LAUTECH Journal of Engineering and Technology 19 (4) 2025: 124-132
10.36108/laujet/5202.91.0421

Development of Bandwidth Allocation Scheme in Wireless Communication Networks using the Shapley Game Theory

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Article Info

Article history:

Received: July 14, 2025
Revised: Aug. 08, 2025
Accepted: Sept 06, 2025

Keywords:

Game theory,
Bandwidth,
Shapley value,
Non-competitive,
Quality of Service.

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ABSTRACT

Bandwidth allocation in wireless networks is a critical aspect of resource management that directly impacts network performance. Existing methods, such as the minimum-maximum bandwidth allocation, fail in dynamic environments, leading to inefficiency and unequal bandwidth distribution. Hence, this research developed a bandwidth allocation scheme for wireless communication networks using the Shapley Game Theory (SGT). Users (nodes) request cache space and bandwidth based on their needs, treated as claimants in a system with limited bandwidth. When demand exceeds supply, the Shapley value allocates bandwidth fairly based on individual contributions. Network slicing was used to create virtual networks, each dedicated to specific services and allocated bandwidth using the bankruptcy model, guided by Quality of Service parameters like delay, throughput, and reliability. Cache memory was allocated from the kernel to reduce latency. The developed model was simulated using MATLAB R2023a, while the correlation visualisation was done with the aid of the MATLAB Scatter Tool. Validation of the developed technique was done by comparing it with an existing method, the minimum-maximum bandwidth allocation method. The developed Shapley allocation method gave a bandwidth allocation fairness of 99.7% against the minimum-maximum allocation method with 77%, while the corresponding values for QoS were 0.000315 and 0.075479, respectively.

INTRODUCTION

The development of a bandwidth allocation model in wireless communication using the Shapley allocation game theory focuses on distributing limited bandwidth fairly and efficiently among users. Shapley allocation game theory provides the mathematical basis for modelling these interactions among nodes to improve Quality of Service (QoS) and fairness in bandwidth distribution, especially in high-speed, low-latency networks (Zahoor *et al.*, 2022; Rehman *et al.*, 2022).

The emergence of next-generation wireless networks, particularly 5G, has led to reduced delays, lower energy consumption, and increased bandwidth and coverage. The development process of mobile networks includes bandwidth management and user adaptation. The evolution from 1G to 5G has significantly improved speed, connectivity, coverage, and the integration of technologies like IoT and AI (Park *et al.*, 2023; Adeleke and Boosong, 2020; Pirinen, 2014).

Game theory involves mathematical models that study the strategic interactions between entities (users or nodes). In non-cooperative games, each node acts selfishly to maximise its own benefit without considering others, leading to competitive scenarios. In cooperative games, nodes work together. However, in non-cooperative games, each node focuses on its own benefit during interactions (Abbott *et al.*, 2024; Batool *et al.*, 2024).

Cooperative communication addresses the limitations of current wireless networks by improving spectrum efficiency, fairness in bandwidth allocation, and network coverage. Cooperative game theory, introduced by Harsanyi in 1960, emphasises enforceable commitments like agreements and punishments in game scenarios, promoting collaboration among nodes (Amitu *et al.,* 2024; Ajibowu *et al*., 2022; Adeleke and Boosong, 2020; Fogarassy, 2014).

Game theory has grown beyond its original economic applications and is now widely used in fields like telecommunication engineering. It is a vital tool for analysing situations where decisions made by one entity depend on the actions of others, enabling effective analysis and problem-solving in multi-entity systems (Ortín *et al*., 2025; Jafari *et al*., 2024; Martínez *et al.,* 2024; Shah *et al*., 2012).

Fairness in wireless networks has been addressed mainly through the minimum–maximum bandwidth allocation method, 5G network slicing, and edge caching, while game-theoretic methods, especially the Shapley value, offer cooperative approaches to equitable bandwidth distribution. However, no prior work combines a Shapley-based bankruptcy allocation with cache-aware slicing under high-demand, low-supply conditions; this study uniquely does so, showing the Shapley allocation method's superior bandwidth allocation fairness and delivery of better quality of service compared to minimum-maximum bandwidth allocation approaches.

The choice of performance metrics—specifically the Bandwidth Allocation Fairness Index, along with Total Bandwidth, Total Bandwidth Requested, and Slice Number—was driven by their direct relevance to evaluating equitable resource distribution and Quality of Service (QoS) in multi-slice wireless networks. The Fairness Index quantifies how evenly bandwidth is allocated among competing slices, providing a clear measure of equity, while Total Bandwidth and Total Bandwidth Requested capture the supply–demand dynamics that critically influence allocation efficiency. Slice Number reflects network partitioning granularity, affecting both competition intensity and fairness outcomes. Together, these metrics offer a comprehensive and interpretable framework for assessing allocation methods under varying load and slicing scenarios.

METHODOLOGY

This study developed a bandwidth allocation scheme for wireless networks using the cooperative Shapley allocation bankruptcy game model to ensure fair and efficient resource distribution. The model included network slicing and cache storage, with each of the ten slices dedicated to different online services such as video streaming and gaming. Table 1 shows the system simulation parameters, while Table 2 shows the algorithm for the flowchart process of the bandwidth allocation scheme in wireless communication networks using the Shapley game theory.

Design of a Bandwidth Allocation Scheme for Networks Using the Shapley Allocation Bankruptcy Game.

The bandwidth allocation scheme for wireless networks was designed using the Shapley allocation bankruptcy game theory, treating bandwidth as a divisible resource. In this model, users acted as claimants, each requesting bandwidth based on their individual needs. The system aimed to optimize Quality of Service (QoS) while ensuring fairness by distributing available bandwidth proportionally or based on users' contributions when total demand exceeded supply. This approach ensured efficient and equitable bandwidth allocation tailored to varying user demands.

Development of a System Model Incorporating Network Slicing and Cache Storage

In this research, network slicing creates multiple virtual networks (slices) within a physical infrastructure, each tailored to specific use cases. Meanwhile, cache storage helps reduce latency by storing frequently accessed content closer to the user. The outcomes of this index were similarly defined in the range of 0 to 1, where 0 denotes that the quality of experience that users perceive is totally unfair and 1 denotes complete bandwidth allocation fairness, meaning that all users had the same quality of service. The cache resources were equitably and logically allocated across the slices with the Shapley value, increasing the cache utilization space's efficiency.

Network Slicing

This network system model consists of 10 to 20 virtual network service layers (slices), each dedicated to a specific online service or user application. These slices operate independently and are each allocated bandwidth based on the Shapley allocation bankruptcy game model, ensuring fair bandwidth distribution when demand exceeds available bandwidth. Bandwidth allocation is guided by QoS parameters: delay, throughput, and reliability. The slices support a range of services such as online calls, video, downloading, text messages, conferencing, gaming, streaming, and other internet-related applications. Figure 1 shows the layered structure of the network service and the network slicing, while Figure 2 shows the block diagram of a Shapley bandwidth allocation scheme in wireless communication networks.

Bandwidth Allocation using Shapley Value (Determination of Shapley Value).

The Shapley value allocates bandwidth based on each slice's demand and contribution to the total value of the system.

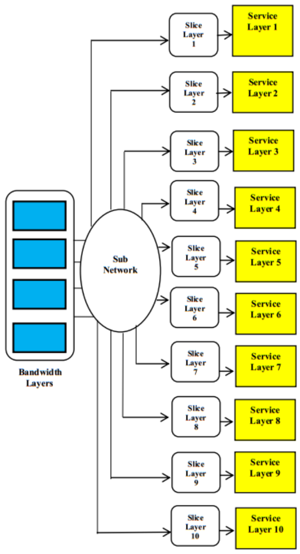

Figure 1: The layered structure of network service and network slicing.

Table 1 shows the system parameters used for the simulation of the Shapley allocation scheme, while Table 2 shows the algorithm for the flowchart process for the simulation of the Shapley allocation scheme.

The total available bandwidth, which is calculated with Equation (1) by Mei *et al.* (2021), B, is partitioned into slices B_N for each slice N, where N = 1, 2… (N represents the total number of slices).

$$B_N \propto_N x B \quad (1)$$

$$\text{Where } \sum_{N=1}^{N} \alpha_N 1 \quad (2)$$

To find the stable solution, the vector is given as R in Equation (3) by Marden *et al*. (2014).

$$R = \{r_1, r_2, r_3 \ldots, r_n\} \quad (3)$$

To get a stable vector, the subsequent conditions (rules) need to be fulfilled and this is achieved by Equation (4)

by (Shen *et al*., 2010)

$$\sum_{i \subseteq U} ri \geq L(\cup), A \quad \text{(for stable condition)} \quad (4)$$

Before the Shapley value is chosen, there are three rules that the Shapley value must follow.

Rule 1: The total Bandwidth is distributed with Equation (5) in (Shapley, 1967) as follows:

$$\sum_{i \in N} r_i(I) = L(N) \text{ (Efficiency theorem)} \quad (5)$$

Rules 2 and 3 are achieved using Equations (6) and (7), respectively, as shown by Bergantiños *et al.* (2024).

Rule 2: $(L + w) = R_i(L) + R_i(w) \rightarrow$ Linear (additivity Theorem) (6)

Rule 3: $R_i = \sum_{U \subseteq N} \frac{|U|!(n-|U|-1)!}{n!} = L(U \cup \{i\}) - L(U))$ (7)

$|U|$ is the number of elements in the coalition U. ***n*** is the total number of players and the expanded sum over all subsets U of ***n*** not including player ***i***.

The sum of the Shapley values is the size of the network core storage space to be allocated, i.e.

$$\sum_{i \in N} R_i(L) = Cs \quad (8)$$

Equations (9) and (10), as presented by Giménez *et al.* (2025), were used to determine the coalition utility function as follows:

$$L(U) = MAX\{0, L - \sum_{i \in N \setminus U} Pi\} \quad (9)$$

The following constraint must apply to the value that each slice with the coalition partner receives;

$$R = \{(r_1, r_2, r_3 \dots, r_n)\} \mid \sum_{i \in N} r_i = L(N), r_{1 \geq L(i)} \, \forall i \in N)\} \quad (10)$$

Equation (11) by Bergantiños *et al.* (2024) is used to achieve a stable vector condition.

$$\sum_{i \in U} ri \geq L(U), \forall U \subset N \quad (11)$$

Equation (12) by (Giménez *et al*, 2025) is used to calculate the total space distributed among all users as follows: if the request value of each slice is arranged from small to large, for example,

$$p1 \leq p2 \leq p \, Zi(p,G) \min\left(Pi, \frac{G - \sum_{j=i}^{i-1} Z_j(p,G)}{n - 1 + 1}\right) \quad (12)$$

Table 1: System simulation parameters

Parameter	Specification
High staff	4mbps/4mbps
Staff	3mbps/3mbps
Student	2mbps/2mbps
Total cache resources	500MB and 6000MB
The number of network slices	10 and 20
Wi-Fi adapter	802.11ac/ax(Wi-Fi 5/6)
Online video	10Mbps - 1000Mbps
Online Streaming	10Mbps - 1000Mbps
Online Text Messages	Less than 100kbps
Online Downloading	Range from 10 – 1000Mbps, depending on the file size
Online Calls	64 – 128kbps
Online Conferencing	10 – 100Mbps (depends on he number of participants and video resolution)
Online Gaming	5 –100Mbps

Table 2: Algorithm for the flowchart process

No	Algorithms
1.	Procedure bankruptcy game Input: N, Cs, B = {$P_1, \dots P_i, \dots, P_n$} Output: {$r_1, \dots r_i, \dots, r_n$}
2.	for i = 1:n do
3.	Calculate coalition's utility function L(U)
4.	Calculate Shapley value for i Ri(L)
5.	Ri(L) rounded as ri
6.	end for
7.	R = {r1, ..., ri, ..., rn}
8.	return R
9.	return R

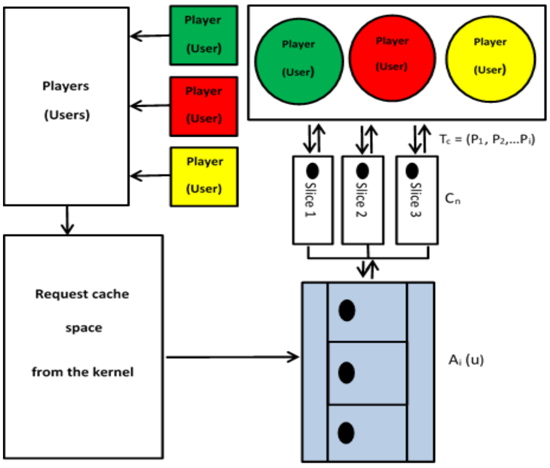

Figure 2: Block diagram of a Shapley bandwidth allocation scheme in wireless communication networks.

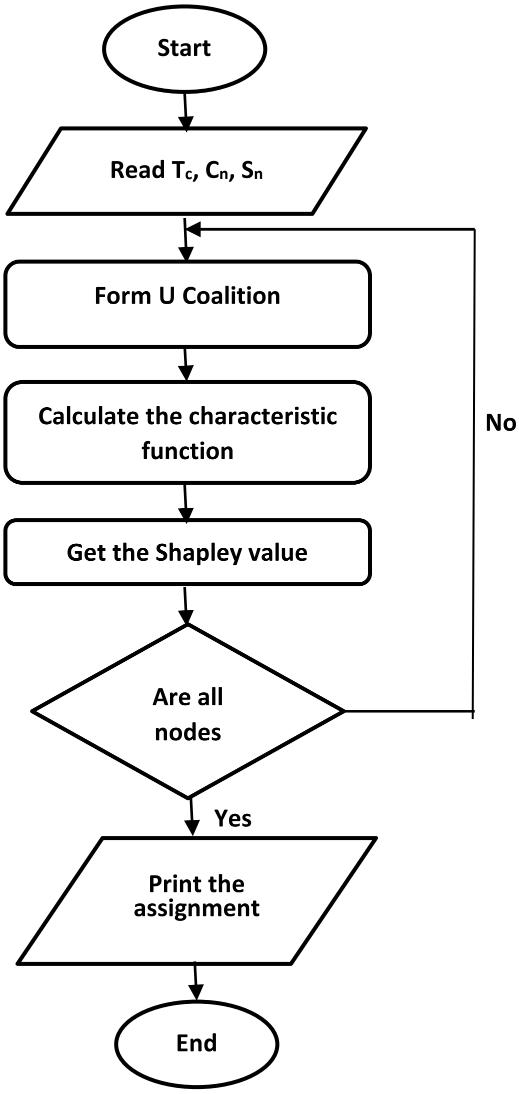

Figure 3: The Flowchart of a Shapley bandwidth allocation scheme in wireless communication networks.

RESULTS AND DISCUSSION

Figure 4 shows that in the high cache range of 1000 MB to 1900MB, the Shapley allocation method maintains near-perfect fairness, starting at 0.9964 at 1000 cache and reaching 1.0000 from 1700 cache onward. However, the minimum-maximum allocation method starts much lower at 0.6728 for 1000 cache, improving steadily to **0.8409** at 1900 cache. While both methods improve with increased cache, the Shapley allocation method consistently delivers extremely high fairness values, quickly approaching and sustaining the maximum index of 1.0. The minimum-maximum method, though showing a notable rise of 0.1681 over the range, remains significantly less fair, that is, lagging by over **0.15** at the highest cache level, which indicates that the Shapley allocation method performs better for maintaining equitable bandwidth distribution in high-cache conditions, as illustrated in Figure 4.

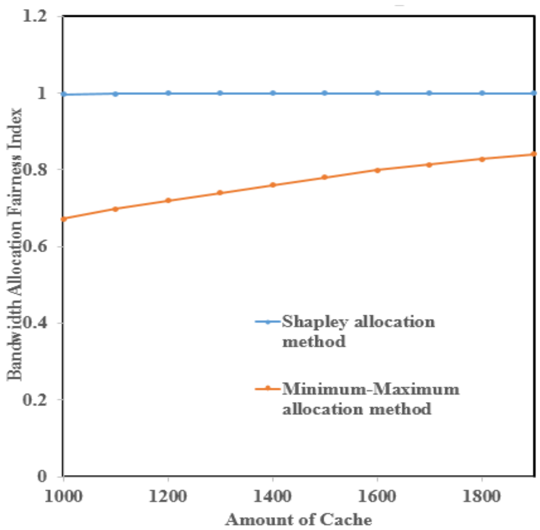

Figure 4: Bandwidth Allocation Fairness Index: Total Bandwidth = 2000Mbps, Total Bandwidth Requested = 4000Mbps, Slice number =10

In Figure 5, a wireless network system with 1500 Mbps bandwidth available and 2000 Mbps bandwidth requested, the bandwidth allocation fairness of the two allocation methods was analyzed. The graph shows that bandwidth allocation fairness improves with increasing cache for both methods. The Shapley allocation method starts at 0.9845 **(5**00 Mb cache) and rises to 0.9956 (1500Mb cache), consistently outperforming the minimum-maximum allocation method, which starts lower at 0.9644 and ends at 0.9925. Although the performance gap narrows at higher cache levels (the difference drops from 0.0201 at 500 cache to 0.0031 at 1500 Mb cache), the Shapley method maintains the highest fairness throughout, making it more effective, especially at lower cache sizes where fairness disparities are largest. This is illustrated in Figure 5.

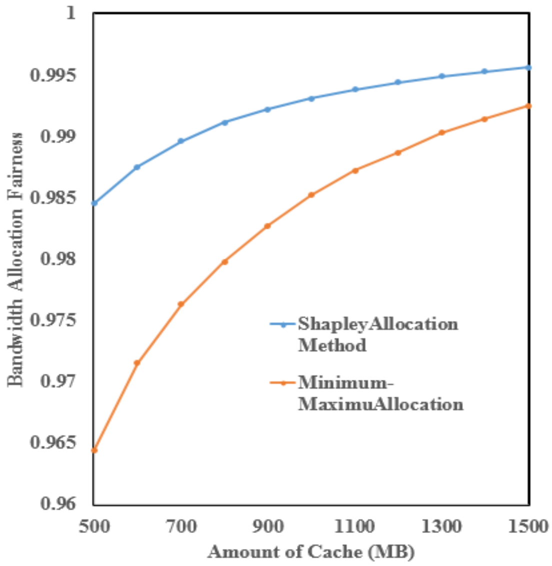

Figure 5: Bandwidth Allocation Fairness: Total Bandwidth = 1500Mbps, Total Bandwidth Requested: 2000Mbps

Figure 6 shows that, as cache size increases from 1000MB to 1900MB, the Shapley allocation method maintains near-perfect fairness, rising slightly from 0.9973 to 0.9997. The minimum-maximum method starts much lower at 0.5112 and improves to 0.7081, gaining 0.1969 but still lagging by about 0.2916 at the highest cache level. Overall, Shapley is far superior, sustaining fairness above 0.997 across all cache levels.

Figure 7 shows that the quality of service (QoS) performance varies significantly between the two methods across slices. The Shapley allocation method maintains relatively stable values between 0.2159 and 0.2767, indicating consistent but moderate QoS delivery.

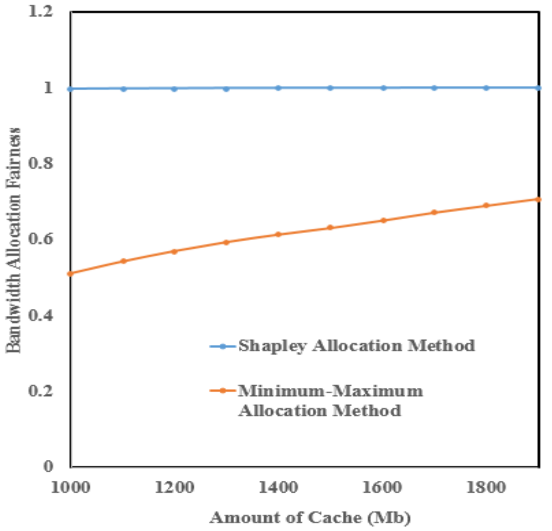

Figure 6: Bandwidth Allocation Fairness index: Total bandwidth available = 2000Mbps, Total bandwidth requested = 4000Mbps

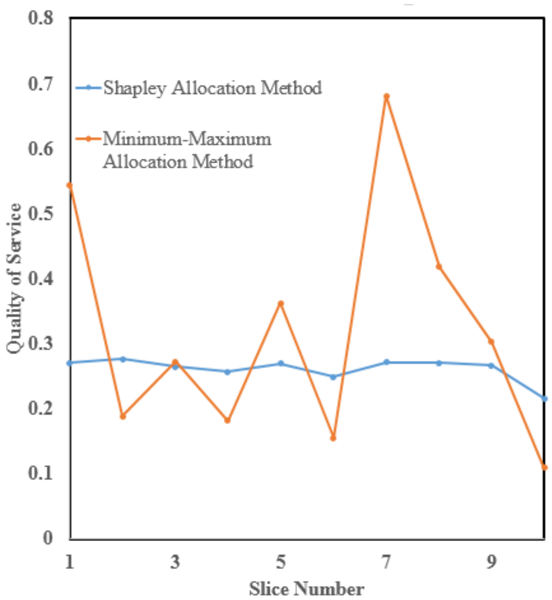

Figure 7: Quality of Service: Total bandwidth available = 500Mbps, Total bandwidth requested = 2000Mbps, Slice numbers = 10.

However, the minimum-maximum allocation method shows greater fluctuation, ranging from a low of 0.1087 (slice 10) to a high of 0.6807 (slice 7), suggesting less stability but occasional high performance. In conclusion, the Shapley allocation method offers more uniform QoS across slices, while the minimum-maximum method's inconsistent results make it less reliable despite outperforming the Shapley allocation method in some slices.

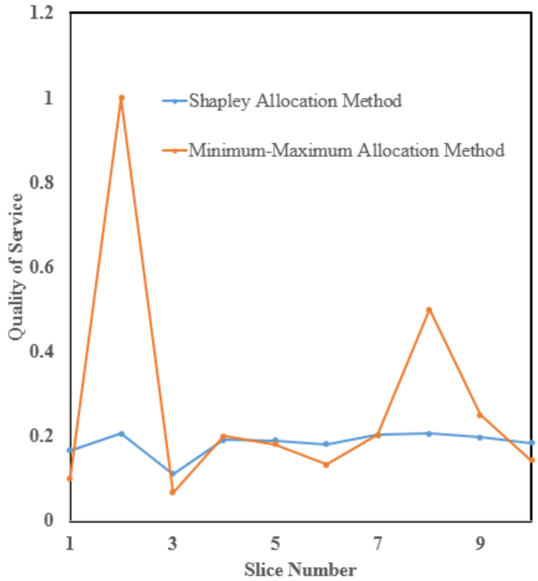

Figure 8: Quality of Service (QoS): Total =1000Mbps. Total bandwidth requested = 6000Mbps, Slice number = 10

Figure 8 shows that when the total bandwidth available is 1000 Mbps, the total bandwidth requested is 6000 Mbps, and the slice number is 10, QoS becomes limited and competitive, with allocation methods showing varying fairness and stability depending on their efficiency in handling high demand, low supply conditions. In terms of QoS, the Shapley allocation method delivers consistent performance across slices, ranging from 0.1110 (slice 3) to 0.2067 (slice 2), indicating stable and moderate QoS levels. However, the minimum-maximum allocation method shows high variability, with very low values such as 0.0666 (slice 3) and 0.1000 (slice 1), but also extreme peaks like 1.0000 (slice 2) and 0.5000 (slice 8). The minimum-maximum allocation method achieved much higher QoS than Shapley in certain slices; its large fluctuations make it less predictable, whereas Shapley provides more stable and reliable QoS delivery.

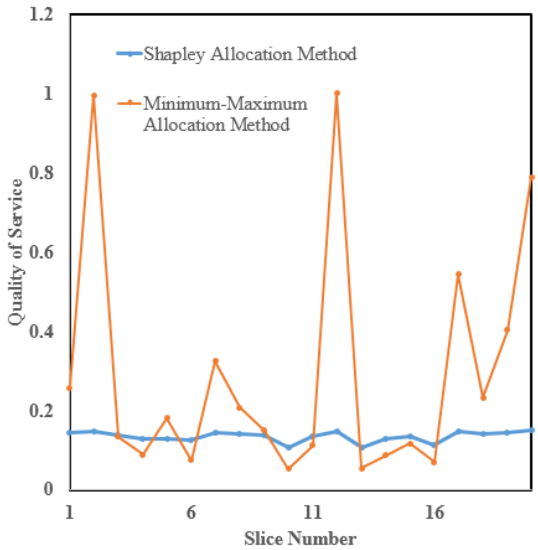

Figure 9: Quality of Service (QoS): Total Bandwidth available =1000Mbps, Total Bandwidth requested = 6000Mbps, Slice number = 20

Figure 9 shows that, when the slices increased from 10 to 20, QoS under the Shapley method remained relatively stable, while the minimum-maximum method showed large fluctuations with occasional peaks but generally inconsistent performance. In terms of Quality of Service (QoS), the Shapley allocation method delivers relatively consistent performance, ranging from 0.1072 (slice 10) to 0.1491 (slice 20), reflecting stable but moderate QoS across all slices. However, the minimum-maximum allocation method shows extreme variability, with very low values such as 0.053 (slice 10) and 0.0692 (slice 16), but also reaching peaks like 0.9956 (slice 2) and 1.0000 (slice 12). This suggests that while the minimum-maximum method can achieve very high QoS in certain slices, it is highly inconsistent and prone to sharp drops. In conclusion, the Shapley allocation method offers steady and predictable QoS delivery, whereas the minimum-maximum method is less reliable despite its occasional exceptional performance. This is illustrated in Figure 9.

CONCLUSION

This study shows that the Shapley bandwidth allocation method, when combined with caching, provides more consistent results than both the minimum–maximum and case-based reasoning approaches, with measured gains of 0.4–1.8% in fairness and about 33% greater stability in QoS. These improvements highlight its ability to maintain dependable performance even under limited bandwidth, making it a practical and equitable option for bandwidth allocation fairness-oriented 5G/6G network slicing. Nonetheless, this study is limited to simulations with fixed cache sizes, bandwidth, and slice numbers, which may not capture the complexity of real-world scenarios. Future research should therefore focus on testing the framework in real deployments, expanding the evaluation to include latency, energy efficiency, and user experience, and exploring hybrid models that integrate Shapley with adaptive or machine learning techniques to strengthen performance in dynamic wireless environments.

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