System Integration for Medical Data Dissemination and Multimedia Communication in the Implementation of Tele-ECG and Teleconsultation

A. A. N. Ananda Kusuma[1], Tahar Agastani[2], Christian W. Purnaadi [3], Triawan Nugroho[4]
[1,2,3,4]Pusat Teknologi Elektronika (PTE), Badan Pengkajian dan Penerapan Teknologi (BPPT)
[1,2,3,4]Gedung Teknologi 3, Lt 2, Kawasan Puspiptek Serpong, Tangerang Selatan 15314, Indonesia
email: [1]ngurah.ananda@bppt.go.id, [2]tahar.agastani@bppt.go.id, [3] christian.wisnu@bppt.go.id, [4]triawan.nugroho@bppt.go.id

ARTICLE INFORMATION

Received 22 October 2019
Revised 1 June 2020
Accepted 3 June 2020

Keywords:
ECG data format
Telemedicine cart/workstation
TCP-Starvation / UDP-Dominance
Performance Test
Open-source

ABSTRACT

One of the options to extend medical services coverage is deploying a telemedicine system, where medical personnel make use of Information and Communication Technology (ICT) to overcome distance and time constraints. The implementation of telemedicine systems in Indonesia faces challenges posed by the lack of ICT infrastructure availability, such as communication networks, data centres, and other computing resources. To deal with these challenges, a telemedicine innovation needs to produce a modular and flexible system that is adaptive to medical services needed and the available ICT infrastructure. This paper presents research and development of a telemedicine system prototype for tele-electrocardiography (tele-ECG) and teleconsultation. The contributions offered are integrating system from various open-source modules and the system operational feasibility based on its function and performance. The research is conducted on a testbed which represents various components involved in the telemedicine system operation. Experiments are carried out to assess the system functionality and observe whether tele-ECG and teleconsultation reach their expected performance. Experiment results show that the system works properly and recommend several multimedia communication modes to achieve the target quality based on the available network bandwidth.

1. Introduction

Telemedicine is a system that utilizes the Information and Communication Technology (ICT) to provide health services that are no longer limited by physical distance and location (Norris, 2001). Telemedicine can be tailored to be suitable to the specified medical science domain, for example: tele-ECG for tele-Cardiology, tele-Radiology, tele-Dermatology, and the like. As for the types of activities carried out, telemedicine can be implemented for teleconsultation, tele-Diagnose, tele-Education, tele-Homecare, tele-Surgery, and so forth.

Telemedicine offers several advantages, for example: ease of accessing specialist doctors in referral centers, easy remote monitoring of patients' conditions, faster handling before patients are brought to the hospital, assisting delivery of health services in remote areas or disaster-affected locations, also providing advanced medical education and training or disseminating medical-related information to the community. Telemedicine system can reduce overcrowding in referral centers that are prone to the spread of infectious diseases. Interestingly, telemedicine system has been brought up to discussion during the Corona Virus Disease 2019 (COVID-19) pandemic because it could prevent doctors, especially specialists, from being exposed to patients who might not show symptoms of COVID-19, and also reduce people's mobility to break the chain of virus spread. The COVID-19 outbreak is a momentum to implement telemedicine services more proactively. Long-term benefits are offered, thus organizers must continue making improvements to confront the various challenges they face (Smith et al., 2020).

The various mentioned advantages of telemedicine are useful for health services in Indonesia. Some notes on Indonesia's conditions that encourage the use of telemedicine include: uneven distribution of specialist doctors which is concentrated in big cities, limited hospital capacity, majority of population in many regions live remotely from health care centers, geographical conditions as an archipelago nation and uneven distribution of population, poor quality of health services, limited medical devices, dominance of imported products, etc. (BPPT, 2018). Utilization of ICTs for health services is also in line with efforts to

DOI: 10.17933/bpostel.2020.180104

utilize national broadband infrastructure that has been announced by the government (Bappenas, 2014). Telemedicine services are regulated by Regulation of Minister of Health No. 20 of 2019 on the Implementation of Telemedicine Services between Health Service Facilities, and supported by Circular of Minister of Health No. HK.02.01/Menkes/303/2020 on the Implementation of Health Services through the Utilization of Information and Communication Technology in the Context of Preventing the Spread of COVID-19.

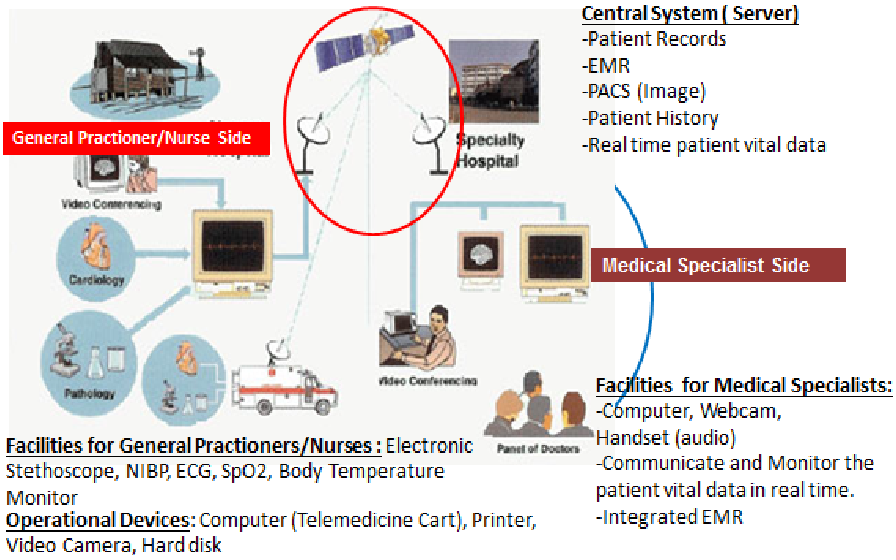


Figure 1. A telemedicine concept (BPPT, 2018).

An example of a telemedicine concept is shown in Figure 1. This system consists of 3 parts, namely: health care facilities on the patients' side, e.g. patients' homes, community health centers (*puskesmas*), hospitals, or ambulance; ICT facilities for data communication and processing; a central system that can be accessed remotely, for example by a number of specialist doctors. It can be seen that on the patient's side there are various medical instruments that can be used depending on the patient's condition, such as a stethoscope, vital-sign monitor, ECG device, and others. Next, an aggregator and an interface to ICT facilities are required for this section, to connect to the central system. The central system requires a storage server to store patients' medical records and other relevant information, which can be accessed remotely by medical practitioners and other relevant parties. The system must also provide tools which enable interactive communication between medical practitioners on the patient side and the remote side. The format of such communication depends on field conditions, available resources, and related medical regulations.

How to implement the telemedicine concept as shown in Figure 1 and gain a scientific justification for its proper operation, guaranteed service quality, and user benefits, are challenges that must be faced. Specific examples of telemedicine services, namely tele-ECG and teleconsultation, are presented in this paper, with the following stages. In section 2, a literature review is presented on the technologies used, their current status, and challenges faced in relation with telemedicine domain. The research method which is tailored to answer the existing research problem is presented in section 3, with the results of research and development, and the discussion presented in section 4. The results of this study can provide an input for those parties who are implementing the telemedicine system in Indonesia, especially tele-ECG and teleconsultation.

2. Literature Review

The challenge in integrating various technology components for telemedicine systems is the availability of a transparent framework and open protocols for interoperability between each subsystem. It starts on the patient side, where a variety of medical equipments are available to measure and record the patient's condition, with various types and formats of medical data. The medical equipments are generally provided by various vendors with proprietary technology and data format. In this regard, it is necessary to have an aggregator that is connected to these various medical devices, to read data and convert it to a format that can be understood by all subsystems. In addition to medical data transmission, telemedicine systems also require communication media between doctors, ideally in interactive multimedia sessions. One of the technologies in the distributed systems for connecting various existing components in either between machines and machines, machines and people, or people and people, is web technology. Therefore, it is necessary to study the extent of the use of web technology in the medical field, ECG medical data format status, web technology for multimedia communication, and its system integration.

2.1. Aggregation of Medical Data and Use of Web Technology

Telemedicine system implementation that includes various technology choices requires interoperability of devices, protocols, and related applications. To support interoperability, it is necessary to develop a system in which each component refers to international and national standards as well as applicable regulations. This is also a challenge because of the wide range of medical standards available, and many related standards and regulations that have not been established. In addition, many medical devices are still using proprietary data formats and technologies.

Simplification of standard choices on the patient side can be realized by deploying a device that acts as an aggregator which connects various medical devices and unifies the format standards and related data exchange. This aggregator concept is implemented in a device called traumastation (Sachpazidis, 2008), which integrates various tools to measure cardiogram, ultrasound, blood pressure, and oxygen levels in the blood. A similar tool is realized in a device called a telemedicine cart/workstation, a device on the patient side as an interface to a telemedicine system developed by the Agency for the Assessment and Application of Technology (BPPT) (Agastani et al., 2018). By using telemedicine carts, the telemedicine system obtains uniformity of data format and communication protocol, which further facilitates the implementation of medical data validity guarantee module. This telemedicine cart has several additional interfaces for other medical or non-medical devices such as a smart card reader and integration modules that utilize web technology on software for patient information system, medical record, and multimedia communication application.

Web technology is commonly used to ensure interoperability in distributed systems, as well as play a role in the ICT for the health sector. Web technology has been used for medical data visualization in remote monitoring of patients' conditions (Makinen, 2016) and the integration of patient supporting medical data in telemedicine systems (Fouad, 2013). One of the open source projects for developing a web-based information system for patients' medical records is OpenEMR (www.open-emr.org) which includes a MySQL database, a web server, and a web browser interface. OpenEMR offers various menus to enter patient information, doctor's schedule, medical status, etc, which are required in medical services. The availability of such source codes provides flexibility in the development and utilization of software, in addition to reducing investment costs. OpenEMR is one of several electronic medical record implementations surveyed in a previous study (Jones et al., 2014). In addition, this product includes additional patient demographic information to help identify and allow data sharing between health service providers. However, along with them come a number of security vulnerabilities that require further handling.

Security of web technology is an important aspect to be paid attention to, yet more focus is placed on applications in the trade and financial sectors. For the health sector, we can refer to the Health Insurance Portability and Accountability Act (HPIAA) and the Office of the National Coordinator (ONC) for Health Information Technology for their security and privacy requirements to ensure compliance with aspects of confidentiality, integrity, availability, and utilization of electronic medical records. A study (Farhadi et al., 2019) reported the use of static code analysis to find security vulnerabilities in OpenEMR applications and map the security and privacy rules of HPIAA and ONC. Furthermore, mitigation techniques are proposed to address security vulnerabilities in an effort to meet security and privacy requirements compliance. Issue of medical data with digital signature validity is discussed in another study (Agastani et al., 2018). This study suggested that it is technologically possible to realize, as applied in the telemedicine systems. As for Indonesia, regulatory support is required to ensure the legality of electronic medical records. Note that medical records in electronic format have not yet been regulated by Regulation of Minister of Health No. 20 of 2019 on the Implementation of Telemedicine Services between Health Service Facilities.

Further development of web technology is indicated by the emergence of services that support mobility and the use of cloud computing for more efficient resource utilization (Husain et al., 2015). In addition to utilizing client-server interactions as in the aforementioned various solutions, the use of peer-to-peer blockchain technology has been discussed recently for the management of medical records (Halamka et al., 2017). This technology is based on distributed ledgers, where for each ledger recording a transaction comes with a hash value that depends on the hash values of the previous ledgers in the previously agreed-upon chain. Such guaranteed data integrity can be used to store encrypted information related to the physical location of the stored medical record and to authenticate the parties who can use it. Apart from its potential utilization, further study is still needed, both in terms of technology and regulation, related to the use of blockchain technology in the health sector.

2.1.1. ECG data formats

A host of choices are available for standard ECG waveform data, and there is no world consensus on which is best to use (Bond et al., 2011; Trigo Vilaseca, 2011). Some open standards that are actively discussed and popularly used include the Standard Communication Protocol for Computer-Assisted Electrocardiography (SCP-ECG), HL7 annotated ECG (HL7 aECG), Digital Imaging and Communications in Medicine (DICOM) Supplement 30. The SCP-ECG standard is supported by the European Committee for Standardization (CEN), encoded in binary format that includes data structures, ECG measurement data, ECG interpretation results, and patient data. Proposal has been made for the standard to be improved into e-SCP-ECG +, which is backward-compatible with SCP-ECG, and includes additional vital-sign information and demographic data. HL7 aECG is the American National Standards Institute (ANSI) standard for ECG data encoded in eXensible Markup Language (XML) format. The use of text XML enables easier reading and supports interoperability considering the increasing number of applications and services that use XML. Whereas DICOM was originally intended for medical images, but a number of new features were added to be used for various other medical diagnostic modalities. An extension was then set to handle biological signals such as ECG waveform, that is, DICOM Supplement 30.

The heterogeneity of ECG data format choices poses a challenge to realize interoperability in the medical record information system. Efforts are needed to understand the format of storage, delivery, and interoperability between the standard formats adopted. Interoperability is needed in utilizing shared information between providers of health service, insurance companies, and other authorized parties. Furthermore, it is needed in the telemedicine system implementation that includes diagnose automation modules using artificial intelligence. Interoperability can be realized through an interface that includes ECG data format conversion modules, one of which is carried out by the OpenECG project that utilizes web portals and web services as a gateway for SCP-ECG conversion to DICOM Supplement 30 (Sakkalis et al., 2003). The provision of general ECG data format conversion modules is included in medical service applications, and one of the most recent is an adapter system called ECGConvert which provides interoperability between raw data of ECG, HL7 aECG, SCP-ECG, and other formats (Stamenov et al., 2018).

The ECG data format standard has been implemented by several open-source projects. Therefore, the reference source codes for the conversion, storage, and visualization of ECG data are available, one of which is ECG Toolkit (van Ettinger et al., 2008). Compared to the SCP-ECG, HL7 aECG, DICOM Supplement 30 (waveform) standards, SCP-ECG is among the most widely used. In addition, because it is encoded in binary, the file size is smaller, making it is suitable for use in environments with limited ICT infrastructure, such as limited bandwidth, limited storage media, and others. Therefore, in the implementation of telemedicine system, storage and transmission of ECG data on community health center (*puskesmas*) or other primary health services side can be done in SCP-ECG format to anticipate its use in remote areas with limited ICT infrastructure (BPPT, 2018).

2.2. Web-based Teleconference

Multimedia conference facilities (video, audio, data) are utilized for various telemedicine services such as teleconsultation, tele-Education, tele-Operation, and others. Rapid developments of technology for network and application protocols, coder/decoder, camera and monitor devices, have made teleconferencing easier and improved service quality. Conferences that involve multiple users can be arranged based on a mesh model, Multipoint Control Unit (MCU), or elective Forwarding Unit (SFU). The mesh model is realized with peer-to-peer connections for each connection, without server assistance, which becomes inefficient when the number of connections increases. On the other hand, the MCU and SFU are centralized models that utilize servers to coordinate connections between users.

In MCU, a server receives streams from all users and makes them into one stream and sends it to each user. Mixing streams into one stream can be done efficiently for audio, but difficult for video because it requires greater computing power for processing and it comes with the risk of quality loss. Whereas in SFU, the server receives streams from all users and delivers each stream to its destination without mixing. This method can maintain video quality and also minimize latency because it does not require computing power for video mixing like MCU. The decision on either using MCU or SFU will depend on the type of application and the availability of computing and network resources.

Further improvement is made to teleconference applications with the development of Web Real-Time Communications (WebRTC) technology. WebRTC enables web-based teleconference applications (using a web browser) that retrieve video, audio, and data streams from the Internet without requiring third-party plugins. It can also access users' cameras and microphones enabling multimedia communication between explorers. WebRTC and SFU models are claimed to be modern teleconferencing techniques, and with the use of techniques such as scalable video coding, efficient video stream forwarding based on audio activities, result in satisfactory performance with efficient use of resources (Grozev et al., 2015).

A number of applications can become options for telemedicine, whether they are proprietary or open source. An example of proprietary application is skype, a popular application which has an interface to the PSTN network but requires plugins that are installed on a web browser. Another option is an application that utilizes WebRTC, so that hypermedia (hyperlink communication) is arranged on the web browser from real time communication users via the web without the addition of other applications or plugins (Antunes et al., 2016). The WebRTC protocol can be used for peer-to-peer communication, or for SFU-based teleconferencing utilizing a media server that supports WebRTC. There are a number of open source media servers such as Jitsi, Janus, etc., whose performance and scalability have been compared on a virtual testbed as reported in Andre et.al (2018).

In WebRTC, speed takes precedence over reliability, and video, audio, and data transmission is done with User Datagram Protocol (UDP). Unlike the Transmission Control Protocol (TCP), UDP does not include acknowledgments, retransmissions, and congestion control, so that it runs faster. On the other hand, sending medical data requires reliability to ensure the integrity of the data used as input for diagnosis, so that transmission is carried out using TCP. This heterogeneous traffic affects Quality of Service (QoS) as a quality measure for the telemedicine services provided. Furthermore, this quality will have an impact on the expectations and perceptions of service users who are subjective, or what is called Quality of Experience (QoE). What these users feel is very important for the implementation of telemedicine services, but it is a challenge to find a correlation between QoS and QoE (Ullah et al., 2012), and the results of recent research to gain insight of QoE in the telemedicine sector is still limited (Diez et al., 2018).

3. Research Method

This research is part of the Agency for the Assessment and Application of Technology's Center for Electronics Technology's (PTE-BPPT) engineering activities. The object of research is a telemedicine system that has been developed for tele-ECG and teleconsultation services. The system is an integration of hardware and software modules in a web technology framework which requires network infrastructure in operation for sending ECG data and multimedia communications. This study aims to answer whether the system is worthy of operation, i.e. when a general practitioner examines a patient in a community health center and can consult an ECG examination with a specialist in a referral hospital. The system is said to be feasible if the ECG data transmission goes well and the quality of multimedia communication reaches a set level.

Challenges of this study are ensuring: a) the system's achievements in integrating various open source modules are as expected; b) the interaction of mixed ECG data traffic and multimedia communication does not interfere with service quality. To support the research, a testbed that represents various components involved in the operation of telemedicine system has been set up. The testbed provides a variable that can be varied; i.e. bandwidth that represents the capacity of the communication path to carry ECG data traffic, multimedia communications, and others. Testbed management involves the Electromedical Laboratory and the Advanced Network Protocol Laboratory in the PTE-BPPT premises, and the BPPT cloud computing infrastructure, in order to obtain a controlled network testing environment.

Functional tests and performance tests are carried out on the testbed. Functional tests are carried out to ensure that the capture, format conversion, storage, transmission, and visualization of ECG data work properly. The presentation of ECG data must be consistent on the local and remote sides, and can be understood by medical practitioners. Also, users can open a conference session to consult. Performance testing is done by varying bandwidth and investigating its impact on the network and application QoS parameter values.

In this study, QoS parameters are limited only to network packet loss, video bit rates and video frame rates that represent multimedia communication, and latency for sending ECG data. Packet loss is the percentage of lost packets in the network domain which impacts transmission performance. Bit rate is the number of bits per second used by the codec algorithm to display videos according to their resolution and quality, while the frame rate is the speed at which video frames are shown per second. How changes in video bit rate and frame rate adjust to network bandwidth conditions become a reference for the adaptability of video conferencing applications. While latency is the time lag between ECG data sent on the local side, until it is received on the remote side.

The QoE aspect also becomes a concern in this study, but it is only as a supporting aspect in the QoS measurement. Estimation is conducted for multimedia communication, where the existing QoS/QoE correlation model is used for video quality, and is based on subjective observations for audio quality and text display.

To complement the research, field trials are also carried out with PTE-BPPT partners to ensure the system is functioning, operational and useful for medical practitioners. Results obtained are used to improve the system.

4. Research Results and Discussion

In this activity, a telemedicine cart/workstation is developed for the aggregation of medical devices based on the Microsoft Windows operating system. This operating system is chosen to facilitate data reading, because generally medical equipments in circulation provide Microsoft Windows-based drivers, libraries, or other supporting applications. For connectivity, a telemedicine cart has been equipped with various interfaces, such as USB, BLE, and others if required, to connect a digital stethoscope, an ECG device, a vital-signs monitor, and a smart card reader to the telemedicine cart. As for the telemedicine central server that can act as a global medical data storage server and a referral source from specialist doctors, a Linux operating system is used. This central server can also be hosted on a cloud computing infrastructure.

For flexibility and good operability, a web-based software framework is used, namely the OpenEMR which is popular in the medical sector for recording medical records. OpenEMR can also be implemented as a distributed system, making it ideal for a telemedicine system.

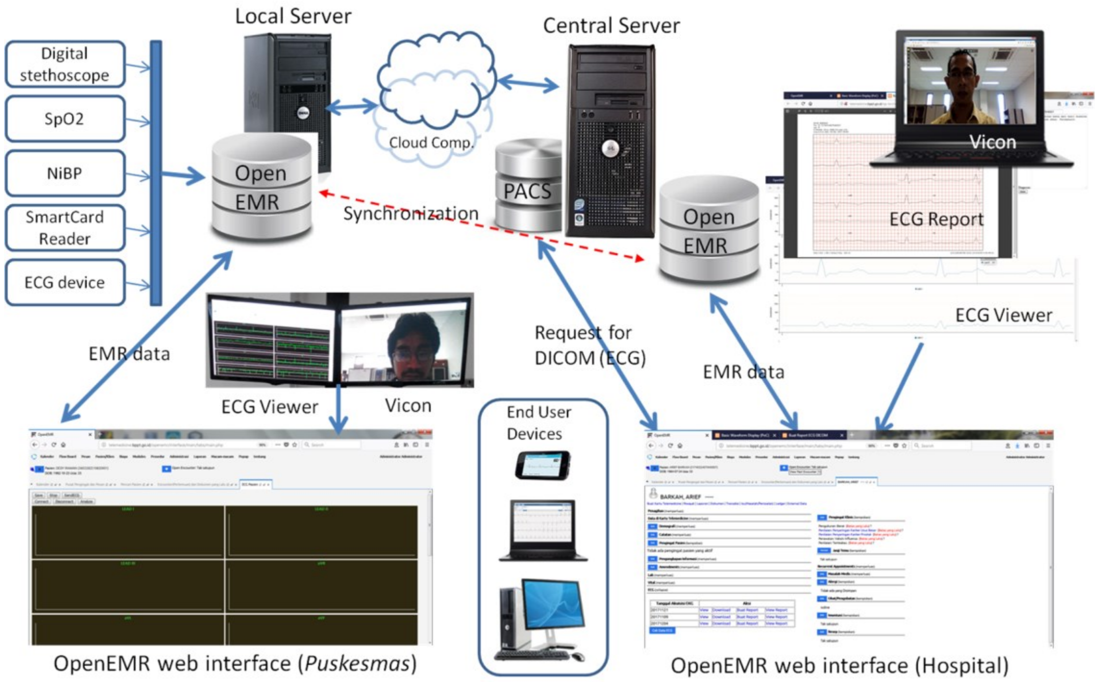


Figure 2. Telemedicine system configuration using OpenEMR.

Figure 2 shows a telemedicine configuration using OpenEMR. On the client side (community health center/*puskesmas*), OpenEMR is installed in the telemedicine cart. Using a web browser, OpenEMR is opened and patient data is entered, and in the same interface medical data from various medical devices can be retrieved, displayed, and stored on the local server. A smart card reader is also included to verify patient data and store medical data on a limited basis. For distributed configurations such as this telemedicine system, the database on the local server is synchronized with the database on the central server, so that doctors who are located in remote locations can access patients' related information. One of the challenges in the implementation is the medical data format options, in this activity is the ECG data format, because of the many options of standards available as explained earlier. Data format in this activity is chosen based on the assumption of saving bandwidth usage between local and central servers. For this reason, the SCP-ECG format is used, so that all ECG data obtained by medical devices is stored in the SCP-ECG format on the local server. Referring to Figure 2, on the central server side there is a PACS (Picture Archiving and Communication System) server aimed at storing various modalities of medical data in the DICOM format. PACS server is used because it supports the waveform format for ECG, and an open source for its implementation is available. Due to differences in ECG data formats, a format conversion module is required to run before the data being stored on the PACS server. For capturing and visualizing ECG data from remote locations, everything is done in the DICOM format and displayed in the interface of OpenEMR.

For communication between doctors in local and remote sides, facilities for real-time and interactive communication are required. The interactive communication can be done through text, audio, and video, depending on the communication network infrastructure. Ideally, all of the above media can be provided in a video conferencing format so that specialist doctors who provide teleconsultation can experience a more realistic atmosphere in examining patients. This application is implemented using web technology so that it is integrated with the OpenEMR framework used.

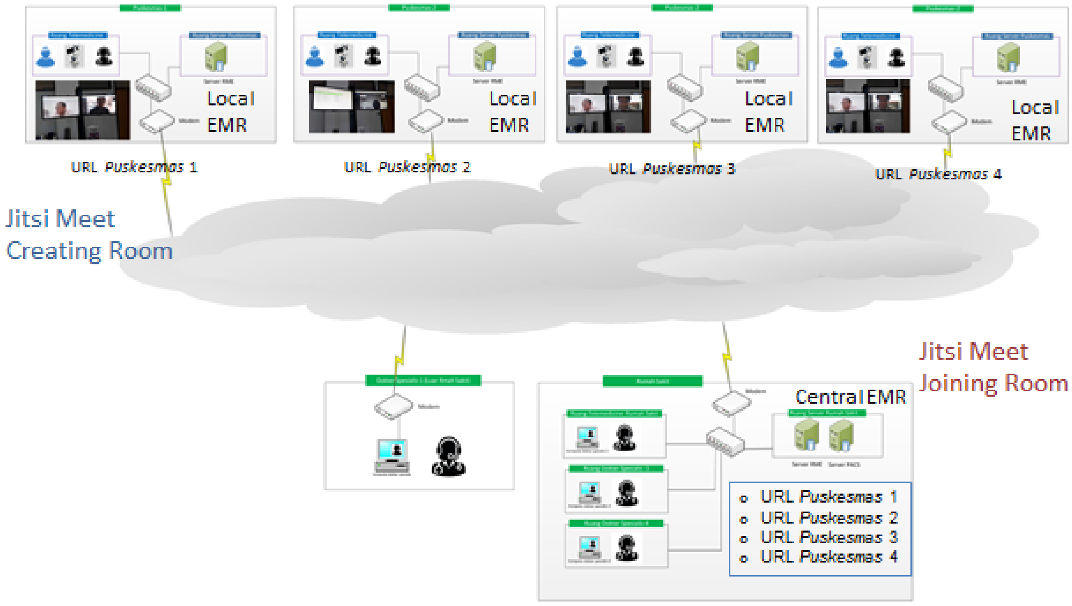


Figure 3. A room concept for multimedia communication between community health center/*puskesmas* and hospital.

One of the open source projects that is compatible with WebRTC is Jitsi, where its components are divided into Jitsi Meet and Jitsi Bridge. Both of these components are installed on the server, and for this activity, they are installed on a virtual server of the cloud computing infrastructure managed by the Agency for Assessment and Application of Technology's Information Management Center (PMI-BPPT). To run a video conference session, users only need to use a web browser and direct it to the link that has been prepared for Jitsi Meet. Whereas Jitsi Bridge is run as a video router that receives video streams from each Jitsi client, and then directs them to all conference participants. This method is more efficient in terms of sending streams from the client, although each client still has to download all streams for the relevant conference. Please be advised that generally, the client side has greater download capacity than upload capacity.

The planned teleconsultation configuration is that general practitioners at community health centers (*puskesmas*) can consult with several specialist doctors at referral hospitals. To that end, separate sessions, or known as a room in the implementation of Jitsi video conferences, are arranged for each *puskesmas*, where general practitioners at the *puskesmas* and specialist doctors join and communicate interactively. Figure 3 illustrates the intended room concept. Mechanism for initiating and joining room can be done in synchronous or asynchronous ways. A synchronous mechanism can be applied if the doctor information that is being logged into OpenEMR is synchronized to all servers so that the general practitioner who initiates a room for his *puskesmas* can send an invitation to a particular specialist to join the room for a teleconsultation session. As for asynchronous mechanism, synchronization is not needed so that the first to click on the URL link for a particular *puskesmas* is considered to be the initiator of the room, and the latter clicks on either by the general practitioner or specialist doctor are considered to join the room. Jitsi provides flexibility for the choice of media exchanged in each room, depending on the communication network infrastructure.

4.1. Design and Testing for ECG Data Conversion, Storage, and Transmission

ECG data conversion and transmission modules are developed based on open source code that refers to the ECG data format standard. These modules are then integrated into a prototype of a web-based telemedicine system using OpenEMR. On the interface to the ECG device, the conversion module receives raw data in the form of voltage from a 12-lead ECG device, which is then converted to the desired ECG data format. Of the various ECG data formats available, the SCP-ECG and DICOM formats are of concern to these engineering activities. The SCP-ECG format results in smaller file sizes that require smaller data storage capacities and smaller transmission bandwidth. Therefore, at the local side, the SCP-ECG format is used, then it is converted to DICOM on the central server, and then stored on the PACS server. If the ICT infrastructure in the *puskesmas* is well established, ECG medical data can also be converted early to the DICOM format at the local side. The implementation of PACS is realized by utilizing the open source version of ORTHANC (Jodogne, 2018).

Figure 4 shows the design of the related modules, starting with the acquisition of raw ECG data from the device at the patient's side at the *puskesmas*, data format conversion, storage, visualization and delivery to the central server. File transfer in SCP-ECG format is done with the scp (secure copy) tool to the central server, which can also be realized in the cloud computing infrastructure. On the central server side (which represents the referral hospital) it appears that the DICOM format is used for storage in PACS. Furthermore, various operations such as querying, downloading, visualizing, and compiling medical reports in pdf format by specialists are based on ECG data in DICOM format. The layout above also shows the synchronization of data between the *puskesmas* and the hospital, so that *puskesmas* doctors can read the results of the analysis from specialist doctors on the remote side.

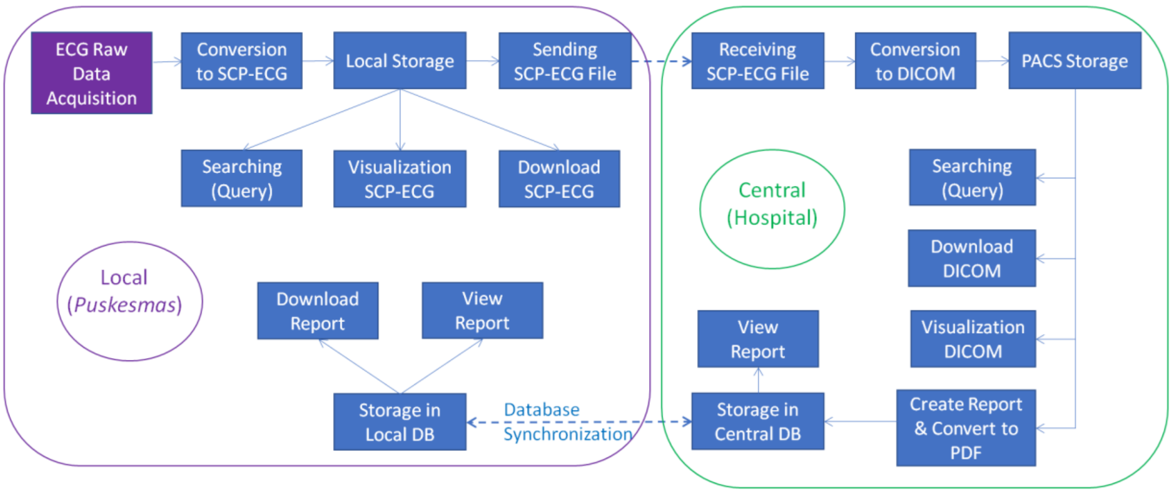


Figure 4. A layout of modules for ECG data conversion, storage, and transmission.

ECG data conversion and storage testing is carried out by acquiring raw ECG data from the simulator and also directly from the human body, converting to SCP-ECG data format, visualizing, storing in a file, and then re-opening and re-visualizing the data. The same method is also applied when the data format has been changed to DICOM. Figure 5 shows an example of ECG data visualization after conversion and storage. Verification is done by comparing the simulator output target with the results of visualization, and also consulting medical practitioners after acquiring data from the human body.

To test the transmission module, an assessment is conducted on whether the file sent has arrived at the server by checking the status of the file presence through the OpenEMR interface. Visualization results from the DICOM format on the remote side are also compared to visualization results on the local side to ensure consistency of conversion to the DICOM format from files received by the central server. Figure 6 shows ECG data files on the local server and those that have been received on the central server. Also shown next to the ECG data display is a column that can be filled with comments and specialists' diagnoses on the interpretation of this ECG data reading.

Figure 5. ECG data conversion and storage testing.

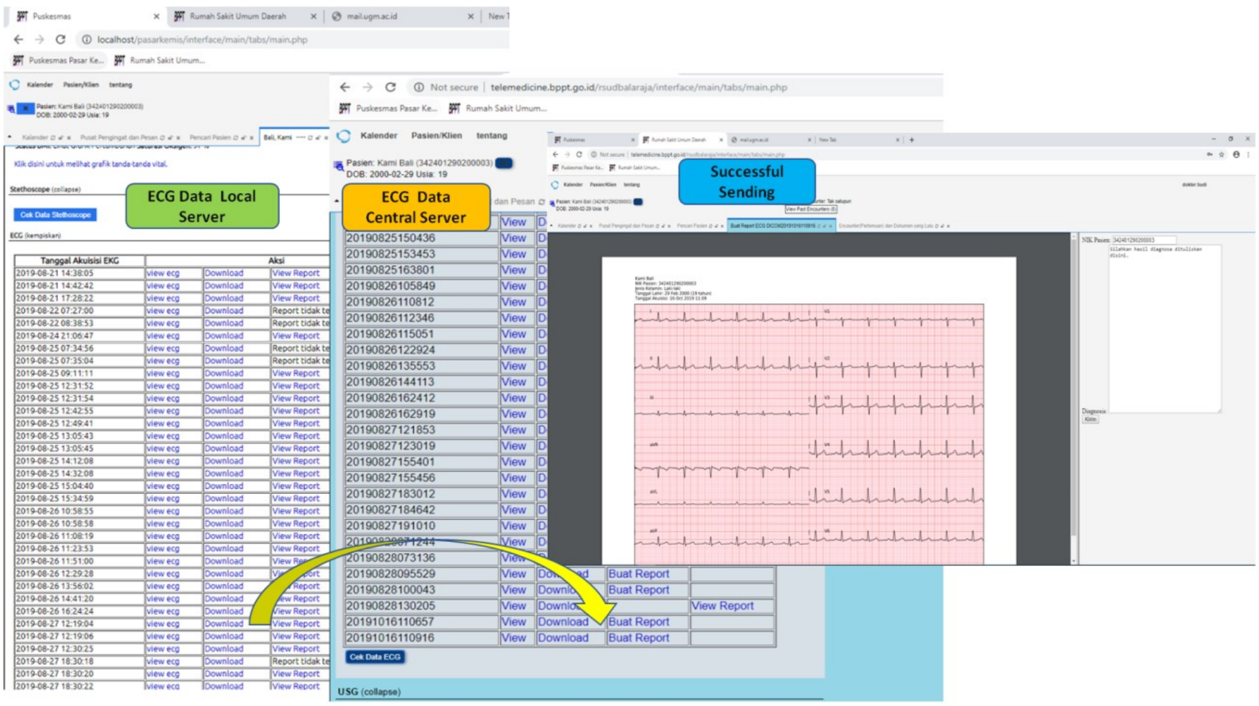


Figure 6. ECG data transmission testing.

4.2. Tele-ECG and Teleconsultation Design and Testing

The challenge in providing multimedia services for teleconsultation is the limited communication network infrastructure that connects telemedicine carts, devices used by specialist doctors, and telemedicine and video conferencing servers. For this reason, a computer network that represents these components, with the topology shown in Figure 7, was set up. In this condition, different subnets are prepared for telemedicine carts, computers for specialist doctors, and servers for each teleconferencing and medical data storage. An external connection is also prepared for later use during field trials.

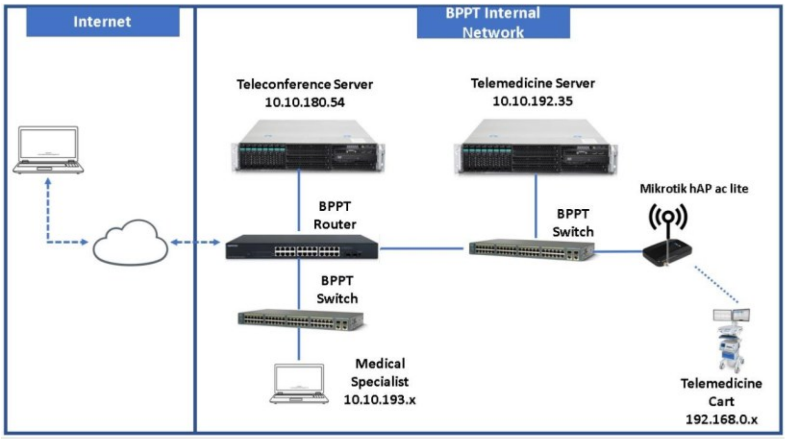
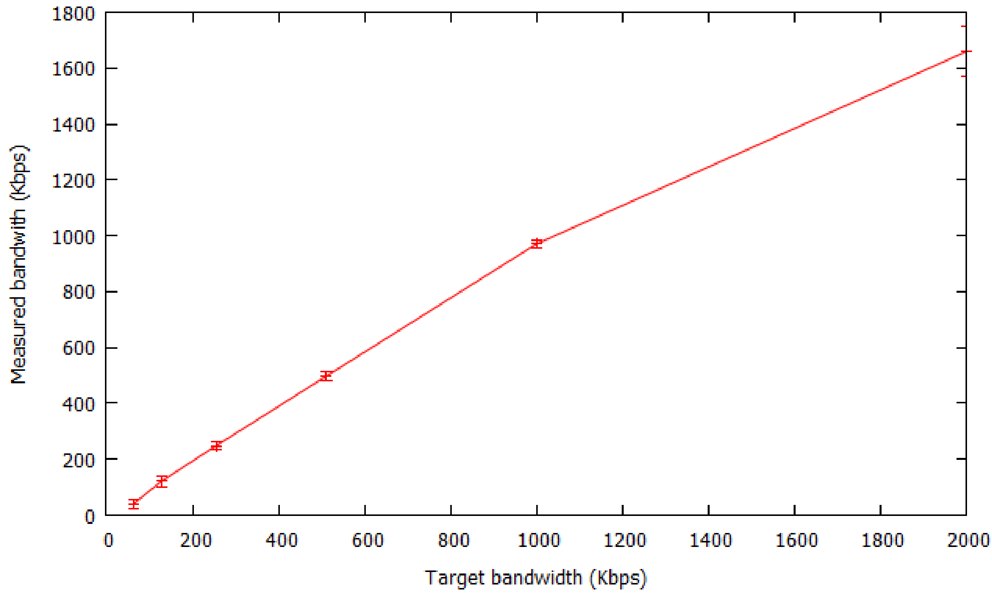


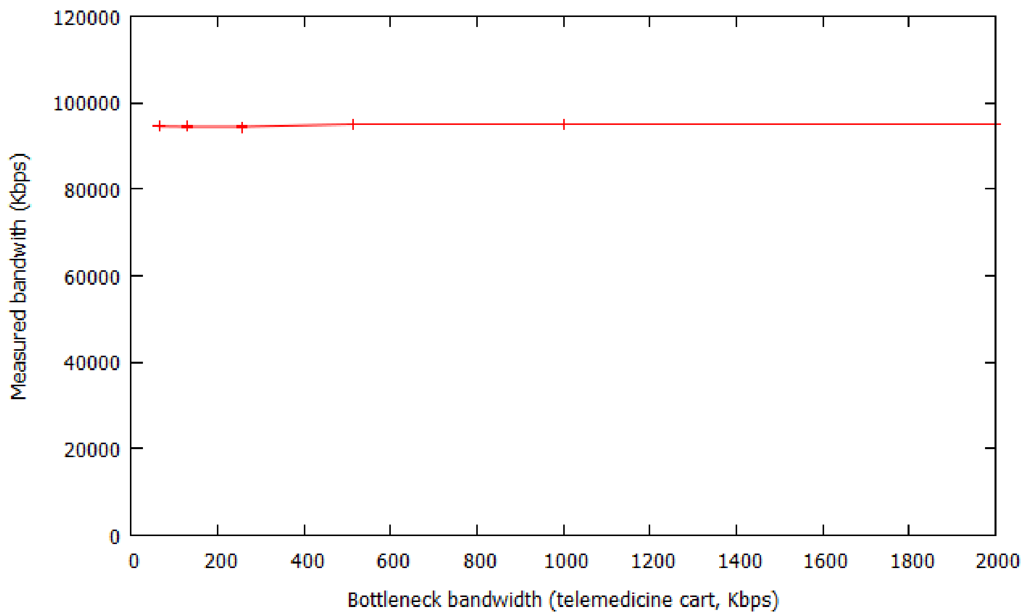
Figure 7. Network topology for telemedicine testing.

What has become an argument at the beginning was the bottleneck on the last line, which is the communication line connecting the telemedicine cart with the Internet. For this reason, at the initial stage, testing is conducted at a laboratory scale, which is a test environment that can be controlled to represent bandwidth variations on the intended bottleneck. This is done by adjusting the bandwidth allocation of the line connecting the telemedicine cart, using the simple queue technique provided by the mikrotik router. Figure 8 (a) shows the measured bandwidth with a number of target bandwidth settings set for the telemedicine cart, and Figure 8 (b) shows the available link bandwidth for the specialist doctor. For the validation of this bottleneck path scenario, performance measurements are carried out only on the condition of the specialist link bandwidth far greater than the one for the telemedicine cart, as shown by the bandwidth availability in Figure 8.

Network quality testing is carried out in several conditions to determine traffic behavior and its interactions when simultaniously using available network bandwidth. For this reason, measurements were made on 4 different conditions, namely idle conditions, ECG data transmission conditions, multimedia communication running conditions, and conditions in which multimedia communication and ECG data transmissions were run simultaneously. In this experiment, multimedia communication is more focused on aspects of video transmission that require greater bandwidth allocation. For idle conditions, the iperf tool is run to measure the characteristics of the available bandwidth. ECG data sending in SCP-ECG format is done periodically for the duration of the trial, although in telemedicine practice, ECG data sending can be done once for one patient session. Video quality measurements that require a similar streaming video input for each measurement is performed by playing the same video file using the fake media feature of WebRTC and Jitsi's media server (Andre et al., 2018). With this fake media, video files in Y4M format can be used to substitute a webcam. The video used is in 5 minutes of duration containing conversations from two people who are considered to represent a consultation session in the doctor's office. Some information from this video file, reported by the ffmpeg tool, is frame rate=25 fps, bit rate (raw video)=622081 Kb/s, resolution=1920×1080, and from network traffic measurements video streams using h264 video compression are reported.



(a) Bottleneck link (telemedicine cart)



(b) Specialist doctor's link.

Figure 8. Bandwidth availability

For each bandwidth bottleneck and several different transmission conditions, QoS measurements are carried out on network and application that have an impact on video quality and medical data transmission. For video transmissions using UDP, which allow some video packets to be lost as compensation for achieving latency that affects video quality, packet loss, bit rate, and video frame rates are measured. On the other hand, medical data sending must be error free, so an scp (secure copy) using TCP is used. For this reason, it is necessary to measure latency as a pause time until the ECG data is sent and successfully received, as compensation for the absence of errors. Measurements are made when there is only one type of traffic, namely ECG data, and when there is mixed traffic of video and ECG data.

Figures 9 and 10 show a number of video transmission characteristics, when running alone and when mixed with ECG data transmission. It can be seen from Figure 9 the ability of Jitsi to stream video efficiently, and how it varies the video bit rate following network conditions. Starting from the 512 Kbps bottleneck bandwidth, the bit rate has reached a stable level to display video on the receiver side.

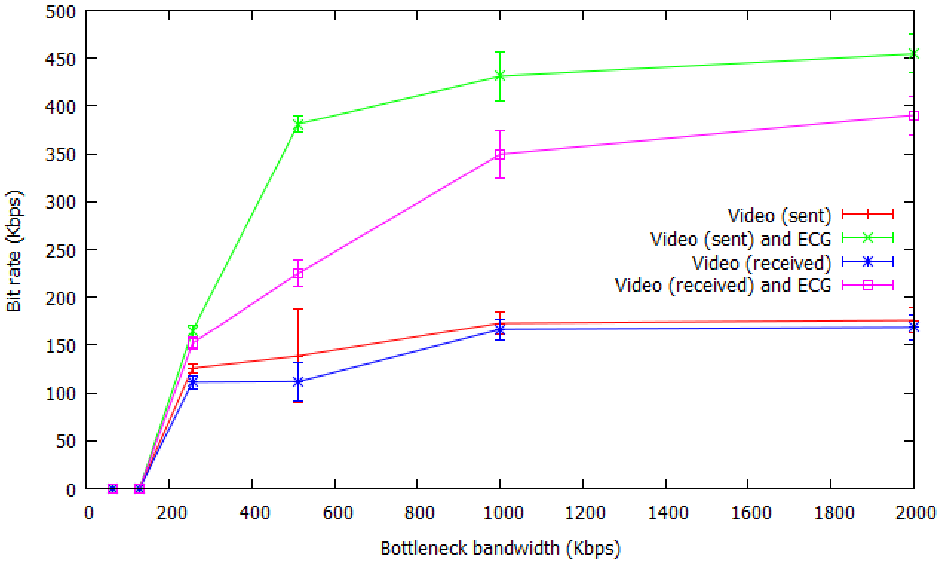


Figure 9. Video bit rate.

It can also be seen that video transmission reacts by increasing bit rate during simultaneous transmission with ECG data transmission using a bottleneck link. This is done to compensate for delay minimizing target using UDP which causes partial packet loss from video traffic. Figure 9 also shows that the received bit rate is lower than what is sent, which indicates degradation in the quality of the video received, compared to the original video file displayed on the sender's side. Referring to Figure 10, it can be seen that at the 256 Kbps bottleneck bandwidth Jitsi is still capable of displaying video on the receiver side with a frame rate of around 25 fps, though with limited quality.

The impact of network conditions on transmission can also be seen from the results of packet loss measurements in Figure 11. It can be seen that video transmission is affected by bottleneck bandwidth, especially in this case there is a large packet loss when the bottleneck bandwidth drops to 256 Kbps. However, video transmission is not very affected by the presence of ECG data transmission.

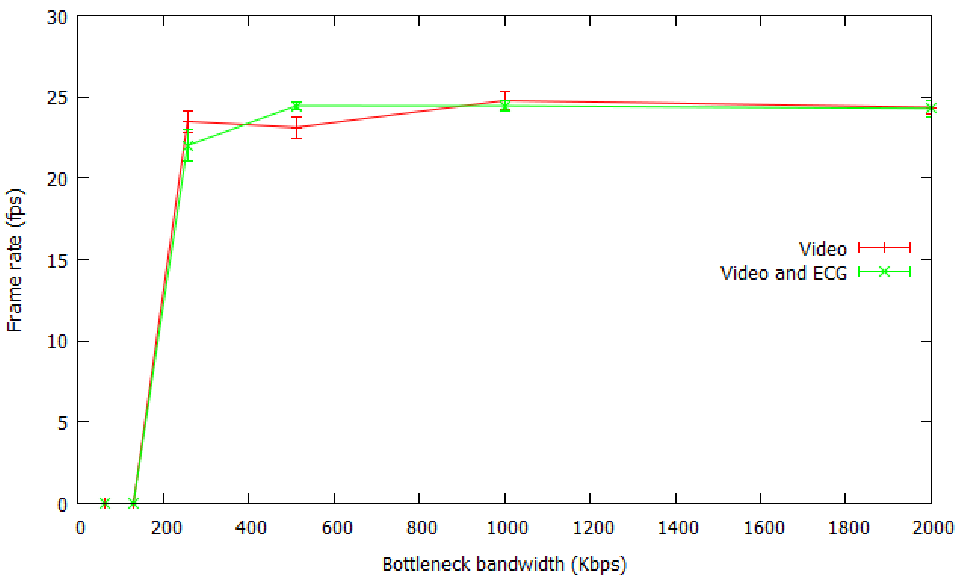


Figure 10. Video frame rate.

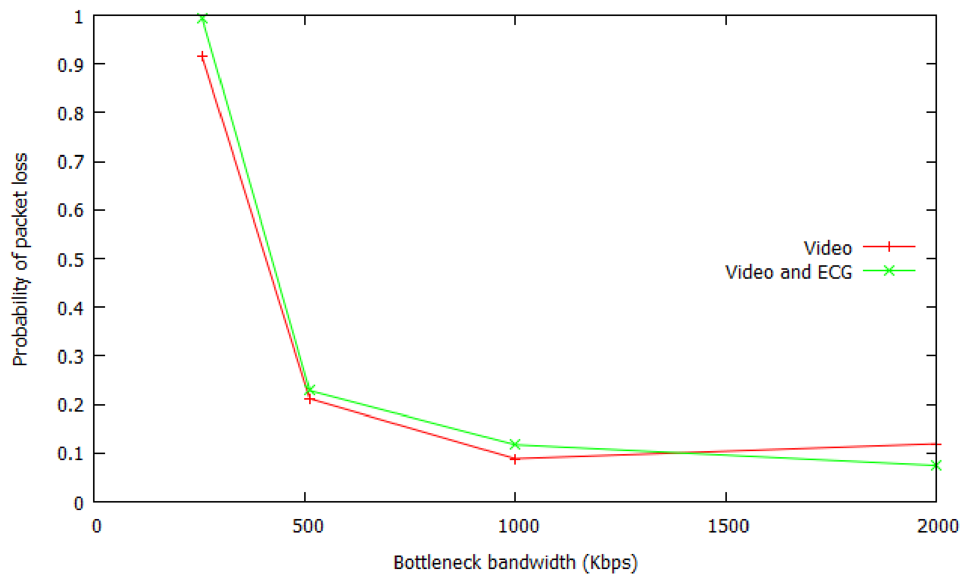


Figure 11. Video packet loss.

From the video's bit rate and frame rate information, and network packet loss, the estimation for MOS (Mean Opinion Score) values can be calculated using the ITU-T G.1070 standard as the user's perception of video quality (Kusuma et al., 2014). MOS values are defined as: 1=Bad, 2=Poor, 3=Fair, 4=Good, 5=Excellent. From Figure 12 we can see that the video quality is considered appropriate for bottleneck bandwidth above 256 Kbps. Increasing bottleneck bandwidth can no longer increase video quality, due to the influence of factors related to other computing resources on the application side.

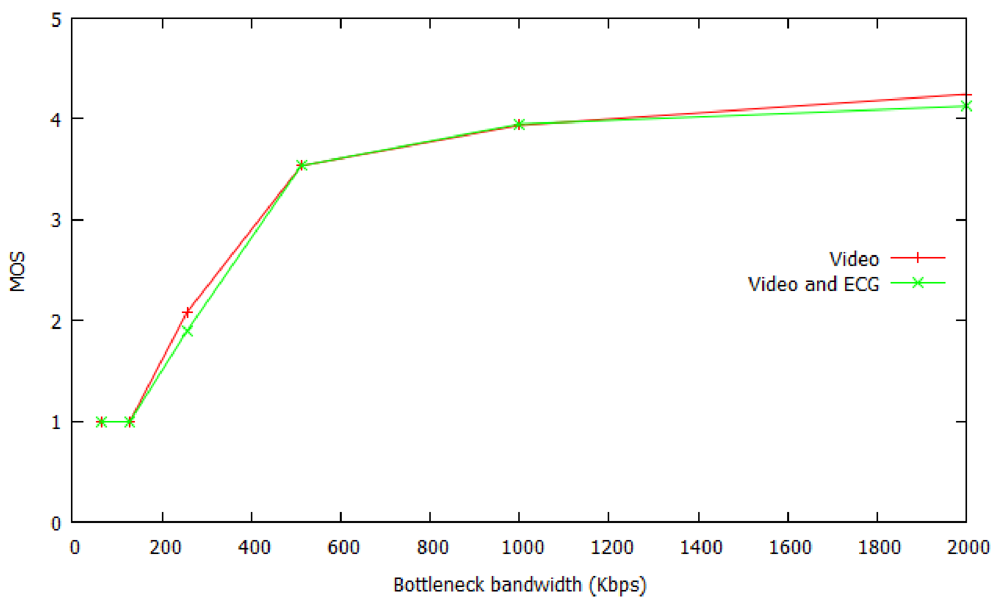


Figure 12. Estimation of video quality perception

The quality of medical data sending is determined by latency, and the measurement results are shown in Figure 13. It can be seen that for bandwidth of above 128 Kbps, latency is around 2 seconds, and it slightly worsen when it is run simultaneously with video transmission. Latency and variability increase sharply for bandwidths of below 128 Kbps. This observation shows a phenomenon called "UDP-Dominance" or "TCP-Starvation", where for mixed traffic and using communication links together, UDP (video) traffic dominates and TCP traffic (ECG data) relents. Because TCP traffic (ECG data) is reliable (error free) as long as the end-to-end communication is not interrupted, data transmission can be repeated so that it increases latency, and it gets worse for small bandwidths. The range of latency values of up to 30 seconds is still considered adequate, because medical practitioners can do other things while waiting for the arrival of ECG data.

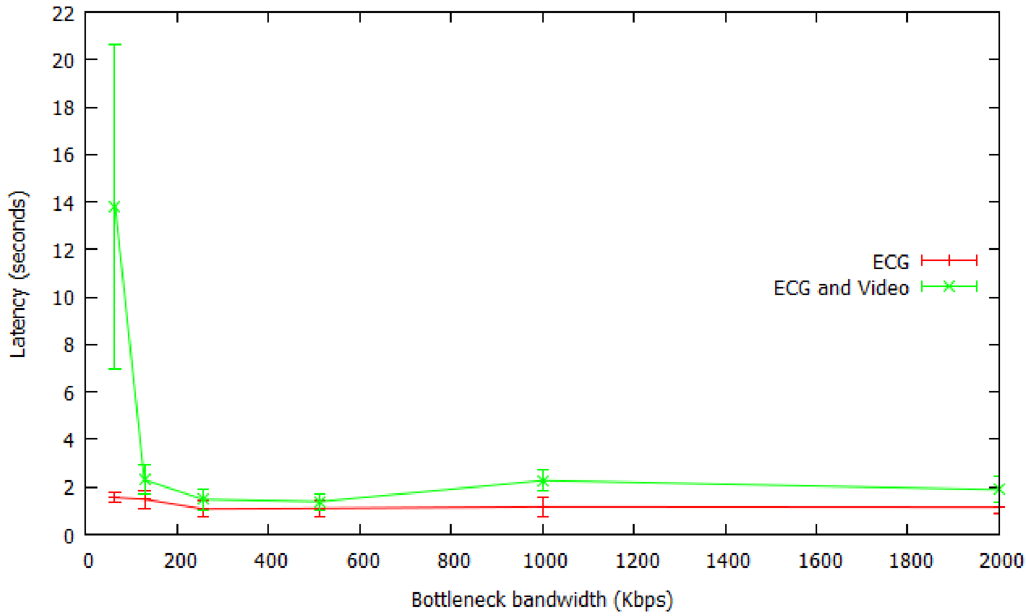


Figure 13. ECG data sending latency.

The phenomena of mixing medical data traffic with multimedia communication traffic, with their objectives in different contexts, were reported in previous research (Malindi 2007; Theodora 2012; Annan & Agyepong 2018; Kusuma et al., 2019). Preliminary studies to understand the optimal transmission of telemedicine services were carried out using discrete-event simulators. It was demonstrated that by using network simulations that support the diffServ protocol, medical and video data traffic can be properly transported (Malindi, 2007). Whereas Theodora (2012) reported cellular network scenarios to review the scheduling of ECG, X-Ray, and other medical data transmission along with video, taking into account user mobility. Although the use of discrete-event simulators is still abstract, there are a number of lessons learned from its reports, for example traffic prioritization, optimal scheduling, and adaptive bandwidth reservations based on user mobility and road maps. This can be considered when the system developed is modified for a different telemedicine system, for example an ambulance service. Trials on real networks were reported by Annan & Agyepong (2018) stating that broadband rental lines were dedicated for telemedicine services testing. In this trial, reserved bandwidths were initially fixed, and starvation phenomena were reported to occur in medical data sending whenever the system required a greater percentage of bandwidth reservations for video call services between doctors. However, the report was qualitative in nature and was not accompanied by research results with quantitative data. Meanwhile, Kusuma et. al. (2019) reported in results of testing on a virtual testbed, where the whole telemedicine system was realized in the form of software. The virtual testbed has an advantage of being flexible and scalable, and it provides broad insight into designing an optimal system. However, the virtual testbed does not adequately represent the actual network conditions when the service is being held. Therefore, the results of measurements made on a real testbed, as reported in this paper, are more representative of their use in understanding the feasibility status of the telemedicine system.

Qualitative observations were made on the quality of video and ECG data transmission, as a basic reference for the developed telemedicine system QoE. The feasibility of the transmission on each bottleneck bandwidth condition is examined for tele-ECG and teleconsultation services. The measurement results at this laboratory scale become a reference for tuning features of telemedicine carts that can be used in the field. Table 1 shows the recommendations of multimedia communication modes, two users in one room, which are activated according to network bandwidth conditions. For example, if the network bandwidth is limited and only suitable for sending text, the interface for teleconsultation only enables the chat feature. Note, for 256 Kbps bandwidth video transmission can be done but the perception of quality needs to be verified to the user, referring to the information from Figure 12.

Table 1. Feasibility of multimedia communication mode for tele-ECG and teleconsultation.

Bandwidth (Kbps)	Feasibility		
	Text	Audio	Video
64	✓		
128	✓	✓	
256	✓	✓	✓*
512	✓	✓	✓
1024	✓	✓	✓
2048	✓	✓	✓

4.3. Field Testing

The developed system has been tested in a limited way in South Tangerang City and Tangerang Regency, referring to PTE-BPPT's collaboration with the local government's Health Office. Sessions tested include tele-ECG and teleconsultation sessions between Pondok Cabe Ilir Community Health Center and South Tangerang District Hospital, and between Pasar Kemis Community Health Center and Balaraja District Hospital. In general, the trials went well, the system was functional, and suggestions from medical practitioners were used to improve the system.

Challenges faced in the field are the variability of available network bandwidth and the heterogeneity of Internet access. For this reason, before activating telemedicine services, available network bandwidths are measured, and then a multimedia communication mode is prepared referring to the feasibility information in Table 1. In addition, the type and version of the web browser used should be paid attention to, to ensure compatibility with the Jitsi media server version used for conferencing services and additional latency due to limited resources on the user's computer.

Retrieving, sending, and storing of ECG data to the PACS server run well. The lag time until the ECG data is displayed on the side of the specialist doctor was also satisfactory despite inadequate network conditions. ECG display can be understood by specialist doctors to be used as a basis for diagnosis. Consultation sessions run well where general practitioners and specialists interact using video, audio, or text, depending on network conditions. According to specialist doctors, for internal medicine examination, for example heart in this case, interactions via text messages are generally sufficient, as long as medical support data such as ECG, vital signs, and other physical examination results are available on the specialist's side.

5. Conclusion and Recommendation

This paper has presented the research and development of a telemedicine system prototype, for tele-ECG and teleconsultation applications. The prototype developed provides a flexible framework with configurations that can be adapted to conditions in the field. This prototype consists of several components, hardware and software, that provides an end-to-end solution. The components include medical devices as ECG sensors on the patient side, telemedicine carts/workstations for the aggregation of medical devices and interfaces to network infrastructure, servers, and modules for medical data storage, conversion, transmission, and retrieval, and video conferencing systems for teleconsultation. This system may play a role in assisting the government in expanding e-Health applications as mandated in the 2014-2019 broadband plan and improving health services in Indonesia.

Laboratory scale tests and functional tests in the field have shown positive results for the feasibility of applying this system. The challenge of limited network resources is answered by adjusting the service features provided. By varying the availability of bandwidth in the path deemed bottleneck, a parameter reference is obtained to map services, whether in the form of video, audio, or only text, the quality of medical data transmission, and system scalability estimation. However, the quality values obtained do not include elements of subjectivity, so performance research needs to be continued with field testing that includes inputs from users' perceptions. In addition, further research is required to understand the impact of increasing the number of users, traffic engineering from network providers, and extreme conditions such as communication infrastructure with very limited bandwidth in some primary service locations.

6. Acknowledgement

Thank you to all members of PTE-BPPT's Telemedicine Innovation project and external advisors who provided valuable suggestions for this research.

References

Agastani, T., Iqbal, M., Kusuma, A., & Purnaadi, C. (2018). Kerekayasaan Modul Penjamin Keabsahan Data Medis pada Inovasi Sistem Telemedicine BPPT. *Jurnal Teknologi Infomasi, Komunikasi dan Elektronika (JTIKE), 1*(1), 1-6.

Andre, E., Le Breton, N., Lemesle, A., Roux, L., & Gouaillard, A. (2018). Comparative Study of WebRTC Open Source SFUs for Video Conferencing. *Principles, Systems and Applications of IP Telecommunications (IPTComm).*

Annan, R. K., & Agyepong, J. T. (2018). Pragmatic Teleconsultation Network Model to Address the Bandwidth Deficiency Inhibiting Real-Time Telemedicine Implementation in the Sub-Saharan Africa. *International Journal of Innovative Research & Development, 7*(1), 203-209.

Antunes, M., Silva, C., & Barranca. (2016). A Telemedicine Application using WebRTC. *Procedia Computer Science, 100*, 414-420.

Bappenas. (2014). *Rencana Pitalebar Indonesia (Indonesia Broadband Plan) 2014-2019: Konekivitas, Inovasi, Transformasi.*

Bond, R., Finlay, D., Nugen, C., & Moore, G. (2011). A Review of ECG Storage Formats. *International Journal of Medical Informatics, 80*(10), 681-697.

BPPT. (2018). *Program Manual 2015-2019 Tahun Anggaran 2018: Inovasi Konvergensi Teknologi Elektronika dan Telekomunikasi Sistem Elektromedika (Inovasi Teknologi Telemedicine).* Jakarta.

Diez, I. d., Alonso, S. G., Hamrioui, S., Lopez-Coronado, M., & Cruz, E. M. (2018). Systematic Review about QoS and QoE in Telemedicine and eHealth Services and Applications. *Journal of Medical Systems, 42*(182).

Farhadi, M., Haddad, H., & Shahriar, H. (2019). *Compliance of Open Source EHR Applications with HIPAA and ONC Security and Privacy Requirements.* Master Thesis, Kennesaw State University.

Fouad, H. (2013). Web-based Medical Informatics to support Telemedicine System. *International Journal of Engineering & Computer Science IJECS-IJENS.*

Grozev, B., Marinov, L., Singh, V., & Ivov, E. (2015). Last N: Relevance-Based Selectivity for Forwarding Video in Multimedia Conferences. *Proc. 25th ACM Workshop on Network and Operating Systems Support for Digital Audio and Video (NOSSDAV).*

Halamka, J. D., Lippman, A., & Ekblaw, A. (2017). The Potential for Blockchain to Transform Electronic Health Records. *Harvard Business Review.*

Husain, W., Jothi, N., Sern, L. Y., Hong, G. S., & Choong, S. S. (2015). A Framework to Enhance Rural Healthcare Services Utilizing Cloud Computing and Videoconferencing. *Proc. 3rd Information Systems International Conference.*

Jodogne, S. (2018). The Orthanc Ecosystem for Medical Imaging. *Journal of Digital Imaging, 31*, 341-352.

Jones, B., Yuan, X., Nuakoh, E., & Ibrahim, K. (2014). Survey of Open Source Health Information Systems. *Health Informatics- An International Journal (HIIJ), 3*(1), 23-31.

Kusuma, A. A., Agastani, T., Iqbal, M., & Nugroho, T. (2019). Preliminary Assessment of Telemedicine Systems using Virtual Testbed. *International Journal of New Media Technology (IJNMT), VI*(2), 98-103.

Kusuma, A. A., & Irawan, D. (2014). Penggunaan Standard ITU-T G.1070 untuk Estimasi Quality of Experience Layanan Video pada Simulasi Jaringan. *Prosiding Seminar Insentif Riset SINas (INSINAS 2014).* Bandung.

Makinen, A. (2016). *Visualization of Medical Data using Web Technologies.* Master Thesis, Tampere University of Technology .

Malindi, P. (2007). *Methods for Providing Rural Methods for Providing Rural Telemedicine with Quality Video Transmission.* PhD Dissertation, Cape Peninsula University ofTechnology.

Norris, A. (2001). *Essentials of Telemedicine and Telecare.* Wiley.

Sachpazidis, I. (2008). *Image and Medical Data Communication Protocols for Telemedicine and Teleradiology.* PhD Dissertation, TU Darmstadt.

Sakkalis, V., Chiarugi, F., Kostomanolakis, S., Chronaki, C., Tsiknakis, M., & Orphanoudakis, S. (2003). A Gateway between the SCP-ECG and the DICOM Supplement 30 Waveform. *Proc. Computers in Cardiology*, (pp. 25-28).

Smith, A. C., Thomas, E., Snoswell, C. L., Haydon, H., Mehrotra, A., Clemensen, J., & Caffery, L. J. (2020). Telehealth for global emergencies: Implications for coronavirus disease 2019 (COVID-19). *Journal of Telemedicine and Telecare*.

Stamenov, D., Gusev, M., & Armenski, G. (2018). Interoperability of ECG Standards. *Proc. International Convention on Information and Communication Technology, Electronics and Microelectronics (MIPRO).*

Theodora, K. (2012). *Scheduling for Efficient Telemedicine Traffic Transmission over Next Generation Cellular Networks.* PhD Dissertation, Technical University of Crete.

Trigo Vilaseca, J. (2011). *Telemedicine Frameworks in Cardiology Environment: Contributions to Follow-up Services in Specific Scenarios and The Integration and Harmonization of Interoperability and Cardiology Standards.* PhD Dissertation, Universidad Zaragosa.

Ullah, M., Fiedler, M., & Wac, K. (2012). On the ambiguity of Quality of Service and Quality of Experience requirements for eHealth services. *International Symposium on Medical Information and Communication Technology (ISMICT).* La Jolla.

van Ettinger, M., Lipton, J., de Wijs, M., van der Putten, N., & Nelwan, S. (2008). An open source ECG toolkit with DICOM. *Proc. Computers in Cardiology.*