to connect to a doctor, who can then advise on diagnoses, prescriptions, referrals, and other medical decisions. Medical devices including a vital sign monitor, otoscope, dermascope, stethoscope, electrocardiogram, and glucometer integrate with an online web-based application to provide additional real-time medical information to the remote doctor. Figure 1 shows the web application consultation platform, which includes real-time video conferencing. The doctor and nurse users can both record medical information regarding the patient such as measurements (heart rate, blood pressure, etc.) and exam notes.

The system was developed using user-centred design methods. This consisted of first conducting a situational analysis to understand healthcare and digital health environments in South Africa. This led to the development of system requirements, dictated by the needs of the users, that assisted development of the virtual clinic system. An initial prototype of the virtual clinic was developed, and this prototype was assessed over mobile networks in lab [8] and field [9] settings, as well as through usability tests with end-users (doctors and nurses). An overview of the entire system design, including medical device selection and integration, can be found in previous publications [10].

B. Quality of Service in Telemedicine

Quality of service (QoS) as defined by the International Telecommunication Union is “the collective effect of performance which determines the degree of satisfaction of a user of the service” [11]. It can be quantified through parameters such as delay, throughput, jitter, and packet loss. In telemedicine applications, QoS is important in order to ensure that medical information is transmitted accurately and effectively [12]. Literature provides guidelines for telemedicine QoS, demonstrated in Table I, which can be used by developers during design and validation of telemedicine solutions. The reported values vary between sources but can be characterized as: 100-400ms delay, 4kbps-10Mbps throughput, 50ms jitter, 1-5% packet loss,

TABLE I
Reported QoS Parameters for Telemedicine

Paper	Type	Delay (ms)	Throughput (kbps)	Jitter (ms)	Packet Loss (%)
Chandy, et al [13]	Voice	150-400	4-5		$\leq$ 3
Chandy, et al [13]	Video	150-400	768-10Mbps		$\leq$ 1
Hassan & Li [14]	Audio	150-400	4-26		$\leq$ 3
Hassan & Li [14]	Video	150-400	32-384		$\leq$ 1
Putra, et al [15]		≤ 100	>323	$\leq$ 50	$\leq$ 5
Kaliwo, et al [16]	Video		$\leq 10Mbps$		

III. Methodology

A. Optimisation of the Virtual Clinic System

The developed virtual clinic system had four main challenges that required redesign. The first challenge was the QoS measured during field evaluations [9]. While mock consultations could be completed over 3G networks in rural areas, the QoS parameters collected during these consultations were not within the reported values stated in literature. Particularly, jitter and packet loss were high when conducting video consultations over mobile networks. This could have been a result of the system design (depicted in Figure 2) which utilised Zoom for video consultations. Zoom transmits video and audio streams via the Zoom server, which could have resulted in increased latency during peak traffic times.

Secondly, during virtual clinic consultations redundant data was being sent and received from the server. Within the consultation platform, the user has the ability to manually enter measurements into the system such as blood pressure, blood glucose, weight, etc., as well as exam notes and prescriptions. This is shown at the bottom of Figure 1. In the initial prototype, this information was automatically sent back to the server once every few seconds to save the information to the patient’s record. Once saved to the database, this information would then update on the other client’s side. Often, the data being sent to the server was unchanged between each delivery. This caused unnecessary data transmission between client and server, and required additional processing costs on both ends of the application.

The third issue with the system was the restrictions that using a commercial application such as Zoom introduced. In

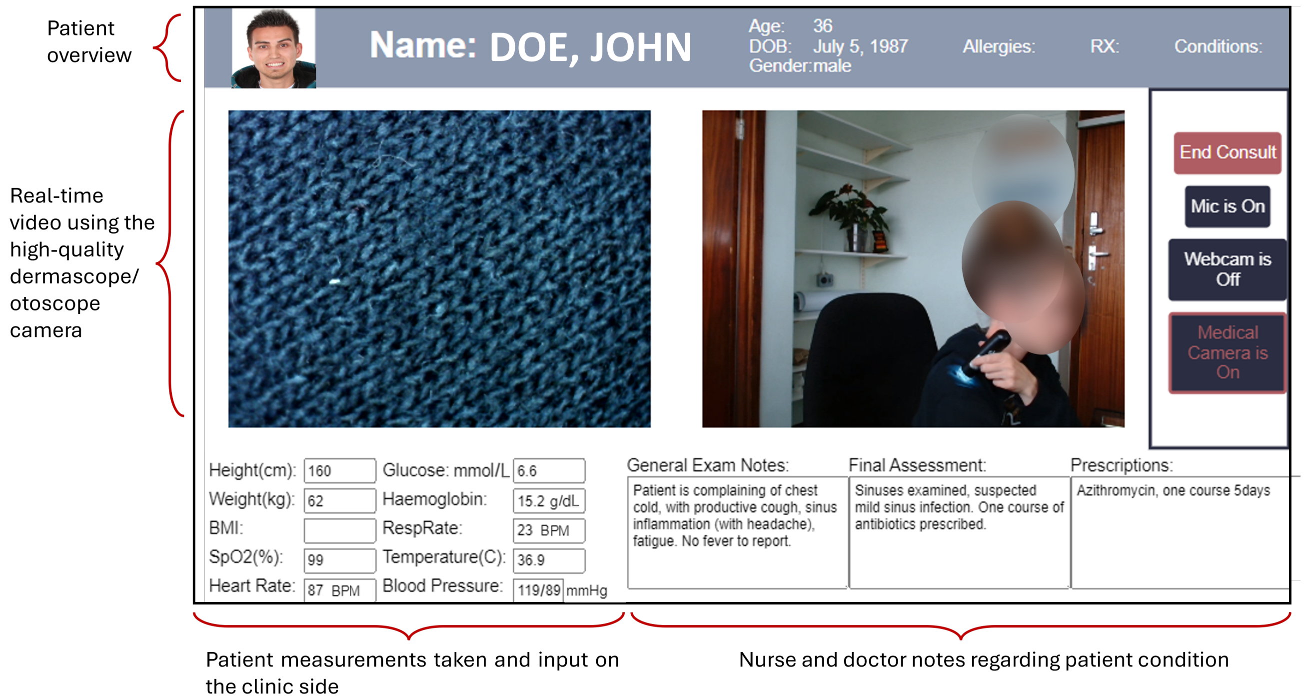

Fig. 1. An overview of the virtual clinic consultation platform during a mock virtual clinic consultation, using the dermascope medical camera to transmit a high quality video stream.

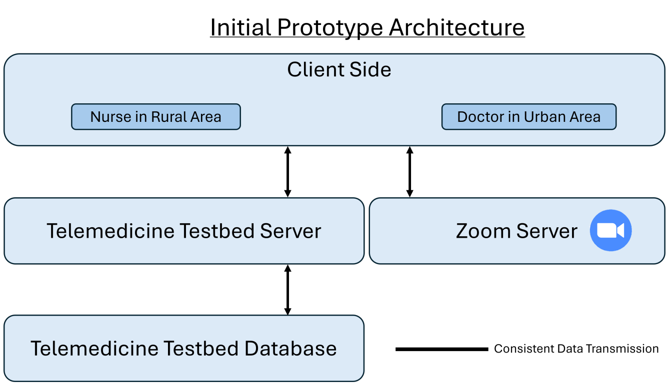

Fig. 2. Architecture of the initial virtual clinic prototype showing consistent data transmission between the clients and servers.

integrating the Zoom software development kit (SDK), there was very little customisation of the way that the video feeds were displayed and what the user interface looked like. While the Zoom SDK did allow for additional medical cameras to be connected as various camera inputs, these were labelled with generic names (i.e. USB camera). This made it difficult for users, particularly those with limited digital literacy, to identify and select the medical camera. Utilising Zoom also required the user to have a Zoom account, and possibly a paid subscription to access additional features such as video calls over 40 minutes.

Finally, there was a challenge regarding the transmission and storage of sensitive patient data over Zoom. When using the Zoom SDK for video conferencing, the real-time video data and any recorded sessions were subject to the data security provided by Zoom.

To optimise the virtual clinic web application, the consultation system architecture was changed as described in Figure 3. The Zoom SDK was replaced with WebRTC, an open-source application programming interface (API) which can be used in browser-based web applications to host video conferences [17]. WebRTC allows for a direct peer-to-peer (P2P) connection to be established between clients. This allows for not only video and audio stream transmission, but also data channels for transmitting text data. The P2P connection is established through usage of a signaling server, which is contacted upon initiation of the connection. In this application, Google Firebase was used as the signaling server due to its advantages over traditional methods such as WebSockets [18]. The signaling server allows the peers to exchange information that then establishes the P2P connection. Once the connection is established, communication between the clients and signaling server is no longer needed, and instead communications go directly between the two clients.

The improved system architecture aimed to address the above stated challenges. By implementing WebRTC, the architecture aimed to improve the QoS during video consultations, as WebRTC has shown to have improved video quality and reduced delay during bandwidth fluctuations in comparison to Zoom [19]. In addition, the optimised prototype utilised WebRTC data channels to transmit text data directly between

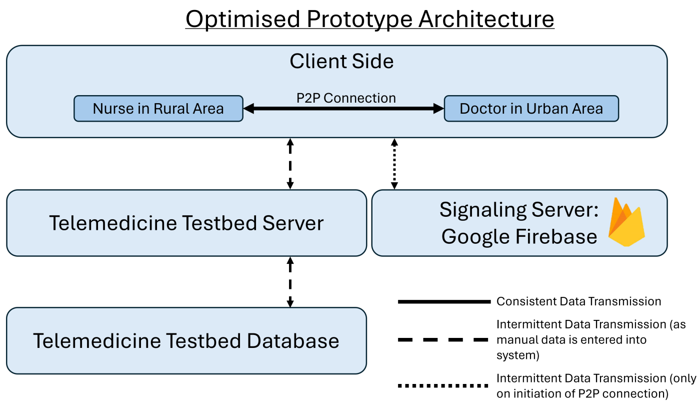

Fig. 3. Architecture of the optimised virtual clinic system demonstrating the consistent peer-to-peer connection for video conferencing and intermittent data transmissions between client and servers.

clients. These transmissions would only occur when the user changed patient data on the system, reducing redundancy from the previous prototype which sent and received text data every few seconds. This aimed to reduce the total amount of data being sent, as well as the frequency of data being sent, while still ensuring that the client received updated information. Furthermore, the additional customisation that WebRTC provided over Zoom allowed for several features of the virtual clinic web application to be improved [20]. The medical camera devices were displayed clearly on buttons on the user interface, which were labelled “Medical Camera.” This is demonstrated on the right-hand side of the image in Figure 1. The WebRTC application was also customised to prioritize video streams from the medical cameras over other streams, to ensure continued high-quality in medical data transmission. The authentication for video calls was further customised to fit the existing system authentication methods. This is compared to the previous prototype, which required that the user authenticate using Zoom before starting the consultation. Images and recordings of the sessions could then be saved and stored to the system database, allowing for additional security to be implemented to protect sensitive patient data.

B. Quality of Service Validation

To assess QoS of the virtual clinic application, virtual clinic consultations were hosted over various network connections. This involved conducting 10-minute mock health consultations over 3G, 4G, and 5G Vodacom and MTN mobile networks in Cape Town, South Africa. Web cameras and medical cameras were used to transmit video streams during each consultation. In addition, mock medical information was manually entered to mimic a true health consultation. Only mock information was used, and no real patient data was transmitted. The client acting as the doctor was connected to a stable fibre Ethernet connection during all consultations. The doctor client connected to the virtual

TABLE II
SUMMARY OF THE CONSULTATIONS CONDUCTED

Consultation No.	Network	Provider
1-3	Fibre Ethernet	Eduroam
4-6	5G	Vodacom
7-9	5G	MTN
10-12	4G	Vodacom
13-15	4G	MTN
16-18	3G	Vodacom
19-21	3G	MTN

clinic web application via Chrome web browser on an Asus computer. The client acting as the nurse was connected to the various mobile networks outlined above via a mobile phone hotspot. The nurse client accessed the virtual clinic application via Chrome web browser on an HP laptop, and the mobile phone hotspot used was a Samsung Galaxy A54. Consultations were conducted over the course of three days, during afternoon working hours from 13h00 - 16h00. These times were selected to maintain consistency of network traffic between consultations.

Throughput, delay, jitter, and packet loss were collected throughout each consultation. Three consultations were conducted per network connection, totalling 21 consultations as outlined in Table II. Data was analysed through the following methods. Raw QoS data was extracted using the WebRTC Internal tool [21]. The data through this tool was reported only when QoS values changed, leading to inconsistent time intervals between data points. Therefore, the data was normalised to reflect regular time intervals of one second using MATLAB. Once the data was normalised, QoS values were averaged for all consultations conducted over fibre (consultations 1-3 in Table II). The maximum value and minimum value across all fibre consultations for each QoS parameter were then extracted. This process was repeated for the following groups of consultations: those conducted over 5G (consultations 4-9 in Table II); those conducted over 4G (consultations 10-15 in Table II); and those conducted over 3G (consultations 16-21 in Table II). This data was then compared to the reported values for telemedicine QoS and previously collected data from the initial virtual clinic prototype.

IV. Results

QoS data was collected and analysed for the 21 mock consultations conducted over fibre and mobile network connections. Table III shows the average QoS results from the consultations conducted with the newly optimised prototype, which used WebRTC, in comparison to the initial prototype, which used Zoom. The fibre network connections compared between each prototype were the same fibre Ethernet connection in Cape Town, South Africa. The mobile network connections tested with both prototypes were measured over Vodacom and MTN 4G and 3G networks. However, the initial prototype testing over 4G and 3G networks was conducted in a rural environment, while the optimised prototype testing

TABLE III
AVERAGE QoS VALUES DURING VIRTUAL CLINIC CONSULTATIONS

Application Version	Network	Delay (ms)	Audio Jitter (ms)	Video Jitter (ms)	Audio Packet Loss (%)	Video Packet Loss (%)
New	Fibre	1.136	0.00280	0.01653	0.521	0.5695
Prototype	5G	2.248	0.00969	0.02135	1.422	1.065
(WebRTC)	4G	2.871	0.01416	0.01872	1.636	1.236
	3G	9.101	0.01906	0.02849	2.665	1.942
Initial	Fibre	167.8		2.500		0.2800
Prototype	4G	268.2		51.21		61.34
(Zoom)	3G	211.5		71.40		59.57

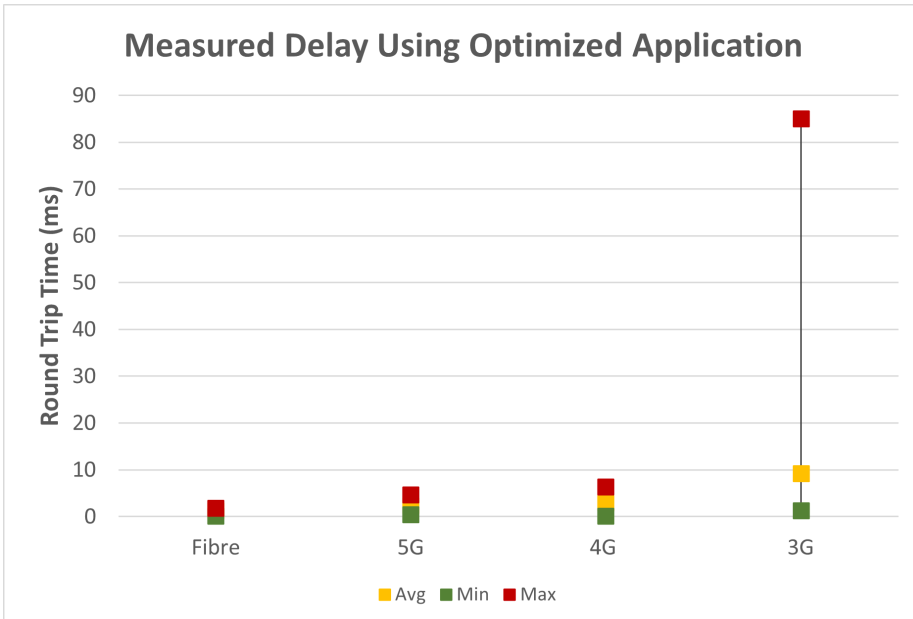

Fig. 4. Maximum, minimum, and average measured delay from mock virtual clinic consultations conducted over fibre and mobile networks.

was conducted in Cape Town, South Africa.

The average throughput for the application over the course of all consultations was 1.625 Mbps. This included video, audio, and text data being sent through the P2P connection. This value is within the reported values from literature. Although throughput from the initial prototype consultations was not collected, Zoom reports in their system requirements that a bandwidth of 600kpbs - 3.8Mbps is needed for 1:1 video calling (depending on the video quality used) [22]. The throughput of the optimised virtual clinic application is within these bounds, indicating that the amount of data being sent using the optimised application is similar to that of a Zoom video call.

The measured delay during consultations is reported in Figure 4. Maximum delay was reported at 85ms, which was seen during consultation 19 over the 3G MTN network. All reported delay values were below the 100-450ms reported values from literature. Using the direct comparison between the initial and optimised application consultations over the fibre network, delay was reduced in the optimised application. This could be a result of the architecture change, as data does not have to travel as far to move between clients. Although the mobile network tests between the initial and optimised prototype are not directly comparable as they were conducted in different geographic locations, it is demonstrated that delay was also reduced in the optimised application.

Jitter values for both audio and video during consultations are reported in Figure 5. The highest reported audio jitter was during consultation 15 on the 4G MTN network, and the highest reported video jitter was during consultation 19 over the 3G MTN network. All reported jitter values were below the reported value of 50ms. In comparing the measured jitter of video streams over the fibre network connection, it is demonstrated that jitter was reduced between the initial and optimised prototypes. In comparing the video jitter over mobile networks, the jitter was reduced. This may also be attributed to the architecture changes of the system.

Audio and video packet loss during consultations is reported in Figure 5. Packet loss was the highest at 4.94% during consultation 19 over the 3G MTN network. All values for packet loss were within the reported values of 1-5% packet loss. In comparing video packet loss between the initial and optimised prototype over the fibre network connection, video packet loss was higher in the optimised prototype by 0.2895% but both measurements were within the same order of magnitude. When comparing the video packet loss between

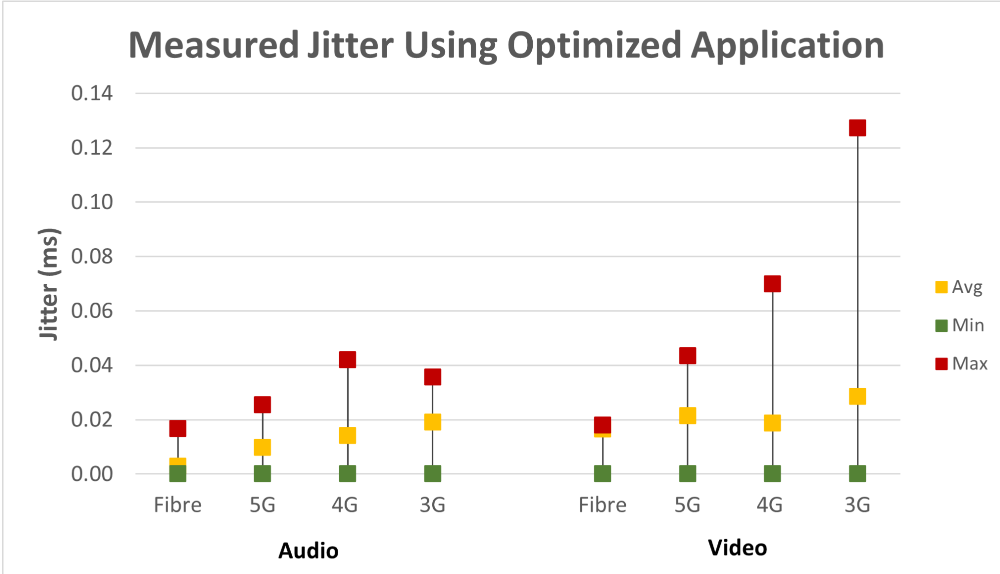

Fig. 5. Maximum, minimum, and average measured jitter from mock virtual clinic consultations conducted over fibre and mobile networks.

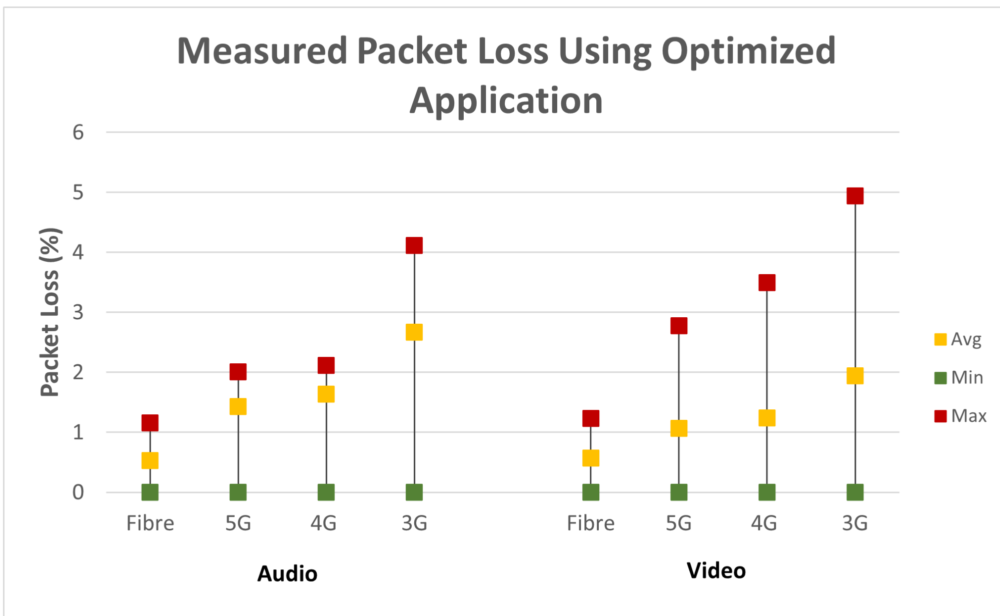

Fig. 6. Maximum, minimum, and average measured packet loss from mock virtual clinic consultations conducted over fibre and mobile networks.

the initial and optimised prototypes over the mobile network, packet loss was reduced by one order of magnitude.

V. Discussion and Conclusion

The results indicate that the optimised prototype application for the virtual clinic system may provide better QoS for end-users than the previous system. Delay is reduced within the new application, which supports the indication that WebRTC reduces latency in comparison to Zoom. Jitter and packet loss are also reduced, and these values are now within the reported values for telemedicine services. This data provides a preliminary validation for the optimisation of the virtual clinic system.

One exception to the improvements from the initial prototype to the new prototype is the video packet loss on fibre connection, which was slightly lower when using Zoom compared to WebRTC. This may be due to the nature of the algorithms used for optimisation on either system. Zoom optimisation algorithms may operate better in higher-bandwidth network connections compared to low-bandwidth. This may also support why there was a drastic difference in packet loss between low-bandwidth mobile network connections and the fibre control test when using the initial prototype. Because the virtual clinic application did not adapt these optimisation algorithms from either service, this further supports the usage of WebRTC for low-bandwidth scenarios because of it's stable performance on limited and non-limited bandwidth networks.

The limitations of this study include that comparison data from the initial prototype consultations conducted over mobile networks were collected in a rural environment, while the data collected from consultations over mobile networks for the optimised prototype were collected in Cape Town, an urban environment. The telecommunication infrastructure may be more advanced in Cape Town than in the rural environment, which could lead to results that differ between the two environments. Further work will be undertaken to evaluate the performance of the optimised system over rural mobile networks, in order to conduct a true comparison of system performance between the previous version and the new version. Additionally, the networks used to evaluate the system were public networks, and therefore certain conditions could not be controlled for. Attempts to mitigate variability in network quality included conducting tests during the same period of time over the course of the three-day experiment. Despite these limitations, this work provides a necessary first step in improving the virtual clinic system and evaluating its effectiveness before conducting a field evaluation. The results from this study provide promise that the virtual clinic system is ready for further evaluation.

In addition, further work must be done to ensure that the clinic is designed for the various other considerations that austere environments present, including limited digital literacy of users, inconsistent power, and non-English speaking users. Previous work comments on the efforts done to design the system according to the user needs. Ultimately, the virtual clinic system should be technically validated based on these user requirements. Once this is complete, the system may then be implemented in the field with patients for long-term evaluation. By continuing virtual clinic development, the system can be improved to provide a viable alternative for patients requiring primary care in austere environments.

Acknowledgment

This document has been produced with the financial assistance of the European Union (EU) and co-funding from the Carnegie Foundation of New York (Grant no. DCI-PANAF/2020/420-028), through the African Research Initiative for Scientific Excellence (ARISE), pilot programme. ARISE is implemented by the African Academy of Sciences (AAS) with support from the European Commission and the African Union Commission (EUC). The statements made and views expressed are solely the responsibility of the authors. The research is also supported by Telkom South Africa, via the Telkom Centre of Excellence (CoE) in Broadband Networks at the University of Cape Town.

References

[1] S. Lord and J. Lee. "Critical Care in the Austere Environment." *Critical Care Clinics*, vol. 40, no. 3, pp. 451-462, 2024. https://doi.org/10.1016/j.ccc.2024.03.006

[2] N. Geyer and M. Cur. "Legal Limitations for Nurse Prescribers in Primary Health Care." Democratic Nursing Organisation of South Africa, *Curationis*, vol. 21, no. 4, pp. 28-33, 1998. Available at: https://curationis.org.za/index.php/curationis/article/download/668/606 : :text=Each%20license%20will%20be%20accompanied,schedule%201 %20%2D6%20EDL%20drugs.

[3] C.G. Kemp, N. Mntambo, B.J. Weiner, et al. "Pushing the Bench: A Mixed Methods Study of Barriers to and Facilitators of Identification and Referral into Depression Care by Professional Nurses in KwaZulu-Natal, South Africa." *SSM Mental Health*, vol. 1, e100009, 2021. https://doi.org/10.1016/j.ssmmh.2021.100009

[4] V. Vas, S. North, T. Rua, et al. "Delivering Outpatient Virtual Clinics During the COVID-19 Pandemic: Early Evaluation of Clinicians' Experiences. *BMJ Open Qual*, vol 11, pp. e001313, 2022. https://doi.org/10.1136/bmjoq-2020-001313

[5] J.T. Atmojo, W.T. Sudaryanto, A. Widiyanto, et al. "Telemedicine, Cost Effectiveness, and Patients Satisfaction: A Systematic Review." *J Health Policy Manage*, vol. 5, pp. 103-107, 2020. https://thejhpm.com/index.php/thejhpm/article/view/172

[6] J.E. Dodoo, H. Al-Samarraie, and A. Alsswey. "The Development of Telemedicine Programs in Sub-Saharan Africa: Progress and Associated Challenges." *Health Technol (Berl), vol. 12, pp. 33-46, 2022. https://doi.org/10.1007/s12553-021-00626-7*

[7] Global System for Mobile Communications Association (GSMA). "The State of Mobile Internet Connectivity Report 2023." GSMA, 2023 [Online]. Available at: https://www.gsma.com/r/somic/

[8] A. Blocker, A. Oladokun, J. Mwangama, M.I. Datay, and B. Malila. "Evaluating the Capability of 3G, 4G, and 5G Networks in Delivering a Virtual Clinic Solution." In: *Proceedings of IEEE AFRICON 2023*, Nairobi, Kenya, 2023. http://dx.doi.org/10.1109/AFRICON55910.2023.10293519

[9] A. Blocker, M.I. Datay, J Mwangama, and B. Malila. "Evaluating network Performance of a Virtual Clinic System in Rural Sub-Saharan Africa." In: *Proceedings of Southern Africa Telecommunication Networks and Applications Conference (SATNAC)*, Drakensberg, South Africa, 2023 Aug 27-29, pp.151–156. Available from: https://www.satnac.org.za/proceedings

[10] A. Blocker, M.I. Datay, J. Mwangama, B. Malila. "Development of a Telemedicine Virtual Clinic System for Remote, Rural, and Underserved Areas Using User-Centered Design Methods." *Digit Health*, 2024. https://doi.org/10.1177%2F20552076241256752

[11] International Telecommunication Union. "Terms and Definitions Related to Quality of Service and Network Performance Including Dependability." *ITU-T Recommendation*, 1994. Available at: http://www.itu.int/rec/T-REC-E.800/en

[12] I. de la Torre Diez, S. G. Alonso, S. Hamrioui, et al. "Systematic Review About QoS and QoE in Telemedicine and eHealth Services and Applications." *J Med Sys*, vol. 42, no. 182, 2018. https://doi.org/10.1007/s10916-018-1040-4

[13] D. Chandy, A. Soto, M Huerta, et al. "Evaluation of QoS in Data Mobile Network for Vital Signs Transmission." *2016 IEEE Healthcare Innovation Point-Of-Care Technollogies Conference (HI-POCT)*, 2016 Nov. http://dx.doi.org/10.1109/HIC.2016.7797718

[14] S. A. Hassan and Y. Li. "Medical Quality-of-Service Optimization in Wireless Telemedicine System Using Optimal Smoothing Algorithm." *E-Health Telecommunication Systems and Networks*, vol. 2, pp. 1-8, 2013. http://dx.doi.org/10.4236/etsn.2013.21001

[15] E.H. Putra, E. Supriyanto, J. Din, and M.H. Satria. "Cross Layer Design of IEEE 802.11e Enhanced Distributed Channel Access Wireless Network for Telemedicine Application." *Innovative Technologies in Intelligent Systems and Industrial Applications (CITISIA) 2009*, 2009 Aug. http://dx.doi.org/10.1109/CITISIA.2009.5224228

[16] A. Kaliwo, T. Mutsvangwa, J. Mwangama, and B. Malila. "Identification, Characterisation and Classification of Digital Health Traffic Using the Shannon Entropy Theorem: Towards Intelligent Network Slicing on 5G+ Health Networks." In: *Proceedings of Southern Africa Telecommunication Networks and Applications Conference (SATNAC)*, Drakensberg, South Africa, 2021.

[17] "WebRTC 1.0: Real-Time Communication Between Browsers." *World Wide Web Consortium*, 2018 Sep 27. Available at: https://www.w3.org/TR/webrtc/

[18] C. Tucker. "Replacing WebSockets with the Auto-Scaling Firebase Database." *Medium*, [Online] 1 Oct 2017. Available at: https://medium.com/@christian.tucker68732/replacing-websockets-with-the-auto-scaling-firebase-database-b451531acea9

[19] E. Ivov. "WebRTC vs. Zoom - A Simple Congestion Test." *Jitsi*, [Online], 2018 Oct 1. Available at: https://jitsi.org/blog/a-simple-congestion-test-for-zoom/

[20] J Wills. "The Battle of New Industry Standards: Is WebRTC Making Zoom Redundant?" *DZone* [Online], 2022 Apr 28. Available at: https://dzone.com/articles/is-webrtc-making-zoom-redundant

[21] D. Ammar, K. de Moor, M. Fiedler, and M. Xie. "Video QoE Killer and Performance Statistics in WebRTC-Based Video Communication." *2016 IEEE Sixth International Conference on Communications and Electronics (ICCE)*, 2016 July. http://dx.doi.org/10.1109/CCE.2016.7562675

[22] Zoom. "Zoom System Requirements: Zoom Web App and Web Client." Zoom [Online], 2024 Feb 1. Available at https://support.zoom.com/hc/en/article?id=zmkb&sysparmarticle=KB0058323