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Enhanced congestion control in transmission control protocol using harmonic red panda optimisation for heterogeneous networks

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Abstract: Transmission Control Protocol (TCP) plays a crucial role in daily activities, from accessing emails to internet browsing. To ensure consistent and secure data delivery while minimising data loss, innovative mechanisms are essential. While TCP performs well in conventional environments with traditional Congestion Control (CC) approaches, achieving high utilisation, stability and fairness in heterogeneous networks remains a challenge. This research introduces the Harmonic Red Panda Optimisation (HRPO) method for CC in TCP, a novel approach combining harmonic analysis with Red Panda Optimisation (RPO). Initially, TCP system model is simulated and then, a designed TCP algorithm performs the following steps. Firstly, Congestion Window (CWND) is initialised and next, estimation of bandwidth (BW) is carried out. Thereafter, computation of CC factor is done and finally, convergence factor is estimated. The estimation of convergence factor is performed by HRPO. Experimental results demonstrate that HRPO achieves significant improvements, including a maximal goodput of 1951.352 Mbps, throughput of 1587.167 Mbps and a Signal to Interference Noise Ratio (SINR) of 39.595 dB. These results highlight the superiority of HRPO in delivering higher performance and stability compared to existing CC methods, particularly in heterogeneous network environments.

Keywords: transmission control protocol; congestion control; congestion window; harmonic analysis; red panda optimisation.

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Anita Yadav is a Professor in Harcourt Butler Technical University, Kanpur. Her research interests include networking, security and machine learning, mobile ad hoc networks, computer networks and mobile computing.

1 Introduction

The Information and Communication Technology (ICT) is considered as significant constituent for economic and social developments as it has been created newer conveniences and advantages that are not previously experienced (Yu et al., 2017). The mobile networks are making crucial progression during past decades and these networks perform a vital part in accessing networks. The fifth generation (5G) mobile networks are probable to offer downlink or uplink speeds,

enormous connectivity and ubiquitous accessibility. With an advancement of mobile networks and smart phone technologies, various real-time applications are evolved demanding higher throughput and lesser end-to-end delay that causes congestion at a network. 5G networks employ millimetre wave (mm Wave) for meeting high bandwidth (BW) and less latency necessitates of diverse services (Kanagarathinam et al., 2020). The possible utilisation state for 5G network is delivering critical data since it can offer higher throughput (enhanced mobile connectivity) and quick

as well as accurate solutions (low latency and ultra-reliable). As 5G network utilises mmWave range that has broad frequency range, it enables higher BW. Even though mmWave has enormous capability, it also has vital route deterioration and high-quality factor, requiring beamforming techniques (Kuppusamy and Subramaniam, 2023). 5G technology guarantees an entire networked community with limitless accessing to data regarding everything for anybody demands critical features more than existing 4G provides. Some of the features are assistance for newer kind of several devices, incorporation of heterogeneous accessing technologies, for higher mobile traffic volume, ever-present admittance for the users, end-to-end network security, high frequency reutilisation in wireless technologies, automatic provisioning, management and configuration of extensive range of newer network services, tremendous reliability as well as ultra-low latency (Khodashenas et al., 2016).

Transmission Control Protocol (TCP) is a crucial protocol employed in wireless networks and moreover, wireless has become the significant part in daily network. TCP is widely adopted during last few decades for obtaining reliable as well as error-validated delivery of the data. TCP deserves a compliment for achievement on account of its capability to usually execute adequately better despite of critical variations in the internet technologies. Furthermore, TCP is the transportation protocol, which offers byte-stream and consistent data transmission over a packet-enabled better-effort Internet Protocol (IP) layer (Al-Saadi et al., 2019). Several applications on a network over TCP or IP are HyperText Transfer Protocol (HTTP), peer-to-peer file sharing, steaming media, telnet, simple mail transfer protocol, secure shell and file transfer (Fu and Liew, 2003; Kanagarathinam et al., 2020). Most of the data applications are constructed in top of TCP, as TCP offers end-to-end reliability through retransmission while IP packets are lost (Song et al., 2006). Since TCP is originally developed for the wired networks, wherein packet loss is happened owing to network congestion and subsequently, TCP window size is adjusted based on identification of loss (Kong et al., 2018). Nevertheless, packet loss amongst the wireless networks is mainly due to worse radio condition and not by network congestions. The errors in air-connection are frequently caused by various factors namely interfering from some other sources, scattering owing to larger count of reflection surfaces, fading owing to mobility and so on (Kanagarathinam et al., 2020). TCP's performance measure in the cellular state is an average throughput that is similar to wired networks (Abed and Badrawi, 2014).

In the wireless networks, packet loss is concerned as a congestion loss in wired network. Thus, throughput is decreased that outcomes in depletion of BW. Hence, various CC algorithms in TCP are presented for tackling this problem (El Khayat et al., 2010). CC (Sander et al., 2019)] refers to the integral model of TCP, which directly identifies protocol's performance (Lim and Jang, 2007). Thus, CC is a vital component of TCP that influences the whole operation of network directly. In addition, CC intends to control the

network resources in an effectual way and to offer sharing of resources amongst challenging flows when securing networks from collapses (Al-Saadi et al., 2019). CC approaches intend to enhance the performance of network by mitigating or avoiding congestion while it happens. Moreover, CC is an essential element in the data as well as network communication that identifies the significant parameters such as packet drop rate, fairness and latency (Elbery et al., 2023). Generally, CC in TCP researches the capacity of path by transferring data and observing an incoming implicit or explicit feedback signals. With regard to feedback signals, TCP decreases or increases the count of difficult bytes in a flight for reducing congestion during attainment of higher link utilisation (Sun et al., 2018). Additionally, CC in TCP can benefit from an explicit feedback like Explicit Congestion Notification (ECN), wherein bottlenecks and end hosts assist such features (Al-Saadi et al., 2019). Machine Learning (ML) approaches are required for intellectual CC algorithms of 5G mmWave networks. Furthermore, Deep Learning TCP (DL-TCP) (Na et al., 2019; Kuppusamy and Subramaniam, 2023) and FB-TCP (Fuzzy-Based TCP) (Poorzare and Augé, 2021) are employed in unfavourable conditions or even the decision tree algorithm for enhancing CC on 5G (Poorzare and Calveras, 2023).

1.1 Motivation

TCP is a cornerstone of modern network communication, enabling reliable data delivery in applications ranging from email to web browsing. Over the years, various CC mechanisms have been developed to enhance performance of TCP by managing data flow, reducing packet loss and maintaining network stability. Traditional CC methods have proven effective in conventional wired networks with predictable traffic patterns and well-modelled packet loss. However, their performance significantly deteriorates in heterogeneous network environments, such as those involving wireless or high-latency connections, where conditions are dynamic and unpredictable. Key challenges include limited adaptability to varying bandwidth conditions, sub-optimal utilisation of network resources, instability under high congestion and unfair resource allocation among competing flows. These limitations hinder the ability of existing CC mechanisms to achieve high throughput, minimal latency and robust stability in complex network scenarios. To address these challenges, this research introduces the HRPO method, a novel approach combining Harmonic analysis and RPO. The HRPO method is designed to optimise TCP performance by dynamically adjusting the congestion window, estimating bandwidth, and calculating a convergence factor to enhance throughput, goodput and stability.

The contribution of this research is: TCP refers to a legacy protocol that executes reliable transmissions and CC in an internet. Here, HRPO is newly presented for CC in TCP and it is designed by incorporating RPO with harmonic analysis.

The organising of following sections is: Section 2 specifies literature survey of classical approaches and their shortcomings, Section 3 represents TCP system model, Section 4 elucidates HRPO methodology, Section 5 reveals HRPO outcomes and finally, Section 6 describes conclusion of HRPO.

2 Literature survey

Kanagarathinam et al. (2020) introduced Dynamic TCP (D-TCP) CC algorithm for the mm Wave New Radio (NR). This technique enabled entire utilisation of BW in the higher Bandwidth-Delay Product (BDP) network and lessened packet loss owing to wireless loss and congestion. However, consumption of resources was increased and thus, network efficiency as well as performance was affected. Kuppusamy and Subramaniam (2023) presented Deep Learning-oriented Congestion Control Approach (DLCCA) for disaster 5G environments. It improved an effectiveness of wireless network even for cases like unpredicted link failures and several connections, but the performance was degraded owing to complexity of system. Zhang et al. (2023) designed proximal bandwidth-delay quick optimisation enhanced Quick User Datagram Protocol Internet Connection (PBQ-enhanced QUIC) for CC process. This model effectively identified overall conditions of network, even though throughput performance was affected while increasing packet loss rates. Elbery et al. (2023) devised Machine Learning Aided Congestion Control (MLACC) for minimising packet loss rate and queuing delays while controlling fairness over diverse links. The effects of prediction error were less in cases of high network abilities, but still it failed to optimise rate impact factor and aggressiveness factor mathematically.

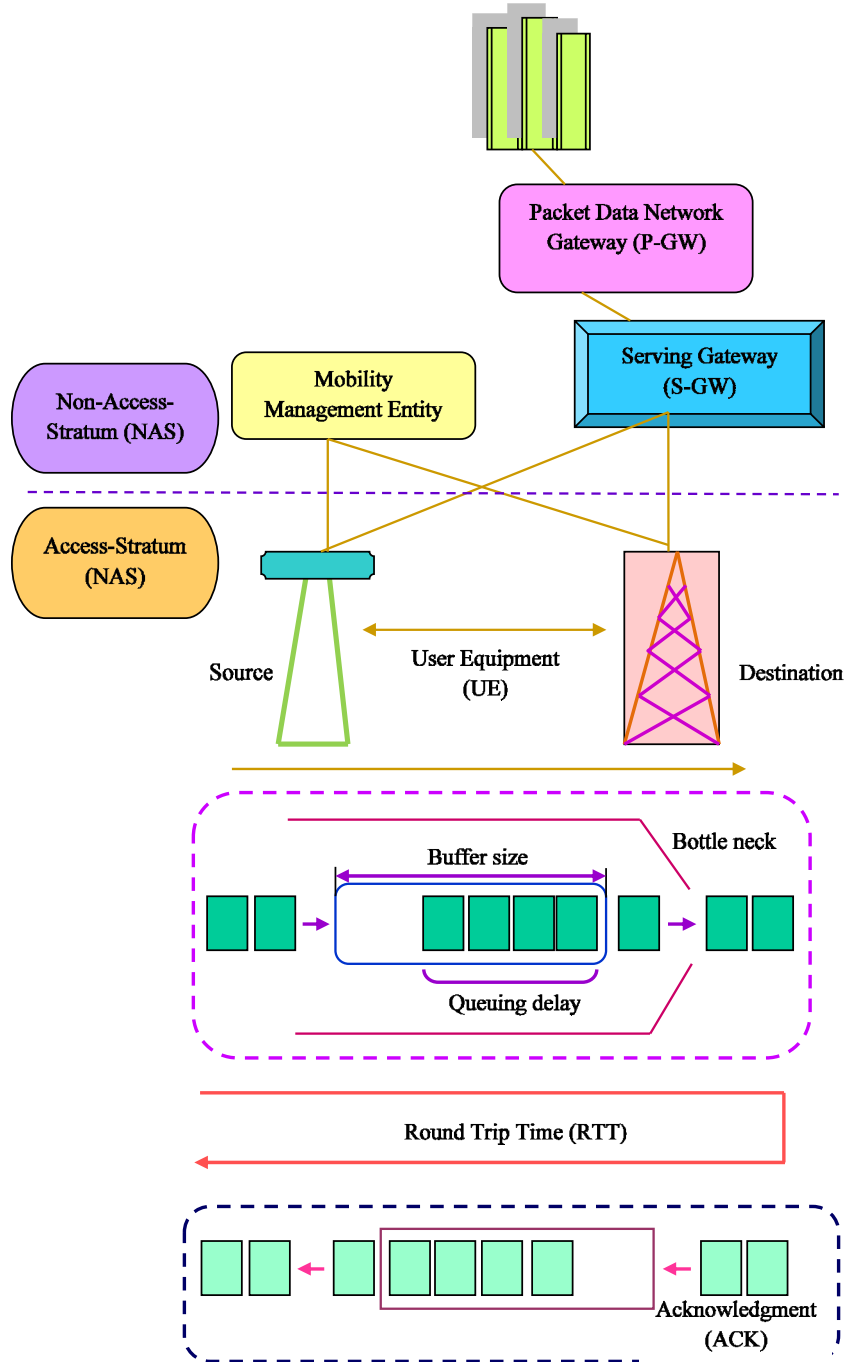
Bai et al. (2022) developed Multi-Agent Congestion Control (MACC) for managing network resources and maintained less delay as well as higher throughput in similar time. This approach combined diverse layer protocols and utilised network resources effectively, though performance was affected due to communication overhead amongst agents. Srinivasan and Garcia-Luna-Aceves (2022) introduced TCP Real-time Topology Adaptiveness (TCP-RTA) for dynamically detecting topology variation and adapted to suitable CC strategy for maximising effectual utilisation of

overall available BW. The robustness of model was higher, but it failed to distinguish long Round-Trip Time (RTT) owing to real congestions and topology changes. Kim and Cho (2022) designed mmWave Scalable TCP (mmS-TCP) for higher-speed networks and to provide more consistent performance. It efficiently decreased overall replicated acknowledgements during transmission of data. However, this scheme developed interoperability issues in the heterogeneous networks. Wang et al. (2021) presented TCP-DQN (Deep Q network) for achieving reliable and efficient data migrations in the virtual data space. This technique assured effectual network resource utilisation under altering traffic loads, network topology and connection capacities. Nevertheless, optimisation algorithm was not included to train DQN.

3 System model of TCP

TCP (Kanagarathinam et al., 2020) learned the available BW based upon channel criterions. It is significant to learn BW as mmWave-enabled wireless connections suffer from extreme route as well as penetration losses that outcome in higher alterations in the Reference Signal Received Power (RSRP). In the condition when there is no series of sight route amongst receiver and transmitter, the losses of channel are masked with an assist of transfer and TCP algorithm is unconscious of such alterations. The discrete time filter is utilised for approximating available bandwidth based upon channel states and traffic intensities on connection. Afterwards approximating BW, CC factor (F) is computed that is employed for controlling Congestion Window (CWND). The congestion factor specified as (F) is evaluated utilising size of window, estimated BW and length of queue at r -th period. F is utilised for adjusting CWND is Adaptive Increase or Adaptive Decrease (AIAD) model, instead of conventional technique additive increase or multiplicative decrease. CWND is enhanced by F_r on successful distribution of packets and CWND is lessened by $(1 - t)$ during packet loss. If the packet drop is identified, TCP algorithm attempts to take CWND to prior level, with an assist of computed BW and it outcomes in better utilisation of the network resources. Figure 1 illustrates the system model of TCP.

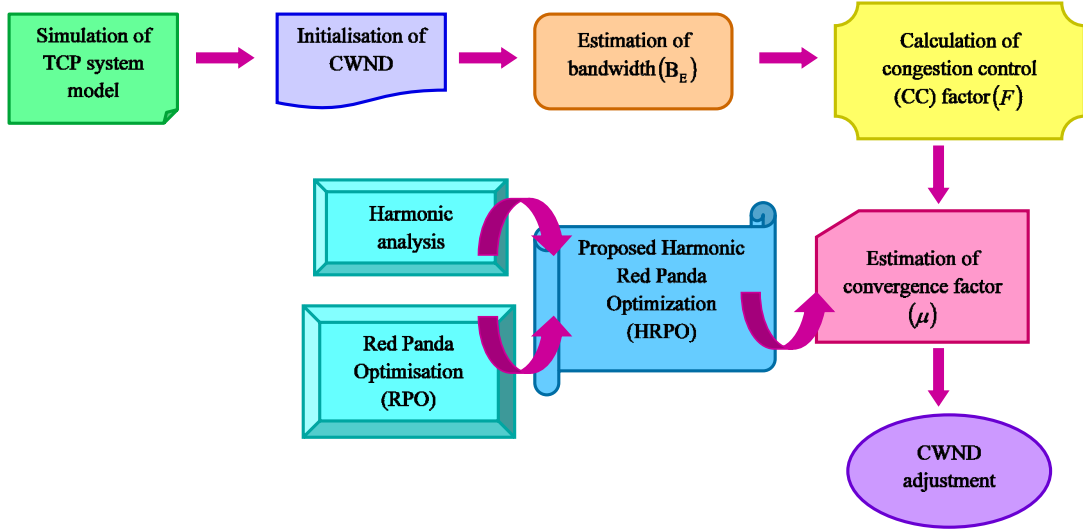
Figure 1 System model of TCP (see online version for colours)



4 Proposed HRPO for CC in TCP

TCP is accountable for the reliable data communication in higher BW longer distance network. This protocol is reliable owing to its CC techniques and recently, various CC approaches are developed for diverse operating systems. In this research, an approach termed HRPO is designed for CC in TCP. Initially, TCP system model is simulated and an introduced TCP algorithm has the steps as follows. At first,

CWND is initialised and the bandwidth (B_E) is estimated. Thereafter, CC factor (F) is calculated and then, convergence factor (μ) is estimated. The estimation of convergence factor (μ) is performed utilising HRPO and finally, CWND adjustment is done. However, HRPO is devised by the combination of RPO with harmonic analysis. Figure 2 manifests schematic depiction of HRPO for CC in TCP.

Figure 2 Schematic depiction of HRPO for CC in TCP (see online version for colours)

4.1 Initialisation of CWND

The first step to conduct CC in TCP is initialisation of CWND, wherein CWND size is initialised. CWND size identifies the overall packets to be transferred by a sender before receiving an affirmation from receiver.

4.2 Estimation of $BW(B_E)$

The estimation of BW (Kanagarathinam et al., 2020) is a significant attribute for designing CC algorithms. The algorithms namely TCP Westwood and TCP Bottleneck Bandwidth and Round-rip Time (BBR) compute BW for controlling CWND. Nevertheless, these algorithms do not include altering 5G network criterions.

Let us consider m_r be a transferred data during the time interval a_{r-1} and a_r . Then, BW specified as T_r at a time period r can be stated as the allowance of totally transferred data in specific time period that is formulated by

$$T_r = \frac{m_r}{a_r - a_{r-1}} = \frac{m_r}{\Delta_r} \quad (1)$$

where Δ_r represents time variation amongst a_r to a_{r-1} . The predicted available BW is modelled as a discrete time linearity system and utilise discrete time filter. Employing Tustin approximation, filtered available BW denoted as T_p at an interval Δ_r can be specified by

$$T_p = \left[\frac{2\eta - 1}{\Delta_r} \times (T_{r-1}) \right] + \left[\frac{T_r + T_{r-1}}{2\eta + 1} \right] \quad (2)$$

Here, $\frac{1}{\eta}$ mentions cut-off frequency whereas T_{r-1} symbolises BW at prior time period. Let us consider ϑ_r as constant, which can be expressed by

$$\vartheta_r = \frac{2\eta - \Delta_r}{2\eta + \Delta_r} \quad (3)$$

Therefore, equation (2) is simplified by employing ϑ_r as follows:

$$T_p = \vartheta_r T_{r-1} + (1 - \vartheta_r) \left(\frac{T_r + T_{r-1}}{2} \right) \quad (4)$$

Here, ϑ_r implies constant that has higher effect on a filtered available BW (T_p). The maximal value of ϑ_r signifies that more importance to prior learning whereas minimal value of ϑ_r indicates more significant to present learning. To employ prior learning, ϑ_r is considered as 0.90. Therefore, equation (4) is modelled as

$$T_p = 0.90 T_{r-1} + 0.10 T_r \quad (5)$$

As discrete time filter is considered, the packet aliasing may happen. For removing packet aliasing effects, T_p is normalised utilising low pass filter and the acquired BW is indicated as B_E . In accordance to Shannon expression, a channel capability is directly associated to Signal to Interference Noise Ratio (SINR). Assume, $SINR_r$ and $SINR_v$ reveals present SINR as well as average SINR. Thus, variations in filtered BW is normalised by

$$N = (T_r - T_p) + (SINR_r - SINR_v) \quad (6)$$

$$B_E = T_p + \ell \times N \quad (7)$$

Here, N depicts the error normalisation parameter whereas ℓ denotes clock granularity that is fixed to 0.5 for matching with epoch timer.

4.3 Computation of CC factor (F)

For computing CC factor (F) (Kanagarathinam et al., 2020), predictable queue length is calculated initially. A queue length is proportional to the TCP window size specified by Z . Let, $J[Z_x]$ mentions predicted window size of a TCP flow and an expected queue length $J(A)$ can be estimated by

$$J(A) = \zeta \times J[Z_x] \quad (8)$$

Here, ζ illustrates TCP fairness factor and $J[Z_x]$ for F diverse flows can be given by $\frac{J[Z]}{J[F]}$, wherein $J[Z]$ signifies window size and $J[F]$ mentions prediction of CC factor of F flows. In equation (8), $J[Z_x]$ is substituted and the equation is given by

$$J(A) = \zeta \times \frac{J[Z]}{J[F]} \quad (9)$$

Thereafter, parameter F_{r+1} is updated. Assume F_r, A_r and Z_r represents F , length of queue and window size of r -th period, then utilising $J(A)$, equation (9) during $(r+1)$ -th time, a parameter F_{r+1} can be updated by

$$F_{r+1} \leftarrow \max\left(1, F_r + 1 - \frac{A_k}{\zeta \times qr} F_r\right) \quad (10)$$

Let us consider B_C as present BW and by employing estimated BW denoted by B_E, A_r is represented by

$$A_r = (B_E - B_C) \times \frac{Z_r}{B_E} \quad (11)$$

By integrating equations (10) and (11), updated CC factor (F) can be manifested by

$$F_{r+1} \leftarrow \max\left(1, F_r + 1 - \frac{B_E - B_C}{\zeta \times B_E} Z_r\right) \quad (12)$$

In accordance to equation (12), an expectation of F is elucidated by

$$J[F] = \max\left(1, \frac{\zeta \cdot J[B_E]}{\partial T}\right) \quad (13)$$

Here, $\partial T = J[B_E] - J[B_C]$ denotes over or under employed BW estimation.

4.4 Estimation of convergence factor (μ) utilising HRPO

The convergence factor (Kanagarathinam et al., 2020) refers to rapidness of TCP algorithm that adapts to varying network states and balances its CC mechanism. Generally, convergence factor is popular as it permits TCP to effectively employ network resources and maintain constant performance. Here, convergence factor (μ) is estimated utilising HRPO. However, HRPO is designed by merging RPO with harmonic analysis.

4.4.1 Solution encoding

In solution encoding, the value of convergence factor (μ) with dimension $[1 \times 1]$ is determined and Figure 3 presents solution encoding for estimation of convergence factor.

Figure 3 Solution encoding for estimation of convergence factor (see online version for colours)



4.4.2 Fairness measure

In the computer network, fairness measure is employed for ascertaining that diverse protocols or applications are sharing out fair system resources. The fairness measure specifies to a degree by which an algorithm assures fair sharing of network resources amongst challenging operations. Moreover, fairness measure represents effectiveness of CC algorithm's response to variations in network conditions and its efficiency to avoid congestion. The formulation of fairness can be depicted as

$$\mathfrak{S} = \frac{T + G}{2} \quad (14)$$

Here, T indicates throughput whereas G mentions goodput.

4.4.3 Algorithmic steps of HRPO

Harmonic analysis (Damsleth and Spjøtvoll, 1982) is employed as initialisation point along with consequences estimated by newer and strong technique of Bolviken. In harmonic analysis, frequencies are identified utilising numerical search. Moreover, harmonic analysis is capable to offer more comprehensive and precise understanding of convergence attribute of system. RPO (Givi et al., 2023) mimics the natural characteristics of red pandas. A major design motivation is obtained from two behavioural attributes of red pandas such as foraging strategy and climbing trees to take rest. RPO provided excellent performance by maintaining exploitation and exploration attributes during

search processing. Here, the combined model of harmonic analysis and RPO termed as HRPO is utilised for estimation of convergence factor. HRPO offers important insights regarding convergence behaviours of system and assists to take decisions for enhancing converging performance. The steps of HRPO to obtain optimum solution are described beneath.

Step 1 (Initialisation): During initialisation process of RPO, location of the red pandas in search space \mathcal{W} is initialised randomly that can be expressed by

$$\mathfrak{R} = \{\mathfrak{R}_1, \mathfrak{R}_2, \dots, \mathfrak{R}_\rho, \dots, \mathfrak{R}_i\} \quad (15)$$

Here, \mathfrak{R}_ρ denotes ρ -th red panda in population \mathfrak{R} whereas \mathfrak{R}_i symbolises overall variables.

Step 2 (Computation of objective): The fairness measure is calculated in terms of throughput and goodput utilising an expression formulated in equation (14).

Step 3 (Foraging strategy (exploration)): The red panda's location in exploration phase is derived based upon their movements for foraging in a wild. The group of developed food resource locations for individual red panda concerning comparison of objective measure values can be represented utilising equation (16). Amongst these developed locations, single location is randomly identified as food location chosen by related red panda.

$$S_\rho = \{R_h \mid h \in \{1, 2, \dots, Q\} \text{ and } \mathfrak{S}_h < \mathfrak{S}_\rho\} \cup \{R_\beta\} \quad (16)$$

Here, S_ρ reveals group of developed food sources for ρ -th red panda whereas R_β symbolises position of red panda having optimum value for objective measure. For modelling red panda characteristic during the foraging, newer location is initially computed for individual red panda on basis of movement against food source position as follows:

$$\mathfrak{R}_{\rho,v}^{\text{PI}} = \mathfrak{R}_{\rho,v} + \gamma \cdot (L_{\rho,v} - D \cdot \mathfrak{R}_{\rho,v}) \quad (17)$$

Let us consider,

$$\mathfrak{R}_{\rho,v}^{\text{PI}} = \mathfrak{R}_{\rho,v}(\kappa + 1) \quad (18)$$

$$\mathfrak{R}_{\rho,v} = \mathfrak{R}_{\rho,v}(\kappa) \quad (19)$$

$$L_{\rho,v} = L_{\rho,v}(\kappa) \quad (20)$$

Then, equation (17) becomes

$$\mathfrak{R}_{\rho,v}(\kappa + 1) = \mathfrak{R}_{\rho,v}(\kappa) + \gamma \cdot (L_{\rho,v}(\kappa) - D \cdot \mathfrak{R}_{\rho,v}(\kappa)) \quad (21)$$

$$\mathfrak{R}_{\rho,v}(\kappa + 1) = \mathfrak{R}_{\rho,v}(\kappa)(1 - \gamma * D) + \gamma \cdot L_{\rho,v}(\kappa) \quad (22)$$

For the time series $g_{(1)}, g_{(2)}, \dots, g_{(\kappa)}, \dots, g_{(y)}$, a standard formulation of harmonic analysis is specified as

$$g(\kappa) = \alpha_0 + \sum_{v=1}^c (\alpha_v \cos(2\pi v \kappa / y) + \varepsilon_v \sin(2\pi v \kappa / y)) \quad (23)$$

Assume, $y = 2$ and $c = 1$, therefore equation (23) becomes

$$g(\kappa) = \alpha_0 + \alpha_1 \cos\left(\frac{2\pi \kappa}{2}\right) + \varepsilon_1 \sin\left(\frac{2\pi \kappa}{2}\right) \quad (24)$$

$$g(\kappa) = \alpha_0 + \alpha_1 \cos \pi \kappa + \varepsilon_1 \sin \pi \kappa \quad (25)$$

Here,

$$\alpha_0 = \frac{1}{2} [g_{(1)} + g_{(2)}] \quad (26)$$

$$\alpha_v = \frac{2}{y} \sum_{\kappa=1}^y g_\kappa \cos\left(\frac{2\pi \kappa}{2}\right) \quad (27)$$

$$\alpha_1 = \frac{2}{2} \left[g_{(1)} \cdot \cos\left(\frac{2\pi \cdot 1}{2}\right) + g_{(2)} \cdot \cos\left(\frac{2\pi \cdot 2}{2}\right) \right] \quad (28)$$

$$\alpha_1 = g_{(1)} \cdot \cos \pi + g_{(2)} \cos(2\pi) \quad (29)$$

Here, $\cos \pi = -1$ and $\cos(2\pi) = 1$, hence above equation is manifested by

$$\alpha_1 = g_{(1)}(-1) + g_{(2)}(1) \quad (30)$$

$$\varepsilon_v = \frac{2}{y} \sum_{\kappa=1}^y g_\kappa \sin\left(\frac{2\pi v \kappa}{y}\right) \quad (31)$$

$$\varepsilon_1 = \frac{2}{2} \left[g_{(1)} \cdot \sin\left(\frac{\pi}{2}\right) + g_{(2)} \cdot \sin\left(\frac{2\pi \cdot 2}{2}\right) \right] \quad (32)$$

$$\varepsilon_1 = g_{(1)} \cdot \sin \pi + g_{(2)} \sin(2\pi) \quad (33)$$

Here, $\sin \pi = 0$ and $\sin(2\pi) = 0$, therefore above-mentioned equation is given as

$$\varepsilon_1 = g_{(1)} * 0 + g_{(2)} * 0 \quad (34)$$

In this research, the time series model can be represented by $g_{\rho,v}(\kappa - 1), g_{\rho,v}(\kappa), g_{\rho,v}(\kappa + 1)$. Therefore

$$g_{(1)} = \mathfrak{R}_{\rho,v}(\kappa - 1) \quad (35)$$

$$g_{(2)} = \mathfrak{R}_{\rho,v}(\kappa) \quad (36)$$

$$g(\kappa) = \mathfrak{R}_{\rho,v}(\kappa + 1) \quad (37)$$

Substitute equations (35), (36) and (37) in equations (25), (26), (30) and (34), thus the equations can be modelled as

$$\mathfrak{R}_{\rho,v}(\kappa - 1) = \alpha_0 + \alpha_1 \cos \pi \kappa + \varepsilon_1 \sin \pi \kappa \quad (38)$$

$$\alpha_0 = \frac{1}{2} [\mathfrak{R}_{\rho,v}(\kappa - 1) + \mathfrak{R}_{\rho,v}(\kappa)] \quad (39)$$

$$\alpha_1 = -\mathfrak{R}_{\rho,v}(\kappa - 1) + \mathfrak{R}_{\rho,v}(\kappa) \quad (40)$$

$$\varepsilon_1 = 0 \quad (41)$$

Substitute equations (39) and (40) in equation (38), therefore an equation becomes

$$\mathfrak{R}_{\rho,v}(\kappa+1) = \frac{1}{2}[\mathfrak{R}_{\rho,v}(\kappa-1) + \mathfrak{R}_{\rho,v}(\kappa)] + [-\mathfrak{R}_{\rho,v}(\kappa-1) + \mathfrak{R}_{\rho,v}(\kappa)] \cos \pi \kappa \quad (42)$$

$$\mathfrak{R}_{\rho,v}(\kappa+1) = \frac{1}{2}\mathfrak{R}_{\rho,v}(\kappa-1) + \frac{1}{2}\mathfrak{R}_{\rho,v}(\kappa) - \mathfrak{R}_{\rho,v}(\kappa-1) \cos \pi \kappa + \mathfrak{R}_{\rho,v}(\kappa) \cos \pi \kappa \quad (43)$$

$$\mathfrak{R}_{\rho,v}(\kappa+1) = \mathfrak{R}_{\rho,v}(\kappa) \left[\frac{1}{2} + \cos \pi \kappa \right] + \mathfrak{R}_{\rho,v}(\kappa-1) \left[\frac{1}{2} - \cos \pi \kappa \right] \quad (44)$$

$$\mathfrak{R}_{\rho,v}(\kappa+1) = \mathfrak{R}_{\rho,v}(\kappa) \left[\frac{1+2\cos \pi \kappa}{2} \right] + \mathfrak{R}_{\rho,v}(\kappa-1) \left[\frac{1-2\cos \pi \kappa}{2} \right] \quad (45)$$

$$\mathfrak{R}_{\rho,v}(\kappa) \left[\frac{1+2\cos \pi \kappa}{2} \right] = \mathfrak{R}_{\rho,v}(\kappa+1) - \mathfrak{R}_{\rho,v}(\kappa-1) \left[\frac{1-2\cos \pi \kappa}{2} \right] \quad (46)$$

$$\frac{\mathfrak{R}_{\rho,v}(\kappa)(1+2\cos \pi \kappa)}{2} = \frac{2\mathfrak{R}_{\rho,v}(\kappa+1) - \mathfrak{R}_{\rho,v}(\kappa-1)(1-2\cos \pi \kappa)}{2} \quad (47)$$

$$\mathfrak{R}_{\rho,v}(\kappa) = \frac{1}{1+2\cos \pi \kappa} [2\mathfrak{R}_{\rho,v}(\kappa+1) - \mathfrak{R}_{\rho,v}(\kappa-1)(1-2\cos \pi \kappa)] \quad (48)$$

Substituting equation (48) in equation (22), the equation becomes

$$\mathfrak{R}_{\rho,v}(\kappa+1) = \left[\frac{1}{1+2\cos \pi \kappa} [2\mathfrak{R}_{\rho,v}(\kappa+1) - \mathfrak{R}_{\rho,v}(\kappa-1)(1-2\cos \pi \kappa)] \right] (1-\gamma * D) + \gamma \cdot L_{\rho,v}(\kappa) \quad (49)$$

$$\mathfrak{R}_{\rho,v}(\kappa+1) - \frac{2\mathfrak{R}_{\rho,v}(\kappa+1)(1-\gamma * D)}{1+2\cos \pi \kappa} - \mathfrak{R}_{\rho,v}(\kappa-1)(1-2\cos \pi \kappa)(1-\gamma * D) + \gamma \cdot L_{\rho,v}(\kappa)(1+2\cos \pi \kappa) = \frac{2\mathfrak{R}_{\rho,v}(\kappa+1)(1-\gamma * D)}{1+2\cos \pi \kappa} - \mathfrak{R}_{\rho,v}(\kappa-1)(1-2\cos \pi \kappa)(1-\gamma * D) + \gamma \cdot L_{\rho,v}(\kappa)(1+2\cos \pi \kappa) \quad (50)$$

$$\frac{(1+2\cos \pi \kappa - 2 + 2\gamma * D)\mathfrak{R}_{\rho,v}(\kappa+1)}{1+2\cos \pi \kappa} - \mathfrak{R}_{\rho,v}(\kappa-1)(1-2\cos \pi \kappa)(1-\gamma * D) + \gamma \cdot L_{\rho,v}(\kappa)(1+2\cos \pi \kappa) = \frac{(1+2\cos \pi \kappa - 2 + 2\gamma * D)\mathfrak{R}_{\rho,v}(\kappa+1)}{1+2\cos \pi \kappa} - \mathfrak{R}_{\rho,v}(\kappa-1)(1-2\cos \pi \kappa)(1-\gamma * D) + \gamma \cdot L_{\rho,v}(\kappa)(1+2\cos \pi \kappa) \quad (51)$$

The updated expression of HRPO is explicated as

$$\mathfrak{R}_{\rho,v}(\kappa+1) = \frac{\mathfrak{R}_{\rho,v}(\kappa-1)(1-2\cos \pi \kappa) + (\gamma * D - 1) + \gamma \cdot L_{\rho,v}(\kappa)(1+2\cos \pi \kappa)}{(2\cos \pi \kappa - 1 + 2\gamma * D)} \quad (52)$$

Here, γ signifies random number between 0 and 1, D implies random number amongst 1 and 2, $L_{\rho,v}(\kappa)$ illustrates chosen food source for ρ -th red panda in v -th dimension and $\mathfrak{R}_{\rho,v}(\kappa-1)$ denotes ρ -th red panda in v -th dimension at $(\kappa-1)$ -th.

If objective function value is enhanced in a newer location, the red panda's location is updated to position computed in an exploration stage as follows:

$$R_{\rho} = \begin{cases} R_{\rho}^{P1}, & \mathfrak{S}_{\rho}^{P1} < \mathfrak{S}_{\rho} \\ R_{\rho}, & \text{else} \end{cases} \quad (53)$$

where R_{ρ}^{P1} refers to location of ρ -th red panda regarding initial stage of RPO, $\mathfrak{R}_{\rho,v}^{P1}$ illustrates its v -th dimension, \mathfrak{S}_{ρ}^{P1} mentions its objective measure value.

Step 4 (Proficiency in climbing and taking rest on trees (exploitation)): The red panda's location in second stage of RPO is derived based upon its skill in climbing and taking rest on trees. For mathematical representation of red panda's natural characteristics in climbing trees, initially the newer location for individual red panda is evaluated by

$$\mathfrak{R}_{\rho,v}^{P1} = \mathfrak{R}_{\rho,v} + \frac{W_v + \gamma \cdot (U_v - W_v)}{\kappa}, \quad \rho = 1, 2, \dots, Q, \quad v = 1, 2, \dots, \tau \quad \text{and} \quad \kappa = 1, 2, \dots, K \quad (54)$$

$$R_{\rho} = \begin{cases} R_{\rho}^{P2}, & \mathfrak{S}_{\rho}^{P2} < \mathfrak{S}_{\rho} \\ R_{\rho}, & \text{else} \end{cases} \quad (55)$$

Here, R_{ρ}^{P2} symbolises newer location of ρ -th red panda regarding second stage of RPO, $\mathfrak{R}_{\rho,v}^{P1}$ is its v -th dimension, \mathfrak{S}_{ρ}^{P2} mentions its objective measure, γ depicts random number between 0 and 1, κ denotes iteration count of algorithm and K specifies maximal count of iteration.

Step 5 (Termination): HRPO accomplishes above mentioned steps continuously until achieving optimum solution and then, it is terminated. Algorithm 1 elucidates pseudo code of HRPO.

Algorithm 1: Pseudo code of HRPO

SL. No	Pseudo code of HRPO
1	Input: $\mathfrak{R}_{\rho,v}(\kappa), L, D$ and \mathfrak{S}
2	Output: $\mathfrak{R}_{\rho,v}(\kappa+1)$
3	Begin
4	Set population size (Q) and overall count of iterations (K)
5	Generate population initialisation utilising equation (15)
6	Estimate objective function utilising equation (14)
7	for $\kappa = 1$ to K
8	for $\rho = 1$ to Q
9	Stage 1: Foraging strategy (exploration)
10	Update food location group for ρ -th member of RPO utilising equation (16)
11	Identify chosen food by ρ -th red panda randomly
12	Compute newer location of ρ -th member of RPO based upon first stage of RPO employing equation (52)
13	Update ρ -th member of RPO utilising equation (53)
14	Stage 2: Proficiency in climbing and taking rest on trees (exploitation)
15	Evaluate newer location of ρ -th member of RPO regarding second stage of RPO employing equation (54)
16	Update ρ -th member of RPO by equation (55)
17	end
18	Save the optimum solution determined thus far
19	end for
20	end
21	Terminate

The flowchart of the HRPO is shown in Figure 4.

4.5 Adjustment of CWND

In TCP algorithm, CWND is adjusted (Kanagarathinam et al., 2020) utilising CC factor (F). The CWND is adjusted in an AIAD model relying on loss packets or ACKed packets. On individual RTT, CWND is enhanced by F_k and during packet drop CWND is decreased by $(1-t)$. The CWND adjustment can be described by

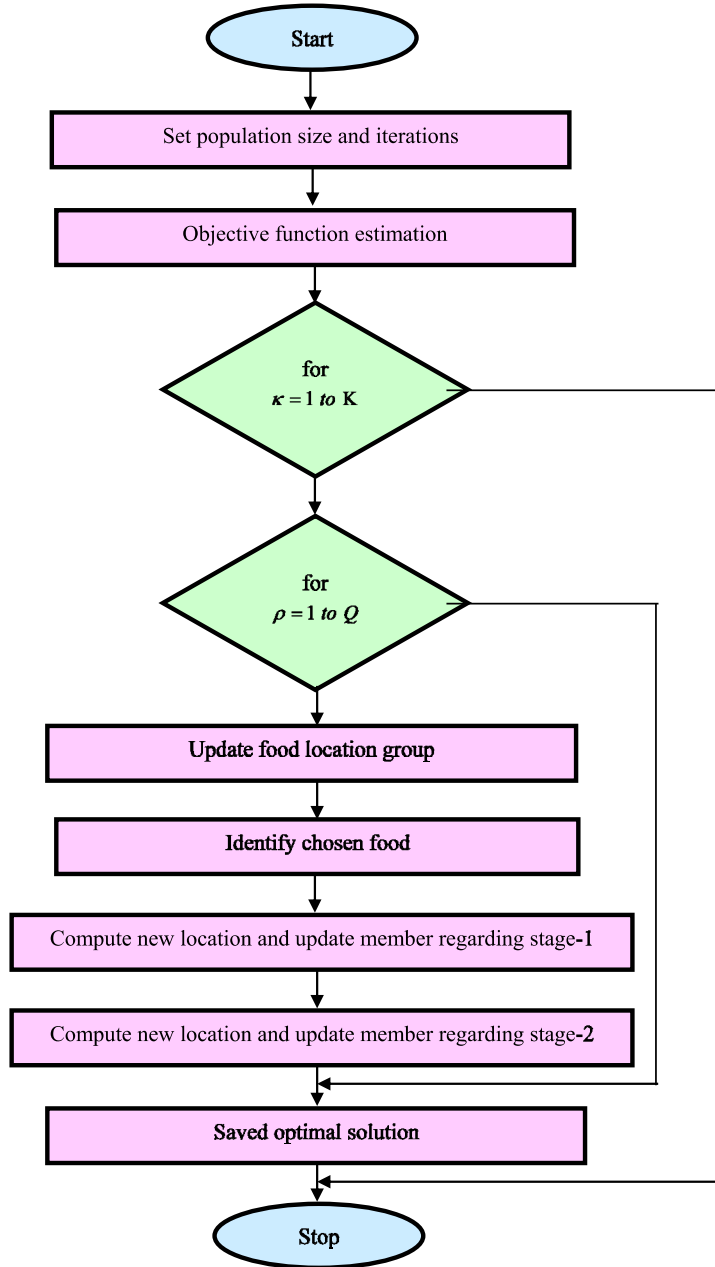
$$\text{For individual RTT: } CWND \leftarrow CWND + F_{r+1} \quad (56)$$

$$\text{For individual loss: } CWND \leftarrow CWND(1-t) \quad (57)$$

$$t = \frac{\phi}{\left(\left[(2\phi-1)F\right]+1\right)} \quad (58)$$

Here, t is computed by equation (58) whereas ϕ s specifies convergence factor for the fairness and it is fixed as $2(\phi=2)$ for preventing aggressiveness. By substituting $\phi=2$, the value of t is given by $t = \frac{2}{3F+1}$. The CWND denoted by Z is adjusted in an AIAD way. If the two packets are dropped successively, this state is considered as No Loss Period (NLP). When an initial packet loss is occurred, CWND signified by Z is adjusted employing equations (56), (57) and (58).

Figure 4 Flowchart of the HRPO (see online version for colours)



5 Results and discussion

The attained outcomes of HRPO for performed analysis are interpreted in this section together with simulation results, experimental setup and performance metrics.

5.1 Experiment setup

HRPO designed for CC in TCP is implemented in NS2 simulator tool and Table 1 expounds simulation parameters.

5.2 Simulation outcomes

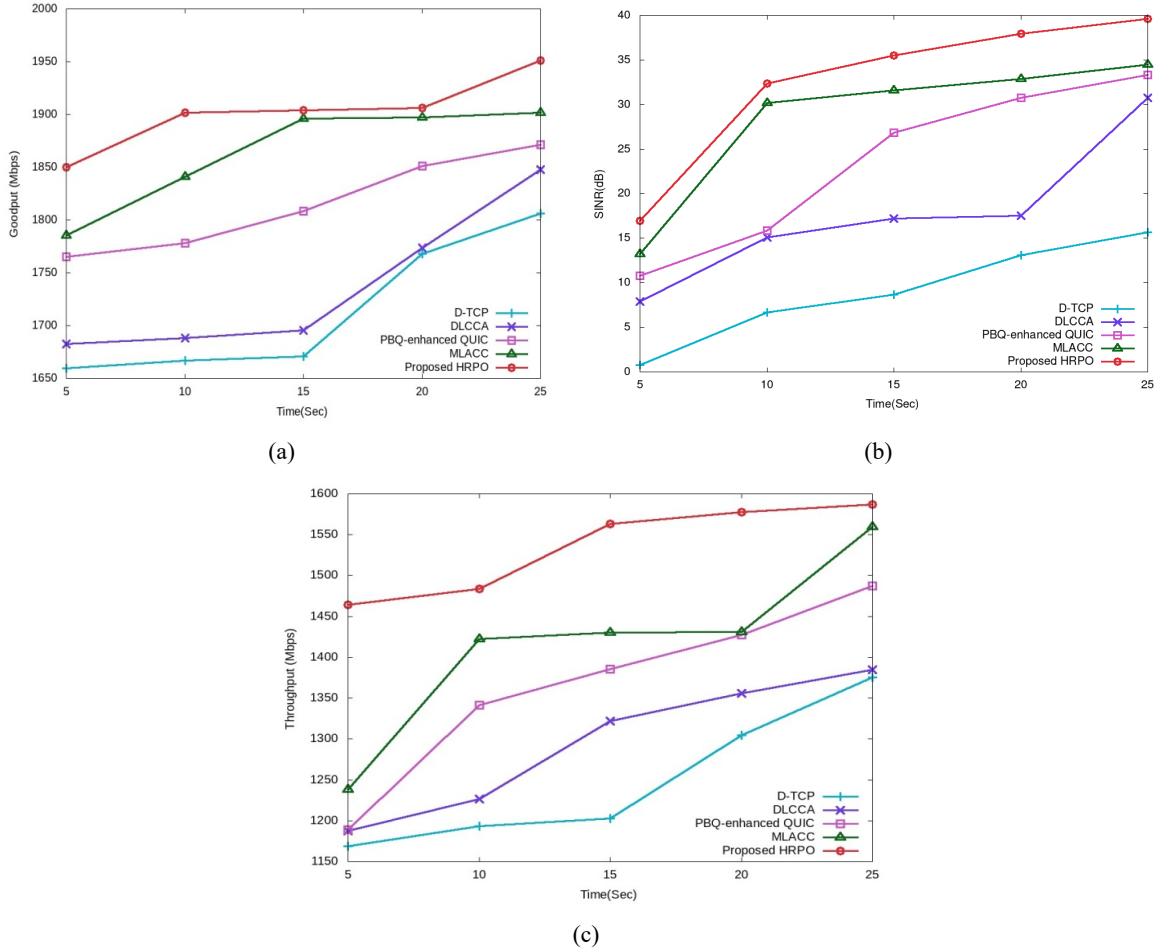
Figure 5 depicts simulation outcomes of HRPO for CC in TCP. Figure 5(a) shows the simulation result for time-2.925

sec, wherein, red, blue and green line represents data transfer from source to destination. Figure 5(b) reveals simulation outcome for time-3.671 sec, wherein red as well as white line denotes data transmission and green arrow specifies packet drop.

Table 1 Simulation parameters

Parameters	Values
Fairness factor	0.2
Current BW	1000 Mbps
Estimated BW	1200 Mbps
Window size	100
Data transferred	1000

Figure 6 Comparative analysis of HRPO for setup-1 (a) Goodput, (b) SINR, (c) Throughput (see online version for colours)



5.5.2 Analysis with regard to setup-2

Figure 7 illustrates analysis of HRPO regarding metrics by changing time. In this section, values attained by conventional approaches and HRPO are explained for time=25sec. Figure 7(a) exhibits evaluation of HRPO based upon goodput. D-TCP, DLCCA, PBQ-enhanced QUIC and MLACC acquired goodput of 1773.678 Mbps, 1812.520 Mbps, 1876.115 Mbps and 1941.676 Mbps while goodput achieved by HRPO is 1954.900 Mbps. Evaluation

of HRPO in terms of SINR is manifested in Figure 7(b). SINR attained by D-TCP is 22.422 dB, DLCCA is 23.311 dB, PBQ-enhanced QUIC is 29.948 dB and MLACC is 34.029 dB whereas SINR achieved by HRPO is 37.184 dB. Figure 7(c) demonstrates estimation of HRPO with respective to throughput. HRPO obtained throughput of 1552.841 Mbps whereas D-TCP, DLCCA, PBQ-enhanced QUIC and MLACC attained 1331.578 Mbps, 1385.967 Mbps, 1413.3257 Mbps and 1486.572 Mbps.

Figure 7 Comparative analysis of HRPO for setup-2 (a) Goodput, (b) SINR, (c) Throughput (see online version for colours)

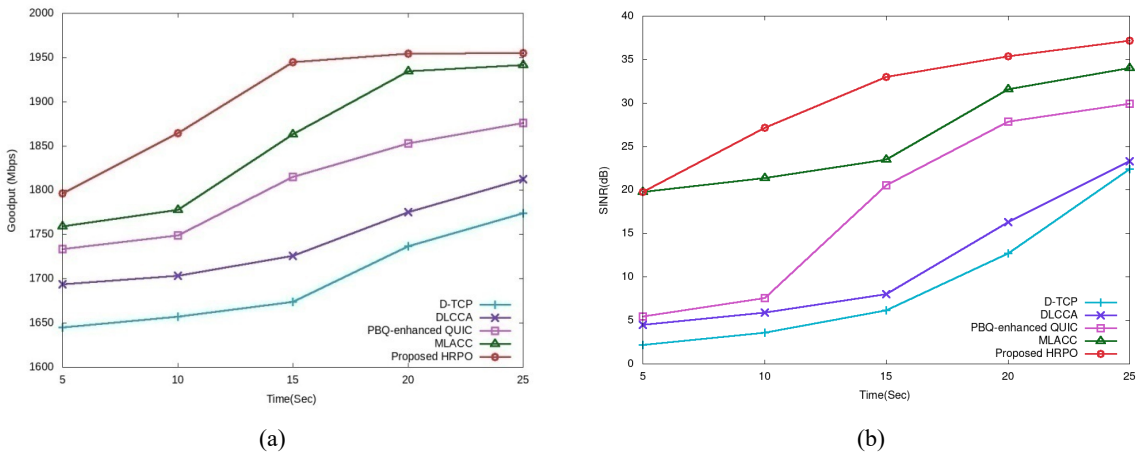
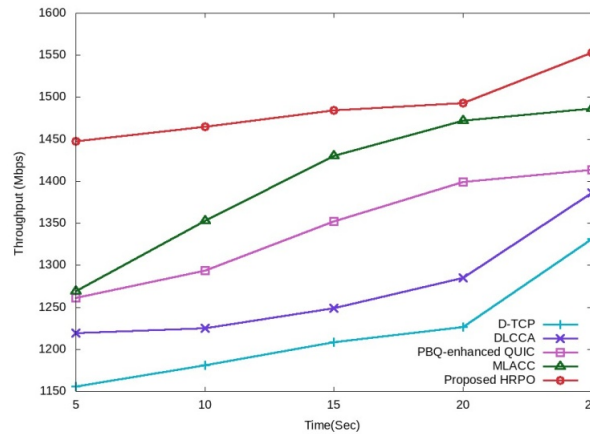


Figure 7 Comparative analysis of HRPO for setup-2 (a) Goodput, (b) SINR, (c) Throughput (see online version for colours) (continued)



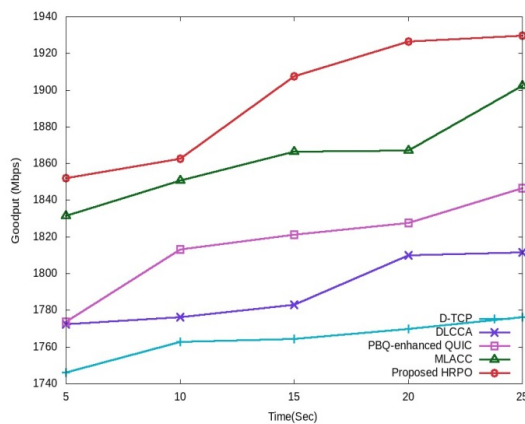
(c)

5.5.3 Analysis with regard to setup-3

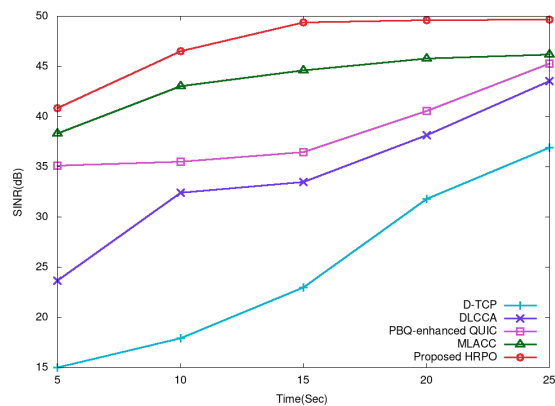
Estimation of HRPO with regard to measures by changing time is shown in Figure 8. The values obtained by HRPO and other approaches while time is 25 sec are mentioned in this part. Figure 8(a) implies analysis of HRPO based on goodput. D-TCP, DLCCA, PBQ-enhanced QUIC and MLACC achieved goodput of 1776.276 Mbps, 1811.492 Mbps, 1846.628 Mbps and 1902.549 Mbps while HRPO acquired

1929.825 Mbps. Evaluation of HRPO concerning SINR is specified in Figure 8(b). HRPO obtained SINR of 39.595dB while SINR attained by D-TCP, DLCCA, PBQ-enhanced QUIC and MLACC is 30.754 dB, 33.340 dB, 34.479 dB and 36.909 dB. Figure 8(c) presents assessment of HRPO in accordance to throughput. D-TCP, DLCCA, PBQ-enhanced QUIC and MLACC achieved throughput of 1309.805 Mbps, 1390.235 Mbps, 1434.824 Mbps and 1513.651 Mbps whereas HRPO acquired 1517.731 Mbps.

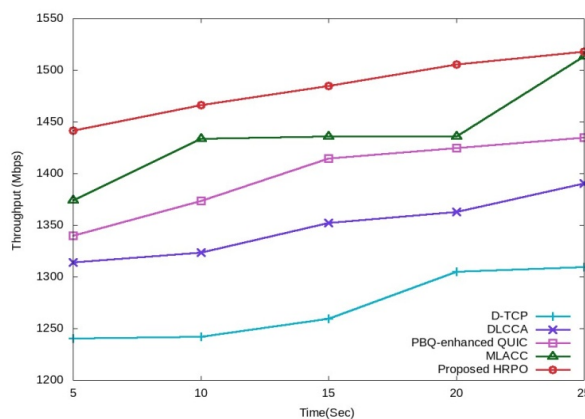
Figure 8 Comparative analysis of HRPO for setup-3 (a) Goodput, (b) SINR, (c) Throughput (see online version for colours)



(a)



(b)



(c)

5.5.4 Analysis with regard to setup-4

Figure 9 represents assessment of HRPO with concern to metrics by varying time. In this part, values acquired by HRPO and classical methods are illustrated when time is considered as 25 sec. Figure 9(a) indicates evaluation of HRPO in respective of goodput. HRPO achieved goodput of 1926.706 Mbps whereas D-TCP, DLCCA, PBQ-enhanced QUIC and MLACC obtained 1789.538 Mbps, 1852.928 Mbps, 1895.375 Mbps and 1907.134 Mbps. Estimation of HRPO by means of SINR is elucidated in Figure 9(b). SINR attained by D-TCP is 19.230 dB, DLCCA is 35.303 dB, PBQ-enhanced QUIC is 35.351 dB and MLACC is 44.570 dB whereas HRPO acquired 47.491 dB. Figure 9(c) exposes analysis of HRPO regarding throughput. D-TCP, DLCCA, PBQ-enhanced QUIC and MLACC achieved throughput of 1358.210 Mbps, 1393.951 Mbps, 1429.789 Mbps and 1448.324 Mbps while throughput obtained by HRPO is 1520.908 Mbps.

5.6 Comparative discussion

Table 2 states the comparative values obtained by D-TCP, DLCCA, PBQ-enhanced QUIC, MLACC and HRPO. When time=25 sec, goodput attained by D-TCP, DLCCA, PBQ-enhanced QUIC and MLACC is 1805.950 Mbps, 1847.677 Mbps, 1871.181 Mbps and 1901.615 Mbps whereas HRPO achieved 1951.352 Mbps. The maximum goodput specifies that HRPO can efficiently control congestion and it assured effectual data transmission over a network. SINR acquired by HRPO is 15.647 dB whereas D-TCP, DLCCA, PBQ-enhanced QUIC and MLACC obtained 39.595 dB, 34.479 dB, 33.340 dB and 30.754 dB while time is 25 sec. The minimal SINR acquired by HRPO indicates that it lessen

the corruptions due to noise and interference. HRPO achieved throughput of 1587.167 Mbps while throughput attained by D-TCP is 1375.123 Mbps, DLCCA is 1384.749 Mbps, PBQ-enhanced QUIC is 1487.391 Mbps and MLACC is 1559.784 Mbps for time=25 sec. The achieved high throughput illustrates that HRPO is quickly adaptable to varying network conditions as well as it can maintain the balance between receiving as well as transferring data by preventing congestion. Therefore, it can be recognised that HRPO is the best algorithm for CC in TCP as it obtained maximum goodput and throughput of 1951.352 Mbps and 1587.167 Mbps as well as minimum SINR of 15.647 dB for Buffer size=5 mb while time is considered as 25 sec. The combination of Harmonic analysis with RPO in the HRPO method is driven by the need to enhance the precision and adaptability of congestion control in TCP, particularly in heterogeneous network environments. Harmonic analysis is utilised for its ability to efficiently model periodic and dynamic changes in network conditions, such as bandwidth fluctuations and varying levels of congestion. This analytical framework enables HRPO to better track and predict network behaviour over time. On the other hand, RPO, a nature-inspired optimisation algorithm, is employed for its robust ability to explore and exploit the solution space. RPO helps in ensuring optimal resource allocation and improving overall network performance. The mathematical precision of Harmonic analysis for dynamic network estimation and the global search capabilities of RPO for optimising the congestion control parameters. This combination results in enhanced stability, better utilisation of network resources and improved throughput in heterogeneous networks compared to conventional congestion control methods.

Figure 9 Comparative analysis of HRPO for setup-4 (a) Goodput, (b) SINR, (c) Throughput (see online version for colours)

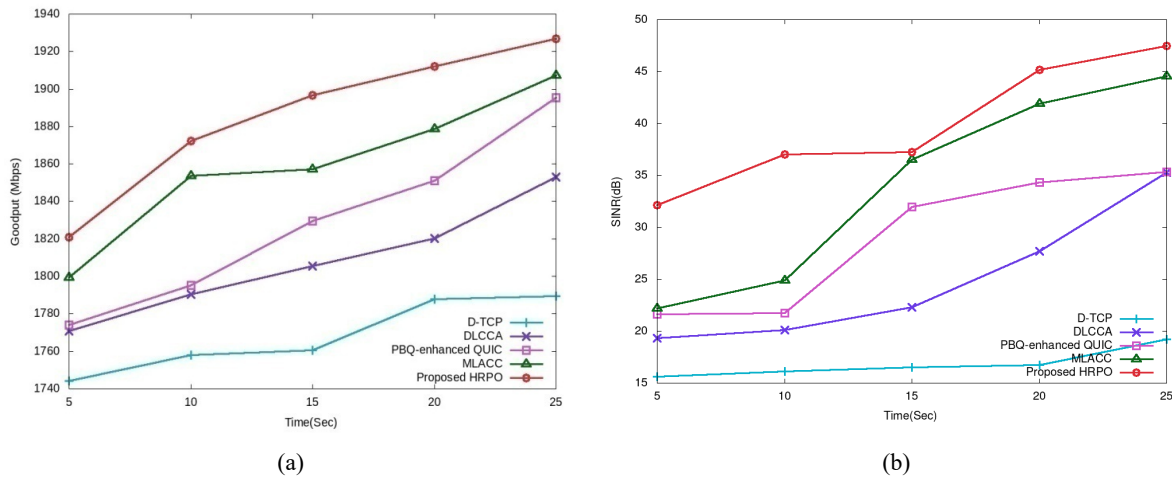
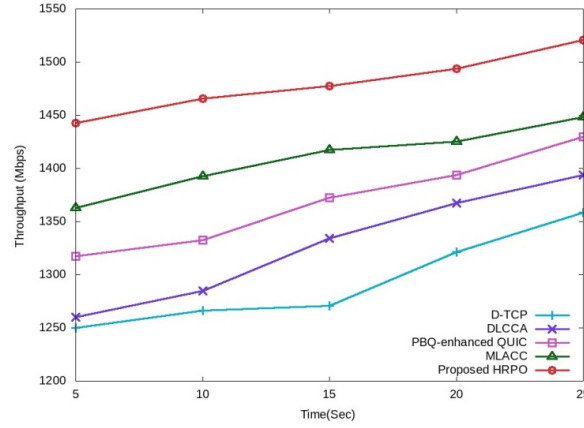


Figure 9 Comparative analysis of HRPO for setup-4 (a) Goodput, (b) SINR, (c) Throughput (see online version for colours) (continued)

(c)

Table 2 Comparative discussion of HRPO

Setups	Metrics/Methods	D-TCP	DLCCA	PBQ-enhanced QUIC	MLACC	Proposed HRPO
Buffer size=5 mb	Goodput (Mbps)	1805.950	1847.677	1871.181	1901.615	1951.352
	SINR (dB)	15.647	30.754	33.340	34.479	39.595
	Throughput (Mbps)	1375.123	1384.749	1487.391	1559.784	1587.167
Buffer size=10 mb	Goodput (Mbps)	1773.678	1812.520	1876.115	1941.676	1954.900
	SINR (dB)	22.422	23.311	29.948	34.029	37.184
	Throughput (Mbps)	1331.578	1385.967	1413.3257	1486.572	1552.841
Buffer size=15 mb	Goodput (Mbps)	1776.276	1811.492	1846.628	1902.549	1929.825
	SINR (dB)	36.909	43.539	45.290	46.176	49.648
	Throughput (Mbps)	1309.805	1390.235	1434.824	1513.651	1517.731
Buffer size=20 mb	Goodput (Mbps)	1789.538	1852.928	1895.375	1907.134	1926.706
	SINR (dB)	19.230	35.303	35.351	44.570	47.491
	Throughput (Mbps)	1358.210	1393.951	1429.789	1448.324	1520.908

5.7 Limitations

While HRPO outperforms existing methods under typical network conditions, its performance may degrade in extreme interference scenarios. Also, the HRPO may be less accurate if the network experiences significant fluctuations in bandwidth or delay, potentially impacting the overall stability. Additionally, the network condition monitoring may present challenges in very high congestion environments.

6 Conclusion

Transmission Control Protocol (TCP) offers reliable transmission of data in every end-to-end data flow service in an internet. Currently, there are few processes that make TCP appropriate for this intention. During past years, there have been adjustments in TCP approaches beginning from fundamental TCP that comprise slower-start and congestion preventable algorithms to additions and modifications of newer techniques. Moreover, TCP emerges in diverse variants and individual TCP variant has irregularities,

advantages and disadvantages. In this research, an algorithm named Harmonic Red Panda Optimisation (HRPO) is presented for Congestion Control (CC) in TCP. Initially, TCP system model is simulated and the following steps are carried out to estimate convergence factor. Firstly, Congestion Window (CWND) is initialised and then, estimation of bandwidth (BW) is carried out. After that, computation of CC factor is done and next, convergence factor is estimated. The convergence factor is estimated utilising HRPO that is modelled by combining Red Panda Optimisation (RPO) with harmonic analysis. Lastly, CWND adjustment is conducted to dynamically change CWND size in the network. Furthermore, HRPO attained high goodput and throughput of 1951.352 Mbps and 1587.167 Mbps as well as Signal to Interference Noise Ratio (SINR) of 39.595 dB for Buffer size=5 mb while time is 25 sec. Future work will investigate the impact of extending TCP window size on efficiency, adaptability and congestion control in dynamic network environments. Additionally, future work will consider the integration of HRPO with emerging technologies, including deep learning for adaptive congestion control and blockchain for secure data transmission.

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