On-Device Multimodal Small Language Models for Privacy-Preserving Edge Intelligence Through Quantization Pruning Distillation and Energy-Efficient Inference

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DOI: 10.56201/wjimt.v9.no12.2025.pg271.302

Abstract
On-device multimodal small language models are emerging as a practical foundation for privacy-preserving edge intelligence, enabling devices to interpret and generate language while processing images, audio, video, sensor streams, and contextual signals without continuous cloud dependence. Their deployment can reduce data exposure, network latency, connectivity costs, and centralized infrastructure demand; however, limited memory, compute capability, battery capacity, thermal headroom, and accelerator support constrain model design and inference. This review examines architectures, compression techniques, privacy mechanisms, and energy-efficient inference strategies for multimodal small language models operating on smartphones, wearables, vehicles, robots, cameras, and embedded Internet of Things platforms. It develops a deployment-centric taxonomy covering weight, activation, cache, and modality-encoder quantization; structured, unstructured, token, channel, and modality-aware pruning; response, representation, cross-modal, and task-specific knowledge distillation; and hybrid compression pipelines. The review analyzes how these methods affect language quality, visual and acoustic understanding, cross-modal alignment, robustness, fairness, privacy leakage, memory consumption, latency, throughput, energy per inference, and thermal stability. Particular attention is given to local retrieval, adaptive modality selection, speculative decoding, cache management, early exiting, hardware-aware scheduling, and heterogeneous CPU, GPU, neural, and digital-signal processing. The paper also evaluates secure personalization, federated updates, trusted execution, encrypted storage, sensor permission controls, and data-minimizing telemetry. Comparative evidence is organized by device class, workload, compression target, and evaluation objective. The gap analysis identifies limited reproducibility, inconsistent energy measurement, weak low-resource language coverage, underdeveloped multimodal privacy benchmarks, and insufficient study of sustained inference under thermal throttling. It distinguishes theoretical compression savings from measurable device-level efficiency improvements. The review concludes with standardized reporting recommendations and research priorities for compact, private, reliable, and energy-efficient multimodal intelligence at the edge.

Keywords: *Edge Intelligence; Energy-Efficient Inference; Model Compression; Multimodal Small Language Models; On-Device Artificial Intelligence; Privacy-Preserving Computing*

1. Introduction and Survey Methodology

1.1 Background and Motivation for On-Device Multimodal Intelligence

Multimodal small language models integrate compact language backbones with vision, audio, video, sensor, and contextual encoders, enabling devices to interpret heterogeneous information and generate task-relevant responses. Unlike cloud-dependent systems, on-device models process sensitive inputs close to their source, reducing network round trips, service interruptions, communication costs, and exposure of raw personal data. Representative applications include smartphones describing camera scenes, wearables interpreting speech and physiological signals, vehicles combining voice commands with road imagery, and industrial devices reasoning over sensor measurements and maintenance records. AI-enabled decision research demonstrates the value of combining data-driven intelligence with domain-specific operational information (Michael & Ogunsola, 2025c). Sensor-network architectures similarly illustrate how distributed observations can support predictive decisions near the point of collection (Kumuyi et al., 2024a).

The motivation for local multimodal inference is strengthened by privacy, responsiveness, personalization, and resilience requirements. Continuous cloud transmission can expose conversations, images, locations, biometrics, and behavioral histories while producing unacceptable delay under poor connectivity. Nevertheless, edge devices impose strict limits on memory capacity, computational throughput, battery energy, thermal headroom, and accelerator compatibility. Energy, reliability, and latency must therefore be optimized jointly because reducing one cost may degrade another dimension of service quality (Asiedu et al., 2025). Model weights, modality encoders, activation tensors, and key–value caches compete for limited memory, while image tokens, audio frames, and video sequences substantially increase inference cost. Cloud-migration research also demonstrates that workload placement should reflect operational requirements rather than technological preference alone (Ladapo et al., 2022). Quantization, pruning, distillation, low-rank factorization, adaptive modality selection, speculative decoding, and cache management offer complementary mechanisms for reducing these costs. The central motivation is to determine how such methods can preserve language quality, cross-modal alignment, privacy, robustness, and fairness while delivering measurable latency and energy improvements on real edge hardware.

1.2 Scope, Objectives, Research Questions, and Survey Contributions

This survey examines on-device multimodal small language models intended for smartphones, wearables, robots, vehicles, cameras, and embedded Internet of Things platforms. Its scope covers compact language backbones, modality encoders, projection layers, fusion mechanisms, local retrieval, personalization, compression, privacy controls, and hardware-aware inference. Compression methods include weight, activation, cache, and encoder quantization; structured, unstructured, token, channel, and modality-aware pruning; knowledge distillation; and low-rank or hybrid approaches. Privacy-preserving governance demonstrates that protection requirements must extend across collection, storage, processing, and transmission stages (Afrihyia et al., 2024). Data-protection impact-assessment models further support examining how architectural choices change privacy risks across distributed computing environments (Mbonu et al., 2022a).

The survey has four objectives: to classify multimodal on-device architectures and compression mechanisms; compare their effects on quality, privacy, and device performance; synthesize

deployment evidence; and identify unresolved research gaps. It asks which model components dominate memory, latency, and energy; how compression affects language generation and cross-modal understanding; which techniques map efficiently to heterogeneous accelerators; and when local processing materially reduces privacy exposure. Additional questions concern secure personalization, federated updates, thermal throttling, low-resource languages, multimodal fairness, and reproducible benchmarking. Automated-decision scholarship emphasizes evaluating discriminatory effects when intelligent systems influence users differently (Annan, 2025a). Performance-measurement frameworks likewise show why governance requires metrics aligned with operational objectives and stakeholder risk (Dosunmu & Ogundele, 2025b). The survey contributes a deployment-centric taxonomy linking compression targets to modality, hardware, and privacy consequences; a comparative evaluation framework encompassing multimodal quality, robustness, memory, latency, throughput, energy, and thermal stability; and a gap analysis addressing inconsistent measurement, weak privacy benchmarks, limited sustained-device testing, and insufficient evidence across languages and device classes. These contributions distinguish theoretical parameter savings from verified improvements in usable edge intelligence.

1.3 Literature-Selection Method and Organization of the Review

The review applies a structured literature-selection process combining database searching, backward and forward citation tracing, and targeted screening. Search concepts cover multimodal small language models, on-device artificial intelligence, edge intelligence, vision-language models, audio-language systems, sensor-language models, quantization, pruning, knowledge distillation, low-rank compression, privacy-preserving inference, federated learning, energy-aware inference, mobile accelerators, and thermal performance. Candidate studies are screened through titles, abstracts, and full texts. Inclusion requires a substantive contribution involving multimodal architecture, compression, privacy, hardware optimization, edge deployment, or relevant evaluation. Generic model-compression studies are retained only where their techniques can be clearly mapped to multimodal components. Studies lacking sufficient architectural, experimental, or measurement detail are excluded.

For each eligible study, the review extracts the model backbone, modality encoders, fusion mechanism, parameter count, compression target, numerical precision, sparsity level, teacher–student design, hardware platform, dataset, task, baseline, and evaluation procedure. Outcomes include language and multimodal quality, cross-modal alignment, robustness, fairness, privacy leakage, model size, memory consumption, latency, throughput, energy per inference, and thermal behavior. Section 2 examines architectural foundations, modality processing, accelerators, memory hierarchies, and deployment constraints. Section 3 organizes quantization, pruning, distillation, factorization, and hybrid compression. Section 4 evaluates local processing, federated personalization, trusted execution, encrypted storage, sensor permissions, and adversarial security. Section 5 analyzes energy-efficient inference mechanisms, deployment metrics, multimodal quality, and comparative cases. Section 6 synthesizes reproducibility requirements, unresolved problems, emerging opportunities, and design implications. This organization connects model-level optimization to privacy protection and measurable device-level performance.

2. Foundations of Multimodal Small Language Models

2.1 Language Backbones, Modality Encoders, Projectors, and Fusion Architectures

An on-device multimodal small language model typically combines a compact autoregressive or encoder–decoder language backbone with specialized modality encoders and lightweight

alignment components. The backbone performs token prediction, instruction following, reasoning, and response generation, while encoders transform images, audio, video, or sensor streams into latent representations. Hybrid deep-learning research demonstrates how complementary model components can be integrated to capture different information structures (Komi, 2021). Language backbones designed for edge use commonly reduce layer count, hidden width, attention heads, vocabulary size, or context length while employing grouped-query attention, parameter sharing, or compact state-space modules. NLP research illustrates the importance of preserving semantic representations when processing heterogeneous natural-language inputs (Atakpa et al., 2023). Vision encoders may use compact convolutional networks or vision transformers, while audio encoders process spectrograms, speech units, or learned acoustic tokens. Predictive-analytics research demonstrates how specialized representations can transform heterogeneous observations into actionable model inputs (Aliliele et al., 2023c). Encoder design must balance representation quality against activation memory, token count, latency, and energy. Data-driven personalization research further shows why compact models must retain sensitivity to user-specific context rather than merely preserve average performance (Yeboah et al., 2022).

Projectors translate encoder outputs into the embedding space expected by the language backbone. Common designs include linear layers, multilayer perceptrons, resamplers, query transformers, and cross-attention adapters. Software-testing research emphasizes verifying interfaces among independently developed AI components because alignment failures can propagate through the complete system (Borah et al., 2022). Fusion may occur early through unified token sequences, intermediately through cross-attention, or late through separately processed modality predictions. Interpretable-machine-learning research supports examining which modalities and latent representations materially influence the final output (Komi & Adamolekun, 2021). Early fusion supports detailed cross-modal reasoning but increases sequence length and attention cost, whereas late fusion is cheaper but may lose fine-grained relationships. Autonomous deep-learning research demonstrates the operational demands associated with integrating complex model components into responsive systems (Odejobi et al., 2025). On-device architectures may freeze encoders, activate only requested modalities, cache stable item representations, or route simple tasks through smaller pathways. AI-control frameworks reinforce the need for deterministic configuration, validation, and monitoring of such adaptive execution paths (Mbonu et al., 2022).

2.2 Vision, Audio, Video, Sensor, and Contextual Input Processing

Vision processing begins with image resizing, normalization, patch extraction, or convolutional feature generation before representations are projected into the language model. Higher image resolution improves recognition of text and small objects but increases token count, activation memory, and prefill latency. Deep-learning classification research demonstrates that visual representation quality depends on retaining meaningful spatial and semantic information (Dagodzo et al., 2022). Dynamic-resolution methods can allocate more tokens to informative regions while compressing backgrounds, and token-merging methods can combine visually redundant patches. Data-driven wildlife monitoring illustrates the operational importance of detecting relevant visual events within complex environments (Adeyelu & Dagodzo, 2024). Audio processing converts waveforms into spectrograms, learned acoustic units, or compressed speech embeddings. Streaming encoders should operate causally, suppress silence, and reuse states across chunks to reduce delay. Sensor-based fault detection demonstrates how temporal measurements can support local interpretation of changing physical conditions (Sunday & Omoegun, 2022). Real-time

analytical systems further show that processed observations must remain available within actionable latency limits (Filani et al., 2022).

Video combines visual complexity with temporal redundancy and can overwhelm edge memory through repeated frame encoding. Efficient pipelines sample keyframes, track objects, reuse cached features, compress temporal tokens, or activate detailed processing only after detecting meaningful changes. Integrated UAV, LiDAR, and GIS research demonstrates the complexity of coordinating spatial and temporal observations from multiple sources (Dagodzo & Ahiaeke Patrick, 2021b). Sensor inputs may include motion, location, temperature, biometrics, depth, radar, device state, or environmental measurements represented through numerical tokens or compact learned projections as seen in Table 1. Reliable communication research shows why sensor processing must tolerate intermittent power and incomplete observations (Asiedu & Quainoo, 2025). Contextual inputs such as time, application state, user preferences, permissions, and connectivity conditions allow models to tailor reasoning and determine which modalities should be activated. Path-planning optimization illustrates how contextual state can guide resource allocation across successive decisions (Akanbi & Sunday, 2024). Multimodal synchronization is essential because audio, video, and sensor streams may arrive at different rates or contain missing segments. Digital coordination research emphasizes the need for consistent interfaces, timestamps, and shared representations across heterogeneous technical components (Ogbete et al., 2025a). Edge pipelines should therefore align timestamps, record provenance, mask unavailable modalities, and distinguish missing data from negative evidence.

Table 1: Multimodal Input Processing for On-Device Edge Intelligence

Input Modality	Processing Methods	Primary Edge Constraints	Efficiency and Reliability Strategies
Vision	Resizing, normalization, patch extraction, convolutional features, and visual-token projection	High resolution increases token count, activation memory, and prefill latency	Dynamic resolution, informative-region selection, patch merging, and background compression
Audio	Waveform conversion, spectrogram generation, acoustic tokenization, and speech embedding	Continuous streams increase latency, memory use, and energy consumption	Causal encoding, silence suppression, chunk processing, and reusable streaming states
Video	Frame encoding, temporal modeling, object tracking, and video-token generation	Temporal redundancy and repeated encoding can overwhelm memory and compute capacity	Keyframe sampling, feature caching, token compression, and event-triggered processing
Sensors and context	Numerical projection of motion, location, biometrics, device state, permissions, and connectivity	Different sampling rates, missing data, intermittent power, and synchronization errors	Timestamp alignment, provenance tracking, unavailable-modality masking, adaptive activation, and context-aware resource allocation

2.3 Edge Devices, Hardware Accelerators, Memory Hierarchies, and Deployment Constraints

Edge platforms range from battery-powered wearables and smartphones to vehicle computers, robots, cameras, gateways, and industrial controllers. Their processors may include CPUs, mobile GPUs, neural-processing units, digital-signal processors, image processors, and microcontroller accelerators with different numerical formats and kernel capabilities. Capacity-planning research demonstrates why computational demand must be matched explicitly to available resources and workload variability (Edivri & Oteri, 2022). Language decoding is often memory-bandwidth-bound because weights and key–value caches are repeatedly accessed one token at a time, whereas modality encoding may be compute-intensive and highly parallel. Scalable gateway research illustrates how system throughput depends on coordinated movement across processing and communication boundaries (Akomolafe et al., 2024a). Memory hierarchies include registers, on-chip caches, shared accelerator memory, system RAM, flash storage, and occasionally remote memory. Infrastructure-resilience research shows why systems must remain functional when capacity and operating conditions deteriorate (Aminu-Ibrahim et al., 2025b). Efficient deployment should place frequently accessed embeddings and caches in faster memory while streaming less active weights from slower tiers. Identity-governance research additionally supports restricting which processes can access models, caches, sensor data, and personalization records (Mbonu et al., 2022b). Hardware accelerators reward regular dense operations, aligned tensor shapes, supported bit widths, and fused kernels. Theoretical parameter reductions may not improve latency when sparse formats require index processing or unsupported operations fall back to the CPU. Continuous configuration monitoring demonstrates why performance and security assumptions must be revalidated after runtime, driver, or model changes (Aliliele et al., 2023a). Battery capacity and thermal headroom further constrain sustained multimodal inference because camera, microphone, display, networking, and model computation draw power simultaneously. Battery-lifecycle research illustrates why repeated high-power operation can degrade long-term reliability beyond immediate energy consumption (Komi & Ganiu, 2022). Energy-sustainability research emphasizes evaluating complete infrastructure demands rather than isolated computational components (Monye et al., 2025). Deployment profiling should report startup memory, peak resident memory, prefill and decoding latency, throughput, energy per query, device temperature, and throttling behavior. Research on future energy infrastructure similarly demonstrates that practical adoption depends on coordinated innovation across technology and supporting systems (Monye et al., 2025). Models should support graceful degradation by reducing image resolution, skipping modalities, shortening context, lowering generation length, or transferring only explicitly authorized tasks to remote services.

3. Compression Methods for On-Device Multimodal Models

3.1 Weight, Activation, Cache, and Modality-Encoder Quantization

Weight quantization converts floating-point model parameters into lower-precision representations such as FP16, INT8, INT4, or binary values. Per-channel and group-wise scaling usually preserve multimodal performance better than one global scale because attention, feed-forward, projection, and encoder layers possess different numerical ranges. Predictive optimization research demonstrates the need to balance computational savings against measurable performance degradation (Tonoyan et al., 2022c). Outlier-aware methods retain a small proportion of sensitive weights at higher precision while aggressively compressing regular values. Lean process-improvement principles similarly support selective intervention that eliminates inefficiency

without damaging essential operations (Asiedu, 2025). Activation quantization is more difficult because visual tokens, acoustic frames, sensor values, and generated language states can exhibit input-dependent outliers. Adaptive-control research provides a basis for changing precision according to workload sensitivity and operating conditions (Sanni et al., 2022). Calibration data should therefore cover varied lighting, accents, noise levels, frame rates, sensor ranges, languages, and prompt lengths. Risk-scoring research reinforces the importance of representing routine and high-consequence input conditions during calibration (Adesuyi et al., 2024).

Key–value cache quantization is critical during autoregressive decoding because cache memory grows with context length, layer count, attention heads, and generated tokens. INT8 or INT4 cache storage can enable longer multimodal contexts, but numerical error may accumulate across decoding steps and alter grounding or instruction adherence. Infrastructure-performance frameworks demonstrate why optimization should be evaluated through sustained service outcomes rather than initial storage savings (Aminu-Ibrahim et al., 2025c). Modality-encoder quantization should account for task sensitivity: image encoders may tolerate INT8 convolution, whereas optical-character recognition, speaker identification, or weak sensor-event detection may require higher precision. Auditing research emphasizes documenting numerical formats, calibration samples, kernel versions, and observed deviations for trustworthy deployment (Fobellah, 2025b). Mixed-precision designs can retain projectors, normalization layers, output heads, and rare-modality pathways at FP16 while compressing dense backbone matrices and common encoder operations. Compliance-oriented technology research also supports maintaining reproducible control over model transformations and deployment artifacts (Annan, 2025b). Evaluation should report language quality, cross-modal alignment, recognition accuracy, hallucination, robustness, peak memory, cache growth, prefill latency, decoding speed, energy, and thermal behavior. A quantized model is operationally successful only when supported accelerator kernels produce measurable device-level gains.

3.2 Structured, Unstructured, Token, Channel, and Modality-Aware Pruning

Unstructured pruning removes individual parameters according to magnitude, gradient sensitivity, regularization, or second-order importance. It can generate high sparsity, but irregular weight locations require indexes and specialized sparse kernels that may eliminate expected latency improvements. Lean operational research demonstrates that removing components creates value only when the surrounding execution process can exploit the reduction (Ike et al., 2022). Structured pruning removes complete neurons, attention heads, feed-forward blocks, channels, or embedding dimensions, producing smaller dense tensors that map more efficiently to mobile accelerators. Process-redesign research similarly shows that local reductions must translate into improved end-to-end operation (Oyeleye et al., 2022). Channel pruning is particularly useful for vision and audio encoders because it reduces both parameter count and activation dimensions. Sustainable resource-selection frameworks support removing components according to measurable utility and lifecycle cost rather than frequency alone (Efobi et al., 2022a). Progressive pruning should begin conservatively, include recovery fine-tuning, and advance only when quality and device measurements remain within tolerance. Maturity-model research provides a basis for increasing optimization intensity after accumulating verified evidence at each deployment stage (Adeyelu & Dagodzo, 2024). Token pruning reduces the number of image patches, audio frames, video tokens, retrieved records, or language positions passed into expensive fusion and attention layers. Importance scores may derive from attention, motion, saliency, entropy, task prompts, or learned token routers. Safety-governance research demonstrates why low-frequency but high-consequence

observations should be protected from indiscriminate removal (Obogo et al., 2022). Modality-aware pruning extends this principle by suppressing entire encoders or branches when a modality is unavailable, redundant, low quality, or unnecessary for the current task. Recurrence analysis cautions that repeatedly eliminating apparently minor signals can normalize systematic failure under uncommon conditions (Obriki & Arumosoye, 2022). For example, a wearable assistant may skip camera processing during a voice-only request but retain visual input when the user asks about an object. Standard operating procedures are necessary for recording masks, thresholds, schedules, recovery training, and stopping conditions (Eyetsemitan et al., 2022). Joint pruning should coordinate language layers, modality encoders, projectors, fusion modules, and serving kernels rather than optimizing each component independently. Integrated optimization research supports managing dependencies across technical components contributing to a common operational outcome (Okonkwo et al., 2025). Evaluation should include multimodal accuracy, grounding, rare-event detection, missing-modality robustness, memory, measured latency, energy, and subgroup performance.

3.3 Knowledge Distillation, Low-Rank Factorization, and Hybrid Compression

Knowledge distillation transfers behavior from a large multimodal teacher to a smaller student. Response distillation trains the student to reproduce teacher-generated answers or logits, while representation distillation aligns language states, visual embeddings, acoustic features, attention maps, or projector outputs. Tiered architectural research demonstrates how information can be consolidated across different operational levels while preserving coordinated control (Dada et al., 2021a). Cross-modal distillation can teach a compact student to infer expensive modality features from cheaper inputs, such as approximating video understanding through selected frames and audio. Geospatial-detection research illustrates the importance of preserving discriminative structure when reducing complex observations (Dagodzo & Ahiaeke Patrick, 2022). Task-specific distillation may focus on visual question answering, speech commands, document understanding, navigation, or sensor interpretation. Due-diligence research supports evaluating whether compressed evidence remains sufficiently complete and reliable for consequential decisions (Eboh & Aliliele, 2025a). Distillation datasets should include difficult, low-resource, adversarial, and missing-modality cases because students otherwise imitate dominant teacher behaviors. Strategic oversight research further emphasizes preserving accountable decision criteria when responsibilities are transferred across components (Isiekwu et al., 2021).

Low-rank factorization decomposes large attention, feed-forward, projector, or encoder matrices into smaller factors. The selected rank controls the trade-off between parameter reduction and representational capacity, and different layers may require different ranks. Capital-allocation research provides an analogy for assigning limited model capacity to components according to expected contribution and risk (Lawal & Oduleye, 2021a). Hybrid compression combines distillation with quantization, structured pruning, token reduction, or low-rank decomposition. Explicit rule-based systems illustrate the value of constraining interactions among multiple mechanisms before consequential deployment (Akomolafe et al., 2024b). Compression order matters because pruning before distillation changes the student architecture, whereas quantizing after distillation may introduce rounding errors the student never learned to compensate for. API-governance research supports documenting interfaces, dependencies, and version changes among jointly optimized components (Aliliele et al., 2023b). A practical pipeline may distill a multimodal teacher into a compact student, factorize projector layers, prune redundant image tokens, and perform quantization-aware training as seen in Table 2. Accountability frameworks demonstrate

why every transformation should remain traceable to validation evidence and an approved configuration (Medon & Oduleye, 2022). Comparative studies should report component-level savings, training cost, language quality, cross-modal alignment, robustness, privacy implications, device latency, energy, and ablations showing each technique's independent contribution.

Table 2: Advanced Compression Strategies for On-Device Multimodal Models

Compression Method	Core Mechanism	Main Benefits and Risks	Evaluation and Deployment Requirements
Knowledge distillation	Transfers responses, logits, hidden states, embeddings, attention maps, or projector outputs from a large teacher to a compact student	Reduces model size and inference cost but may reproduce teacher biases or lose rare and difficult capabilities	Test language quality, cross-modal alignment, low-resource inputs, adversarial cases, and missing modalities
Cross-modal and task-specific distillation	Approximates expensive modality features using cheaper inputs or transfers capabilities for vision, speech, documents, navigation, and sensors	Reduces encoder workload but may weaken modality-specific information and grounding	Measure task accuracy, grounding, robustness, privacy leakage, latency, and energy
Low-rank factorization	Decomposes attention, feed-forward, projector, or encoder matrices into smaller factors	Reduces parameters and matrix-computation cost, but an insufficient rank limits representational capacity	Select ranks by layer sensitivity and report parameter savings, quality loss, and device performance
Hybrid compression	Combines distillation, factorization, quantization, structured pruning, and token reduction	Produces greater efficiency but introduces order-dependent errors and complex interactions	Document compression order, configurations, ablations, training cost, memory, latency, energy, and validation evidence

4. Privacy-Preserving and Secure Edge Intelligence

4.1 Local Processing, Data Minimization, and Privacy-Leakage Threats

Local processing reduces the need to transmit raw images, speech, video, locations, biometrics, and behavioral histories to remote servers. However, keeping inference on-device does not automatically guarantee privacy because sensitive information may persist in prompts, embeddings, key–value caches, temporary files, logs, crash reports, or generated outputs. Data-sensitivity frameworks demonstrate the importance of classifying information before determining its permitted processing and retention conditions (Aliliele et al., 2024a). Data minimization should restrict each multimodal request to the sensors, resolution, duration, context, and output detail required for the immediate task. Privacy-by-design research supports embedding these restrictions into architecture and access controls rather than relying on user caution (Badmus et al., 2024). A camera assistant, for example, may process a selected image region instead of retaining an entire

room recording, while a speech interface may discard raw audio after extracting task-relevant features. Digital-identity research further supports binding sensitive processing to authenticated users and explicit purposes (Kumuyi et al., 2024b). Consent interfaces should identify which sensors are active, whether information remains local, and how long derived data will persist. Comparative AI-governance research emphasizes that technical privacy controls require accountable institutional oversight (Afrihyia et al., 2024).

Privacy leakage can occur through model inversion, membership inference, embedding reconstruction, prompt recovery, cache inspection, side channels, or malicious applications sharing device resources. Multimodal models create additional exposure because combined signals can infer identity, health status, location, relationships, or routines that no individual modality reveals. Access-control research demonstrates why distributed and personally managed devices require contextual authorization rather than static permission alone (Ladapo et al., 2023b). Diagnostic telemetry may also disclose prompt length, modality usage, timing, device identifiers, or error content. Forensic-analytics research illustrates how communication metadata and behavioral traces can reconstruct sensitive activities (Mbonu et al., 2021). Privacy-preserving deployment should encrypt local artifacts, isolate per-user memory, suppress unnecessary logs, rotate identifiers, and apply retention limits to derived representations. Security-analytics research supports continuous detection and investigation of anomalous access to protected information (Ogbole et al., 2025). Excessively restrictive privacy controls can create usability or compliance burdens, so risk-based policies should distinguish routine, sensitive, and prohibited processing categories. Regulatory-burden research highlights the need to evaluate unintended operational consequences when controls are implemented without contextual proportionality (Fobellah, 2025c).

4.2 Secure Personalization, Federated Learning, and Private Model Updates

Secure personalization adapts an on-device model to the user's language, preferences, routines, accessibility needs, environment, and recurring tasks without centralizing raw personal data. Adaptation may update lightweight adapters, prompts, preference vectors, retrieval indexes, or selected normalization parameters while leaving the shared backbone frozen. Data-driven forecasting research illustrates how historical interaction patterns can support individualized predictions across changing channels (Dada et al., 2021b). Personal memories should carry provenance, purpose, confidence, sensitivity, and expiration metadata, with separate namespaces for users and applications. Risk-based information architectures support aligning access and retention controls with the consequence of misuse (Mbonu et al., 2021a). Local updates require bounded learning rates, validation against trusted examples, and rollback checkpoints because adversarial or erroneous inputs could poison preferences. Attribution research provides a basis for tracing which interactions materially influenced a personalized prediction or update (Sanni et al., 2022). Inclusive digital-system research also emphasizes evaluating whether personalization benefits users with different resource, language, and accessibility conditions (Michael & Ogunsola, 2021b). Federated learning coordinates updates from multiple devices while keeping training records local. Devices compute gradients or parameter differences, and a server aggregates them into a shared model. End-to-end visibility research demonstrates the importance of traceability across distributed processes contributing to one shared outcome (Nnabueze et al., 2021). Secure aggregation can conceal individual updates from the coordinator, while clipping and differential privacy reduce reconstruction and membership-inference risks. Supplier-collaboration research offers a useful analogy for coordinating independent participants without surrendering all local control (Ike et al., 2021). Federated multimodal training faces non-identically distributed

data, intermittent connectivity, unequal device capability, sparse modality participation, and poisoning by malicious clients. Forecasting research supports adapting aggregation and participation policies to variable operating conditions rather than assuming stable contributions (Tonoyan et al., 2021a). Private model updates should be signed, versioned, integrity-checked, staged through canary devices, and reversible. Compliance-workflow research demonstrates why abstract policy requirements should be converted into executable validation checkpoints (Eyetsemitan et al., 2021). Devices should verify publisher identity, model hash, compatible runtime, permission changes, and expected resource demand before installation. Update telemetry should be minimized, and failures should not expose personal prompts, sensor samples, gradients, or local memory contents.

4.3 Trusted Execution, Encrypted Storage, Sensor Permissions, and Adversarial Security

Trusted execution environments isolate sensitive inference, keys, memories, and model components from the main operating system. They can protect prompts and intermediate representations from compromised applications, although limited secure memory and context-switching overhead may constrain multimodal workloads. Zero-trust research demonstrates why every application, model component, and service request should be continuously verified rather than trusted by location alone (Ogbole et al., 2021). Encrypted storage should cover model weights, personalization adapters, retrieval indexes, key–value caches, sensor recordings, and diagnostic artifacts. Separation-of-duties research supports isolating cryptographic administration, application permissions, model updates, and audit responsibilities (Dogbatsey et al., 2021). Keys should be hardware-backed, user-bound where appropriate, and rotated after compromise or device transfer. Integrated security operations provide a basis for correlating device, application, model, and network events during monitoring (Ladapo et al., 2024). Sensor permissions should be granular, visible, revocable, and limited by purpose, duration, precision, and foreground status. Hazard-identification research further supports detecting unsafe permission combinations before they produce consequential exposure (Obogo et al., 2025). Adversarial threats include malicious images, inaudible audio commands, sensor spoofing, prompt injection, model extraction, poisoned updates, jailbreaks, evasion attacks, and denial of service through extremely long multimodal inputs. Threat-intelligence integration supports combining observed indicators across attack channels rather than evaluating each modality independently (Dosunmu & Ogundele, 2022). Input validation should restrict file types, dimensions, duration, token count, sampling rates, and metadata while isolating content from system instructions. Leading-indicator research demonstrates the value of monitoring early deviations such as unusual sensor activation, repeated permission denials, abnormal memory growth, or sudden energy consumption (Obriki et al., 2025). Robust inference may use adversarial training, modality consistency checks, confidence estimation, rate limits, and fallback to safer single-modality processing. Cybersecurity-investment research emphasizes comparing defensive value with performance, maintenance, and organizational cost (Ozowara et al., 2022). Incident response should support immediate sensor revocation, model isolation, credential rotation, memory quarantine, evidence preservation, and restoration of a trusted model version. Digital-forensics research demonstrates why containment and reconstruction procedures must be established before an attack occurs (Dosunmu & Ogundele, 2021). Security evaluation should measure both attack resistance and the latency, energy, and quality overhead introduced by protective controls.

5. Energy-Efficient Inference and Comparative Evaluation

5.1 Speculative Decoding, Early Exiting, Cache Management, and Adaptive Modality Selection

Speculative decoding uses a smaller draft model to propose several tokens that the main model verifies in parallel. Accepted tokens reduce sequential decoding steps, but poor draft–target agreement can increase computation and energy. Algorithmic optimization research demonstrates that computational reductions must be validated against realized operational cost rather than theoretical savings alone (Tonoyan et al., 2022b). For multimodal models, the draft may receive compressed visual or acoustic representations while the target retains richer context. Scalable gateway research illustrates the importance of controlling information exchange between components operating at different capacities (Akomolafe et al., 2024a). Early exiting allows simple requests to terminate at intermediate layers when confidence, entropy, or representation stability meets an approved threshold. Longitudinal evaluation research shows why exit policies should be assessed over sustained and changing conditions rather than one static test set (Dada et al., 2024). Incorrect early exits may disproportionately affect difficult accents, crowded images, rare objects, or safety-critical sensor events. Integrated safety-management research therefore supports retaining conservative pathways and escalation rules for consequential cases (Obogo et al., 2025). Cache management covers language key–value states, visual embeddings, acoustic representations, retrieved documents, and personalized context. Reusing cached modality features can reduce prefill latency, but stale or incorrectly scoped caches can produce privacy leakage and context contamination. Strategic alignment research demonstrates the importance of connecting resource-allocation decisions to current operational objectives (Lawal & Oduleye, 2021b). Cache policies should specify maximum size, precision, eviction priority, user isolation, sensitivity, and expiration. Integrated optimization research supports coordinating cache placement across storage, memory, and processing components rather than treating each tier independently (Okonkwo et al., 2025). Adaptive modality selection activates only the encoders required for the current request and device state. A wearable may use audio and motion signals for a routine command but activate the camera when object grounding is required. Lean-digital frameworks provide a basis for combining automated routing with repeatable operational controls (Eyetsemitan et al., 2025). Resource-recovery research similarly illustrates the value of reusing existing outputs before initiating additional resource-intensive processing (Falegan & Aniebonam, 2025). Evaluation should measure acceptance rate, exit depth, cache hit rate, modality-selection accuracy, quality loss, latency, energy, and thermal stability across easy, difficult, adversarial, and missing-modality inputs.

5.2 Memory, Latency, Throughput, Energy, Thermal, and Accelerator-Efficiency Metrics

Memory evaluation should distinguish serialized model storage, resident weights, activation tensors, modality features, key–value caches, runtime workspaces, and peak system memory. A compressed model may have small weights yet exceed device capacity when high-resolution images or long audio sequences create large activations. Cost-control frameworks demonstrate why apparent savings must be compared with complete operational expenditure (Aminu-Ibrahim et al., 2025a). Latency should be separated into sensor acquisition, preprocessing, modality encoding, projection, language prefill, decoding, and post-processing. Risk-stratification research illustrates why multiple indicators should remain visible rather than being hidden within one aggregate measure (Okwah, 2022). Reports should include median, P95, and P99 latency under batch-one requests, cold and warm caches, different modality combinations, and realistic output

lengths. Predictive-risk monitoring research demonstrates the importance of evaluating performance under changing conditions and emerging anomalies (Eboh & Aliliele, 2025b). Throughput should be expressed as completed multimodal requests or generated tokens per second at a declared latency target. Infrastructure research further shows that usable capacity depends on coordinated system resources rather than one component's nominal performance (Aminu-Ibrahim & Ogbete, 2023). Energy measurement should report joules per request, joules per generated token, average power, peak power, and battery-percentage decline over sustained workloads. Project-risk research supports evaluating technical performance alongside operational and compliance constraints (Amayo et al., 2025c). Thermal evaluation should record ambient conditions, device temperature, clock frequency, throttling onset, and performance after repeated inference. Safety-leadership research emphasizes monitoring leading indicators before degraded conditions create significant operational consequences (Arumosoye & Obriki, 2024). Accelerator efficiency should measure supported precision, kernel utilization, memory stalls, tensor occupancy, synchronization, and CPU fallback. Analytics-based auditing demonstrates why hardware, runtime, compiler, and configuration details must remain traceable (Ozowara et al., 2025). Theoretical operation counts are insufficient when sparse kernels, dequantization, token routing, or data copying dominate runtime. Cognitive-bias research cautions against selecting only favorable metrics when interpreting efficiency evidence (Fobellah, 2025a). Experiments should identify the processor, accelerator, RAM, operating system, runtime library, power mode, cooling conditions, and repetition count. Results should present Pareto frontiers linking multimodal quality to peak memory, latency, throughput, energy, and temperature rather than declaring one universally optimal configuration.

5.3 Multimodal Quality, Robustness, Fairness, Deployment Cases, and Comparative Results

Multimodal quality should be evaluated separately for language generation, visual recognition, speech understanding, video reasoning, sensor interpretation, and cross-modal grounding. Aggregate scores can conceal cases in which compression preserves fluent language while weakening alignment with images or audio. Maturity-model research supports evaluating capability across progressive and clearly defined performance levels (Adeyelu & Dagodzo, 2024). Appropriate measures include exact match, task accuracy, caption quality, word-error rate, grounding precision, hallucination frequency, answer relevance, calibration, and human preference. Research addressing specialized learning needs demonstrates why evaluation sets should include users and tasks poorly represented by standard benchmarks (Bobga et al., 2025). Robustness testing should introduce blur, low light, background noise, accents, missing frames, sensor drift, corrupted files, modality conflicts, prompt injection, and out-of-distribution scenes. Trauma-informed research illustrates why apparently equivalent model failures can impose greater harm on vulnerable users (Akinse et al., 2023). Comparative studies should report quality changes relative to the uncompressed model and confidence intervals across tasks, users, modalities, and device classes. Diversity research further supports incorporating heterogeneous perspectives and operating contexts into evaluation design (Amayo et al., 2023c).

Fairness assessment should examine languages, dialects, skin tones, accents, disabilities, age groups, geographic settings, device quality, and socioeconomic conditions. Intersectional research demonstrates that overlapping identities may experience harms hidden by single-group averages (Lilian et al., 2025a). Compression can amplify disparities when rare-language tokens, low-frequency acoustic patterns, or minority visual features receive lower precision or are pruned. Gender-equity research supports reporting quality and error distributions separately across relevant

demographic groups (Michael & Ogunsola, 2022b). Deployment cases should include smartphones, wearables, assistive devices, vehicles, robots, cameras, and industrial gateways under realistic memory, connectivity, battery, and thermal constraints. Reviews of universal interventions show that broadly optimized systems may deepen inequality when contextual differences are ignored (Komi & Ganiu, 2025). Case studies should document model architecture, compression configuration, hardware, runtime, permissions, workloads, latency, energy, temperature, privacy controls, and observed failures. A second maturity-oriented evaluation should determine whether prototypes have progressed from laboratory demonstration to reproducible and supportable deployment (Adeyelu & Dagodzo, 2024). Comparative conclusions should emphasize Pareto-efficient designs that balance multimodal quality, robustness, fairness, privacy, and device efficiency rather than selecting models solely by parameter count or benchmark accuracy.

6. Research Gaps and Future Directions

6.1 Reproducibility, Benchmarking, and Standardized Reporting Requirements

Reproducibility remains limited because studies employ different model backbones, modality encoders, datasets, compression settings, hardware platforms, runtime libraries, and measurement procedures. Standardized benchmarks should represent vision–language, audio–language, video–language, document-understanding, sensor-reasoning, and mixed-modality workloads. Each benchmark should include fixed data partitions, modality-quality variations, missing-input cases, adversarial samples, low-resource languages, demographic groups, and realistic context lengths. Device-level experiments should use declared input resolutions, audio durations, frame counts, prompt lengths, output limits, cache states, batch sizes, and request concurrency.

Reporting should identify the language backbone, encoder architecture, projector, fusion mechanism, parameter distribution, compression target, numerical precision, sparsity pattern, teacher model, student capacity, and training cost. Quality measurements should cover language generation, recognition accuracy, cross-modal grounding, hallucination, calibration, robustness, fairness, and privacy leakage. Systems reporting should include serialized storage, resident memory, peak activation memory, cache growth, prefill latency, decoding speed, throughput, energy per inference, device temperature, and throttling behavior.

Hardware descriptions must specify the processor, accelerator, RAM, operating system, compiler, inference runtime, kernel library, power mode, and thermal conditions. Multiple runs, confidence intervals, subgroup results, and Pareto frontiers should accompany averages. Reproducibility packages should provide code, configurations, random seeds, calibration data, pruning masks, quantization scales, model checkpoints, device-profiling scripts, and compression manifests. Where proprietary models or datasets prevent publication, researchers should release synthetic workloads and complete behavioral specifications. Standardized reporting must distinguish theoretical parameter reductions from measured device-level improvements and explicitly document unsupported kernels, CPU fallbacks, privacy assumptions, failed experiments, and unresolved limitations.

6.2 Under-Explored Problems and Emerging Research Opportunities

Multimodal privacy remains under-explored because combined vision, speech, location, biometric, and behavioral signals can reveal sensitive attributes that are not evident within individual modalities. Future benchmarks should measure reconstruction, membership inference, cross-modal identity linkage, cache leakage, and unintended memorization. Research is also needed on privacy-preserving local retrieval, encrypted multimodal memory, secure deletion of derived

embeddings, and federated adaptation under non-identically distributed device data. Differential privacy must be evaluated against rare-language quality, personalization, and energy cost rather than privacy guarantees alone. Compression research should investigate modality-specific sensitivity and cross-modal error propagation. Reducing visual tokens may alter language reasoning, while audio quantization may weaken speaker or accent recognition. Adaptive systems could assign precision, token budgets, encoder depth, and cache capacity according to task difficulty, privacy level, battery condition, and thermal state. Continual compression presents another opportunity because static quantization ranges, pruning masks, and distilled students may become unsuitable as user behavior, sensors, and application domains evolve. Low-resource languages, dialects, disabilities, cultural contexts, and inexpensive devices require greater representation. Compression may disproportionately remove rare tokens, acoustic patterns, visual features, or sensor events associated with underrepresented groups. Future work should report worst-group quality, calibration, robustness, and energy rather than global averages alone.

Hardware–algorithm co-design is equally important. Emerging research should develop kernels for low-bit multimodal projection, mixed-precision cache access, structured sparsity, token merging, and batch-one decoding. Trusted accelerators could combine secure execution with efficient quantized inference. Longitudinal testbeds should measure sustained operation under thermal throttling, intermittent connectivity, application competition, and battery degradation. The field ultimately needs adaptive systems that optimize quality, privacy, security, energy, and fairness jointly instead of treating them as independent objectives.

6.3 Conclusions and Implications for Privacy-Preserving Edge Intelligence

On-device multimodal small language models offer a viable pathway toward responsive and privacy-preserving intelligence across smartphones, wearables, vehicles, robots, cameras, and embedded systems. Local processing can reduce transmission of images, speech, video, biometrics, locations, and behavioral histories while supporting low-latency operation during limited connectivity. Nevertheless, privacy is not guaranteed merely by moving inference to the device. Sensitive information can remain exposed through caches, embeddings, logs, local memories, model updates, permissions, side channels, and compromised applications.

The principal design implication is that model compression, privacy protection, and hardware optimization must be developed jointly. Weight, activation, cache, and encoder quantization reduce memory and bandwidth, while structured pruning, token reduction, adaptive modality selection, early exiting, speculative decoding, and distillation reduce computation. These methods must preserve language quality, cross-modal grounding, rare-event detection, robustness, fairness, and privacy. Parameter count and theoretical operation reductions are insufficient without verified gains in peak memory, latency, throughput, energy, temperature, and accelerator utilization.

Secure deployment requires data minimization, isolated personalization memory, granular sensor permissions, encrypted storage, trusted execution, signed updates, bounded federated learning, and recoverable model versions. Devices should degrade gracefully by reducing resolution, shortening context, disabling unnecessary modalities, or requesting explicit authorization before remote processing. Evaluation should cover realistic multimodal workloads, adversarial inputs, low-resource languages, demographic subgroups, thermal throttling, and intermittent connectivity.

Future systems should treat the device as an adaptive privacy boundary rather than merely a smaller cloud endpoint. Trustworthy edge intelligence will depend on transparent compression manifests, reproducible benchmarks, continuous monitoring, and user-visible control over sensors, memory, personalization, and data transfer.

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