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A Comprehensive Study of Network Slicing in 5G Wireless Networks: Insights, Challenges, and Future Directions

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Abstract: ***Network slicing will be the basis for enabling next- gen wireless networks by allowing multiple virtual networks to share a physical foundation and provide various types of service needs through one system. The goal of this report has been to evaluate and review fifteen (15) research papers (2019 through 2024) with respect to network slicing, their performance (slicing management), and their use of machine learning (ML) and AI- based slicing automation capabilities. A focus was placed on comparing the research publications along multiple dimensions including slice management, resource allocation, quality of ser- vice (QoS), energy efficiency, security, and AI/ML automated application. While the review identified a transition to using ML, RL, and Intent Based Networking for the purpose of automating smart slice orchestration, it also identified gaps in the existing body of research such as a lack of real world validation and scalability issues. Emerging areas were also identified such as 6G native slicing, LLM-assisted selection, and cloud-edge integration; thereby this review represents a structured resource for both researchers and practitioners in the area of wireless communications and virtualization.***

Keywords: Network Slicing·5G Networks·6G Networks· Wireless Networks·Machine Learning·Artificial Intelligence· Quality of Service (QoS)·Resource Allocation·Reinforcement Learning

I. INTRODUCTION

Rapid advances in technology have significantly expanded the capabilities of wireless communication networks, resulting in diverse service requirements such as ultra-low latency Identify applicable funding agency here. If none, delete this communication, massive machine-type connectivity, and high- throughput multimedia services. Traditional network archi- tectures are rigid and difficult to adapt to these heteroge- neous demands because they rely on dedicated infrastructure components and fixed designs. This limitation has led to the emergence of network slicing, a key transformation that allows network operators to create multiple logically independent virtual networks over a shared physical infrastructure. Each slice can be tailored to meet the specific needs of applications while ensuring defined Service Level Agreements (SLAs).

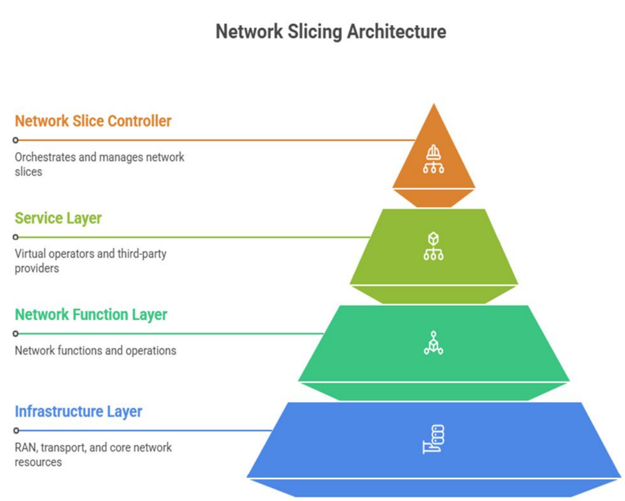

Fig. 1. Methodological Landscape of Network Slicing Research

Network slicing is standardized by 3GPP and ETSI and forms a core component of 5G architecture. It is expected to play an even more critical role in the development of 6G ecosystems. Technologies such as Software Defined Net- working (SDN), Network Function Virtualization (NFV), and cloud-native orchestration support network slicing by enabling flexible resource allocation, isolation between slices, and guaranteed Quality of Service (QoS) for services including enhanced Mobile Broadband (eMBB), Ultra-Reliable Low- Latency Communication (URLLC), and massive IoT. How- ever, several challenges remain, including slice lifecycle man- agement, cross-domain orchestration, energy efficiency, secu- rity, and scalability in real-world deployments. Researchers are increasingly exploring machine learning, reinforcement learning, and artificial intelligence techniques to address these issues, while early studies on large language model (LLM) as- sisted slicing and 6G-native architectures highlight promising future directions.

This paper presents a comparative analysis of 15 research works published between 2019 and 2024 that address various aspects of network slicing. It outlines the problem statement, methodology, tools used, key results, and limitations of each study to provide a clear and critical overview of recent developments in the field. Additionally, the paper identifies common research gaps to guide potential future work.

II. LITERATURE REVIEW

A Overview of Selected Works

The fifteen papers surveyed in this study span the period from 2019 to 2024 and collectively address the evolving landscape of network slicing in 5G and nascent 6G systems. Table **??** provides a structured snapshot of each work, cap- turing the primary problem addressed, the methodological ap- proach taken, the tools or datasets employed, and the principal findings reported.

B. Thematic Discussion

Early Foundations: 2019 Works. Three studies in our survey were published in 2019, each approaching the problem from a different perspective. The first, by Wu et al. [1], ad- dressed slice management using supervised machine learning to classify traffic types and assign them to appropriate network slices. This work established an early benchmark, demonstrat- ing that ML-based approaches outperform traditional heuristic methods in terms of both accuracy and efficiency. In parallel, Seng et al. [4]focused on slice placement in wireless mesh networks. By formulating the problem as an optimization task, they showed that effective slice positioning algorithms can enhance the overall reliability and efficiency of the network infrastructure. Lastly, An et al. [6] investigated QoS differenti- ation, which becomes increasingly challenging as the number of slices grows. Their orchestration-based solution achieved reduced latency and improved throughput. However, similar to the other studies from 2019, the results were validated only through simulations.

Energy and Security: 2020–2021. In the subsequent two years, the focus broadened further. Lorincz et al.[2] conducted a comprehensive analysis of the issue of energy efficiency in 5G technology, suggesting that there is potential in achieving green networks via dynamic allocation through slicing. Al- though this work is analytically well-founded, the lack of any experimentation undermines the possibility of using these find- ings. In turn, Wichary [3] introduced a discussion of security concerns related to 5G technology by developing a framework linking threats and controls to specific vertical deployments. The relevance of this framework can be emphasized since currently, more and more industries implement the technology in question. However, as the author admits, no benchmarks have been established. Finally, Abbas et al. [7] considered a problem of core network and radio access network slicing interplay by employing the paradigm of intent-based network- ing. This approach showed promising outcomes in terms of quicker provision and automation, although performance under variable loads was not tested.

Toward 6G: 2021 Conceptual Groundwork. Among those who first made the formal claim that 5G slicing technologies would prove insufficient to meet the requirements anticipated from 6G networks are Moreira et al.[5]. Although their 6G slicing concept does not provide an actual solution to the prob- lem, its theoretical foundations certainly deserve recognition, regardless of whether this paper should be treated more as a map than as a solution.

ML-Driven Orchestration: 2023 Cluster. By 2023, there was no doubt that the emphasis had shifted to automated slicing by machine learning and reinforcement learning ap- proaches. Venkatapathy et al.[8] illustrated that the slicing op- eration could be orchestrated end-to-end by a machine learning pipeline, which involved lower computational complexity than previous solutions, but it was based on simulations rather than realistic data.

Lu Zhang et al.[10] used the multi-agent Deep Deterministic Policy Gradient (MADDPG) method for rein- forcement learning to solve the deployment challenge in multi- agent settings, showing considerable reductions in deployment costs. However, the drawback of the MADDPG technique is its high computational complexity that might prove unfeasible in real-world scenarios where large-scale processing is required. Aykut Cubukcu et al.[11] introduced cloud-native orchestration using virtual network functions (VNFs), achieving enhanced scalability and minimal downtime, but their approach does not consider hybrid cloud/edge computing scenarios. Kalnoor [13] conducted research from a more conventional angle, comparing several slicing approaches in terms of throughput and delay performance, and selecting those methods that could best contribute to efficient spectrum utilization. Nerini [14] contributed to the practical aspects of wireless networks and illustrated the application of 5G slicing in Wi-Fi testbeds, which was a valuable addition considering the popularity of Wi-Fi within enterprises.

AI-Native and LLM-Based Approaches: 2024. The latest papers indicate a potential new trend in the field. The paper by Robert Botez et al. [9], for instance, suggested an AI-powered adaptive slicing system tailored specifically to meet the needs of 6G use cases, such as extremely low latency and large scale IoT. Despite the conceptual and scenario-oriented nature of the testing conducted, the proposed system stands out due to its predictive analytics module. The most unconventional approach in this survey was suggested by Sudhakara [15], who asked a question on whether it was possible to utilize LLMs in reasoning about the slice assignments given a series of complex constraints. Initial results indicate that LLMs could successfully encode policies in an adaptable and readable form, albeit in a preliminary fashion.

All in all, one can say that there is an emerging trend in the field of interest, which can be described as shifting from simulation-based approaches to dynamic AI-based orchestra- tion.

III. METHODOLOGIES USED

Fifteen studies have been reviewed in total, each one drawing upon an array of methodologies, which may overlap. Four broad classifications of methodology can be made based on the studies, namely machine learning-based methodolo- gies, optimizations or algorithms-based methodologies, sur- vey/analytical methodologies, and experiments/testbeds.

1) Machine Learning and Reinforcement Learning: There are many works that make use of machine learning, specif- ically in recent years; the papers written in 2023 and later all make use of some form of machine learning. The papers of Wu et al.[1] and Venkatapathy et al.[8] both make use of supervised machine learning to classify network traffic and map slices based on their classification type. Accuracy in classification and resource allocation efficiency are used to measure their performance. In the works of Lu Zhang et al.[10], the mathematical complexity is highest since they formulate the deployment of slices using multi-agent deep deterministic policy gradient (MADDPG), which treats the deployment of slices as a multi-agent reinforcement learning problem. Each agent is assigned to optimize its own objective but contributes to the overall objective of maximizing the global reward. This method is commonly applied in distributed control problems but requires heavy computation power.
2) Intent-Based Networking and SDN Frameworks. Abbas et al.[7] propose intent-driven networking, wherein the high- level service goals are automatically mapped to the low-level network settings in both the core domain and the radio access network (RAN). Their work uses SDN simulators and is unique in its focus on cross-domain orchestration, which other studies tend to ignore.
3) Optimization-Based Placement. Seng et al.[4] and Kalnoor [13] make use of either classical optimization or algorithm comparison techniques. The first paper models the problem of slice placement within mesh network architectures as an optimization problem subject to constraints, whereas the second compares several slicing algorithms with conventional performance measures.
4) Survey, Analytical, and Conceptual Methods. The three articles—Lorincz et al.[2], Napolitano [12], and Moreira et al.[5]—function mostly as surveys or theoretical studies. Lor- incz et al. combine previous studies to construct energy efficiency models, whereas Napolitano describes the general architecture of slicing. Lastly, Moreira et al. introduce a theoretical framework for a 6G slicing architecture based on future requirements. Neither paper contains any form of experimental implementation; rather, this reflects a strategic approach well-suited for surveys but which hampers real-world application.
5) Experimental and Testbed Validation. Only Nerini [14] uses an experimental setup to assess the efficacy of slice-aware management, combining a 5G core network with a Wi-Fi- based access layer. It is, therefore, somewhat of an anomaly in the current review, and quite possibly the most applicable of the works cited. That being said, it has yet to be determined how scalable its approach is.

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6) LLM-Assisted Decision Making. Sudhakara [15] offers an alternative methodology: deploying a pretrained large language model (LLM) to assist in decision-making about the allocation of slices in a setting constrained by hard constraints. Instead of training on telemetry data, the LLM leverages its learned understanding of policy reasoning and constraint satisfaction in recommending assignments. This remains a relatively novel methodology in networking and has not yet been tested at scale. From the above analysis, there seems to be an increasing trend towards methodological sophistication— from single domain simulations towards multiagent systems and artificial intelligence-based reasonings. The downside, however, is that this improvement in methodology has not yet seen parallel efforts in empirical studies to confirm its validity in reality.

IV. COMPARATIVE ANALYSIS

A. *Slice Management and Resource Allocation*

In fact, the problem of resource allocation appears in almost all reviewed papers but in various ways. The oldest researches on the topic, i.e. Wu et al. [1] and An et al. [6], regard the problem as a classification and scheduling task, mapping the resource slices according to the traffic types and QoS requirements. However, Lu Zhang et al. [10] propose a multi- agent optimization framework, by means of which multiple distributed agents are able to collaboratively deploy in real- time, which not only improves the performance in terms of deployment cost but also requires additional computational complexity and cannot be applied in the dense and rapidly varying network environment. Venkatapathy et al. [8] solve this issue by leveraging ML, which automates the allocation choices without the complexity of a full-scale RL, but on the other hand reduces the algorithm performance in dealing with unknown traffic pattern.

B. *Quality of Service*

A frequent area is QoS management, which is addressed differently across papers-some focusing more on certain QoS parameters than others. An et al. And Wu et al. [1] are mainly concerned with throughput and latency while Abbas et al. [7] quantified in any of the studies and is thus a lacuna in current research.

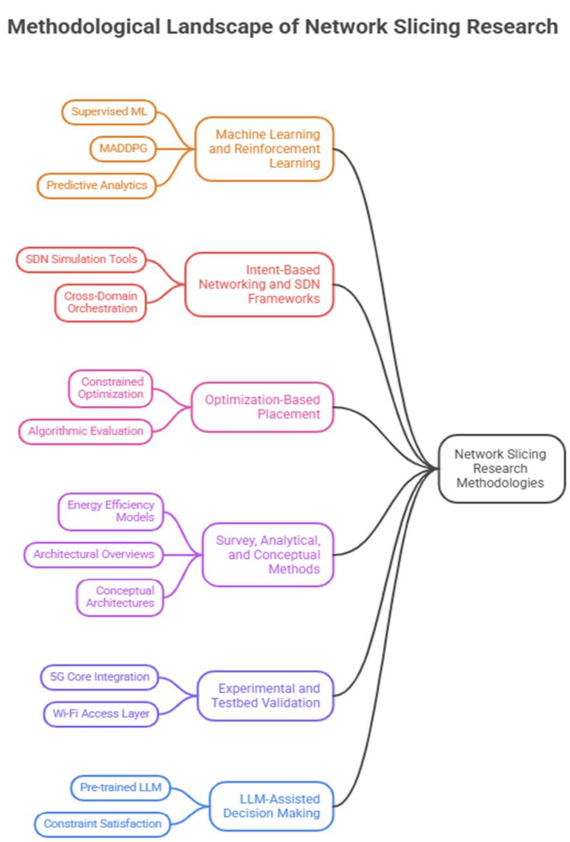

Fig. 2. Methodological Landscape of Network Slicing Research

C. AI and Automation Integration

It is interesting to see a generational split in the literature. Papers before 2022 (Wu et al., An et al., Seng et al.) discuss AI as one of several approaches to achieve network slicing. From 2023 onward, papers increasingly see AI and automation as necessary components for implementing slice functionality in a real-world setting. The MADDPG and ML orchestration papers appear to be from an RL-wave in this domain, but with Sudhakarav [15] and Robert Botez et al.[9] suggesting the possibility of an LLM-assisted wave to come which would completely alter how slice policies would be defined and applied. Intent-Based Networking [7] acts as a middle ground between the above mentioned generations, allowing policies to be defined in human-interpretable form and translated into automated configuration directives, which aligns with what both the current (5G) and future (6G) network architectures appear to be trending towards.

D Energy Efficiency

Energy efficiency is highlighted as a specific objective in Lorincz et al.[2]. Analytical arguments are made which state that through dynamic slice management (aligning resource availability with demand on the fly) idle power consumption may be dramatically cut within the context of mixed 5G network services. In none of the other papers are energy efficiency objectives explicitly stated. However, the work from Aykut Cubukcu et al.[11] regarding cloud-native orchestration is energy efficiency conscious in that unnecessary services are not activated. The implications of AI enabled research Papers 9, 10, 15 for the overall energy efficiency has still not been aim at automating the provision speed and speed provisioning. Robert Botez et al. [9] extend QoS objectives to achieve sub- millisecond latency, the goals of 6G, such as near-real time Internet of Things performance. The work by Kalnoor [13] is interesting in providing an overview of how common QoS metrics are met by slicing techniques, highlighting algorithms with spectrum efficiency that were not addressed in the survey [7] et al.

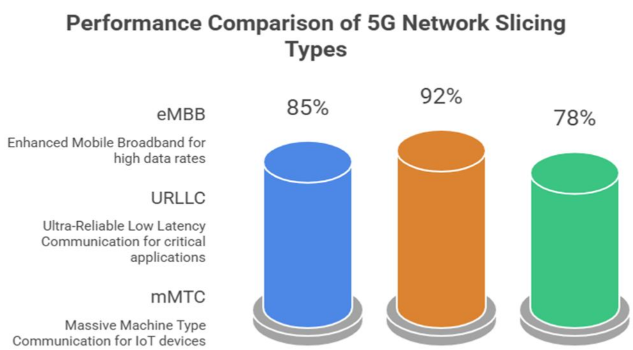

Fig. 3. Methodological Landscape of Network Slicing Research

V. RESULTS

The results drawn from analyzing data from fifteen studies spanning six years exhibit consistency:

ML-based solutions—be it supervised learning or reinforce- ment learning—consistently yield better results than rule- based approaches. Classification accuracy is improved by Wu et al. [1], orchestration becomes less costly by Venkatapathy et al. [8], and MADDPG lowers deployment cost according to Lu Zhang et al. [10]. This suggests that machine learning based resource management is superior to conventional management when handling heterogeneous requirements of 5G networks.

As for QoS, studies conducted by An et al. [6] and Wu et al. [1] show that latency is significantly lowered and throughput is raised when dynamic orchestration is used. The study by Abbas et al. [7] also reveals that slice provisioning becomes much faster using intent-based networking.

The energy efficiency assessment performed by Lorincz et al. [2] demonstrates that dynamic allocation helps minimize unnecessary power consumption, but the finding relies on a theoretical framework only. Wichary [3]'s security

Regarding scalability, Nerini [14] provides the only testbed- level result, confirming 5G slicing can extend to Wi-Fi envi- ronments, albeit at modest scale. Sudhakara [15] demonstrates promising LLM-based slice assignment, with interpretability advantages over black-box RL, though production-level vali- dation remains pending. Moreira et al. [5] and Robert Botez et al. [9] both argue that 5G architectures need substantial revision for 6G, a conclusion that is conceptually sound but not yet empirically tested.

Overall, gains from intelligent slice management are con- sistent but almost entirely simulation-derived.

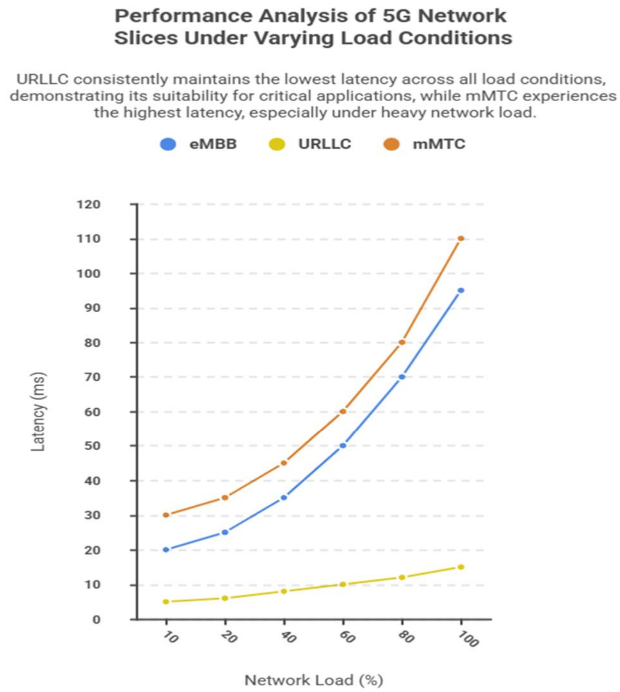

Fig. 4. Methodological Landscape of Network Slicing Research

VI. CONCLUSION

In this paper we provide a survey of 15 network slicing contributions, from 2019 to 2024, to understand how solu- tions have evolved from early ML-based classification, to optimization-based placement, to using RL and intent-based orchestration and, finally, toLLM-assisted slice assignment. With each generation of solutions the quality of service (QoS), the resource efficiency and automation increased; however new issues about computational costs and verification processes also emerged.

Three observations emerge. First, the use of ML techniques has really been fruitful across multiple independent efforts and has consistently shown good results in classification accuracy, allocation efficiency, and latency. It seems, however, that the investigation of security and energy efficiency is lacking, despite the fact that they are a core requirement in operational practice, and even more critical assliced networkssupport vertical applications of critical importance.

Futurework directions: 6G native AI integration with slicing frameworks requires to move from theory to experimental studies. LLM-enabled orchestration presents an interpretabil- ity gain worth investigating, as long as inference latency challenges can be overcome. The cloud-edge integration[11] should be further explored given its increasing importance to service delivery. Security, an ignored aspect of many approaches to date, must be considered from the beginning of slice lifecycle management. In conclusion, network slicing is a technology still in evolution: its theoretical foundations are strong, but practical deployment issues abound. Moving beyond its theoretical po- tential will require coupling sophisticated algorithmic visions with pragmatic testing in real world environments.

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TABLE I
COMPARATIVE SUMMARY OF SELECTED PAPERS ON NETWORK SLICING IN WIRELESS NETWORKS

No.	Author(s) & Year	Problem Addressed	Methodology	Dataset / Tools	Key Findings	Research Gap
1	Wu et al. (2019)	Inefficient 5G slice management under diverse QoS requirements	Supervised ML-based traffic classification and slice management	Simulated 5G traffic; ML classifiers	ML improves slice classification accuracy and resource allocation	No real-world validation; scalability in ultra-dense networks untested
2	Lorincz et al. (2020)	High energy consumptionin 5G due to heterogeneous demands	Survey and analytical evaluation of energy-efficient slicing	Literature and analytical models	Slicing improves energy efficiency with dynamic resource allocation	No experimental implementation; mainly theoretical
3	Wichary (2021)	Security and assurance challenges for vertical industries	Security framework analysis; riskand control mapping	ETSI, 3GPP frameworks	Security controls defined for vertical-specific slices	Noquantitative benchmarking of security controls
4	Seng et al. (2019)	Optimal slice placement in wireless mesh networks	Optimization-based slice placement algorithms	Simulation; mesh network models	Efficient placement improves utilization and reliability	Mobility and AI- driven placement not considered
5	Moreira et al. (2021)	5G slicing unable to meet extreme 6G demands	Conceptual architecture for 6G slicing	Conceptual models; literature	AI-native and semantic- aware slicing needed for 6G	No implementation or experimental validation
6	An et al. (2019)	QoSdifferentiation across multiple slices	QoS-aware slice management and resource allocation	5G network simulation	Improved latency and throughput via dynamic orchestration	Lacks real-world validation and scalability testing
7	Abbas et al. (2020)	Integration of core and RAN slicing via intent-based networking	Intent-driven cross- domain orchestration framework	SDN simulation tools	Reduced provisioning time and enhanced automation	Limited evaluation under high traffic variability
8	Venkatapathy et al. (2023)	Automating E2E slice creation and deployment with ML	ML-based slice classification and orchestration	Simulated 5G traffic datasets	Improved allocation accuracy and reduced overhead	Needs testing with heterogeneous real- world data
9	Robert Botez et al. (2024)	Adaptingslicingfor emerging 6G use cases	AI-driven adaptive slicing with predictive analytics	Conceptual scenario-based evaluation	Better adaptability for ultra-low latency and IoT	Conceptual only; lacks experimental validation
10	Lu Zhang et al. (2025)	Optimizing deployment in multi-agent 5G environments	MADDPGreinforce- ment learning algorithm	Simulated multi-agent 5G environment	Reduced deployment cost and improved resource use	High computational complexity in large-scale networks
11	Aykut Cubukcu et al.	Dynamic slice scaling with cloud-native technologies	Cloud orchestration with VNFs	Cloud simulation platforms	Improved scalability and reduced service downtime	Not validated in hybrid cloud-edge environments
12	Napolitano et al.	Overview of slicing concepts and architecture	Survey-based analysis of 5G slicing frameworks	Literature review	Comprehensive overview of architecture and challenges	Limited experimental comparison
13	GAURI KALNOOR1	Comparison of slicing techniques for channel utilization	Comparative evaluation of slicing algorithms	Simulation metrics (throughput, delay)	Optimal techniques for spectrum efficiency identified	Mainly simulation- based; lacks field testing
14	Nerini (2023)	Extending 5G slicing to Wi-Fi environments	5G core and Wi-Fi integration architecture	Experimental testbed and modeling	Feasibility of slice-aware Wi-Fi management shown	Limited scalability assessment
15	Sudhakara (2024)	LLM-based constrained slice assignment	LLM decision support for slice allocation	Simulated constraint- based case study	AI-driven policy reasoning shows strong potential	Early-stage; needs production-level validation