Taming the Titans: A Survey of Efficient LLM Inference Serving

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Abstract

Large Language Models (LLMs) for Generative AI have achieved remarkable progress, evolving into sophisticated and versatile tools widely adopted across various domains and applications. However, the substantial memory overhead caused by their vast number of parameters, combined with the high computational demands of the attention mechanism, poses significant challenges in achieving low latency and high throughput for LLM inference services. Recent advancements, driven by groundbreaking research, have significantly accelerated progress in this field. This paper provides a comprehensive survey of these methods, covering fundamental instance-level approaches, in-depth cluster-level strategies, and emerging scenarios. At the instance level, we review model placement, request scheduling, decoding length prediction, storage management, the disaggregation paradigm, and multiplexing. At the cluster level, we explore GPU cluster deployment, multi-instance load balancing, and cloud service solutions. Additionally, we discuss specific tasks, modules, and auxiliary methods in emerging scenarios. Finally, we outline potential research directions to further advance the field of LLM inference serving.

1 Introduction

With the rapid evolution of open-source Large Language Models (LLMs), weekly updates to model architectures and capabilities have become the norm in recent years. The surging demand for these models is evident from Huggingface download statistics, which range from hundreds of thousands for models like Mistral-Small-24B-Instruct-2501 (Mistral, 2025), phi-4 (Abdin et al., 2024), and Llama-3.3-70B-Instruct (Grattafiori et al., 2024) to millions for DeepSeek-V3 (DeepSeek-AI et al., 2024) and DeepSeek-R1 (DeepSeek-AI et al., 2025) over recent months. However, when deploying these models, their large-scale parameters and attention mechanisms impose substantial demands on memory and computational resources, presenting significant obstacles to achieving the desired low latency and high throughput in processing requests. These challenges have spurred extensive research across multiple domains of inference serving optimization to meet Service Level Objectives (SLOs).

This paper presents a systematic survey of LLM inference serving methods, organized hierarchically from instance-level optimizations to cluster-scale strategies and emerging scenarios.

Instance-Level optimization (§3) begins with model placement (§3.1), essential for distributing parameters across devices when single-GPU memory is insufficient. Subsequent request scheduling (§3.2) prioritizes batched processing through decoding length prediction (§3.3), where shorter requests are prioritized to reduce overall latency. Dynamic batch management then governs request insertion/eviction during iterative processing. While KV cache (§3.4) mitigates redundant computation, challenges persist in storage efficiency, reuse strategies, and compression. Due to the distinction between the prefill and decoding phases, the disaggregated architecture (§3.5) was introduced, facilitating the optimization of each phase. And how multiple LLMs efficiently share the same computing resources through multiplexing (§3.6).

Cluster-Level optimization focuses on deployment strategies (§4), particularly cost-effective GPU cluster configurations with heterogeneous hardware, as well as service-oriented cluster scheduling (§4.1). Scalability introduces load balancing challenges (§4.2) to prevent resource underutilization or overload across distributed instances. When local hardware infrastructure is inadequate to fulfill deployment requirements, cloud-based solutions (§4.3) are necessary to address dynamic LLM serving demands.

Emerging Scenarios (§5) include advanced

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Metric	Definition	Key Focus
TTFT	Latency from input to first token.	Critical for real-time apps (e.g., chatbots).
TBT	Time interval between consecutive tokens.	Reflects step-by-step responsiveness.
TPOT	Average time per token during decoding.	Measures token generation efficiency.
Throughput	Tokens generated per second across all requests.	Evaluates system capacity under high load.
Capacity	Maximum throughput while meeting SLOs.	Represents system's upper performance limit.
Normalized Latency	Total execution time divided by token count.	Holistic view of system efficiency.
Percentile Metrics	Latency distribution (e.g., P50, P90, P99).	Evaluates stability and performance bounds.

Table 1: LLM Inference Service Evaluation Metrics.

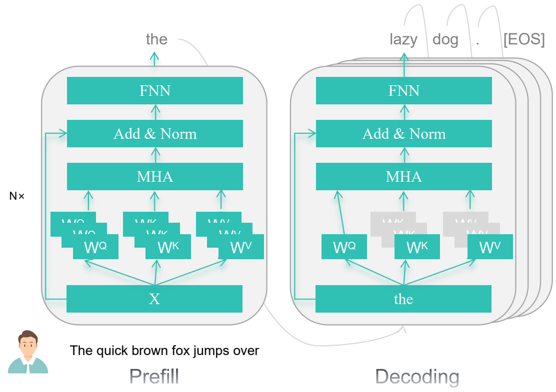

Figure 1: Illustration of the LLM Inference process.

tasks such as Long Context processing (§5.1), as well as techniques like Retrieval-Augmented Generation (RAG) (§5.2), Mixture of Experts (MoE) (§5.3), Low-Rank Adaptation (LoRA) (§5.4), Speculative Decoding (§5.5), Augmented LLMs (§5.6), Test-Time Reasoning (§5.7), and Multimodal (§5.8), all of which require adaptability to address evolving demands.

While previous work (Miao et al., 2023; Yuan et al., 2024; Zhou et al., 2024; Li et al., 2024a) has built a strong foundation, the rapid development of the field calls for an urgent summary of emerging methods and scenarios to support deeper research. Our work integrates a wide range of both classical and cutting-edge methods, and adopts a forward-looking perspective and highlights several promising directions for future research. We also provide a detailed overview of niche but critical areas in Appendix A, aiming to equip researchers with both foundational knowledge and inspiration for novel innovations.

2 Background

This section provides an overview of LLM fundamentals, aimed at enhancing the understanding of inference serving, along with the relevant evaluation metrics.

2.1 Transformer-based LLM

The LLM is primarily constructed on the foundation of the vanilla Transformer architecture, with a particular emphasis on its decoding component. The architecture is composed of multiple layers, primarily consisting of two key components: Multi-Head Self-Attention (MHA) and Feedforward Network (FFN), complemented by the LayerNorm operation.

The input representation $\mathbf{X}$ of the model is initially processed by tokenizing the user input and incorporating positional information. Subsequently, it is transformed through three learnable weight matrices, denoted as $\mathbf{W}^Q$, $\mathbf{W}^K$, and $\mathbf{W}^V$, to obtain the corresponding query ($\mathbf{Q}$), key ($\mathbf{K}$), and value ($\mathbf{V}$) vectors which are utilized as inputs for the subsequent MHA:

$$\begin{aligned} \text{MHA}(\mathbf{Q}, \mathbf{W}, \mathbf{V}) &= \text{Softmax}\left(\frac{\mathbf{Q}\mathbf{K}^T}{\sqrt{\mathbf{d}_k}}\right)\mathbf{V} \\ \mathbf{Q} = \mathbf{X}\mathbf{W}^Q;\ \mathbf{K} &= \mathbf{X}\mathbf{W}^K;\ \mathbf{V} = \mathbf{X}\mathbf{W}^V \end{aligned} \tag{1}$$

where $\mathbf{d}_k$ denotes the dimensionality of each attention head. The model processes $\mathbf{m}$ heads separately and concatenates the results:

$$\begin{aligned} \mathbf{O} &= \text{Concat}(\mathbf{H}_1, \mathbf{H}_2, \ldots, \mathbf{H}_m)\mathbf{W}^O \\ \mathbf{H}_i &= \text{MHA}(\mathbf{Q}_i, \mathbf{W}_i, \mathbf{V}_i) \end{aligned} \tag{2}$$

The FFN applies two linear transformations to its input, which is first processed by LayerNorm and residual connection:

$$\text{FNN}(\mathbf{x}) = \max(0, \mathbf{x}\mathbf{W}_1 + \mathbf{b}_1)\mathbf{W}_2 + \mathbf{b}_2 \tag{3}$$

2.2 Inference

LLM inference involves two phases: prefill and decoding, as illustrated in Figure 1. In prefill, the model processes the entire input in a compute-bound forward pass to produce the first token, while caching $\mathbf{K}$ and $\mathbf{V}$ (**KV cache**) to avoid recomputation. During decoding, tokens are generated sequentially using KV cache (gray blocks), which reduces the time complexity to $\mathcal{O}(n)$ at the cost of increased memory overhead. For each new token $\mathbf{X}_{new}$, the corresponding $\mathbf{Q}_{new}$, $\mathbf{K}_{new}$, and $\mathbf{V}_{new}$ are computed, ensuring efficient generation and terminate at the [EOS] token.

2.3 Evaluation

These are the conventional metrics (Agarwal et al., 2023; Zhong et al., 2024; Qin et al., 2024; Yu et al., 2022) listed in Table 1. In addition, Goodput (Zhong et al., 2024), or "effective throughput", measures the maximum request rate that meets SLOs. Etalon (Agrawal et al., 2024a) is used to evaluate fluency to maintain smooth output during real-time interactions and its maximum output rate while preserving a certain level of fluency.

3 LLM Inference Serving in Instance

3.1 Model Placement

Due to the large number of parameters in LLMs, which exceed a single GPU's capacity, distributing them across multiple GPUs or offloading them to CPUs has become a common practice.

Model Parallelism. This part focuses on several parallelism strategies. *Pipeline parallelism* (Huang et al., 2019; Harlap et al., 2018; Narayanan et al., 2021) distributes distinct model layers across multiple devices, enabling concurrent processing of sequential data to accelerate training/inference. *Tensor parallelism* (Shoeybi et al., 2020) splits individual operations or layers into smaller sub-tensors computed in parallel across devices, enhancing computational efficiency and enabling larger model dimensions. *Sequential parallelism* (Korthikanti et al., 2022) partitions LayerNorm and Dropout activations along the sequence dimension for long-context tasks. *Context parallelism* (NVIDIA, 2024) extends this by splitting all layers along the sequence dimension. *Expert parallelism* (Fedus et al., 2022) allocates sparse MoE components across GPUs, optimizing memory usage for sparse LLMs. More details can be seen in §5.3.

Offloading. When resources are limited, balancing GPU and CPU usage is essential. Some techniques (Ren et al., 2021; Aminabadi et al., 2022; Sheng et al., 2023) store most of a model's weights in system memory or storage, loading only the necessary portions into GPU memory on demand. PowerInfer (Song et al., 2024) computes hot neurons on the GPU and cold ones on the CPU, reducing both GPU memory usage and data transfer overhead. TwinPilots (Yu et al., 2024) integrates GPU and CPU with their hierarchical memories in an asymmetric multiprocessing framework. Park and Egger (2024) propose dynamic, fine-tuned workload allocation for efficient resource use.

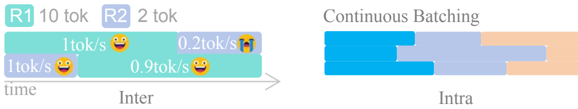

Figure 2: An example of inter- and intra-scheduling. **R** represents a request. In Inter-request scheduling, two requests, **R1** (10 toks) and **R2** (2 toks), arrive simultaneously. Ignoring the prefill process, if **R1** is processed first, its generation rate is 1 tok/s, and **R2**'s rate is 0.2 tok/s. Reversing the order gives **R2** a rate of 1 tok/s and **R1** 0.9 tok/s. The default decoding speed is 1 token/s.

3.2 Request Scheduling

For each instance, request scheduling directly impacts latency optimization. Here, we review relevant algorithms from both inter-request and intra-request scheduling perspectives (as shown in Figure 2).

Inter-Request Scheduling This section explores request batch prioritization under high load, focusing on execution order. Most LLM systems (Yu et al., 2022; Stojkovic et al., 2024; Qin et al., 2024) use First-Come-First-Served (FCFS), which can cause head-of-line blocking (Kaffes et al., 2019), such as a long request delaying a short one. Prioritizing shorter requests can reduce latency and better meet SLOs.

Advances in decoding length prediction (§3.3) have enabled smarter scheduling strategies. FastServe (Wu et al., 2024b) uses a Skip-Join MLFQ to prioritize urgent or long-waiting requests while preempting long ones to speed up shorter tasks. Fu et al. (2024c) approximate Shortest Job First (SJF) by using predicted decoding times. Shahout et al. (2024b) improve Shortest Remaining Time First (SRTF) with dynamic length prediction and a preemption ratio, though frequent model calls introduce overhead. Prophet (Schwinn Saereesitthipitak, 2024) applies SJF in prefill and Skip-Join MLFQ in decoding. Kim et al. (2024) shows that cost-guided preemption lowers GPU usage. BatchLLM (Zheng et al., 2024b), instead, focuses on maximizing global sharing.

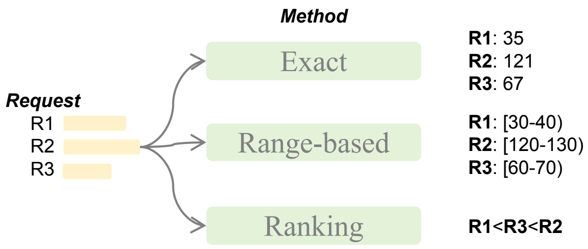

Figure 3: Overview of Length Prediction Methods.

Intra-Request Scheduling This section covers scheduling within concurrent request batches to enhance parallel decoding by handling variations in arrival, completion, and output length. Orca (Yu et al., 2022) offers iteration-level scheduling for dynamic request management per iteration, improving flexibility over inter-request methods. Dynamic SplitFuse (Holmes et al., 2024) and chunked-prefills (Agrawal et al., 2024c) break the prefill stage into smaller parts merged with decoding to cut delays from long prompts. SCLS (Cheng et al., 2024b) divides generation into fixed-length slices, controlling service time and memory use precisely.

3.3 Decoding Length Prediction

Uncertain generation length complicates scheduling, but recent work classifies prediction methods into three categories (as shown in Figure 3).

Exact Length Prediction predicts token counts using methods like BERT embeddings with random forest regression (Cheng et al., 2024a), small OPT models (Hu et al., 2024b), or simpler regression under constraints (Qiu et al., 2024b).

Range-Based Classification classifies requests into length bins. Some approaches (Zheng et al., 2024a; Jin et al., 2023; Jain et al., 2024; Qiu et al., 2024a; Stojkovic et al., 2024) predict length ranges directly from prompts. Notably, several works (Shahout et al., 2024b) leverage classifiers on token embeddings in real-time.

Relative Ranking Prediction predicts relative relationships between requests. Fu et al. (2024c) predicts relative relationships within the same batch, enhancing robustness and reducing overfitting.

Relative Ranking Prediction simplifies batch processing by only ordering requests, but requires re-ranking for carry-over requests, unlike other methods that avoid this overhead.

Other alternative approaches include SkipPredict (Shahout and Mitzenmacher, 2024), which uses quick classification for short/long tasks before detailed prediction, and BatchLLM (Zheng et al., 2024b) that predicts lengths through prompt analysis and statistical patterns.

3.4 KV Cache Optimization

KV cache cuts inference time from quadratic to linear but poses challenges in memory management, reuse, and compression. Optimizations for specialized storage are in §5.1 and 5.2.

Memory Management. *Lossless Storage Techniques* Kwon et al. (2023) propose PagedAttention and vLLM, using OS-style paging to nearly eliminate memory fragmentation. FastDecode (He and Zhai, 2024) offloads cache to CPU memory through distributed processing, while LayerKV (Xiong et al., 2024) uses hierarchical allocation and offloading with layer-wise. KunServe (Cheng et al., 2024c) frees space for cache by removing model parameters, compensating via a pipeline mechanism from other instances. InstCache (Zou et al., 2024) enhances responsiveness through LLM-driven instruction prediction. PagedAttention's non-contiguous layout adds complexity and overhead, while vAttention (Prabhu et al., 2025) reduces fragmentation and preserves virtual memory contiguity via CUDA-based memory decoupling.

Approximation Methods PQCache (Zhang et al., 2024a) uses Product Quantization to compress embeddings and cut computation. InfiniGen (Lee et al., 2024) improves performance through dynamic KV cache prefetching and reduced data transfer.

Reuse Strategies. *Lossless Reuse* PagedAttention (Kwon et al., 2023) enables multi-request cache sharing through page-level management. Radix tree-based systems (Hu et al., 2024a; Srivatsa et al., 2024) implement global prefix sharing with dynamic node deletion. CachedAttention (Gao et al., 2024) minimizes redundant computation in dialogues through cross-turn cache reuse.

Semantic-aware Reuse GPTCache (Bang, 2023) uses semantic similarity to cache and reuse LLM outputs, while SCALM (Li et al., 2024c) clusters queries to uncover meaningful semantic patterns. Compared with those two matching approaches in Table 2.

Compression Techniques. To reduce inference overhead, tensor quantization and compact representations are used to balance performance and

Dimension	Lossless	Semantic-Aware
Matching	Exact	Semantic similarity
Requests	Fixed patterns, repeats	Diverse, open-ended
Consistency	✓✓✓	✓✓
Overhead	✓	✓✓

Table 2: Comparison of KV cache reuse strategies.

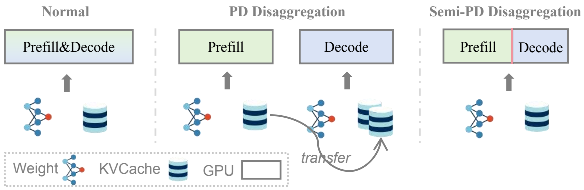

Figure 4: Comparing with normal, PD and Semi-PD Disaggregation.

efficiency (Wang et al., 2024b).

Quantization-based Compression This method reduces memory by lowering precision. (Sheng et al., 2023) applies group-wise 4-bit KV cache quantization without I/O overhead. AWQ (Lin et al., 2024c) highlights that quantizing non-salient weights reduces quantization loss. Kivi (Zirui Liu et al., 2024) uses per-channel/token cache quantization. MiniCache (Liu et al., 2024a) exploits inter-layer KV similarity for compression. Atom (Zhao et al., 2024b) adopts mixed-precision and fine-grained quantization. QServe (Lin et al., 2024d) co-designs W4A8KV4 quantization to boost GPU efficiency. OTT quantization (Su et al., 2025), which incorporates outlier token tracing, has made significant progress.

Compact Encoding Architectures It is also desirable to use smaller matrix representations instead of the previous heavy matrix. CacheGen (Liu et al., 2024c) employs a custom tensor encoder to compress KV cache into compact bitstreams, saving bandwidth with minimal decoding overhead.

3.5 Prefill-Decoding Disaggregation

Prefill-Decoding (PD) disaggregation separates computation-bound prefill from memory-bound decoding, enabling specialized optimization for each (as shown in Figure 4).

DistServe (Zhong et al., 2024) minimizes communication overhead by optimizing resource allocation and bandwidth-aware placement. Splitwise (Patel et al., 2024b) and HEXGEN-2 (Jiang et al., 2025b) explores homogeneous and heterogeneous device designs to optimize cost, throughput, and power. DéjàVu (Strati et al., 2024) eliminates pipeline stalls via microbatch swapping and state replication. Mooncake (Qin et al., 2024) uses a KVCache-centric disaggregated design, leveraging idle CPU, DRAM, and SSD with early rejection under load. TetriInfer (Hu et al., 2024b) applies two-level scheduling with resource prediction to avoid decoding hotspots. P/D-Serve (Jin et al., 2024b) tackles LLM deployment challenges via fine-grained prefill/decode organization, dynamic adjustments, on-demand request allocation, and efficient cache transmission.

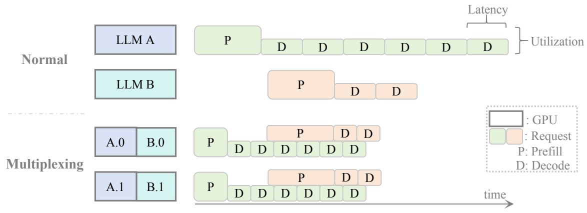

Figure 5: An example of Normal and Multiplexing.

KV Cache Transfer Problem. Semi-PD (Hong et al., 2025) separates the two stages on the same GPU by leveraging the streaming multiprocessor (SM) method, eliminating KV cache transfer overhead and enabling weight sharing. FlowKV (Li et al., 2025b) reduces KV cache migration time by minimizing communication, optimizing memory continuity, and using strategies like bidirectional alignment and merged transfers.

3.6 Multiplexing

Running a single LLM across multiple GPUs often leads to idle time due to varying model sizes and usage. To improve utilization, multiplexing multiple LLMs on a single GPU has gained attention (as shown in Figure 5).

AlpaServe (Li et al., 2023b) adopts a more rudimentary approach, resulting in suboptimal GPU utilization. To improve efficiency, MIG (NVIDIA, 2025) introduces hardware-level partitioning by dividing a single physical GPU into multiple isolated virtual instances, allowing parallel execution of multiple models. In contrast, MuxServe (Duan et al., 2024) partitions GPU Streaming Multiprocessors (SMs) via CUDA MPS and fully shares memory, requiring workload-dependent ratio tuning, they both well-suited for stable workloads with strong isolation requirements. Unlike these static methods, QLM (Patke et al., 2024) switches models on the GPU to handle different requests. Prism (Yu et al., 2025b) goes further by dynamically adjusting GPU resource allocation, enabling flexible and efficient multi-model sharing.

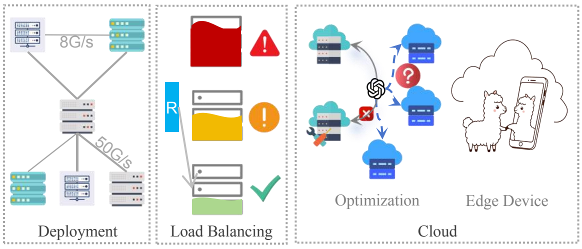

Figure 6: Overview of the deployment, load balancing, and cloud-based in cluster-level optimization. **R** represents a request.

4 LLM Inference Serving in Cluster

4.1 Cluster Optimization

Internal optimizations for homogeneous devices require more machines as parameter scale increases, while heterogeneous machines are preferred for their flexibility, efficiency, and cost-effectiveness (Mei et al., 2024). External optimizations, like service-oriented cluster scheduling, further enhance internal optimizations.

Architecture and Optimization for Heterogeneous Resources. Jayaram Subramanya et al. (2023) propose a joint optimization framework for adaptive task allocation across GPU types and batch sizes, demonstrating significant throughput improvements over static configurations. Helix (Mei et al., 2024) models the execution of LLM services on heterogeneous GPUs and networks as a maximum flow problem in a directed weighted graph, where nodes represent GPU instances and edges encode GPU and network heterogeneity through capacity constraints. LLM-PQ (Zhao et al., 2024a) advocates an adaptive quantization and phase-aware partition scheme tailored for heterogeneous GPU clusters. HexGen (Jiang et al., 2024c) supports asymmetric parallel execution on GPUs with different computing capabilities. Splitwise (Patel et al., 2024b), DistServe (Zhong et al., 2024) and HEXGEN-2 (Jiang et al., 2024d) optimize computation on heterogeneous disaggregated architectures, with the latter focusing on LLM serving via constraint-based scheduling and graph-based resource optimization. Hisaharo et al. (2024) integrate advanced interconnect technology, high-bandwidth memory, and energy-efficient power management.

Service-Aware Scheduling. DynamoLLM (Stojkovic et al., 2024) optimizes service clusters by adjusting instances, parallelization, and GPU frequencies based on input/output lengths. Splitwise (Patel et al., 2024b) proposes cluster-level scheduling across prefill and decoding on separate devices.

4.2 Load Balancing

Cluster-level load balancing optimizes request distribution to prevent node overload or underutilization, improving throughput and service quality. While most frameworks (Yu et al., 2022; Kwon et al., 2023) rely on traditional methods like Round Robin and Random (Deepspeed, 2023), recent advances in heuristic, dynamic, and predictive scheduling provide more sophisticated solutions.

Heuristic Algorithm. SCLS (Cheng et al., 2024b) employs a max-min algorithm (Radunovic and Le Boudec, 2007) to balance the workloads. It assigns the batch with the longest estimated serving time to the instance with the lowest score, where the score represents the total serve time of all batches in the instance's queue. SAL (Kossmann et al., 2024) quantifies the load on two key factors: (1) the number of queued prefill tokens and (2) the available memory. This ensures that requests are dispatched to the server with the lowest load, addressing scenarios where delays occur due to either a full token batch or insufficient memory.

Dynamic Scheduling. Llumnix (Sun et al., 2024) dynamically reschedules requests across model instances during runtime to handle request heterogeneity and unpredictability. It uses real-time migration to transfer requests and memory states, enabling mid-operation migration to the least loaded instance based on real-time load growth.

Intelligent Predictive Scheduling. Jain et al. (2024) propose a reinforcement learning-based router that models request routing as a Markov Decision Process, aiming to derive an optimal policy for maximizing discounted rewards. It integrates response length prediction, workload impact estimation, and reinforcement learning.

4.3 Cloud-Based LLM Serving

If local LLM deployment lacks resources, cloud services offer a more economical alternative, with recent research focusing on optimizing cloud deployment and edge collaboration for efficiency.

Deployment and Computing Effective. To reduce LLM deployment costs, spot instances are used despite preemption risks. SpotServe (Miao et al., 2024b) mitigates this with dynamic reparallelization, parameter reuse, and stateful inference recovery. ServerlessLLM (Fu et al., 2024a) tackles serverless cold start latency via optimized checkpoints, live migration, and locality-aware scheduling. Mélange (Griggs et al., 2024) optimizes GPU allocation based on request patterns, lowering costs. POLCA (Patel et al., 2024a) boosts efficiency through power management, while Imai et al. predict inference latency to enhance cluster management. Borzunov et al. (2023) propose a way to integrate idle resources through geodistributed devices connected via the internet. Jiang et al. (2025a) found that optimizing GPU combinations, deployment setups, and workload distribution boosts LLM cost efficiency on heterogeneous cloud platforms.

Cooperation with Edge Device. To meet SLOs amid cloud latency and bandwidth limits, edge computing offers solutions. EdgeShard (Zhang et al., 2024b) leverages collaboration between distributed edge devices and cloud servers. PreLLM (Yang et al., 2024b) uses a multi-armed bandit framework for personalized scheduling. Hao et al. (2024) integrate small edge models with cloud LLM to address memory constraints, while He et al. (2024) apply deep reinforcement learning for efficient, latency-aware inference offloading.

5 Emerging Scenarios

5.1 Long Context

As LLMs evolve, context lengths have expanded significantly, reaching hundreds of thousands or even millions of tokens (moonshot, 2023). This growth presents both opportunities and challenges for distributed deployment, computation, and storage, especially in parallel processing, attention computation, and KV cache management.

Parallel Processing. Loongserve (Wu et al., 2024a) enhances this with elastic sequence parallelism for efficient long-context LLM serving.

Attention Computation. The attention mechanism encounters significant challenges in parallel processing and resource management. RingAttention (Liu et al., 2023) uses blockwise self-attention and FFN computation to distribute long sequences across devices, overlapping KV communication with attention. StripedAttention (Brandon et al., 2023), an extension of RingAttention, addresses imbalances from causal attention's triangular structure. DistAttention (Lin et al., 2024a) subdivides attention across GPUs, avoiding cache transfer during decoding and enabling partitioning for arbitrary sequence lengths with minimal data transfer. InstInfer (Pan et al., 2024b) offloads attention and data to Computational Storage Drives, reducing KV transfer overheads significantly.

KV Cache Management. Efficient storage for growing KV cache is crucial for generating new tokens. Infinite-LLM (Lin et al., 2024a) manages dynamic LLM contexts by scheduling cache at the cluster level, balancing resources, and maximizing throughput. InfiniGen (Lee et al., 2024) optimizes cache management in CPU memory for offloading-based systems. Marconi (Pan et al., 2024a) introduces tailored admission and eviction policies for hybrid models, using experimental and theoretical analysis to show that personalized cache sizing per layer reduces memory usage significantly.

5.2 RAG

RAG enables LLMs to retrieve external knowledge for responses, but the diversity and complexity of processing pose challenges in optimizing latency and KV cache storage for large retrieval contexts.

Workflow Scheduling. Several recent innovations have focused on improving the efficiency, flexibility, and optimization of RAG workflows. PipeRAG (Jiang et al., 2024b) improves efficiency via pipeline parallelism, flexible retrieval intervals, and performance-driven quality adjustment. Teola (Tan et al., 2024) models LLM workflows as data flow nodes (e.g., Embedding, Indexing, Searching) for precise execution control. RaLMSpec (Zhang et al., 2024d) employs speculative retrieval with batched verification to reduce serving overhead. RAGServe (Ray et al., 2024) schedules queries and adjusts RAG configurations (e.g., text chunks, synthesis methods) to balance quality and latency.

Storage Optimization. Efficient storage management is critical for RAG systems, particularly in handling large-scale KV caches. Recent studies include RAGCache (Jin et al., 2024a), which employs knowledge trees and dynamic speculative pipelining to reduce redundancy. SparseRAG (Zhu et al., 2024) manages cache efficiently with prefilling and selective decoding, focusing on relevant tokens. CacheBlend (Yao et al., 2024) reuses cache and selects tokens based on a fixed per-

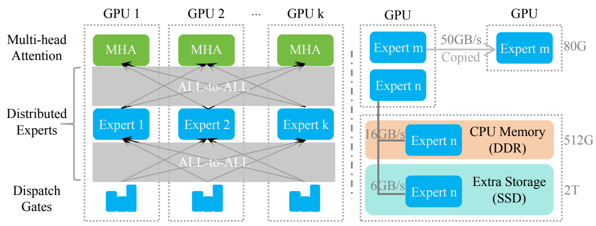

Figure 7: This figure illustrates a MoE architecture, highlighting expert placement, All-to-All communication (left), and load balancing (right). On the right, high-traffic Expert m and low-traffic Expert n are shown. For example, two strategies are presented: replicating m to a new GPU or offloading n to free space for m.

centage to recompute KV values for partial updates, enhancing efficiency and reducing latency. In contrast to CacheBlend, EPIC (Hu et al., 2024c) introduces position-independent context caching via static sparse computation, recomputing only a small number of tokens at the beginning of each block.

5.3 MoE

MoE models, known for parameter sparsity, excel in LLMs (e.g., DeepSeek-V3 (DeepSeek-AI et al., 2024), Mixtral 8x7B (Jiang et al., 2024a)). Key inference latency challenges include expert parallelism, load balancing, and All-to-All communication (Figure 7), with Liu et al. (2024b) offering a comprehensive optimization survey.

Expert Placement. Tutel (Hwang et al., 2023) introduces switchable parallelism and dynamic pipelining without extra overhead, while DeepSpeed-MoE (Rajbhandari et al., 2022) combines expert parallelism (He et al., 2021; Lepikhin et al., 2020) with expert-slicing. CoEL (Li et al., 2025a) leverages the sparse activation of MoE to enable resource collaboration both within and across devices. fMOE (Yu et al., 2025a) effectively guides expert prefetching, caching, and offloading decisions through its expert graph and semantically enhanced search mechanism.

Expert Load Balancing. Imbalanced token distribution causes device underutilization. Expert Buffering (Huang et al., 2023) allocates active experts to GPUs and others to CPUs, pairing high- and low-load experts using historical data. Brainstorm (Cui et al., 2023) dynamically assigns GPU units based on load, while Lynx (Gupta et al., 2024) adaptively reduces active experts. ExpertChoice (Zhou et al., 2022) selects top-k tokens per expert, rather than the reverse. High-load experts in DeepSeek-V3 (DeepSeek-AI et al., 2024) are identified using deployment statistics and periodically duplicated to optimize performance.

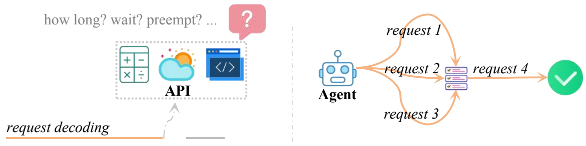

Figure 8: Overview of augmented LLMs, such as LLM with API, and LLM-based Agent.

All-to-All Communication. Expert processing involves all-to-all exchanges for token dispatch and output gathering. Tutel (Hwang et al., 2023) uses a 2D hierarchical All-to-All algorithm, Aurora (Li et al., 2024b) optimizes token transmission order during All-to-All exchanges, and Lina (Li et al., 2023a) prioritizes All-to-All operations over concurrent All-Reduce whenever feasible, leveraging tensor partitioning to improve performance.

5.4 LoRA

LoRA (Hu et al., 2021; Chen et al., 2024; Dettmers et al., 2023) adapts LLMs to various tasks with small, trainable adapters. CaraServe (Li et al., 2024e) enables GPU-efficient, cold-start-free, SLO-aware serving via model multiplexing, CPU-GPU coordination, and rank-aware scheduling. dLoRA (Wu et al., 2024c) dynamically merges and unmerges adapters with the base model, and migrates requests and adapters across worker replicas.

5.5 Speculative Decoding

Speculative decoding (Xia et al., 2024; Wang et al., 2024a) speeds up inference by generating draft tokens with smaller LLMs and verifying them in parallel with target LLM, reducing latency and costs without quality loss. SpecInfer (Miao et al., 2024a) uses tree-based speculative inference for faster distributed and single-GPU offloading inference.

5.6 Augmented LLMs

LLMs increasingly integrate with external tools like APIs and Agents (Figure 8). APISERVE (Abhyankar et al., 2024) dynamically manages GPU resources for external APIs, while LAMPS (Shahout et al., 2024a) leverages predicting memory usage. Parrot (Lin et al., 2024b) optimizes scheduling by identifying request dependencies and commonalities, particularly in Agent scenarios, using Semantic Variables to tag each request. While Parrot is

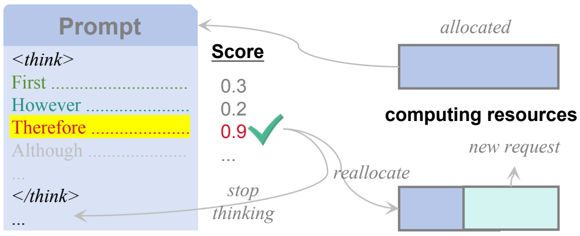

Figure 9: An example of efficient reasoning serving.

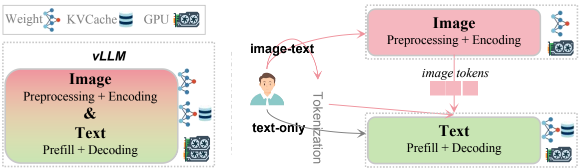

Figure 10: vLLM vs. decouple way in MLLM.

a pioneering approach to addressing agent-related challenges, it has significant limitations in practice. Tempo (Zhang et al., 2025) handles collective LLM requests by modeling execution dependencies as a DAG, with nodes as requests and edges as dependencies. Luo et al. (2025) considers the Agent as a program-level problem rather than a request-level one, which offers a valuable insight. Li et al. (2025c) uses a fluid queuing model to analyze Agent workload stability.

5.7 Test-Time Reasoning

Inference-time algorithms (OpenAI, 2024) enhance the reasoning ability (Ji et al., 2025; Qu et al., 2025) of LLMs but achieve this by generating a large number of tokens, which can strain computational resources (Figure 9). Dynasor (Fu et al., 2024b) introduces the Certaindex metric to dynamically track a model's reasoning progress, adjust computational resources based on task difficulty, and proactively terminate unpromising requests. Damani et al. (2024) optimizes resource allocation (e.g., different LLMs, computing budgets) by using a built-in reward model to assess the marginal benefit of additional computation for each request.

5.8 Multimodal LLM

As Multimodal LLM (MLLM) matures, the resulting surge in traffic presents significant deployment challenges (Figure 10). To address stage heterogeneity, image encoding latency, modality interference, and long-tail workload issues in multi-modal inference, ModServe (Qiu et al., 2025) introduces a decoupled architecture. It separates key stages such as image preprocessing, encoding, and LLM operations into independently scalable components, enabling fine-grained resource management and workload-aware optimization.

6 Future Works

Given the rapid evolution of LLM inference services, we present several recommendations for future research.

- *General Agent Scheduling*: Real-world demands for integrating audio, image, video, and text agents add complexity to inference serving.
- *Intelligent LLM Inference Service*: Utilizing the capabilities of smaller LLMs to optimize the deployment, scheduling, and storage management of larger LLMs.
- *Safety and Privacy*: As most services rely on cloud computing, it is essential to prevent cache leaks and ensure that any leaked data cannot be used to reconstruct user conversations.
- *Hardware-Accelerated and Energy-Efficient Inference*: Future research should focus on co-designing inference software with emerging accelerators to enhance performance-per-watt through optimized kernels, memory hierarchies, and adaptive quantization techniques.

Other directions, though smaller, are significant in impact, are presented at §A. We hope that these suggestions will provide valuable insights for advancing future research.

7 Conclusion

The primary challenge in LLM inference serving stems from the significant memory requirements caused by the scale of parameters and the computational load associated with attention mechanisms. This paper presents a thorough and hierarchical review of methods, encompassing approaches from basic instance-level to more advanced cluster-level techniques, as well as a variety of emerging scenarios. Additionally, we explore small yet significant areas and suggest potential directions for future research. We hope this work provides valuable insights for ongoing research in this crucial field.

8 Limitations

This paper provides a summary and categorization of methods for LLM inference services, with the following limitations:

- While we have not conducted detailed experiments or comparative analyses of all approaches, we have presented critical insights on some key points.
- In the instance sections, there may be some overlap with previous surveys, primarily involving a few classic papers. However, since the most recent survey (Zhou et al., 2024) only covers literature up to July 2024, many of the references we include were published after that date.
- The scope of this survey is time-sensitive, with coverage concluding at the end of April 2025.

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A Miscellaneous Areas

There are also other niche but important research directions, such as hardware, fairness, energy, privacy, and simulator, that are driving the LLM inference service towards a better, more comprehensive, and farther-reaching future.

A.1 Hardware

Recent advancements in optimizing LLM inference have focused on improving efficiency, speed, and resource utilization in various hardware techniques.

Peng et al. (2024) propose a mixed-precision, multi-level caching system (HBM, DRAM, SSDs) and a model modularization algorithm to enable LLM inference on resource-constrained, outdated hardware. Wu et al. (2024d) explore inference service solutions on Intel GPUs. LLM-Pilot (Łazuka et al., 2024) benchmarks LLM inference across GPUs and recommends the most cost-effective GPU for unseen LLMs. GenZ (Bambhaniya et al., 2024) is an analytical tool for studying the relationship between LLM inference performance and various hardware platform design parameters. Li et al. (2024d) present Transformer-Lite, an innovative inference engine optimized for mobile GPUs, designed to enhance the efficiency and inference speed of LLM deployment on mobile devices. LLMS (Yin et al., 2024) is an innovative system on mobile devices that, under stringent memory constraints, implements fine-grained, chunk-based KV cache compression and a globally optimized swapping mechanism to decouple applications from LLM memory management, thereby minimizing the overhead of context switching. Xu et al. (2024) utilize on-device Neural Processing Unit (NPU) offloading to enhance NPU offloading efficiency and reduce prefill latency.

A.2 Fairness

In LLM inference services, request frequency limits are typically imposed on each client (e.g., user or application) to ensure fair resource allocation. These limits prevent excessive requests from monopolizing resources and degrading service quality for others. However, they may also result in underutilized resources. Sheng et al. (2024) propose a novel fairness definition, based on a cost function considering input and output tokens. Additionally, a new scheduling algorithm, the Virtual Token Counter (VTC), introduces fair scheduling through a continuous batching mechanism.

A.3 Privacy

Protecting user conversation content in LLMs from potential leakage is an important issue. Yang et al. (2024a) adopt weight permutation to shuffle KV pairs, preventing attackers from reconstructing the entire context. Zhang et al. (2024c) quantify the trade-off between privacy protection and utility loss, pointing out that privacy protection mechanisms (such as randomization) can reduce privacy leakage but will introduce utility loss. MARILL (Rathee et al., 2024) achieves substantial reductions in the costly operations required for secure inference within multi-party computation by optimizing the architecture of LLMs during the fine-tuning phase.

A.4 Energy

Given the substantial power demands of LLM computations, optimizing energy usage is a critical challenge that must be addressed. Nguyen et al. (2024) investigate the carbon emissions of LLMs from operational and embodied perspectives, aiming to promote sustainable LLM services. Researchers analyzed the performance and energy consumption of the LLaMA model across varying parameter scales and batch sizes, incorporating the carbon intensity of different power grid regions. This study provides insights into the environmental impact of LLMs and explores opportunities to optimize sustainable LLM systems.

A.5 Simulator

Considering the diversity of computing devices and their associated high costs, a comprehensive simulator is indispensable for conducting trials in virtual environments. Agrawal et al. (2024b) introduce Vidur, a scalable, high-fidelity simulation framework for evaluating LLM performance under various deployment configurations, alongside Vidur-Search, a tool for optimizing deployments to meet performance constraints and reduce costs. The Helix system (Mei et al., 2024), featuring an event-based simulator, enables accurate simulation of LLM inference in heterogeneous GPU clusters by adjusting factors like network conditions, machine heterogeneity, and cluster scale, providing rapid and cost-effective deployment evaluations.