Telemedicine via Satellite: Improving Access to Healthcare for Remote Rural Communities in Africa

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***Abstract*—In this paper, realistic telemedicine implementation scenarios with architecture are proposed to help in extending quality healthcare using satellite and integrated satellite-terrestrial networks (ISTNs). Telemedicine is the use of telecommunications and information technology to extend healthcare service delivery to underserved, remotely isolated communities. Global coverage, broadcast/multicast capability and the high capacity of satellites in Geostationary Earth Orbit (GEO) could potentially serve as a tool to extend quality healthcare to underserved remote rural areas. However, Long End-to-End latency or Round-Trip-Time (RTT) attributed to the GEO satellites could degrade the performance of data communications leading underutilisation of the high available capacity due to high link errors and the long latency, particularly when using Transmission Control Protocol (TCP) over the internet, which accounts for about 90% of the internet traffic today. The actual latency (RTT) of GEO satellites is about $1700ms$ to $3000ms$, which could lead to capacity utilisation as low as 39% of maximum $464kbps$ available capacity of our testbed service provider. However, TCP Performance could be improved by adopting other transmission protocols which we are currently testing and investigating possible modifications for even more enhance performance over satellite and hybrid ($ISTN$) channels network environment.**

***Index Terms*—Telemedicine, Satellite, Latency, Healthcare, Telecommunications, Information Technology, Throughput.**

I. Introduction

The population of Africa is increasing rapidly with projected growth from 1.288 billion to 2.528 billion people by 2050 [1]–[3], yet Sub-saharan Africa (SSA) has lowest health workforce capacity of 3% and healthcare expenditure of 1% globally, which has contributed to the region's highest burden of communicable diseases (25% of global) such as malaria, HIV/AIDS tuberculosis [5]. Today, about 58% of African population live in remotely isolated rural areas [3], mostly sparsely populated with little or no access to medical care due to the lack of medical facilities and professionals at a time when 55% of the world population lives in urban areas with 53% of the world digitally connected and having advanced healthcare [4, 6]. Moreover, 3.4 billion of the world population live in rural areas and this figure is expected to rise before its decline in 2050 due to urbanisation. Africa and Asia contribute about 90% of the global rural population [4].

Although sustainable urbanisation has been identified as key to successful development as the world continues to urbanise, sustainable development largely depends on successful management of urban growth, particularly in low-income and lower-middle-income countries like Africa [4]. However, policies to improve the lives in both urban and rural areas are required to ensure access to infrastructure and services such as healthcare for all [4]. Telemedicine is becoming vital to the healthcare system as it has the potential to help deliver quality medical care to isolated rural areas and, when implemented correctly, it can be a cost-effective way of expanding access to excellent medical care. However, because it is a relatively new and quickly changing field, some challenges need to be addressed.

Telemedicine, which is the use of telecommunications and information technology also known as the use of Information and Communications Technology (ICT) to extend access to quality medical care and to provide improved health care using remote diagnosis, treatment and health information to underserved isolated rural areas by removing distance and cost barriers [5, 7].

The Telemedicine Task Force (TTF) set up in Brussels in January 2006 during a workshop sponsored by European Space Agency (ESA) and European Commission (EC) is tasked with the mandate to develop a comprehensive picture of telemedicine opportunities in Africa on recognition of the potential of Satellite Communications (SatComs) technology to strengthen health systems in Africa and significantly extend the reach of communication to remote and isolated areas of the continent, given the limited reach of terrestrial communication networks. Africa remains the most disenfranchised region in the world with regards to Internet access, with only 34% internet users as of 2018 [6]. The TTF is convinced that by complementing terrestrial infrastructure with SatComs, complete coverage of the African region can be achieved thereby enabling effective and sustainable telemedical services in the region [5].

This paper looks at the digital connectivity challenges in Africa which may impact the effective and sustainable implementation of telemedicine. We propose scenarios for implementation using satellite communications and hybrid networks. We present a review of related recent research and case studies on telemedicine in Africa for the provision of healthcare services is discussed in Section II. The proposed telemedicine implementation scenario, topology and architecture are described in Section III. End-to-End (E2E) performance evaluation and analysis followed in Section IV based on experimental results obtained using Geostationary Earth

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Orbit (GEO) satellite networks. Finally, Section V concludes the findings and details future work.

II. Related Work

Since the World Health Assembly (WHA) resolution in 2005 [8], which encouraged countries to take advantage of the potential offered by eHealth to strengthen health systems and led to the inauguration of the TTF in the Brussels workshop of 2006 [5], with a mandate to develop a comprehensive picture of telemedicine opportunities in Africa using satellite technology. Research and case studies were conducted on the use and feasibility of telemedicine in remote areas to extend healthcare access delivery to the underserved isolated rural communities, particularly in Africa. These recognise the potential impact that advances in ICT and SatComs technologies could have on health-care services delivery, public health surveillance, health education, research and health-related activities for the benefit of both low and high-income countries cost-effectively [5, 8, 9]. However, the key challenge for effective implementation of telemedicine in Africa is the lack of terrestrial communications infrastructure and Internet access, especially in remote rural areas. The TTF was convinced that by complementing terrestrial infrastructure with SatComs, complete coverage of the region can be achieved to enable telemedicine [5]. Recently, a number of research projects by individuals [14]–[17] and organisations [10]–[13] have been carried out to assess the feasibility and implementation of telemedicine via satellite in remote areas of Africa.

The Satellite African E-Health (SAHEL) validation project by ESA, in cooperation with EC and TTF [10], conducted a demonstration for a telemedicine service in SSA to support the extension of eHealth services in Africa through the use of satellite-based technology to complement of other forms of ICT [10]. SAHEL accomplished the first phase in 2014 with collection and analysis of the user requirements for the eHealth solutions in the SSA region through an extensive survey, which then entered its final and engineering-centred phase devoted to three services of SAHEL platform; medical eLearning, Clinical Services and eHealth Management Information System (eHMIS) in line with the TTF objectives [5, 10]. This project demonstration did not consider sustainable topology and architecture for telemedicine centre implementation [10]. However, the SAHEL project proposes efficient cooperation between technological players (industries, operators), health stakeholders (health workers, nurses, specialists), centres of excellence providing medical content for eLearning and NGOs for local implementation with the support of regional actors [10]. In an effort to achieved the initiative of extending health care to remotes locations using SatComs, ESA support and funded the development of *Tempus Pro* (see Figure 3) by Remote Diagnostic Technologies (RDT); a robust portable telemedicine device combining the diagnostic facilities found in a standard hospital with two-way communications via satellite, tested in Algeria and Nigeria [18].

Fig. 1. Thuraya WiCis Telemedicine Solution [13]

Fig. 2. Inmarsat BGAN Link for eHealth [12]

A satellite-based eHealth communications platform (SATMED) [11] was developed to provide a high-quality e-health platform that is open, easy-to-use, readily available and accessible anywhere using SatComs for remote, resource-poor areas of developing countries as shown in Figure 4. Additionally, Inmarsat and Thuraya SatComs operators also conducted some case studies with telemedicine to improve medical care using satellites as shown in Figures 1 and 2, more details can be found from [12, 13]. Most recently, there has been research which addresses medical data compression for enhancing information transfer rate and storage capacity [14], the use of telemedicine in different environments [15, 16] and methodologies used to evaluate telemedicine service in hospital facilities [17].

Although there is growing interest in telemedicine research and with various case study type projects, a gap exists in looking at the implementation topology and architecture. Therefore, our study proposes a topology and architecture for implementation in the future, we hope to study and analyse medical data transmission using the proposed scenarios in our future work.

Fig. 3. Tempus Pro: A Robust Portable Telemedicine Device [18]

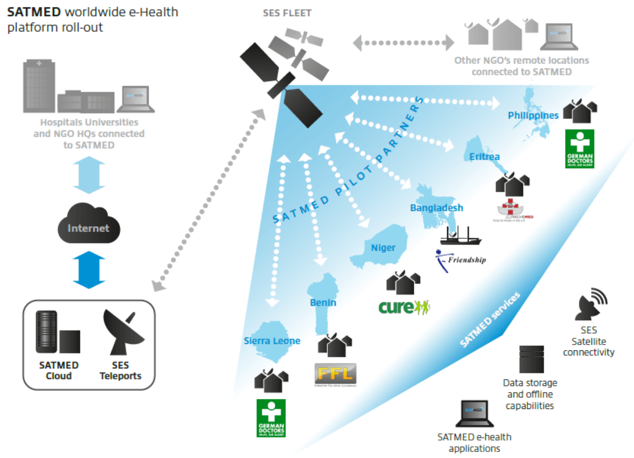

Fig. 4. SATMED Worldwide e-Health Platform Architecture [11]

III. Implementation

The proposed scenarios, topology and architecture for effective implementation and analysis of telemedicine services for improving and extending access to quality health care are discussed in this section.

A. Scenarios and Topology

In this paper, we propose three different scenarios for implementing telemedicine services in remote, isolated rural areas, particularly underserved communities in Africa. The scenarios depict the possible situations in remote rural areas in Africa as described below.

1) Rural-to-Rural Telemedicine Scenario: This scenario establishes digital connectivity via satellite link between two remotely isolated rural health clinics or centres for sharing and exchanging medical data, the two rural clinics were assumed to be unconnected due to the complete absence of terrestrial communications infrastructure. Though very rare in a real implementation, it is possible, particularly in difficult and poor remote African villages, which are also sparsely populated where terrestrial communications are not economically feasible. The topology of the Rural-to-Rural Scenario (RRS) is shown in the upper right of Figure 5 connecting two remote clinics using only a satellite channel.

2) Rural-to-Urban Telemedicine Scenario: The Rural-to-Urban Scenario (RUS) establishes digital connectivity via a satellite link between remotely isolated rural health clinic (s) or centre (s) to urban hospital (s) with enough medical experts and facilities for more advanced diagnostic and the exchange of medical data, the rural clinic was assumed to be unconnected due to the complete absence of terrestrial communications infrastructure. This is the more realistic scenario to implement particularly in difficult and poor remote African villages, which makes terrestrial communications not economically feasible. The topology of Rural-to-Urban Scenario (RUS) is shown from the upper right down to the lower section of Figure 5 connecting remote clinic (s) using only satellite channel or Integrated Satellite-Terrestrial networks (ISTNs) such as a public land mobile network (PLMN) found in developed urban areas.

3) Hybrid Telemedicine Scenario: In the case of Hybrid Scenario (HRS), it combines the features of both RRS and RUS to digitally connect remote rural clinic(s) to the urban hospital(s) through another remote rural clinic using both satellite channel and ISTN. Figure 5 shows the topology of HRS from the direction of RRS to the upper left to the lower side connected using PLMN.

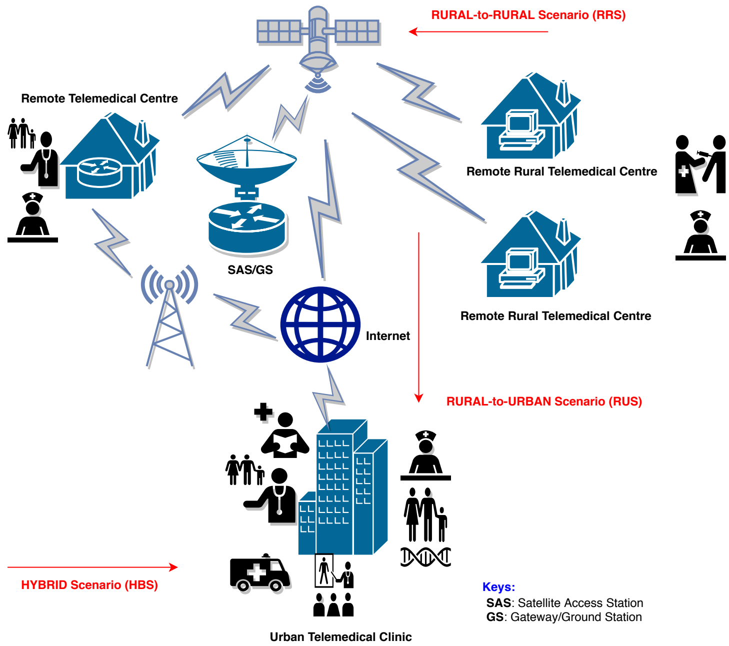

Fig. 5. Propose Telemedicine Scenarios and Topology

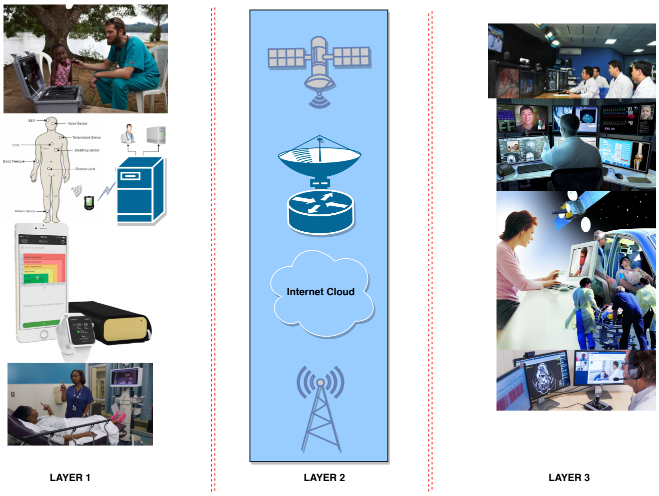

Fig. 6. Propose Layered Architecture for Telemedicine Implementation

B. Architecture

The proposed architecture constitutes of the three layers dividing access technologies with communications links connecting remote rural clinic(s) patients/medical team with urban hospital experts and facilities as shown in Figure 6 and described in the following sections.

1) Layer 1: This layer serves as the point of medical data collection in the remote rural clinic(s) using different access and connection technologies from patient (s), smart body sensors/medical instruments, support team, data storage and network access. As shown in Figure 6, the smart body sensors, medical data loggers and measurement equipment are connected using small distance communication technologies such as Bluetooth, WiFi and Ethernet links to the data storage or server for onward transmission over the satellite link. Medical data and records of the remote patient(s) will be acquired at this layer using the ICT capabilities mentioned.

2) Layer 2: This layer is responsible for providing backbone link satellite link using either SatCom or a hybrid comprising terrestrial/satellite links (ISTNs) and other network infrastructure for connecting remote rural clinics/health centre to an urban hospital for access quality and improved health care service as shown in Figure 6.

3) Layer 3: The final layer for accessing telemedicine services as shown in Figure 6, the layer consisting of enough medical experts/specialists, advanced medical facilities for more advanced diagnostic and treatment of the patient(s) located in urban medical facility to provide services.

IV. End-to-End Performance Evaluation

In this section, we evaluate and analyse the impact of E2E long latency (delay) in both scenarios involving satellite and hybrid links on data transmission. Observing how much throughput could be achieved from the available capacity of the real/practical system used as the testbed.

The E2E latency measurement used for performance evaluation for different scenarios are described in [28], the setup consisted of real Wi-Fi and Satellite hybrid links connected to a Broadband Global Area Network ($BGAN$). The satellite BGAN link has maximum Achievable Throughput (ATP) of $464kbps$ connecting three Wi-Fi nodes with two of the nodes generating TCP traffic over the link while the other node serve as TCP traffic sink.

A. End-to-End Latency and Throughput

The long propagation latency or delay attributed to satellite links, particularly on Geostationary Earth Orbit (GEO) has an impact on data communication performance and the waste of capacity (also known as underutilisation of capacity in satellites). Transmission Control Protocol (TCP) is the most widely used protocol for data transmission over the internet [19]–[24], including telemedicine applications. Performance of TCP-based applications can be degraded due to the combined effect of long E2E latency and high wireless link transmission errors leading to high packet/bit errors according to equation 1 [25].

$$R_{TCP}[kbps] = (\frac{MSS}{RTT})\frac{1}{\sqrt{PER}} \tag{1}$$

Where $R_{TCP}[kbps]$ is the achievable throughput of any TCP connection, $MSS[bytes(B)]$ is the maximum segment size in TCP connection, $RTT[ms]$ is the round-trip-time of E2E connection path (in this case, $RTT = 2 * \Phi_{E2E}$; Φ_{E2E} is E2E One-Way-Delay [OWD]) and PER is the packet error (loss) rate. Equation 1 can also be simplified to Equation 2 using maximum congestion window based analytical assumptions [24].

$$R_{TCP}[kbps] = \frac{MSS}{RTT}\sqrt{\frac{3}{2PER}} \tag{2}$$

Comparing Equations 1 and 2, $\sqrt{\frac{3}{2}} \approx 1$ in Equation 1.The transmission rate (achievable throughput) can equally be computed using Equation 3 which takes into account the effect of link congestion in the connecting E2E path which includes the sending and receiving end users equipment (UE).

$$R_{TCP}[kbps] = \frac{cwnd_{max}}{RTT} \tag{3}$$

Where, $cwnd_{max}[bytes(B)]$ is the maximum congestion window, which is the TCP state variable that limits the amount of data any TCP connection could send or receive. This variable sets limits to the amount of data the sender can transmit into the network path before an acknowledgement is received. The results obtained in this paper using Equation 3 were used to compute and evaluate E2E capacity utilisation with knowledge of the system's available capacity $C[kbps]$. The system efficiency $\eta[\%]$ was determined using Equation 4 and testbed Available Throughput (ATP) as $C[kbps]$.

$$\eta[\%] = \frac{R[kbps]}{C[kbps]} \tag{4}$$

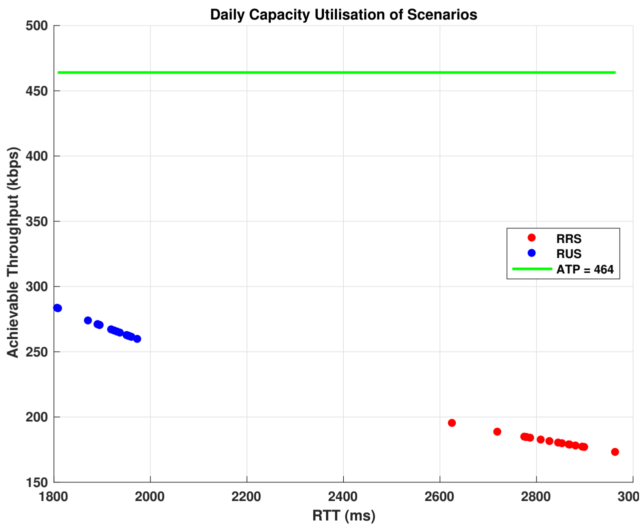

Fig. 7. E2E Throughput and RTT Daily Performance of the Scenarios

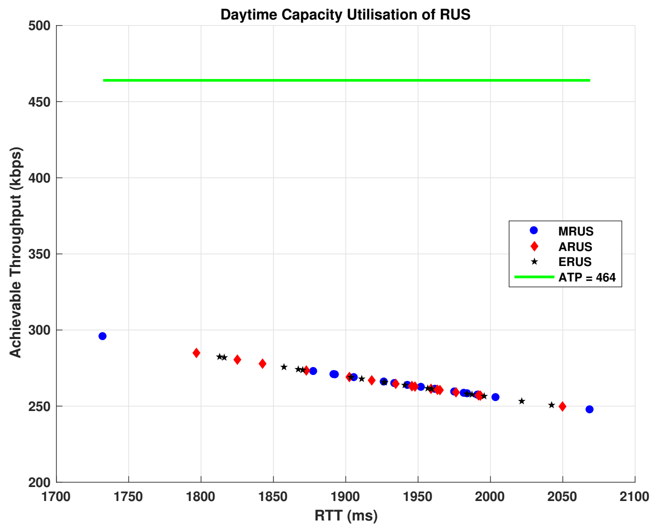

Fig. 8. E2E Throughput and RTT Daytime Performance of the Scenarios

The E2E latency measurement results obtained experimentally in [28] using real SatComs network environment showed that the E2E latency is much higher than assumed by many studies related to SatCom, particularly geostationary [25]–[27].

The negative impact of long latency was observed on the transmission rate (Achievable Throughput) performance, which shows inverse proportionality as in Equations 1 to 3 and Figures 7 and 8. The results in Figure 7 showed the daily achievable throughput against the E2E latency (RTT) and Figure 8 showed the daytime performance based on capacity utilised at a particular time of the day (M is Morning, A Afternoon and E Evening). The horizontal (green) line on both Figures indicates the achievable throughput of the testbed service provider.

The achievable throughput of the propose scenarios (RRS and RUS) decreases with the increased RTT during the day (Figure 7) and during specific times of the day, mostly in the morning with average of $263.98kbps$ (56.89%) shown in Table II and Figure 8, which led to the daily capacity underutilisation (low efficiency η) as low as $182kbps$ (39.22%) on average and maximum of $195kbps$ (42.03%) as shown in Table I using RRS scenario. The results were consistent in both daily and daytime experiment using RUS scenario (see Tables I and II) with average capacity utilisation of about $265kbps$ (57%) and overall maximum of $287.64kbps$ (61.99%) as in Table II.

TABLE I
DAILY CAPACITY UTILISATION SUMMARY OF SCENARIOS

Scenario	$R_{max}(kbps)$	$R_{avg}(kbps)$	$\eta_{max}(\%)$	$\eta_{avg}(\%)$
RRS	195	182	42.03	39.22
RUS	283	268	60.99	57.76

TABLE II
DAYTIME CAPACITY UTILISATION SUMMARY OF RUS SCENARIO

Daytime	$R_{max}(kbps)$	$R_{avg}(kbps)$	$\eta_{max}(\%)$	$\eta_{avg}(\%)$
M	299.55	263.98	63.70	56.89
A	284.95	265.42	61.41	57.20
E	282.43	265.85	60.87	57.29
Overall	287.64	265.08	61.99	57.13

The more likely scenario to be implemented in telemedicine for transmission of medical data or records will be RUS, since most urban areas have available Public Land Mobile Networks (PLMN) available that are also reliable. The achievable throughput performance ($57 - 62\%$ of $464kbps$ in our case study) of RUS may be sufficient for most telemedicine applications and data.

Although the throughput of SatComs with large bandwidth-delay product (BDP) deteriorated when data transmission used the original standard TCP, efficient capacity utilisation could be improved by TCP enhancement to reduce the impact of long RTT and high wireless link errors. An effective compression technique could also be used to improve the bandwidth efficiency by transmitting more data using the available capacity of the system, this will be the recommendation for future work.

V. Conclusions and Future Work

Telemedicine implementation scenarios, topology and architecture proposed in this paper, provide a practical way to extend quality healthcare in remote rural areas that can improve healthcare service delivery to underserved communities, particularly in isolated rural areas of Africa where healthcare workforce capacity is extremely low or completely absent and terrestrial communications are not available or are unreliable due to the cost of deployment and maintenance, which makes them not economically feasible. The results of our experimental study of performance indicated the possibility of using most telemedicine services and more could be supported by the use of enhanced TCP protocol and compression technique. Research and case study are still going on for effective and sustainable use of telemedicine in remote rural areas. Our future work will focus on TCP and compression techniques enhancement for efficient use of satellite capacity by reducing the impact of long RTT and packet error rates of satellite wireless link.

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