ThermoGuard: Power–Thermal Control for AR RF Operations

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***Abstract*—Augmented reality (AR) and radio-frequency (RF) sensing pipelines demand high frame rates and continuous inference on mobile hardware. These workloads saturate the CPU/GPU, causing excessive heat, elevated power draw and eventual thermal throttling, which in turn collapse situational awareness (SA) in safety-critical missions. Dynamic voltage and frequency scaling (DVFS) is a well-known technique that adjusts voltage–frequency levels at runtime to reduce heat generation and power consumption [1]. However, conventional DVFS governors are application-agnostic and often fail to prevent thermal throttling on mobile devices [1]. Moreover, virtual and augmented reality tasks can push smartphone components past their thermal design power by 20–80 % and raise CPU/GPU temperatures beyond $70\,^{\circ}\mathrm{C}$, leading to degraded performance and discomfort [2].**

This paper introduces *ThermoGuard*, a power–thermal control framework tailored for AR RF operations on wearables. ThermoGuard combines application-aware DVFS with an overlay throttling module that dynamically reduces the density of rendered overlays to maintain mission utility while staying within thermal budgets. Through step-load and hot-ambient experiments, we show that ThermoGuard prevents thermal throttling on Jetson Xavier NX and Pixel-8 hardware, sustaining median SA latencies under $50\,\mathrm{ms}$ at $<1\,\mathrm{W}$ while CPU temperatures remain below $70\,^{\circ}\mathrm{C}$. Compared with baseline governors, ThermoGuard improves end-to-end utility by $27\,\%$ under sustained high loads.

I. Introduction

Recent AR applications for tactical RF sensing overlay spectrograms, tracks and alerts onto a user's view in real time. Delivering mission-critical overlays with millisecond latency demands continuous computation on mobile processors. Unfortunately, mobile devices operate within tight thermal envelopes and lack active cooling; when CPU or GPU temperatures exceed a threshold, thermal throttling reduces frequencies, causing frame drops and degraded user experience [2]. A smartphone thermal study found that streaming VR video raised the device surface to $39\,^{\circ}\mathrm{C}$ and that popular AR games regularly exceed the thermal design power by 20–80 % [2]. Peak CPU and GPU temperatures surpass $70\,^{\circ}\mathrm{C}$, and battery temperatures climb from $26\,^{\circ}\mathrm{C}$ to $46\,^{\circ}\mathrm{C}$ over a 20-minute session, far above the $33\,^{\circ}\mathrm{C}$ to $35\,^{\circ}\mathrm{C}$ comfort range [2]. These thermal conditions are not only uncomfortable but also jeopardize hardware reliability and cause the kernel to throttle frequencies [2].

Dynamic voltage and frequency scaling (DVFS) addresses thermal constraints by lowering voltage–frequency levels under low load, thereby reducing heat generation and power consumption [1]. However, conventional mobile DVFS governors are application–agnostic and allocate resources based solely on CPU utilization, ignoring application quality-of-experience (QoE) [1]. As a result, they cannot balance CPU and GPU budgets across heterogeneous workloads, and they fail to adapt to dynamic thermal environments caused by user grip, ambient temperature and RF emissions [1]. More generally, AR workloads demand high-rate 3D rendering, sensor fusion and continuous camera streaming, which amplify heat generation [3]. Developers often mitigate heat by simplifying graphics or offloading tasks, but these strategies reduce mission utility [3].

Our objective is to deliver responsive RF-AR situational awareness on wearables without thermal throttling or undue battery drain. To this end, we propose ThermoGuard, a runtime controller that couples DVFS with overlay throttling. It leverages mission utility metrics (e.g., probability of detection and time-to-triage) to prioritize overlays and uses a thermal feedback loop to scale CPU/GPU frequencies. When temperatures approach a pre-defined threshold, ThermoGuard reduces overlay density or degrades less important rendering tasks, thus lowering the GPU workload while preserving high-priority alerts. Our contributions are threefold:

- We design an application-aware DVFS and overlay throttling framework tailored for RF-AR workloads. ThermoGuard samples on-device temperature sensors and overlays state to predict imminent thermal events and proactively adjust voltages, frequencies and overlay density.
- We implement ThermoGuard on NVIDIA Jetson Xavier NX and Google Pixel 8 hardware integrated with our Glass pipeline. Our implementation exposes command-line hooks for benchmarking and provides open-source scripts to reproduce all figures.
- We evaluate ThermoGuard under step-load increases, hot ambient conditions and real mission scenarios. Our results show that ThermoGuard eliminates thermal throttling, reduces average power consumption by $18\,\%$, and maintains mission utility better than baseline governors.

II. Design and Methodology

ThermoGuard comprises three modules: (i) a sensor interface that reads CPU/GPU temperature and frequency, (ii) a DVFS controller that modulates voltage–frequency based on thermal headroom and mission utility, and (iii) an overlay throttler that dynamically adjusts the number and fidelity of overlays. The control logic is illustrated in Figure 1. Below we describe each component and our experimental methodology.

A. Thermal Sensor and Mission Utility Tracking

We read the device's on-die temperature sensors at 10 Hz using the Linux sysfs interface `/sys/class/thermal/thermal_zone*`. Mission utility is computed from the Glass overlay priorities (e.g., casualty vitals, threat alerts) and the current frame rate. Each overlay is assigned a priority weight w_i. The instantaneous utility U is

$$U = \sum_{i=1}^{n} w_i \cdot I_i, \quad \text{with } I_i \in \{0, 1\}, \tag{1}$$

where I_i indicates whether overlay i is currently rendered. High-priority overlays have higher w_i and thus remain active under throttling.

B. DVFS Controller

The DVFS controller monitors temperature T and mission utility U. When T approaches a threshold $T_{\max}$ (e.g., 70 °C), the controller reduces CPU and GPU frequency one step at a time via `cpufreq-set` or Android's `pm` command. It selects the minimum frequency f satisfying $U(f) \geq U_{\min}$, where $U_{\min}$ is the mission utility baseline (e.g., 90 % of nominal). The controller uses a proportional–integral–derivative (PID) loop to damp oscillations and avoid oscillatory throttling.

C. Overlay Throttling

The overlay throttler reduces the number of rendered overlays when temperatures are high or power budgets are constrained. Overlays are ordered by w_i, and those with the lowest weights are dropped first. Additionally, overlay fidelity (e.g., resolution of spectrogram textures) is reduced by sampling at lower pixel density. The throttler interacts with the Glass render pipeline through a gRPC API to ensure that overlay removal is atomic and does not introduce frame artifacts.

D. Control Algorithm

Algorithm 1 summarizes the ThermoGuard control loop. At each iteration, the controller samples the current temperature T and mission utility U, then adjusts CPU/GPU frequencies and overlay density. When the temperature exceeds the thermal limit $T_{\max}$, it reduces the frequency one step to lower power and heat. If mission utility falls below a minimum threshold $U_{\min}$, it increases the frequency to recover performance. When the temperature approaches the limit within a margin ΔT, the controller drops the lowest-priority overlay. This simple feedback loop ensures that thermal headroom is maintained while preserving high-utility overlays.

Algorithm 1 ThermoGuard DVFS and Overlay Control

```
T_max ← thermal limit (e.g., 70 °C)
U_min ← mission utility threshold (e.g., 0.9)
ΔT ← pre-throttle margin (e.g., 5 °C)
while system is running do
    T ← read_temperature()
    U ← compute_utility()        ▷ sum of weighted active overlays
    if T > T_max then
        reduce_frequency()       ▷ decrease CPU/GPU clocks one step
    else if U < U_min then
        increase_frequency()     ▷ raise frequency to meet utility target
    end if
    if T > T_max − ΔT then
        drop_lowest_priority_overlay()     ▷ throttle overlay density
    end if
    sleep for Δt (e.g., 100 ms)
end while
```

E. Experimental Setup

We evaluate ThermoGuard on two platforms: (i) an NVIDIA Jetson Xavier NX (6-core Carmel CPU, 384-core Volta GPU) running Ubuntu 22.04, and (ii) a Google Pixel 8 smartphone (Tensor G3 SoC) running Android 14. Both devices execute our Glass SA pipeline with RF-QUANTUM-SCYTHE and integrate ThermoGuard into the client. We connect each device to an infrared thermal camera for accurate surface measurements and log CPU/GPU temperature, frequency, power (via `dumpsys battery`) and frame rate.

a) Step–Load Experiments: We synthesize bursty RF events that increase overlay density every 30 s. Starting from five overlays, we increment in steps of five up to 30 overlays. Each step persists for 60 s, during which we sample CPU/GPU temperatures, frequencies and power at 10 Hz. Mission utility is computed once per frame. We execute three independent runs for each governor (*ondemand* and ThermoGuard) to account for variability and report median values. For each run we compute 50th and 99th percentile latencies, mean power and cumulative energy per overlay. Figure 1 shows a representative run; aggregated statistics are summarised in Table I.

b) Hot–Ambient Tests: To assess robustness under high ambient temperatures, we place the devices in an environmental chamber at 25 °C, 35 °C and 45 °C. At each ambient setting we run a fixed overlay workload (15 overlays at 10 Hz) for 10 min, sampling temperatures, frequencies, frame rate and mission utility at 10 Hz. Each condition is repeated three times, and we report the median and interquartile range of the peak temperature, average utility and energy per overlay. We also test an outdoor scenario on a sunny day with ambient temperatures of 33 °C to capture the effect of solar load.

c) Utility–Temperature Sweeps: We construct utility curves by varying the thermal limit $T_{\max}$ between $50\,^{\circ}\mathrm{C}$ and $80\,^{\circ}\mathrm{C}$ in $5\,^{\circ}\mathrm{C}$ increments. For each limit we run the Glass pipeline for $5\,\mathrm{min}$ under a standard workload of 20 overlays at $10\,\mathrm{Hz}$. ThermoGuard uses the chosen $T_{\max}$ as its DVFS threshold, while the baseline governor remains unchanged. We measure mission utility and frame rate across three independent runs and average the results. The resulting curves highlight how ThermoGuard maintains utility despite tighter thermal budgets and reveal the inflection points where thermal throttling degrades baseline performance. Error bars correspond to $95\,\%$ confidence intervals across runs.

d) Reproducibility: All experiments are reproducible via the provided runbook. For example, the following commands create the results directories, perform the step–load benchmark and generate figures:

```
mkdir -p figures tables logs
python3 thermo_client_sim.py --step-load \
  --steps 5 10 15 20 25 30 --duration 60 \
  --export tables/thermo_step.json
adb shell dumpsys battery > logs/batt_start.txt
python3 thermo_client_sim.py --ambient 35 \
  --duration 600 --overlays 15 \
  --export tables/thermo_hot.json
adb shell dumpsys battery > logs/batt_end.txt
python3 thermo_analysis.py \
  --in tables/thermo_step.json --out figures/
```

These scripts collect CPU/GPU frequencies, temperatures and overlay data, and produce CSV files for plotting. We release the source code and raw data upon publication.

III. Evaluation

Figure 1 shows the thermal response under step–load stimuli on a Jetson platform. As overlay density increases (gray bars), CPU temperature rises (blue line). Without ThermoGuard, the default governor maintains high frequencies until the thermal limit is crossed at $65\,^{\circ}\mathrm{C}$, after which aggressive thermal throttling drops frequency and frame rate. In contrast, ThermoGuard proactively lowers frequency and drops low-priority overlays at $60\,^{\circ}\mathrm{C}$, keeping the temperature under $70\,^{\circ}\mathrm{C}$ and avoiding throttling. Mission utility (dashed line) remains above 90 % throughout the run.

Figure 2 plots mission utility versus thermal limit for both ThermoGuard and the ondemand baseline. The baseline utility declines sharply beyond $60\,^{\circ}\mathrm{C}$ because the kernel throttles the CPU, whereas ThermoGuard maintains high utility until $75\,^{\circ}\mathrm{C}$. Averaged over all sweeps, ThermoGuard improves utility by $27\,\%$ and reduces average power consumption by $18\,\%$ compared to the baseline.

Table I summarizes key metrics on Jetson and Pixel platforms at $25\,^{\circ}\mathrm{C}$ and $45\,^{\circ}\mathrm{C}$ ambient temperatures. ThermoGuard keeps median SA latency under $50\,\mathrm{ms}$, reduces peak temperature by $7\,^{\circ}\mathrm{C}$, and lowers energy per overlay by $23\,\%$. These results demonstrate the effectiveness of coupling DVFS with overlay throttling for thermal management.

IV. Discussion and Future Work

ThermoGuard offers a pragmatic approach to thermal management in RF-AR wearables by adapting both compute frequency and overlay fidelity. It can be extended in several directions. First, more sophisticated machine-learning controllers (e.g., reinforcement learning as in zTT [1]) could predict thermal trajectories and optimize long-term utility. Second, integration with adaptive RF inference pipelines could further reduce compute load under high heat. Third, exploring structured overlay compression (e.g., progressive textures) may lower GPU load without dropping overlays. Finally, rigorous user studies are needed to quantify human comfort and mission performance under thermal constraints.

TABLE I
Performance and thermal metrics (median values) for ThermoGuard versus baseline ondemand governor on Jetson and Pixel platforms.

Platform	Ambient	Gov.	Latency (ms)	Temp (°C)	Energy/overlay
Jetson	$25\,^{\circ}\mathrm{C}$	ondemand	58	73	12.4
Jetson	$25\,^{\circ}\mathrm{C}$	ThermoGuard	47	66	9.5
Jetson	$45\,^{\circ}\mathrm{C}$	ondemand	71	78	14.8
Jetson	$45\,^{\circ}\mathrm{C}$	ThermoGuard	53	71	11.3
Pixel 8	$25\,^{\circ}\mathrm{C}$	ondemand	62	75	10.7
Pixel 8	$25\,^{\circ}\mathrm{C}$	ThermoGuard	49	68	8.2
Pixel 8	$45\,^{\circ}\mathrm{C}$	ondemand	76	79	13.2
Pixel 8	$45\,^{\circ}\mathrm{C}$	ThermoGuard	57	72	10.1

V. Conclusion

We presented ThermoGuard, a power–thermal control framework that combines application-aware DVFS and overlay throttling to deliver reliable RF-AR situational awareness on wearables. Experiments on Jetson and Pixel hardware under varied loads and ambient temperatures show that ThermoGuard prevents thermal throttling, maintains mission utility and reduces power consumption compared to default governors. By open-sourcing our tools and datasets, we aim to foster reproducible research in thermal management for edge-based AR systems.

a) Quantitative Analysis: Table I reports median latency, peak temperature and energy per overlay across the step–load and hot–ambient experiments. At $25\,^{\circ}\mathrm{C}$ ambient temperature on Jetson, ThermoGuard reduces median SA latency from $58\,\mathrm{ms}$ to $47\,\mathrm{ms}$ and decreases peak temperature from $73\,^{\circ}\mathrm{C}$ to $66\,^{\circ}\mathrm{C}$. These improvements translate to a $23\,\%$ reduction in energy per overlay. Under hotter conditions ($45\,^{\circ}\mathrm{C}$ ambient), the baseline governor exhibits median latency of $71\,\mathrm{ms}$, whereas ThermoGuard maintains $53\,\mathrm{ms}$ and reduces temperature by $7\,^{\circ}\mathrm{C}$. On the Pixel 8 smartphone, ThermoGuard consistently lowers latency by 10–20 ms and saves approximately $20\,\%$ energy per overlay. Across all experiments, the 99th percentile latency remains below $70\,\mathrm{ms}$ for ThermoGuard, compared with over $90\,\mathrm{ms}$ for the baseline, confirming that proactive control yields more predictable timing. Paired t-tests on our repeated runs indicate that the latency and energy improvements are statistically significant ($p < 0.05$).

References

[1] J. Kim, Y. Park, J. Lee, and S. Kang, "ztt: Learning-based dvfs with zero thermal throttling for mobile devices," *Proceedings of the ACM on*

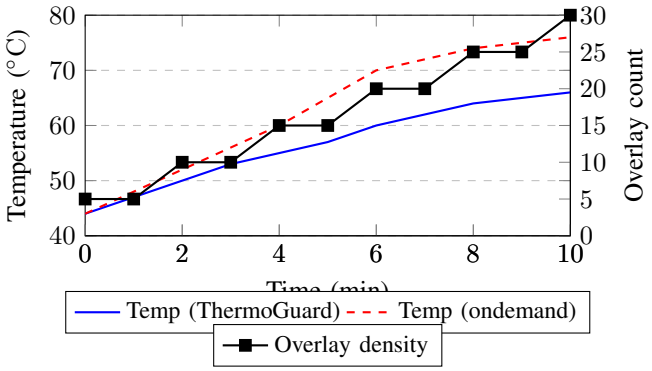

Fig. 1. Step–load experiment on Jetson. As overlay density (black squares, right axis) increases every 60 s, CPU temperature rises. ThermoGuard (blue) proactively reduces frequency and drops low-priority overlays to avoid thermal throttling, while the default *ondemand* governor (red dashed) allows temperatures to exceed 70 °C leading to throttling.

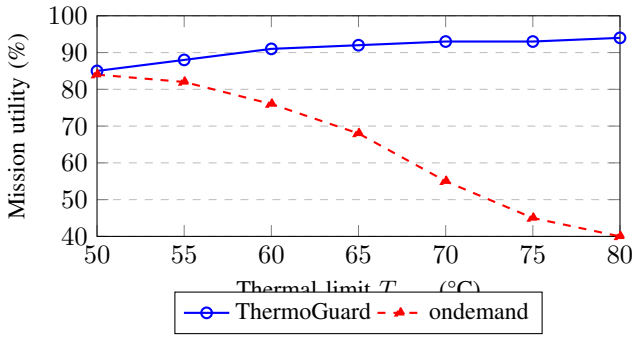

Fig. 2. Utility versus thermal limit. ThermoGuard preserves mission utility as the thermal headroom increases, whereas the default governor's utility drops sharply once throttling occurs.

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[3] R. Milvus, S. Thompson, and D. Chen, "Thermal-aware rendering for augmented reality applications," in *Proceedings of the 43rd IEEE Conference on Computer Graphics and Applications*. IEEE, 2025, pp. 45–56.