HYBIC: An Improved Congestion Control Algorithm for Integrated Satellite-Terrestrial Networks in 5G and Beyond Communications

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***Abstract*—In this paper, we propose an improved Transmission Control Protocol (TCP) algorithm called HYBIC, building upon existing CUBIC and HYBLA algorithms. This HYBIC algorithm is designed for improving capacity utilisation and transmission rate of heterogeneous networks such as the Integrated Satellite-Terrestrial Networks (ISTN) and long delay High Throughput Satellites (HTS) networks on Geostationary Earth Orbit that are characterised with high bandwidth-delay product path. Results analysed indicated that better performance is achieved using the proposed HYBIC algorithm. Considering the results, HYBIC achieved better performance in terms of window growth of $23x10^3$ $segments$, transmission rate of $3Gbps$, and capacity utilisation of 60 % compared with both CUBIC and HYBLA. However, the proposed HYBIC inherits the features of Round-Trip Time fairness, scalability, and friendliness of HYBLA and CUBIC algorithms.**

***Index Terms*—Algorithm, Bandwidth, Delay, ISTN, Protocol, Performance, RTT, SatComs, TCP, HYBIC.**

I. Introduction

The emerging and future communication networks such as fifth/sixth generations (5G/6G) and beyond are characterised by increased bandwidth/capacity, ubiquitous connectivity, massive connectivity, integrated sensing and communication [1]. Non-Terrestrial Networks (NTNs) are increasingly gaining popularity as an excellent candidates to provide connectivity in remote isolated areas due to the growing integration of satellites and Unmanned Aerial Vehicles (UAVs) with cellular networks [1], [2]. Using heterogeneous networks with Geostationary Earth Orbit-High Throughput Satellites (GEO-HTS) lead to increase in the Bandwidth-Delay Product (BDP) of the network path [3]. This increase in BDP has a significant impact on Internet Congestion Control Algorithms (CCA) such as the Acknowledgement and Round-Trip Time (ACK/RTT) based Transmission Control Protocol (TCP) [4]–[6]. Most of the TCP schemes [7]–[12] proposed to handle issues related to high link error such as satellite radio links experience performance degradation and capacity underutilisation when using these schemes [9], [10]. The increasing demands for capacity, coverage, and massive machine-type communications make Geostationary Earth Orbit High Throughput Satellites (GEO-HTS) and Integrated Satellite-Terrestrial Networks (ISTNs) indispensable components to support and complement the key enhanced capabilities of 5G New Radio (NR) and 6G networks [13]–[16]. The widely used TCP has become a de facto transport protocol for most Internet applications and accounts for 80-90% of the Internet data traffic nowadays due to its End-to-End (E2E) reliable delivery feature [3]. TCP is gradually replacing the data frame formats such as frame relay and HDLC in satellite communication networks [3]. This congestion control mechanism of TCP is the major reason the Internet has not collapsed. Therefore, enhanced CCA is required for efficient capacity utilisation of the huge available bandwidth and better performance of the emerging and future communication networks. Several high-speed TCP schemes were proposed with the most popular being HS-TCP, Scalable TCP, BIC-TCP, CUBIC, FAST, H-TCP [8], [18], [19], and HYBLA [20], [22]. However, most of these enhanced algorithms [18], [19] focused on resolving losses due to the congestion window *cwnd* dynamics that lead to congestion event. The HYBLA [20] proposal removed the performance dependence on RTT which disadvantaged the long RTT channels in ISTNs environment [6], [21]. The exponential growth of Internet users and the need for ubiquitous connectivity triggers the increasing demands for high capacity and reliable connectivity. While satellite and heterogeneous networks provide global coverage and extremely high capacity using HTS and other NTNs, their long delays on GEO and high BDP limit and degrade the performance of TCP based applications and services such as delay-sensitive (real-time) and jitter sensitive data transmission applications. Therefore, to achieve better performance with TCP over heterogeneous ISTNs, there is a need for optimum CCA that is both independent of the RTT and better utilisation of high capacity networks.

In this paper, we propose an improved CCA known as HYBIC that combined the features of RTT independent HYBLA [20] and CUBIC [18], [19] friendliness with competing flows, as well as better capacity utilisation with transmission rate optimisation. HYBIC scheme removed the aggressive *cwnd* growth in HYBLA by modifying its Congestion Avoidance (CA) phase with cubic function, while adapting effective Slow Start (SS) phase that removed the slow increase of standard TCP *cwnd* in CUBIC. These modifications enhanced the achievable throughput of long RTT paths and better utilisation of high capacity networks. Thus, performance improvements were achieved through modification of the *cwnd* dynamics in both the SS and CA phases as described in this letter. Section I highlights the need and motivation of better performing TCP scheme over ISTN environment, section II provides the design of the HYBIC scheme, section III discuss the performance analysis and evaluation based on the results obtained using HYBIC scheme, and section IV give the conclusions.

II. HYBIC Algorithm

A. Mathematical Model

The optimum performance of TCP at the transport layer and efficient utilisation of the channel capacity C over a large BDP path is achieved by maximising the transmission rate, $R(t)$ as in (1).

$$\max_{R} = \sum_{i=0}^{N} W_i(R_i) \tag{1}$$

Subject to:

$$W \leq cwnd \tag{2}$$

$$R \leq C \tag{3}$$

where R is the aggregate throughput achieved and R_i is the average throughput of the i^{th} flow at any instant of transmission, referred to as instantaneous transmission rate, $R_i(t)$ and W is the current window growth rate obtained from the measured congestion window, $cwnd$ of the flow path and the receiver advertised window, $rawnd$, usually derived from $W = min(cwnd, rawnd)$ in algorithms such as TCP Reno. Considering the physical layer, R is also is limited by the capacity C as expressed (constrained) in (3).

ISTN star topology given by Fig.1 was considered as a reference network model for the performance optimisation in this paper. This network topology is characterised by having high capacity and long RTT that resulted in an extremely large BDP path for evaluating the performance of new HYBIC proposal. Considering Fig.1, L_i is the t^{th} link with capacity C_i and R_i is the average source/transmitter (Tx) rate. TCP flows are penalised with an unfair share of available capacity of the bottleneck link due to shorter (terrestrial) and longer (GEO satellites) RTT flows sharing the same path [6], [7], [17], [18], [20], [22]. Therefore, minimising the dependence of *cwnd* evolution, $W^m(t)$ on RTT in (4) maximises $R^m(t)$ in (5) and (6) for heterogeneous IST networks.

$$W^m(t) = \begin{cases} \rho * 2^{\left(\frac{t}{RTT_{ref}}\right)} & SS \\ A(t - \sqrt[3]{\frac{\beta W_{max}}{A}})^3 + W_{max} & CA \end{cases} \tag{4}$$

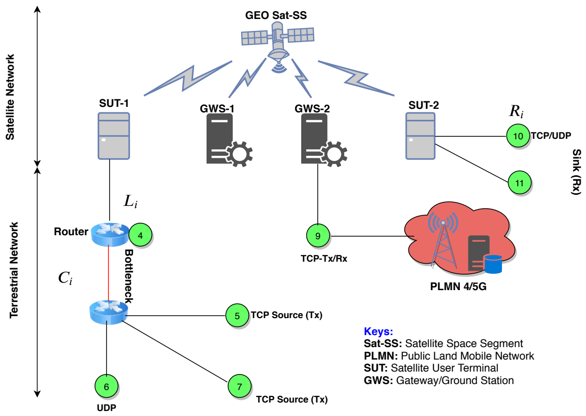

Fig. 1. Reference ISTN Topology Model

Such that SS phase is executed within $0 \leq t < t_\gamma$ and CA executed within $t \geq t_\gamma$. In this cases, $\rho = RTT_{sat}/RTT_{ref}$ is the normalised RTT of long path (e.g. GEO satellite), RTT_{sat} and a fast/short path (e.g. terrestrial), RTT_{ref}, A is scaling factor (usually 0.4) that determines the aggressiveness of *cwnd* increase in large BDP networks, t is elapsed time since the transmission start under ideal conditions or from the last window reduction at the event of packet loss (CA start), W_{max} (origin point) is window size just before the last reduction at the event of loss or the maximum at the end of the SS ($t \geq t_\gamma$), β is a constant Multiplicative Decrease (MD) factor for window reduction at the time of loss, which replaced the TCP halving of *cwnd* in CUBIC algorithms [18], [19]. The factor $K = \sqrt[3]{\frac{\beta W_{max}}{A}}$ during CA phase is a constant that determines how *slow* or *fast* the *cwnd* size increases or decreases, i.e. the time interval that the CUBIC window function takes to increase W_i to W_{max} when no further loss event occurred within that period [18], [19].

$$R(t) = \frac{W^m(t)}{RTT} \tag{5}$$

Standard TCP throughput, $R(t)$ expression in (5) was used to arrived at (6) by substituting (4) in (5). This depends on both *cwnd* dynamics, $W^m(t)$ and RTT with negative consequence on performance.

$$R^m(t) = \begin{cases} \frac{2^{(t/RTT_{ref})}}{RTT_{ref}} & SS \\ \frac{A}{RTT_{ref}}(t - \sqrt[3]{\frac{\beta W_{max}}{A}})^3 + \frac{W_{max}}{RTT_{ref}} & CA \end{cases} \tag{6}$$

Therefore, to achieve optimum performance over long RTT channels such as satellite paths, we focused on improving the SS and CA phases of $W(t)$ in the standard TCP [5], [20]. These modifications mitigated the negative impact of increased RTT on $cwnd$ as well as the throughput performance. This modification resulted in (4) and (6) for $W^m(t)$ and $R^m(t)$ respectively. The $W^m(t)$ in (4) was derived from HYBLA and CUBIC [18]–[20]. Moreover, *cwnd* update rule, W^m_{i+1} was also modified to reflect the improvements in *cwnd* dynamic of (4). The SS phase of $W^m i + 1$ in (7) was adapted to the original HYBLA while the CA is similar to CUBIC with TCP friendly (FR), and concave/convex (CR) regions and modified ρt to eliminate the dependence of W^m on a long RTT path in CA/FR (7).

$$W_{i+1}^m = \begin{cases} W_i^m + 2^\rho - 1, & SS \\ \beta W_{max} + \frac{3t(1-\beta)}{(1+\beta)RTT_{ref}}, & CA/FR \\ (target - W_i^m)/W_i^m, & CA/CR \end{cases} \quad (7)$$

As a result of our modifications, the time at which *cwnd (W)* reached the *ssthresh*, γ or the switching time, t_γ between SS and CA is redefined as the time at which W reaches the value $\rho\gamma$ and rewritten in (8). This includes an error merging of $RTT_{ref}\log_2(\rho)$ that compensates for the effect of division by RTT.

$$t_{\gamma,ref} = RTT_{ref}\log_2(\rho) + RTT_{ref}\log_2(\gamma) \quad (8)$$

The time, t_γ is different for various RTT_{sat} contrary to HYBLA where it is the same for all values [20]. In our case, as the RTT_{sat} increase the switching time increase additively by a factor of $t_{\rho,ref} = RTT_{ref}\log_2(\rho)$ as in (8).

The capacity utilisation is being determined by (9). Considering Fig. 1, R_i is the average throughput of i^{th} source and C_i is the capacity of i^{th} bottleneck link L_i, along the TCP connection in a ISTN path. Therefore, efficiency is given by

$$\eta(\%) = \frac{R_i}{C_i} * 100 \quad (9)$$

B. Algorithm Implementation

Numerical simulation using MATLAB under ideal conditions (error-free channel) were conducted for analysis and evaluation of the performance of the proposed CCA. Long RTT connections of the ISTN topology in Fig. 1 are the focus of our proposed algorithm implementation. We assumed standard TCP for the short RTT paths without performance degradations due to lower BDP path. The implementation flow diagram in Fig. 2 involved executing six key steps described below.

1) *Initialisation:* The required and necessary initial (constant/variable) values of the TCP parameters for the start of execution were supplied at this stage. These include Initial *cwnd (IW), Maximum Segment Size (MSS), Slow Start Threshold* (ssth), γ), *different RTTs* (RTT_{sat} *and* RTT_{ref}), *CUBIC constants (A and* β) and the *elapse time, t*. The TCP connection is establish using the handshake procedure at this stage [5].
2) *Constant Parameters Computation:* Parameters necessary for executing both SS and CA phases of the CCA were computed at this stage, these include the normalised RTT (ρ) and the time to reach the threshold value,t_γ.
3) *Acknowledgement Reception:* This step increment the number of ACKs received to keep track of the data segments ACKed for loss/congestion detection.
4) *Algorithm Phase Selection:* The stage to start the execution of the CCA by checking the condition of whether SS or CA needs to be executed based on the value of W compared to the threshold value, γ.
5) *Variable Parameters Computation:* New state variable values of the CCA (*W(t), W, K, R(t)*, W_{max} etc.) are computed and updated accordingly at this stage, the loop continues until the transmission elapsed.
6) *Return Values and Exit:* Computed values of parameters are returned at this stage, and then execution of CCA is terminated at the end of the flow with termination procedure described in [5].

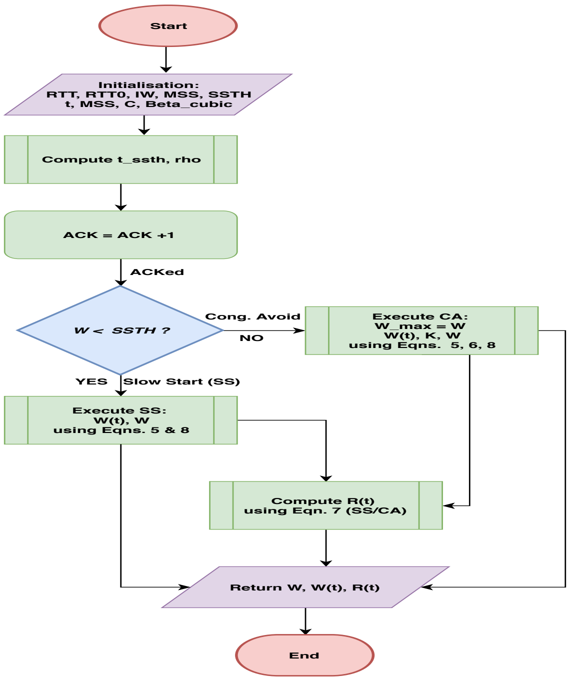

Fig. 2. HYBIC Implementation Block Diagram

III. Performance Analysis and Evaluation

Performance analysis and evaluation of our proposed CCA, HYBIC compared to HYBLA and CUBIC under ideal conditions are presented in this section.

Considering the practically measured average $RTT_{sat} = 2287$ ms [23], and $RTT_{ref} = 100$ ms using the reference ISTN topology, TCP parameters that were used for the numerical implementation are $MSS = 1448$ bytes, $IW = 10$ seg, $\gamma = 128$ seg and transmission elapse time $t = 0 - 60$ s in step of 200 ms. A scenario using single TCP flow was employed for fair analysis and evaluation each of the CCA considered by subjecting them to the same conditions mentioned. Performance was evaluated based on the numerical results of the *W(t), R(t)* and η described in this paper.

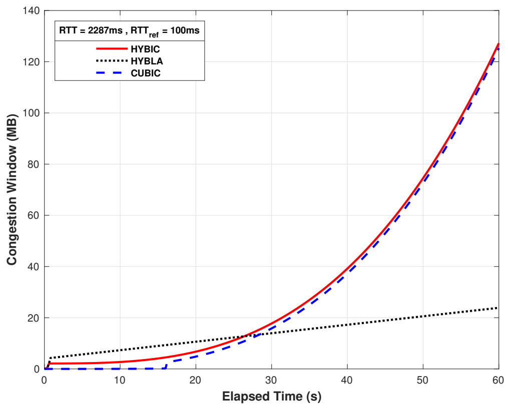

Fig. 3. HYBIC Window Evolution, W(t) Performance Comparison

TABLE I
PERFORMANCE COMPARISON SUMMARY

Algorithm	$W_{avg}(seg)$	$R_{avg}(bps)$	$\eta_{avg}(\%)$
$HYBIC^{*}$	$23x10^3$	$3x10^9$	60
$CUBIC$	$22x10^3$	$110x10^6$	2.2
$HYBLA$	$10x10^3$	$1.1x10^9$	22

*Our proposal

Fig. 3 and Table I show the performance of HYBIC, CUBIC, and HYBLA schemes on executing the SS and CA phases of the algorithms. HYBIC was observed to have better SS than CUBIC and about the same with HYBLA while achieving better and stable performance than both HYBLA and CUBIC. These resulted due to the combined excellent features of HYBIC as described and given in (4) and (7).

A summary of average performance in terms of *cwnd* growth, $W(t)$, achievable throughput, R_{avg} and utilisation, η_{avg} is given in Table I. A single flow of E2E connection scenario using HYBIC, CUBIC and HYBLA on a network path with Bottleneck Link (BL) of capacity $C = 5$ Gbps and established connection of TCP data traffic lasting for 60 s was considered. The average capacity utilisation, $\eta_{avg}(\%)$ of each flow was computed using (9) and summarised in Table I. Results obtained as in Fig. 3 showed that, throughout the data transmission period, HYBLA *cwnd* growth was less than 25 MB and increased faster during the SS than in CA, while HYBIC was able to achieve over 120 MB *cwnd* with more consistent and stable growth than CUBIC and HYBLA from the start to the end of the transmission period as shown in Fig.3. The significant implication of more *cwnd* growth with respect to the data transmission time is that, more *throughput* is achieved (6) , which indicates better utilisation of the available capacity (9).

The results in Fig. 3 also show the improved algorithm (HYBIC), has more stable *cwnd* growth in both SS and CA phases and better performance than HYBLA within 25 s of the data transmission time. Therefore, under these test conditions when the data transmission duration increases, HYBIC algorithm has better performance in terms of stability, throughput and utilisation efficiency as summarised in Table I. Our proposal, HYBIC was able to achieved average throughput of $R_{avg}3Gbp$ compare with $1Gbps$ achieved by HYBLA as shown in Table I. Moreover, HYBIC achieved an average utilisation of $\eta_{avg}60\%$ compared with 22% using HYBLA.

IV. CONCLUSION

Non-Terrestrial Networks (NTNs) particularly satellite networks will continue to play vital role in the future communication networks due to their advantage of global coverage and huge capacity. This characteristics of the NTNs are the key part of the vision of 5G/6G and beyond that will provide ubiquitous connectivity, massive communications, and integrated sensing and communication. However, to achieve these more efficiently with optimum utilisation of this futures, there is a need to develop new and improved transport protocol that will achieve high transmission rate and high capacity utilisation. In this paper, we proposed an improved CCA algorithm called HYBIC, which is derived from CUBIC and HYBLA schemes. The numerical implementation and evaluation of HYBIC against CUBIC and HYBLA have shown better performance of HYBIC in terms of improved *W(t)*, *throughput* and capacity utilisation. The results also showed that our proposed algorithm has consistent and stable *cwnd* growth in both SS and CA phases compared with HYBLA and CUBIC that either increase aggressively in SS and decreases during CA as transmission time increase (HYBLA), or a very slow increase during the SS (CUBIC) until half of the transmission time. Practical values of RTT_{sat} measured using GEO real ISTN testbed were used for the simulation and performance evaluation. our future work would further study the performance by implementing HYBIC as TCP module in Linux testbed. This will enable simulations with multiple flow scenarios under the non-ideal channel of various error models and queue management disciplines. This will also allow more analysis, evaluation, and confidence in statistical results. The simulation results would allow more performance metrics to be measured such as packet delivery ratio, Internet packet delay variation (Jitter), the total transmitted and received data using single and multiple flow scenarios.

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