Integrated Satellite-Terrestrial Network for Smart Grid Communications in 6G Era

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***Abstract*—In this work, we developed and proposed a real testbed with Integrated Satellite-Terrestrial Network (ISTN) scenario. This topology was used to measure the actual parameters that were used as the Smart Grid (SG) Quality of Service (QoS) metrics. Performance was evaluated with reference to the QoS requirements of SG applications. The emergence of new and evolving technologies, such as smarter energy utilities enabled by advanced communications technologies, necessitated evolutionary enhancements of both satellite and terrestrial communications systems. These would help improve energy efficiency and sustainability through the effective acquisition and analysis of data from energy systems. Hybrid communication technologies can be used to collect and share energy data efficiently and ubiquitously from generation stations to consumption sites. Thus, a topology using Inmarsat-4 satellites is presented that connects a robust, portable, and energy-efficient Broadband Global Area Network ground terminal. Performance evaluation was performed using measured parameters from the real ISTN topology testbed against key SG applications. The latency and bandwidth requirements for the 80-90% key SG applications were found to be within the QoS requirements range.**

***Index Terms*—Bandwidth, capacity, communication, latency, performance, 6G, SatCom, Smart Grid.**

I. Introduction

Satellite Communications (SatComs) will play a critical and complementary role in sixth generation (6G) and beyond mobile networks [1], to help achieve most of the key requirements for the new enhanced capabilities of 5G and future networks as shown in Fig. 1 [2]–[5]. The smarter energy utility, called Smart Grid (SG), requires the support of Integrated Satellite-Terrestrial Network (ISTN) technologies. Several SG applications like supporting consumers, remote generation facilities, and utility corporate headquarters in high-dense urban areas require ISTN scenario for effective communication. Recent development in SatComs with flexible, portable, reliable and energy-efficient terminals connecting extremely high-capacity satellites for broadband services could be leverage for the benefit of the key SG applications. Distribute Automation (DA), Substation Automation (SSA), and Advanced Metering Infrastructure (AMI) are some of the key SG applications to benefit from ISTNs. SatComs is one of the key network technologies for achieving ubiquitous, reliable, robust, and secured SG Communications (SGC) of the future power utilities.

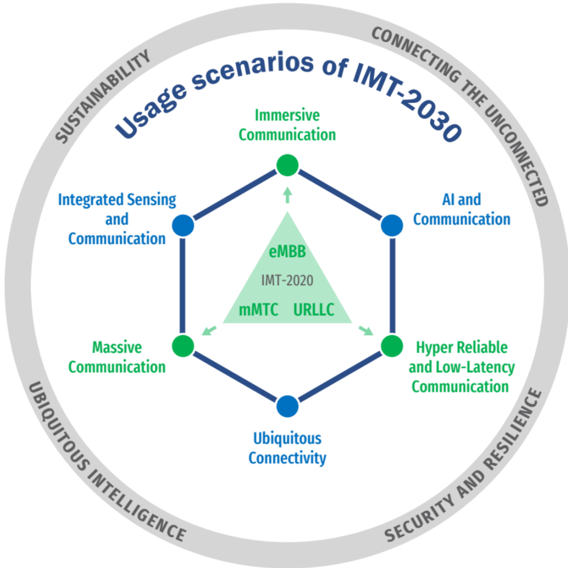

Fig. 1. Use Case Scenarios for IMT-2030 and beyond [2], [3]

SG applications located in isolated rural areas or difficult terrain environments requires the use of SatCom networks and systems.

SatCom's unique features like ubiquitous connectivity, availability (99.999%), huge bandwidth of High Throughput Satellites (HTS), asymmetric bandwidth capabilities, backhauling and resilience can be exploited [5]–[9]. Power grid networks are evolving and transforming into more dynamic, resilient, and adaptable for future electric utilities [10]–[12]. The challenge of transforming electric utilities in generation, transmission, distribution, and consumption to a smarter one is critical and requires understanding of evolving communications technology requirements and development due to inherent complexity [10], [11]. Incorporating advanced communications and network technologies (5G and 6G) in electric power systems to form SG Communications (SGC) is the key to achieving smarter grid networks that will make energy data exchange reliable, secure, and sustainable [11], [13]. In addition, ubiquitous connectivity is vital for connecting intelligent devices distributed in urban and remote locations to provide duplex communications of data, control and monitoring instructions to smart utilities' main control centres. This would revolutionise electricity generation, delivery, and usage by integrating the two-way flow of electricity and information. Providing the capability to monitor and respond to changes from power generation plant to end-user with potential benefits of increase reliability, energy-efficiency, harnessing and integrating renewable energy, reduce CO_2 emissions, better consumer's control to electricity demand/usage and cost-effective energy system from generation to consumption [10], [12], [14], [15]. Therefore, need to develop a real testbed and scenario utilising Satellite-Terrestrial Network Link (STNL). This propose ISTN topology is used to measure actual parameters that are used for determining SG Quality of Service (QoS) metrics. This paper developed and proposed a real testbed using Integrated Satellite-Terrestrial Network (ISTN) scenario with section I presenting an introduction to SG and SatCom, and the est of the paper organised as follows; section II reviewed some of the key requirements of SG communications and applications, section III discuss the SatCom for SG communications. Section IV discusses the SGC experiment using the proposed topology, section V presents the performance evaluation and analysis.

II. Smart Grid Quality of Services Requirements

The goal of SG to allow utility companies to generate, distribute energy efficiently and consumers to optimise energy consumption is enabled by smart communications technologies, which rely on successful design and implementation of reliable, secure, robust, and cost-effective communications network infrastructure. This is challenging, SGC needs integration of unique elements for effective communication among an extensive number of homogeneous devices across large geographical areas and diverse applications. These applications require high availability of communications with different QoS constraint as shown in Fig. 2 [14], [15]. The layered architecture of SGC network consists of two main layers [14] *(1) The power system layer, which integrates different power generation, transmission grid, distribution grid/substations, and consumption* as in Fig. 2a and *(2) The communication system layer, this is the unique feature of SG compared to the existing electrical grid that forms the SGC networks responsible for intelligent monitoring, grid control and automation* as in Fig. 2b. This paper focused on layer (2) and is represented in three segments; Home Area Network (HAN), Neighbour Area Network (NAN) and Wide Area Network (WAN) as in Fig. 2b. This can only be realised by integrated technologies like ISTNs, wireless, and wired communications technologies [14], [16], [17]. Technologies such as WiMAX, ZigBee, WiFi, Public Land Mobile Network (PLMN) and OFC networks play indispensable role in achieving the primary goal of the future SGC networks. SatComs offer huge bandwidth in GHz using K-bands (Ka/Ku-bands) and HTS that translate to high data rate up

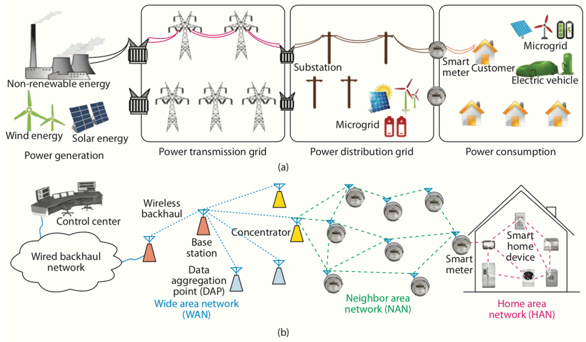

Fig. 2. Layered Architecture of SG and SGC [14]

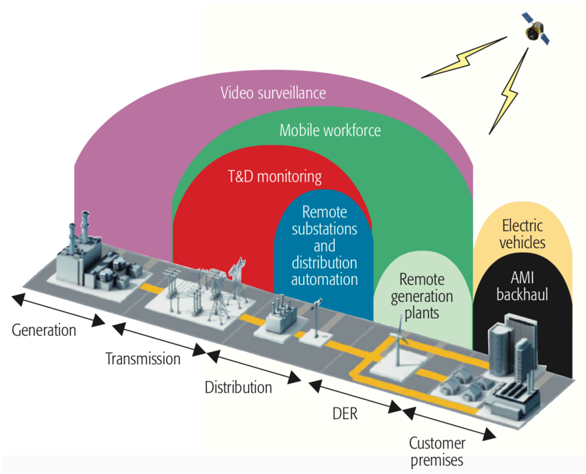

Fig. 3. Smart Grid Applications and Domain for SatCom [21]

to 90 $Gbps$ and high capacity of up to 1 $Tbps$ in the future [18], [19]. These features are ubiquitous and ensure 100% network availability even in remote and isolated areas that are difficult to connect using terrestrial networks.

Utilities in SG applications require high availability communications that are cost-effective and highly redundant connections at critical sites where terrestrial communications might not cope or near impossible due to severe disruptions or damage on fixed and wireless infrastructure caused by natural disasters. SatComs is the preferred candidate in these scenarios [15], [20]. SatComs providers provide services exclusive to Machine-to-Machine (M2M) communications that are essential to core SG applications such as SSA with Supervisory Control and Data Acquisition (SCADA), telemetry, AMI backhaul and DA. These applications cover generation, transmission, distribution, and Distributed Energy Resources (DER) domains [12], [20], [21] as in Fig. 3.

Key SG applications include AMI/Smart Meter (SM), Distribution Grid Management (DGM), Demand Response (DR), DER and storage, Wide-Area Situational Awareness (WASA), and Electric Vehicles (EV). These require different levels of QoS requirements in terms of *bandwidth, latency, reliability, security, cost and backup power* network parameters. These are designated using (*low/loose (L), medium (M), and*

TABLE I
SG APPLICATIONS AND COMMUNICATIONS QOS REQUIREMENTS

	Key Applications and QoS Requirement					
Net Parameter	**AMI/SM**	**DR**	**DERS**	**EV**	**WASA**	**DGM**
Bandwidth (kbps)	10-500	14-100	9-56	9-100	600-1500	9-100
Latency	2-15s	$\geq 500ms$	20ms-15s	2s-5min	20-200ms	100ms-2s
Reliability(%)	99-99.99	99-99.99	99-99.99	99-99.99	≥ 99.999	99-99.99
Security	H	H	H	Rel. H	H	H
Cost	L					M-H
Redundancy(hrs)	NN	NN	1	NN	24	24-72

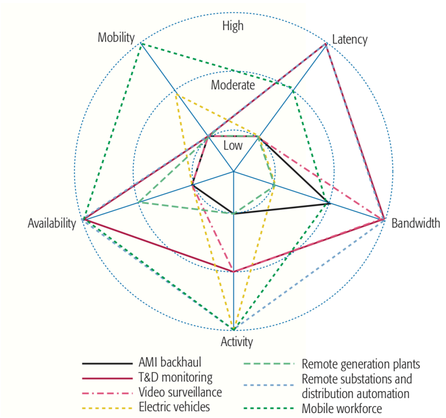

Fig. 4. QoS Requirements Map for Key SG Applications [21]

high/tight (H/T)) as given in Table I and Fig. 4 [12], [21]. DGM consisted of sub-applications like DA, SSA, Video Surveillance (VS) and fleet management using Automatic Vehicle Location (AVL). Levels of QoS requirement for SG applications can be described using a map shown in Fig. 4 [21].

Therefore, considering the QoS requirement in Table I, SatComs will be an excellent candidate for actualising the smart power grid using SG. This brings more efficient, reliable, secure, intelligent, and cost-effective power system from generation to consumption phases. SatComs capabilities to provide extended coverage, fast deployment, high capacity, and high availability of up to 99.999% for achieving reliable communications where terrestrial communications infrastructures are not feasible [21].

III. SATELLITE FOR SMART GRID COMMUNICATIONS

Reliable Internet data transportation across E2E network path can be achieved using *de-facto* TCP over ISTN link. However, Satellite links attributes such as long RTT, high error rates, and high BDP, particularly when connected to the Geostationary Earth Orbit (GEO) HTS. These present challenges that affect the performance and behaviour of data delivery [24], [25]. This can also lead to under-utilisation of the huge capacity of the satellite channel. To address these, Congestion Control Algorithms (CCA) need to be improved for satellite channel and Long-Fat-Nettwork (LFN) environments. Several solutions were proposed until around year 2010 [23]–[27], and research in this area has slowed down.

However, popular improved CCA over satellite links include; Performance Enhancing Proxies (PEPs), which changed the E2E semantics of TCP. PEPs were developed to enhance the performance of TCP/IP over networks with link characteristics that suffer performance degradation using the original TCP over ISTN [34]. Moreover, enhancements that do not infringe the E2E semantics of the TCP such as TCP Hybla (based on TCP NewReno) [30], were proposed to improve performance deterioration in heterogeneous networks involving satellite links characterised by long $RTTs$ that led to capacity under-utilisation. Another scheme TCP CUBIC was proposed based on Binary Increase Congestion Control (BIC) [31]. This was designed to improve the window growth function such that it became independent of RTT, include TCP-friendliness, scalability, and RTT-fairness [29], [31]. CUBIC allows the window size of the competing TCP flows that share the same bottleneck to be approximately the same [29], [31]. Details on E2E TCP enhancements designed to mitigate performance deterioration of the standard TCP in a large BDP environment such as LFN and ISTN, particularly involving GEO HTS, can be found in [23]–[27], [29], [31]–[33].

Another alternative to improving the performance of TCP due to long RTT, is to use utilise high-capacity lower altitude satellites such as Medium/Low Earth Orbit (MEO/LEO) satellite constellations. Recently, high capacity and low latency mega satellite constellations like Starlink, and Other 3 billion (O3b) were developed and operational with large global coverage and low latency of about 25 ms. Geographical deployment of smart grid utilities prompted the issue of accessibility. This advancements in satellite network and technology [11], could replace broadband and WAN [11]. Using SatComs for backhaul network and other smart grid infrastructure eliminates the need for internet access. SatComs has been used to provide SCADA connectivity and communication among remote sub-stations. VSATs have facility to support bidirectional data rate up to 1 $Mbps$ with coverage of 6000 km [11]. Availability of 99.999% can be achieved using SatComs dual frequency and dual access capabilities [11].These features make ISTN an excellent candidate for SG applications. Although there were research efforts to develop a new TCP and to improve performance over satellite channels and ISTN environment [23]–[27], [29], [31]–[33]. Little or no efforts were made to evaluate the performance of these algorithms using the actual parameters like actual latency measured from practical experiments using GEO satellites. This paper developed a real ISTN testbed using Broadband Global Area network (BGAN) Satellite User Terminals (SUT) shown in Fig. 5. This real testbed was used to measure practical parameter values for the SG communications and applications. These practical values were compared with the applications' QoS requirements in Table I in order to verify and validate the proposed topology.

IV. Smart Grid Communications Experiment

Experimental measurements were conducted using practical GEO SUT from a satellite network provider and mobile User Equipment (UE) from a PLMN provider in England, United Kingdom. Measurements were conducted by transmitting and receiving data in the morning, afternoon, and evening times in a day for fifteen and thirty days in two months. The testbed assumes a Bent-Pipe (BP) satellite hop, which doubles the latency due to intermediary gateway stations (GWS). Scenarios and topology were developed to have a framework for the measurements [36]. In this paper, real testbed using STNL scenario representing ISTN topology was developed as shown in Fig. 5. This topology depends on GWS for processing and routing without On-board processing and routing. However, considering the dual-hop connection and configuration of the topology in Fig. 5, SUT also served as a router and access point, this does little or no data processing like GWS. The ISTN topology in Fig. 5 used TCP/IP to transport data across the STNL to analyse how performance deteriorates over a heterogeneous network environment used for SGC and applications. Key parameter to determine the performance of any network using TCP/IP is the congestion window, W (in segments unit), and evolution/growth rate function $W(t)$ (in segments or bytes). This is also the key to evaluating the performance of TCP algorithms. For example, the instantaneous transmission rate $R(t)$ (in segments/secs or bytes/secs) is dependent on $W(t)$ from which efficiency (capacity utilisation) can be derived. This parameters that affect performance and provide analytical expressions for subsequent evaluation and analysis were defined from (1) to (4). The focus is on SG application QoS evaluation and analysis using the actual latency measured practically.

TCP implements the window growth function (1) and updates the window after receiving acknowledgment from the receiver using the window update rule (2) [22], [30]. Achievable throughput, $R(t)$ is determined from (1) and RTT value using (3), while the total data transmitted since the transmission started $T_D(t)$ (in segments or bytes) is determined by integrating $R(\tau)$ over the time elapsed from start to the end

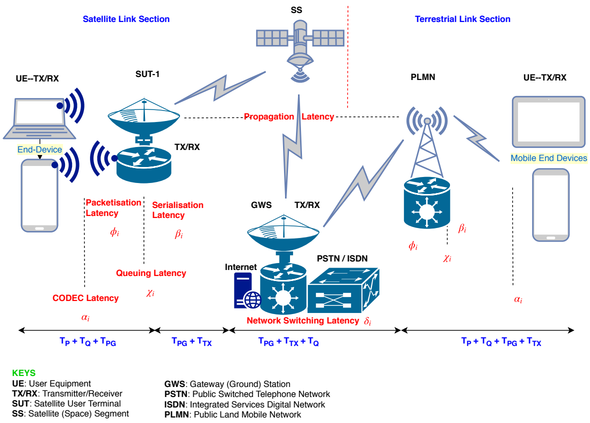

Fig. 5. Integrated Satellite-Terrestrial Network Scenario & Topology

of the transmission, this is simplified analytically in (4) [22], [30].

$$W(t) = \begin{cases} 2^{\frac{t}{RTT}} & 0 \leq t < t_\gamma \quad SS\ (Exponent) \\ \frac{t-t_\gamma}{RTT} + \gamma & t \geq t_\gamma \quad CA\ (Linear) \end{cases} \tag{1}$$

where $t_\gamma = RTT \log_2(\gamma)$, is the time that the Slow Start Threshold (ssthresh) value γ is reached with RTT.

$$W_{i+1} = \begin{cases} W_i + 1 & SS \\ W_i + \frac{1}{W_i} & CA \end{cases} \tag{2}$$

TCP instantaneous transmission rate $R(t) = W(t)/RTT$ was derived from (1) and simplified as;

$$R(t) = \begin{cases} \frac{2^{t/RTT}}{RTT}; & 0 \leq t < t_\gamma \quad SS \\ \frac{1}{RTT}\left(\frac{t-t_\gamma}{RTT} + \gamma\right); & t \geq t_\gamma \quad CA \end{cases} \tag{3}$$

$$T_D(t) = \begin{cases} \frac{2^{t/RTT}-1}{\ln(2)} & 0 \leq t < t_\gamma \\ \frac{\gamma-1}{\ln(2)} + \frac{(t-t_\gamma)^2}{2RTT^2} + \frac{\gamma(t-t_\gamma)}{RTT} & t \geq t_\gamma \end{cases} \tag{4}$$

From (1) to (4), the effect of RTT on the performance of ACK-based TCP algorithms such as Reno and NewReno can be observed.

V. Results and Performance Evaluation

Actual latency was measured experimentally using a real ISTN topology and testbed over GEO satellite and PLMN as described in section IV. Results obtained were summarised in Table II. These results were numerically computed from the practically measured one-way delay (OWD) given by $RTT = 2 * OWD$ as described in [36]. Implementing the CCA in (1) to (4) using MATLAB resulted in Figures 6, 7, and 8. An ideal channel was considered during the algorithm implementations, i.e an error-free ($PER = 0$) and in the absence of congestion. These conditions were considered for effective evaluation and analysis and to better understand the impact of latency on key SGC

TABLE II
SUMMARY OF DAYTIME PRACTICAL RTT

Time	RTT_{max}	RTT_{min}	RTT_{avg}
Morning (ms)	2070	1732	1942
Afternoon (ms)	2050	1796	1932
Evening (ms)	2042	1812	1928
Overall	2054	1780	1934

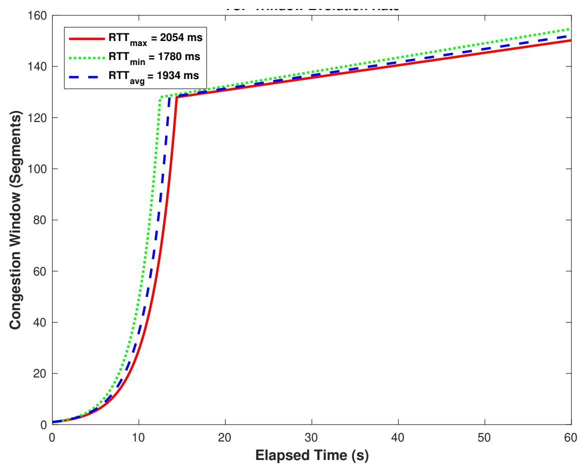

Fig. 6. Congestion Window Growth Rate ($W(t)$) Function

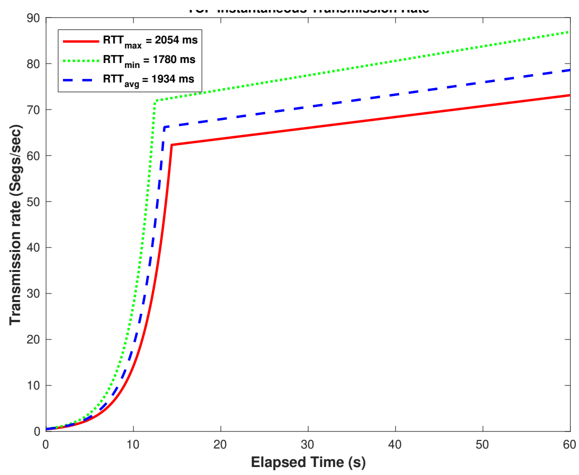

Fig. 7. Instantaneous Transmission Rate ($R(t)$) Function

applications parameters. The *overall* RTT values, i.e RTT_{max}, RTT_{min} and RTT_{max} from Table II were used to implement the TCP algorithms.

The values of $W(t)$, $R(t)$, and $T(t)$ were also computed numerically by considering *ssthresh* (γ) value of 128-segments as a global variable in both algorithms' implementation. Window growth rate in TCP is slow (larger t_γ and longer elapsed time t) with higher values of RTT as shown in Fig. 6, especially during the slow start (SS) phase. This slower window growth takes longer time to update the window size using (2) and has a negative impact on $R(t)$ and $T_D(t)$ as shown in Fig. 7, and 8. This can be verified analytically by simple inspection of RTT dependence on (3) and (4). Throughout the transmission period of 60 $secs$,

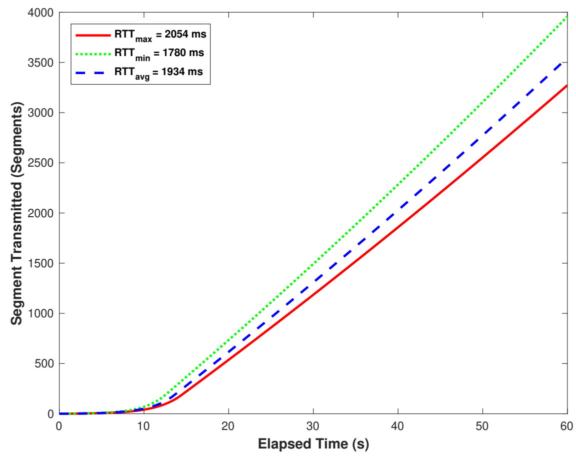

Fig. 8. Total Transmitted Data ($T_D(t)$) Function

TABLE III
SUMMARY OF DATA TRANSMISSION RATE BASED ON RTT

Rate	RTT_{max}	RTT_{min}	RTT_{avg}
R (seg/s)	73	88	80
R (bps)	59016	720896	655360
R (kbps)	598	721	655

$W(t)$ was less than 160 $segs$, while the transmission rate and total data transmitted within the same time period are below 90 $segs/secs$ (737.28 $kbps$) and 4000 $segments$ respectively. These results were based on the Maximum Segment Size $(MSS) = 1024\ bytes$ such that $R[kbp] = R[segs/sec] * MSS[bits]$.

Considering the high bandwidth of GEO satellite and recently enhanced capabilities of 5G/6G networks, the bandwidth requirements can be achieved. The proposed scenario achieved up to 721 $kbps$ with $RTT_{max} = 2054\ ms$ and an average of 655 $kbps$ at $RTT_{avg} = 1934\ ms$ as shown in Table III.

The minimum transmission rate achieved was 598 $kbps$ at $RTT_{min} = 1780\ ms$, this is within the QoS requirements of most of the applications in Table I. Thus, almost all of the SG applications would perform better using our proposed ISTN topology considering the satisfactory QoS requirements like latency, bandwidth, reliability, cost and security.

VI. CONCLUSIONS

SatComs will continue to play vital role in 6G and beyond networks due to high-capacity, high-bandwidth, and global coverage for connecting the unconnected. Ubiquitous connectivity can be achieved using unique features of SatComs as well as complementary to terrestrial counterparts. In this paper, we propose ISTN scenario and topology for SG applications and discussed performance over long RTT heterogeneous network environment. The maximum actual latency ($RTT_{max} = 2054\ ms$) achieved the minimum data rate of 598 $kbps$. The average data rate value of 655 $kbps$ was obtained at $RTT_{avg} = 1934\ ms$. These results satisfied the key QoS requirement of most SG applications. Using satellite link as part of the ISTN testbed would provide $reliability$ of $99.999\ \%$ for the proposed scenario. Results showed that RTT is one of the key parameters that affects the performance of transport protocol over IP. Our proposal and findings have global and societal impacts interms of sustainability and cost-effectiveness of utilising ISTN in both urban and rural isolated areas where terrestrial network infrastructure are difficult or costly to deploy. In the future, we would like to investigate the performance of using enhanced TCP schemes and LEO satellite link such as Starlink for application in SG communications networks. These results will be compared with the existing solution at the time.

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