UNRAVELING 5G NETWORKS: EXPLORING CONGESTION MANAGEMENT AND QUALITY OF SERVICE DYNAMICS

[1]Nebo A.N., [2]Olofin B.B., [3]Asogwa T.C.
[1,2,3] Computer Science Department, Enugu State University of Science and Technology, Enugu State, Nigeria
Email: [1]neboannenkemdilim@gmail.com, [3]tochukwu.asogwa@esut.edu.ng,

ABRSTRACT

The proliferation of 5G networks has revolutionized communication paradigms, introducing unprecedented speeds and connectivity. However, the dense deployment of heterogeneous networks and the surge in data demand have escalated concerns regarding congestion management and quality of service (QoS) assurance. This paper provides an in-depth examination of key facets within the realm of 5G networks, including an overview of heterogeneous networks, QoS metrics, congestion control mechanisms, and pertinent literature reviews. In addition, factors influencing QoS were scrutinized and congestion detections methods were explored, along with strategies for effective congestion control. By identifying research gaps and proposing targeted solutions, this study contributes to the ongoing discourse on congestion management in 5G networks, offering valuable insights for enhancing network efficiency and user experience.

Keywords: 5G Network, Congestion, Quality of Service, User Experience, Efficiency

1. INTRODUCTION

Today the introduction of 5G network has provided a significant paradigm shift in the telecommunication sector. This technological invention promises unprecedented data speed, massive connectivity, reliability, improved throughput, low latency, real time monitoring and control, among many other benefits (Haile et al., 2021). However the need of optimal quality of service continued to be on the rise, as users continue to engage on the technology for data exchange. In addition, 5G has spurred a widespread of Internet of Things (IoT), thereby allowing for an extensive network of interconnected devices span across various sectors which ranges from industrial, domestic, agriculture, government, etc (Al-Allaf and Jabbar, 2020).

In the last 3 decades, the telecommunication industry has constantly witness increased number of user connectivity across every part of the world (Christopher, et al., 2022). Coupled with the heterogeneous nature of operating system running on these user equipments, the variation of data types and the highly nonlinear of user behavioral patterns, it has consistently remained an issue to sustain Quality of Service (QoS) in 5G network (Hamzah and Athab, 2022). QoS refers to the ability of a network to meet expected performance requirements capable of delivering satisfactory user experience (Iliey eta l., 2019). Understanding the QoS constraints in 5G networks is essential for network operators, service providers, and regulators. It enables them to optimize network performance, allocate resources efficiently, and ensure a high-quality user experience (Albanna and Yousefizadeh, 2020). Additionally, identifying the challenges and limitations of QoS in 5G networks helps in developing effective strategies and solutions to overcome these obstacles and improve network performance (Danladi and Faruku, 2019). However, while 5G has offered many benefits to facilitate communication in wireless network, the ever increasing number of users resulted to a major problem of congestion on the network.

Over the years, congestion has been singled out as one of the most challenging and recurring problems in the 5G network. It occurs when the demand for network resources surpasses the available capacity, leading to degraded performance and a decline in the overall user experience (Tshilongamulenzhe et al., 2020). Congestion can have various impacts on the QoS in 5G networks, including reduced data speed, increased latency, packet loss, poor connection, and uneven user experience, among many other challenges that require immediate solutions. In this work an investigation on the impact, challenges and solution to congestion in 5G network was presented. The study organization begin with an overview of 5G network, overview of the concept of heterogeneous network, quality of service in 5G network and factors which affects it, congestion control in 5G network, congestion detection method, methods of congestion control, review of relevant literatures on studies relating to congestion management in 5G network, research gap and suggested solution as recommendations.

2. Overview of 5G Network Technology

5G represents the fifth generation of wireless communication technology and signifies a profound evolution from its predecessor; 4G (Shen and Wu, 2022).This network architecture incorporates a diverse range of frequencies, including millimeter waves, to deliver data at substantially higher speeds and with significantly reduced latency. Its capabilities pave the way for an entirely new era of connectivity and innovation (Hamzah and Athab, 2022; Shen and Wu, 2022). The advent of 5G networks has ushered in a host of remarkable advantages. Foremost, 5G delivers exponentially faster data speeds, redefining our digital experiences with seamless streaming, ultra-rapid downloads, and the ability to support emerging technologies like virtual reality and augmented reality (Haile et al., 2021). Additionally, its lower latency empowers near-instantaneous communication, a vital feature for applications such as autonomous vehicles, remote surgery, and real-time gaming. Furthermore, Figuera et al. (2019) posited that 5G networks boast the capacity to accommodate a vastly larger number of connected devices per unit area, making them indispensable for the proliferation of the Internet of Things (IoT) and the realization of smart city initiatives. Lastly, 5G is designed to enhance network efficiency, reducing the overall energy consumption of wireless communication and contributing to a greener, more sustainable technological landscape.

2.1 5G Heterogeneous Network

Figure 1 below presents the three-tier architecture of the 5G heterogeneous network. The network is made of three supporting cells which are the micro cell (SBS1), femto cell (SBS2), pico cell (SBS3), main cell (MBS) which is the macro cell, finally the backhaul link. The mobile phones are example of user equipments which are used for communication within the wireless channels.

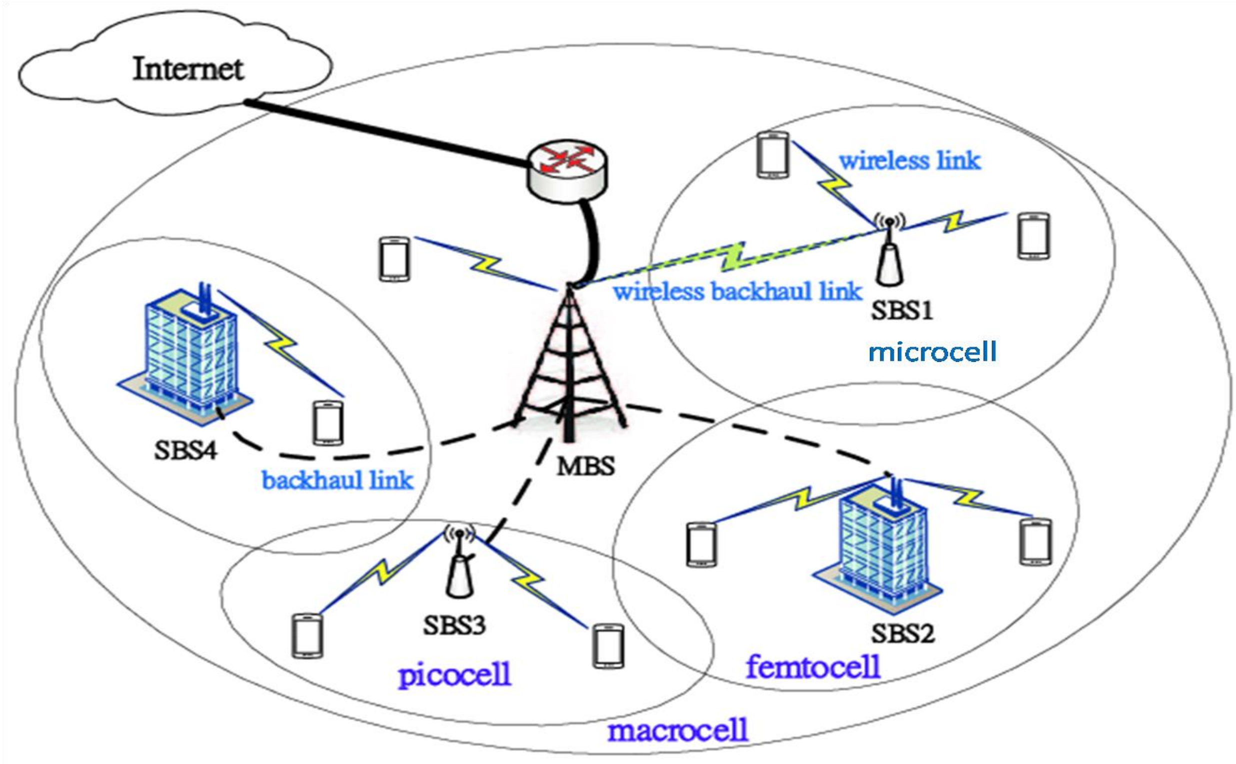

Figure 1: The heterogeneous network

3. **Quality of Service (QoS) in 5G Networks**:

Quality of Service (QoS) in 5G networks is a critical aspect that addresses the performance, reliability, and consistency of network services. With 5G's ability to support a wide array of applications, each with varying requirements, QoS mechanisms are essential. These mechanisms prioritize network traffic, allocate resources efficiently, and ensure that critical applications, like autonomous vehicles or telemedicine, receive the necessary bandwidth and low latency to operate flawlessly. QoS in 5G is a key enabler for delivering a superior user experience and enabling mission-critical applications that rely on dependable network performance (Danladi and Faruku, 2019). It involves advanced traffic management, network slicing, and Quality of Experience (QoE) monitoring to maintain high standards of service across diverse use cases.

3.1 Key Factors That Affect the Quality of Service (Qos) in 5G Networks

Several key factors can affect the quality of service (QoS) in 5G networks. These factors influence the performance, reliability, and overall user experience. Here are some of the key factors (Christopher et al., 2022):

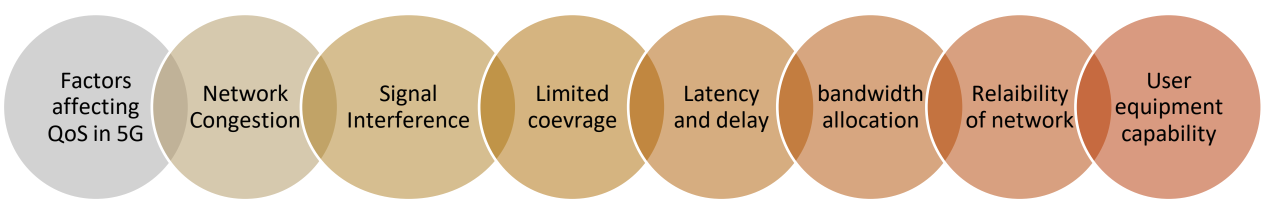

Figure 2: Factors affecting QoS in 5G Network

3.2 Congestion in 5G networks

Network congestion in 5G networks is a critical issue that arises due to various factors and has a significant impact on the overall performance and quality of service. One primary reason for congestion is the substantial increase in data demand brought about by the enhanced capabilities of 5G networks (Umoh et al., 2019). With faster speeds and lower latency, users are more inclined to consume data-intensive services such as high-definition video streaming, online gaming, and real-time applications. This surge in data consumption puts immense strain on the network infrastructure, leading to congestion as the network struggles to handle the high volume of traffic. Another contributing factor to congestion is the massive device connectivity facilitated by 5G. With the proliferation of smartphones, tablets, IoT devices, and smart appliances, the number of simultaneous connections to the network has significantly increased. Each connected device generates its own data traffic, adding to the congestion problem (Figuera **et al**., 2019). The network must manage and allocate resources efficiently to accommodate the substantial device density, but even with advanced techniques, congestion can still occur. Spectrum limitations also play a role in network congestion (Attar et al., 2022). While 5G networks utilize higher frequency bands, such as mmWave, to provide greater capacity, these frequencies have a limited coverage range and are susceptible to signal attenuation. This limitation results in the need for a larger number of small cells and base stations to ensure adequate coverage. In densely populated areas or during peak usage times, the limited availability of spectrum can lead to congestion as the network struggles to accommodate the data traffic. The transition from previous network generations to 5G can also contribute to congestion. Coexistence and interworking between 4G/LTE and 5G networks can introduce complexities and challenges. Issues such as interference and handover problems between different network generations can impact network performance and exacerbate congestion during the transition phase (Tshilongamulenzhe **et al**., 2020). Unpredictable traffic patterns further exacerbate congestion issues. The dynamic and diverse applications enabled by 5G result in varying and unpredictable traffic patterns. Sudden spikes in demand, such as during major events or in highly populated areas, can overload the network resources and lead to congestion (Tshilongamulenzhe **et al**., 2020). Anticipating and managing these traffic variations effectively is crucial to preventing congestion and maintaining a high-quality user experience.

3.3 Methods of congestion detection

Several methods are employed to identify congestion issues and manage network resources effectively. Some of the methods of congestion detection in 5G are illustrated in Figure 23:

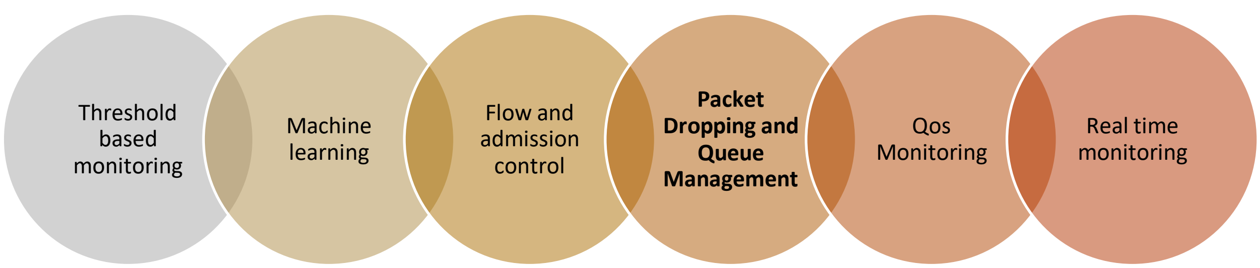

Figure 3: Methods of congestion detection

In the figure above, threshold-based monitoring involves setting predefined thresholds for different network parameters; machine learning analyzes historical data and real-time network performance to predict congestion trends; flow and admission control regulate the rate at which new connections are admitted to the network; packet dropping and queue management help to drop or mark packets based on congestion levels; QoS monitoring triggers congestion alerts, allowing network operators to prioritize traffic; and real-time monitoring identifies congestion hotspots and enables operators to take immediate actions.

3.4 Methods of congestion control

This study introduced different methods for congestion control, which include:

1) **Traffic Policing and Shaping:** Congestion control in 5G often begins at the edge of the network, where traffic is policed and shaped. Traffic policing enforces traffic profiles and drops packets that exceed specified rates, while traffic shaping smooths out bursts of data, preventing sudden spikes in network traffic that can lead to congestion (Balasingam et al., 2019; Figuera et al., 2019).
2) **Dynamic Resource Allocation:** 5G networks employ dynamic resource allocation techniques, such as dynamic spectrum sharing (DSS) and dynamic bandwidth allocation. These methods allow the network to allocate resources (e.g., spectrum and bandwidth) based on real-time demand, ensuring that resources are efficiently distributed to meet changing traffic patterns (Umoh et al., 2020).
3) **Load Balancing:** Load balancing techniques distribute network traffic evenly across available resources. This prevents specific network elements from becoming overloaded, reducing the risk of congestion. Load balancers intelligently route traffic to underutilized paths or servers, optimizing resource utilization (IIiev et al., 2019).
4) **Congestion-aware Routing:** Congestion-aware routing algorithms consider the current network conditions when making routing decisions (Guo and Yuan, 2021). They route traffic along paths with lower congestion levels, avoiding congested links or nodes. This helps reduce the chances of congestion buildup in the network.
5) **Feedback Mechanisms:** Congestion control mechanisms often use feedback mechanisms like explicit congestion notification (ECN) and TCP congestion control algorithms (Mouna, 2021). These mechanisms allow routers to notify endpoints of congestion, prompting them to adjust their transmission rates to alleviate congestion proactively.
6) **QoS-Based Congestion Management:** Quality of Service (QoS) mechanisms play a vital role in congestion control. By classifying and prioritizing different types of traffic, 5G networks ensure that critical services receive the necessary resources, even in congested conditions (Adesh and Renuka, 2019).

4. Relevant literature review on congestion

Kanellopoulos (2019) presented an overview of congestion control in mobile ad-hoc networks. The work is focused on discussing the transmission control protocol in an in-depth manner and how it can be enhanced over a wireless network using congestion control schemes for the mitigation of congestion in a mobile ad-hoc network. The congestion control schemes discussed in this study include cross-layer congestion solutions and transport protocol mechanisms for packet loss discrimination. The study finally recommended a future research direction that recommends the adoption of various congestion control schemes, such as congestion control in media access control, load-balanced congestion adaptive routing, and congestion control in multipath routing control. In another study, Magbo et al. (2019) presented a survey on the control of congestion in a 4G random access channel using congestion control mechanisms. The survey presented various works by researchers that adopt different mechanisms for the control of congestion on a network running on contention-based random-access procedures and contentionfree random-access procedures. It then proposes the application of a collaborative and distributive Q-learning-based algorithm that applies the congestion level of the random-access slot as a reward to the algorithm during learning. The result of the study stated that the Q-learning approach will provide better system performance considering the convergence time, system throughput, and collision probability. Adesh and Renuka (2019) further presented work on how to use congestion feedback mechanisms to avoid queue overflow and reduce delays in queueing on an eNodeB LTE network. The system uses this mechanism to vary the congestion window size of the sender by estimating the congestion level of the eNodeB. The implementation of the technique has increased the package delivery fraction of the system and maintained the throughput of the network. The result of the work presented shows that the algorithm implemented reduces packet delay and improves fairness for the users of the network. Additionally, Perez-Murueta et al. (2019) presented a deep learning system for avoiding congestion and rerouting vehicular networks. The deep learning model applied in this work uses information from past steps to know the zones that experience congestion and then perform redirection operations on the network to achieve a better connection. It uses the entropy-balanced K shortest path algorithm to generate alternative routes. The results of the system operation show that the model presented can reduce the network congestion experience of users by about 19%. Figuera et al. (2019) also presented a low-complexity mechanism for congestion notification in rural IPSec-enabled heterogeneous backhaul networks. The work uses the explicit congestion notification approach in the outer IP headers of a 3GPP IPsec interface. This is done to notify the system about the backhaul congestion state while accessing the network. The scenario, compatibility, and security details of the approach are analyzed and validated by running and implementing the notification mechanism through numerous simulations. The result of the study showed that the system has 2% accuracy in backhaul notification with less than 10 ms latency, or 80% of the implemented time. To address the gap, Arieth et al. (2022) researched the application of the K-means algorithm for managing congestion in the Cluster General Self-Organized Tree-Based Energy Efficient Routing Protocol (CGSTEB) routing protocol. The work uses k-means clustering node energy to alter the type of input parameters. When there is an occurrence of congestion, the algorithm improves the clustered highly prioritized application-specific congestion control clustering protocol (CHPASCCCP) approach for the management of congestion. The result of the study shows that the technique applied improves system lifetime, throughput, energy, and packet loss.

Umoh et al. (2020) presented uncertainty and congestion elimination in 4G network call admission control using Interval Type-2 Intuitionistic Fuzzy Logic (IT2IFL). The work uses a gaussian membership function, an intuitionistic inference system, and defuzzification to obtain the crisp output. Artificially generated datasets are applied with four matrices for performance evaluation. The result of the work presented is that the technique applied has better performance than the conventional system, is fair in its utilization of resources, and equally maintains a good quality of service. Tshilongamulenzhe et al. (2020) also presented an algorithm for traffic congestion management on a wireless sensor network. The algorithm presented in the study involves the integration of routing congestion control and traffic rate adjustment algorithms. It uses Network Simulator 2 as the tool for implementing and testing the algorithm presented. The result of the work reported that the algorithm presented a package delivery of 68.7%, 98.9% on network throughput, and reduced end-to-end delay by 34.2%. In another study, Haile et al. (2021) researched the control of congestion using an end-to-end approach to ensure high throughput and low delay in 4G cellular networks. The work is focused on the deployment of the end-to-end congestion control algorithm (CCA) on the two ends of a network to improve the fairness of the network interaction and limit the chances of congestion. This is done by reducing the flow of interaction between multiple users in the network and increasing the allocation of per-user queues in the cellular networks, which improves the user's access to the network bottleneck. The work is aimed at being a starting point for researchers who hope to apply the CCA technique for congestion control in networks. Additionally, Gaili and Yigit (2021) presented that congestion management can be improved using an intelligent radio access network (RAN). The work is focused on improving network quality of service performance during the pandemic era by optimizing the radio access network system on a 4G infrastructure. This is done by adopting an intelligent RAN framework using congestion management systems. The study recommended the implementation of intelligent RAN optimization and congestion management techniques in future works for improved quality-of-service and quality-of-experience on 4G connections. Mouna (2022) also researched the mitigation of congestion and management of network selection over a heterogeneous C-ITS communication architecture. The work presented the application of a replacement, amplification, and transformation (RAT) selection framework called Distributed Context Aware Radio Technology Selection (DICART) to improve the decision-making process during connectivity (Tshimangadzo et al., 2020). The available RATs are ranked using an approach called Technique for Order Preference by Similarity to an Ideal Solution (TOPSIS). The results of the system reported that the applied technique provided a service of latency that does not exceed 3 ms with high reliability. To address the gap, Shen and Wu (2022) consider the management of congestion in a distribution network using a robust dynamic tariff method in their work. The system uses a three-level model that is designed to acquire solutions based on network constraints, especially in the worst network situations. The work uses the Roy Billinton Test System as a case study for the validation of the effectiveness of the method applied for day-ahead congestion management in distribution networks. The result of the work presented is that the method applied could be ineffective because of the forecast errors in the distribution system operator. Khan et al. (2022) further presented robust multi-objective congestion management in distribution networks. The work applied an optimization technique for scheduling load flexibility in order to alleviate potential congestion. The technique used helps the user reduce the cost of the application, which incurs congestion, and minimizes power consumption by the device. The technique is focused on an uncertainty analysis of the customer's load flexibility schedule, which is dependent on consumer load consumption. The result of the system application presented is that the technique presented is cost-effective and reduces the load curve of the network, thereby alleviating congestion. Additionally, Hamzah and Athab (2022) reviewed the control of transmission control protocol (TCP) congestion using artificial intelligence (AI) in 4G networks. The work presented an examination of how artificial intelligence techniques were used to solve congestion problems in a network, such as congestion avoidance, congestion prediction, and TCP development congestion. It also presented the various fields of AI, such as supervised, unsupervised, and reinforcement learning, which can be applied to solving congestion problems in a 4G network.

Table 1: Summary of Reviewed Relevant Literatures

Author	**Work Done**	**Technique/ Methodology**	**Weakness/problems**
Hamzah and Athab (2022)	Examines the impact of artificial intelligence in network congestion prediction and avoidance	Artificial Intelligence	Key parameters to defined success of congestion management were not

			mentioned in the study
Kanellopoulos (2019)	Discusses the transmission control protocol in network congestion in mobile ad hoc network	Cross-layer congestion solutions and transport protocol mechanisms	The solution despite the success is not proactive
Haile et al., (2021)	Focused on improving network fairness and interaction between multiple users of a network	Congestion Control Algorithm (CCA)	Solution proposed was not proactive to congestion detection and management
Magbo et al., (2019)	Surveyed past works done by researchers to control congestion	Collaborative and distributive Q-learning based algorithm	Despite the success, the solution was not validated with life data.
Gaili and Yigit (2021)	Focused on improving the network Quality of Service performance during the pandemic era by optimizing the radio access network system on a 4G infrastructure	Intelligent Radio Access Network (RAN)	The solution was not proactive to congestion detection and management
Adesh and Renuka (2019)	How to use congestion feedback mechanism to avoid queue overflow and reduce delays in queuing on an eNodeB LTE network	Congestion Feedback Mechanism	The solution proposed is not proactive
Mouna (2022)	Mitigation of congestion and management of network selection over a heterogeneous C-ITS communication architecture	Distributed Context Aware Radio Technology selection (DICART)	Only latency was considered as key congestion parameter
Balasingam et al., (2019)	The reduction of congestion over an intelligent traffic system using collaborative and adaptive signaling on a network	Reinforcement learning	Latency is the main congestion parameters considered, while neglecting other parameters
Perez-Murueta et al., (2019)	deep learning system for avoiding congestion and re-routing vehicular network	Deep learning (k shortest path algorithm)	reduce the network congestion experience of users by about 19%, but leave room for improvement
Umoh et al., (2020)	Uncertainty and congestion elimination in 4G network call admission control using Interval Type-2 Intuitionistic Fuzzy Logic (IT2IFL)	Gaussian membership function, intuitionistic inference system and defuzzification	Not proactive and limited to 4G network.
Figuera et al., (2019)	Low complexity mechanism for congestion notification in rural IPSec-enabled heterogeneous backhaul networks	3GPP IPsec interface	The system has 2% accuracy in backhaul notification with less than 10ms latency 80% of the implemented time, which is good but leaves room for improvement
Tshilongamul	The algorithm presented in the study	Routing congestion	Algorithm presented a

enzhe et al., (2020)	involves the integration of routing congestion control and traffic rate adjustment algorithms	control and traffic rate adjustment algorithms	package delivery of 68.7%, 98.9% on network throughput and reduces end-to-end delay by 34.2% which is good but leaves room for improvement
Arieth et al., (2022)	the application of K-means algorithm for managing congestion of Cluster General Self-Organized Tree-Based Energy Efficient Routing Protocol (CGSTEB) routing protocol	K-means clustering and Cluster General Self-Organized Tree-Based Energy Efficient Routing Protocol (CGSTEB)	The result of the study shows that the technique applied the solution is not proactive to congestion management
Shen and Wu (2022)	The management of congestion in a distribution network using a robust dynamic tariff method in the work	Robust dynamic tariff method	Suffers issues of forecasting error
Khan et al., (2022)	Applied an optimization technique for scheduling the load flexibility in order to alleviate potential congestion	Multi-objective congestion management	the technique is cost effective and reduces the load curve of the network thereby alleviating congestion, but is not proactive
Danladi and Faruku (2019)	DyRED which is an adaptive congestion control system for random early detection of congestion in a network	Dynamic Random Early Detection (DyRED) system and Active Queue Management (AQM) technique	The solution is not proactive

4.1 RESEARCH GAP

From the literatures reviewed, many work have been presented to solve the problem of congestion in wireless network, however solution have not been presented that can detect and manage congestion proactively considering key parameters such as load factor, latency, throughput and packet losses and this has remained a critical gap.

5. Recommended congestion detection and control solution

The proposed system will be developed through the integration of the congestion detection algorithm called Multi-Parameters Adaptive Swarm Optimization Techniques (MPASOT algorithm) and also through congestion control algorithm. The congestion detection algorithm will use the particle swarm optimization approach which computes the fitness of particles of congestion such as throughput, loss and load factor to determine the condition of the network and then control the problem. The flow chart of the congestion detection and control model is presented as below presented in the figure 4;

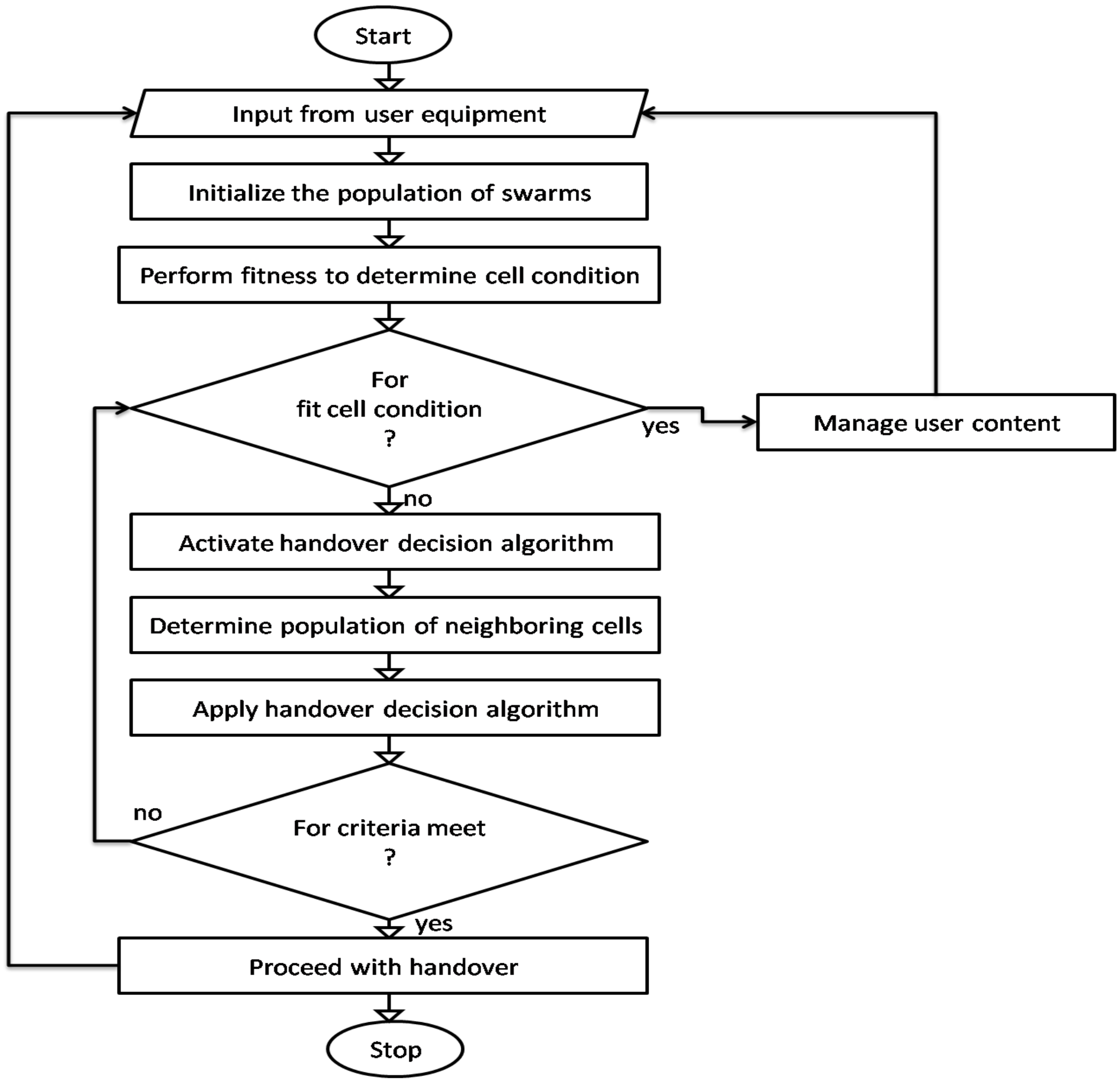

Figure 4: Flow chart of the congestion detection and control system

In the figure 4, the user equipment that transmits the signal to the main cell will be identified, then the congestion detection and control parameters initialized to manage the network condition. The MPASOT which is the congestion detection will employ fitness computation to read and monitor the cell condition continuously. When congestion is detected, the control mechanism is activated. The control algorithms gather the population of cells within the area and then apply decision comparing their position, signal strength and distance to a defined threshold in the algorithm and then determine the best fit cell to manage the user content.

6. CONCLUSION

The advent of 5G networks has ushered in a new era of connectivity, promising unparalleled speed and reliability for users worldwide. However, the dense deployment of heterogeneous networks coupled with escalating data demands has underscored the need for robust congestion management strategies and enhanced quality of service (QoS) provisions. Through our comprehensive analysis, we have elucidated the intricacies of 5G networks, shedding light on the multifaceted challenges posed by congestion and its ramifications on user experience and network efficiency. We have examined the diverse factors influencing QoS in 5G networks, ranging from network topology to traffic patterns, highlighting the critical need for adaptive congestion control mechanisms. Furthermore, our review of relevant literature has underscored both the advancements made in congestion management methodologies and the existing research gaps that warrant further exploration. From congestion detection techniques to proactive congestion control algorithms, a plethora of solutions have been proposed to mitigate congestion-induced performance degradation in 5G networks using MPASOT. By embracing this holistic approach to congestion management, we can unlock the full potential of 5G networks and deliver unparalleled connectivity experiences to users across the globe.

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