

Network-Level Insights into Google-Free Android Operating Systems

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Abstract. This paper presents a comparative analysis of privacy in Android operating systems through network traffic inspection. Using a controlled man-in-the-middle setup and traffic decryption techniques, six Android distributions were evaluated: stock Google Android, GrapheneOS, iodéOS and LineageOS (stock, Gappr, microG). The study examined outbound connections, transmitted identifiers, and network traffic patterns to assess the impact of integrated Google services on user privacy. Results indicate that stock Android maintains the most communication with Google servers, transmitting identifiers and metadata even when idle. In contrast, privacy-focused systems minimize unsolicited traffic and offer stronger user control. The findings demonstrate that alternative Android distributions can substantially improve privacy without sacrificing core functionality, highlighting the potential of open-source ecosystems as viable, privacy-respecting alternatives to Google-dependent mobile environments.

Keywords: Android · Privacy · Network traffic.

1 Introduction

Android is the dominant mobile operating system and acts as a primary gateway to digital world for billions of users. It's crucial for core OS to be a reliable, stable and trustworthy platform, that allows users to run apps and services of their choice. While mobile app privacy has been widely studied [2, 10, 8, 13], less attention is typically paid to the operating system layer and to privileged service frameworks that silently enable additional functionality. Standard unprivileged apps are constrained by Android's permission model, although some attempt to circumvent it in creative ways [9, 7]. In contrast, privileged system apps operate with higher access to the device and OS, which makes them harder to understand and control. Most user-facing privacy controls focus on applications and permissions, yet a substantial amount of data exchange can occur below the app layer, through OS services, vendor components, and Google service frameworks. This work therefore compares the network behavior of multiple Android distributions and their preinstalled/privileged system components under controlled, reproducible conditions.

1.1 Android dependency on privacy-threatening services

While Android’s core is the Android Open Source Project (AOSP), most consumer devices ship with additional proprietary components layered on top. They are often implemented as privileged system apps and service frameworks to provide baseline functionality such as push notifications, location assistance, app distribution/updates, device integrity checks and many more. Users and app developers commonly assume their presence and availability by default.

These components exist for a practical reason. Centralized services can significantly improve usability and efficiency, for example by reducing battery drain compared to per-app background connections, and by providing faster, more accurate location through fused network and sensor-based methods. However, this design also tightly couples many functions into a single service stack, so enabling useful capabilities may implicitly enable others that a user would not choose, such as advertising identifiers, telemetry, and behavioral tracking. In practice, the result is a large proprietary bundle that is difficult to audit and decompose into only the features a user actually wants.

On Android, these baseline capabilities are most commonly delivered through GMS (Google Mobile Services). Because Google’s business model is strongly advertising-driven, many users may be unwilling to entrust this provider with broad access to device and their data. In principle, users should be able to choose which services they rely on and have confidence that these choices are enforced by the platform’s permission and isolation mechanisms. This demand for transparency and controllability motivates alternative approaches such as microG and GrapheneOS sandboxed Google Play. These solutions aim to preserve device functionality and app compatibility while reducing privilege and improving user control over Google-related components.

1.2 Privacy-focused Android operating systems

Privacy-focused Android operating systems (also referred to as *custom ROMs*) are distributions derived from AOSP that aim to reduce data exposure at the OS level. They achieve this by limiting preinstalled privileged components, tightening default settings, and providing more transparent controls over permissions and network access. In contrast to *stock Android* (the factory system shipping with Google Mobile Services enabled by default) privacy-oriented systems minimize background communication, restrict persistent identifiers, and strengthen user enforcement mechanisms over non-essential components.

In this work we focus on three representative approaches. GrapheneOS prioritizes a hardened security model and strong isolation. Google components are not included by default, but can be installed in a dedicated sandboxed mode as ordinary apps, without the special privileges that Google Mobile Services (GMS) typically hold on factory systems. This design targets improved containment and user control while preserving high compatibility when the user decides to install Google services. GrapheneOS also improves low-level security, for example by replacing Android’s default memory allocator with its own hardened implementation to make memory corruption exploitation harder [12].

LineageOS provides a lightweight, broadly supported AOSP-based system with minimal preinstalled software and extensive device compatibility. It can be deployed in multiple configurations: without Google services, with official proprietary Google Play Services and Play Store (Gapps), or with microG as an open-source reimplementation of key Google APIs. These configurations represent different trade-offs between privacy, compatibility, and reliance on proprietary services.

Finally, iodéOS is a privacy-oriented distribution based on LineageOS that combines a de-Googled baseline with additional privacy features and preconfigured app ecosystem choices, shipping with microG. For completeness, CalyxOS and /e/OS follow a similar privacy-oriented direction (AOSP-based, microG-enabled, and designed for practical daily use). They were considered for the study, but were excluded because they did not receive updates to the current Android version during the measurement period.

Privacy-focused Android operating systems do not uniformly improve security. Some strengthen the platform through tighter defaults, hardening, and timely patching, while others may weaken it through slower updates or changes that reduce the strength of certain platform guarantees. In particular, microG support often requires signature spoofing, which weakens Android’s signature-based authenticity checks. Systems that enable it typically try to minimize the risk by restricting spoofing to just microG. Some distributions do not support verified boot chain or re-locking the bootloader after installation, which weakens protection against physical tampering.

1.3 Challenges of network traffic analysis on Android

Network traffic analysis on Android is difficult by design and that is largely a security benefit. Modern protocols increasingly hide data behind encryption (TLS 1.3, QUIC/HTTP3, encrypted DNS). Even when traffic is captured, compression and binary encodings can make payloads hard to interpret without schemas or additional context. As a result, MITM-based decryption is inherently incomplete. Certificate pinning and anti-tamper mechanisms can block interception or break app functionality. Circumvention of these security mechanisms do not reliably yield a full plaintext view. While emulator-based setups enable highly reproducible traffic capture [1], this work uses a physical device to analyze behavior in a real environment, at the cost of reduced control and reproducibility. We accept that some flows will remain opaque, not all network communication will be revealed or understood. Our focus is on differences between studied Android systems and on general patterns.

In this work we captured traffic using a controlled man-in-the-middle gateway around a physical device. A Linux host acted as the Wi-Fi router and transparently redirected the device’s HTTP(S) traffic through an intercepting proxy, while QUIC over UDP/443 was blocked to force TCP where decryption is feasible. To enable TLS inspection, the proxy CA was installed and promoted to a system-trusted certificate on the device (requiring root access). Where certificate pinning prevented interception, we attempted runtime unpinning via dynamic

instrumentation, acknowledging that this only worked for a subset of apps. Full packet captures were recorded and compared across Android distributions to analyze differences in network communication.

2 Related work

Prior work has established that Android privacy risks arise not only from user-installed applications but also, from the operating system and its preinstalled components. Privacy-focused Android distributions have gained popularity as alternatives to stock vendor firmware, yet they remain comparatively understudied in the measurement literature. Consequently, there is limited empirical understanding of what practical privacy and control benefits different Android distributions provide to users.

A key OS-level measurement study addresses this gap by comparing several vendor-customized Android variants with two open-source distributions under a privacy-conscious baseline configuration [5]. It reports that all tested stock/vendor builds transmit substantial data to OS vendors and third parties even when the handset is idle, and that this collection persists without an effective opt-out. In contrast, the privacy-focused open-source /e/OS in their comparison exhibits minimal data transmission, whereas LineageOS still shows substantial communication to Google because it was evaluated with Google’s proprietary app stack present. This distinction is important for studies like ours that evaluate multiple distributions and configurations (including variants with and without integrated Google services), since the presence of Google system components can dominate observed traffic and shape the overall privacy profile.

Follow-up work focusing specifically on OEM telemetry further shows that Samsung, Xiaomi, Huawei and Realme make extensive use of long-lived hardware identifiers and also collect installed-app lists and analytics data, sometimes even in connections that should not require persistent identifiers, enabling straightforward linkage to a user’s identity when an OEM account is used [6].

Additional work by the same authors analyzes telemetry from two core Google system apps, Google Messages and Google Dialer, by decrypting and decoding the logging channels that forward data to Google [4]. The study reports that these apps disclose sensitive communication metadata, including when SMS messages and calls are sent or received, with timestamps and for calls duration. Messages also sends a hash derived from message content that can uniquely identify messages and link participants. It further finds that phone numbers may be transmitted and that events are tagged with persistent identifiers such as the Android ID, undermining anonymity and leaving users with no effective opt out. Taken together, these results suggest that even basic default communication apps on Google Android cannot be assumed to be trustworthy from a privacy perspective.

Complementing OS-level telemetry measurements, a recent study focuses specifically on what pre-installed Google components persistently store on-device and shows that Google’s role in Android privacy extends beyond outbound traf-

fic [3]. It reports that Google Play Services, the Play Store, and other bundled Google apps receive and store multiple cookies, advertising-related identifiers, and tracking links even after a factory reset and even when the user has not opened Google apps, with no dedicated consent prompt and no practical opt-out. The study highlights the Google Android ID as a persistent identifier provisioned early and widely reused in subsequent Google connections, and documents how additional tokens and cookies can be stored and later transmitted alongside telemetry or analytics events. Together, these findings reinforce that Google’s integrated service stack functions as a central privacy-relevant layer of the Android ecosystem, shaping device identification and data handling independently of user-installed applications.

A broader view of Google’s privacy impact is given in a report that describes data collection as an ecosystem across platforms, apps, and advertising services, not as a single feature of Android [11]. It distinguishes "active" data sharing (when users directly use Google products) from "passive" collection that happens in the background via Android/Chrome and via tracking/analytics components embedded in many third-party apps and websites. The report argues that these different data sources can be combined to build detailed user profiles, and that "pseudonymous" identifiers (like ad IDs or cookies) can still be linked back to user accounts when they appear together in the same workflows.

Overall, prior work consistently indicates that Google’s integrated service stack is a dominant driver of privacy-relevant data flow on Android. It enables persistent device identification, background telemetry, and cross-context linkage between app usage, web activity, and advertising infrastructure, often with limited user visibility and weak practical opt-out mechanisms. At the same time, the literature suggests that meaningful reductions in unsolicited communication are possible when Google components are absent or replaced with open source variants [5]. Alternative configurations and distributions remain less widely deployed, less familiar to typical users, and comparatively under-explored in reproducible measurement studies. This motivates systematic, real-device comparisons of stock systems versus privacy-oriented alternatives and configurations to quantify what privacy improvements are achievable in practice and what trade-offs they entail.

3 Experiment design

3.1 Hardware and software

We used a single Google Pixel 6a (codename *bluejay*) to install and evaluate studied Android distributions. This model was chosen due to its broad compatibility with alternative operating systems. The full measurement setup is shown in Fig. 1. All tested builds base on Android 16 and were obtained in December 2025:

- Stock Android: BP4A.251205.006
- LineageOS: lineage-23.0-20251206 (BP2A.250805.005)

- LineageOS for microG: lineage-23.0-20251203-microG (BP2A.250805.005)
- GrapheneOS: 2025121200 (BP4A.251205.006)
- iodeOS: 7.0-20251129-bluejay (BP2A.250805.005)

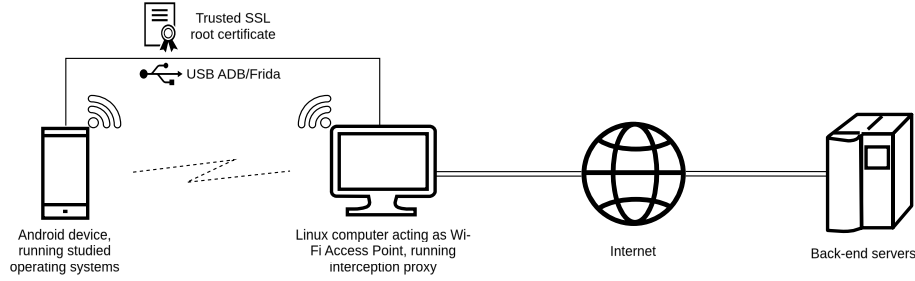


Fig. 1. Measurement setup. Android device running studied operating systems is configured to access Internet using Wi-Fi. Access point is hosted on a Linux computer, running traffic interception and capturing software. Custom system certificate is installed on the phone using root access. USB connection is used for ADB/Frida communication.

3.2 Measurement scenarios

To enable consistent, comparable measurements across Android distributions, four setup scenarios were defined. Each scenario specifies the Google account state, consent and permission posture, and which Google components are present. Not all scenarios apply to every operating system due to their characteristics. Scenarios were adapted to each system’s capabilities: on GrapheneOS, sandboxed Google Play Services were installed immediately after setup; on systems with microG, the component was enabled during initial setup when prompted, or activated manually immediately afterward. As a general principle, any required configuration step not available during initial setup was performed as soon as possible thereafter.

Scenario A: Default Setup with Google Account. The device is configured to reflect a typical user path. Google account sign-in is performed during setup (or immediately after) and default recommendations are accepted (including prompted permissions).

Scenario A2: Minimal Setup with Google Account. This scenario extends *Scenario A* by adjusting settings towards privacy while retaining Google account functionality. During and after initial setup, all optional consents and permissions are declined. System and account settings are adjusted to maximize user privacy. This scenario is not applicable to systems using microG or GrapheneOS, as these distributions are already designed to minimize privacy risks and do not

implement or prompt users for privacy-threatening features characteristic of the factory system.

Scenario B: Minimal Setup without Google Account. The device is configured with maximum privacy in mind, avoiding Google account sign-in entirely. During initial setup, only strictly required prompts are accepted and optional data-sharing is declined. System settings are adjusted to maximize user privacy. Google components or their functional replacements remain present and enabled to preserve baseline device functionality and app compatibility, but operate without account.

Scenario C: Extremely Minimal Setup without Google Components. This scenario applies only to distributions that do not bundle or enable Google services by default. It is not applicable to the official factory system, which enables Google components by default. If microG is preinstalled, it remains disabled.

3.3 Measurement tasks

We performed the following measurement tasks sequentially for each scenario. Network traffic was captured using Wireshark for basic analysis.

Task 0: Initial setup. Configure the device according to the target scenario, connect to Wi-Fi, complete account sign-ins and install components as specified. Network traffic capture begins with the device’s first Internet connection and continues until 10 minutes after setup completion.

Task 1: System idle. Ensure the system and apps are up to date and that no update-related background jobs are running. Reboot the device to begin capture, then keep it connected to the monitored network for at least 30 minutes. During this period, unlock the device three times and scroll through the app list. Do not open any apps.

Task 2: Basic apps interactions. Open preinstalled apps and perform simple actions that should not require an Internet connection

- Settings: disable haptic feedback; toggle dark mode; check per-app battery usage
- Clock: set an alarm
- Files: create a folder
- Contacts: create a local (on-device) contact

Beyond direct task comparisons, additional packets of interest were examined to compare data transmission practices across different system configurations and to characterize what data is sent and how. This analysis required TLS decryption via the intercepting proxy and, in some cases, runtime certificate unpinning with Frida using scripts from HTTP Toolkit.¹ Although Frida-based

¹ <https://github.com/http Toolkit/frida-interception-and-unpinning>

unpinning failed in most attempts, it was useful in a small number of cases. When useful, we used publicly available Protocol Buffer definitions from microG’s source code to decode payloads.

To complement network-level observations, Google Takeout² was used to inspect server-side data associated with the test Google account after running scenarios involving Google services (Stock Android, GrapheneOS with sandboxed Google Play Services, and microG-based distributions).

4 Results

4.1 Data usage across operating systems and scenarios

Total network data usage across all operating systems and applicable scenarios for performed tasks, is presented on charts in Figures 2–4. To keep the results comparable and avoid dominance by bulk transfers, we excluded traffic to domains used for app and system update payload delivery (large binary downloads), though this exclusion was not perfect and some residual update-related traffic remains in the dataset. Generally, we expect lower network traffic in configurations with fewer Google services present.

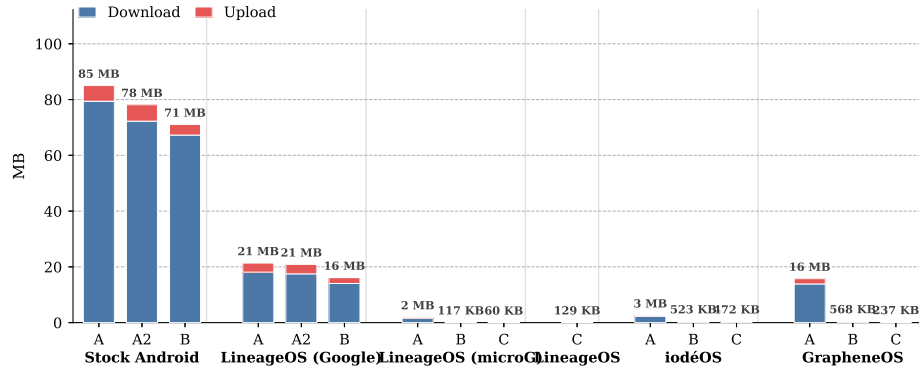


Fig. 2. Task 0: Initial setup data usage

Figure 2 illustrates network activity during initial device setup. As expected, stock Android shows the highest data usage (71–85 MB). The modest reductions between privacy-adjusted scenarios indicate that configuration choices provide little control over automatic updates and background synchronization. Across all distributions, variations align with service architecture: configurations incorporating more Google services generate proportionally higher traffic, while de-Google'd baselines demonstrate substantially reduced exchange. LineageOS

² <https://takeout.google.com/>

with official Google Play Services generates substantially less traffic (16-21 MB) than stock Android due to its more minimal base system, yet remains considerably higher than configurations without proprietary Google services, with the microG variant and Google-free installation achieving notable further reductions (0-3 MB). On GrapheneOS, Scenario B demonstrates that even when sandboxed Google Play Services are installed and granted network and background permissions, they remain largely inactive when not deliberately invoked, contrasting with the persistent background activity characteristic of integrated GMS deployments.

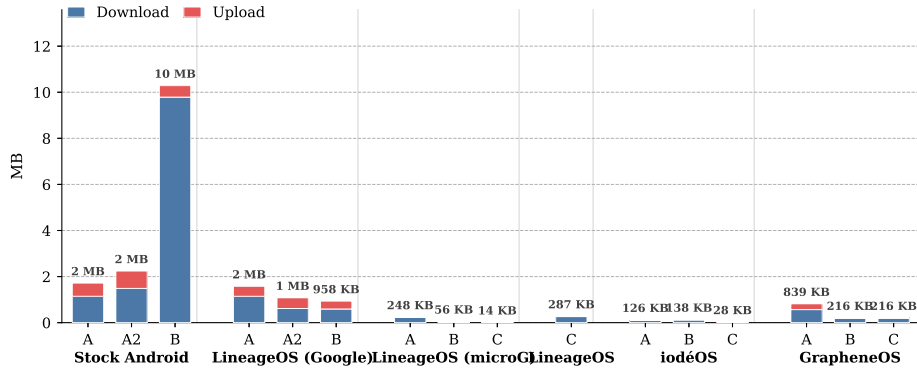


Fig. 3. Task 1: Idle data usage

Network activity observed during system idle following a reboot is presented in Figure 3. Stock Android again shows the highest data usage, though Scenario B exhibits unexpectedly elevated traffic compared to both Scenario A2 and Scenario A. This anomaly stems from substantial background communication with www.gstatic.com, likely triggered by automatic updates or other background activity during the measurement time.

LineageOS in Scenario C similarly deviate from anticipated patterns, generating more idle traffic than its microG variant. GrapheneOS exhibits virtually identical idle traffic in Scenarios B and C, confirming that sandboxed Google Play Services generate minimal background activity when not actively in use.

Figure 4 shows network activity during basic app interactions that should not require Internet connectivity. Stock Android dominates with substantial data usage mostly by uncontrolled updates. All alternative distributions demonstrate dramatically lower traffic, with de-Google'd configurations remaining effectively silent. Notably, whenever official Google Play Services were present and a Google account logged in at least a single request to Google infrastructure occurred.

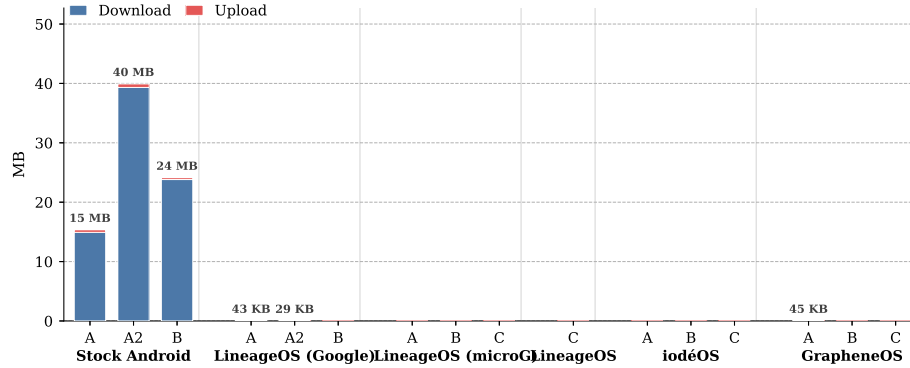


Fig. 4. Task 2: Basic apps interactions data usage

4.2 Domain distribution and Google dependencies

Figure 5 presents the domain-level distribution of network traffic for Scenarios A and B. They were selected as the most realistic configurations incorporating essential Google functionality while differing in account linkage and privacy-related settings. Overall traffic is dominated by large content transfers, as systems download necessary resources and updates. Stock Android contacts the widest range of Google domains, spreading traffic across many different endpoints. Alternative systems show less Google communication, though patterns vary by design. GrapheneOS makes more requests than microG-based systems because it downloads Google services on demand from its own app store rather than having them preinstalled. IodéOS and LineageOS with microG reach fewer Google servers overall, as microG minimizes Google connectivity while still enabling basic features. IodéOS additionally relies on some Mozilla infrastructure not present in other systems.

Table 1 shows the infrastructure dependencies for basic system functions. LineageOS variants remain closest to stock Android, relying entirely on Google servers for connectivity checks, remote provisioning, and location assistance. IodéOS adopts an intermediate position, using independent infrastructure for connectivity checks while still depending on Google for remote provisioning and location services. GrapheneOS demonstrates the strongest de-Googling, substituting all three functions with its own or independently operated infrastructure. Both iodéOS and GrapheneOS expose these mechanisms through explicit system settings toggles, though GrapheneOS offers more granular control: users may choose between its independent proxy infrastructure and official Google servers for each function, with defaults configured to avoid Google connections entirely.

4.3 Additional findings

Beyond aggregate traffic measurements, we examined specific data transmissions revealed through TLS interception and payload analysis. Some observations were

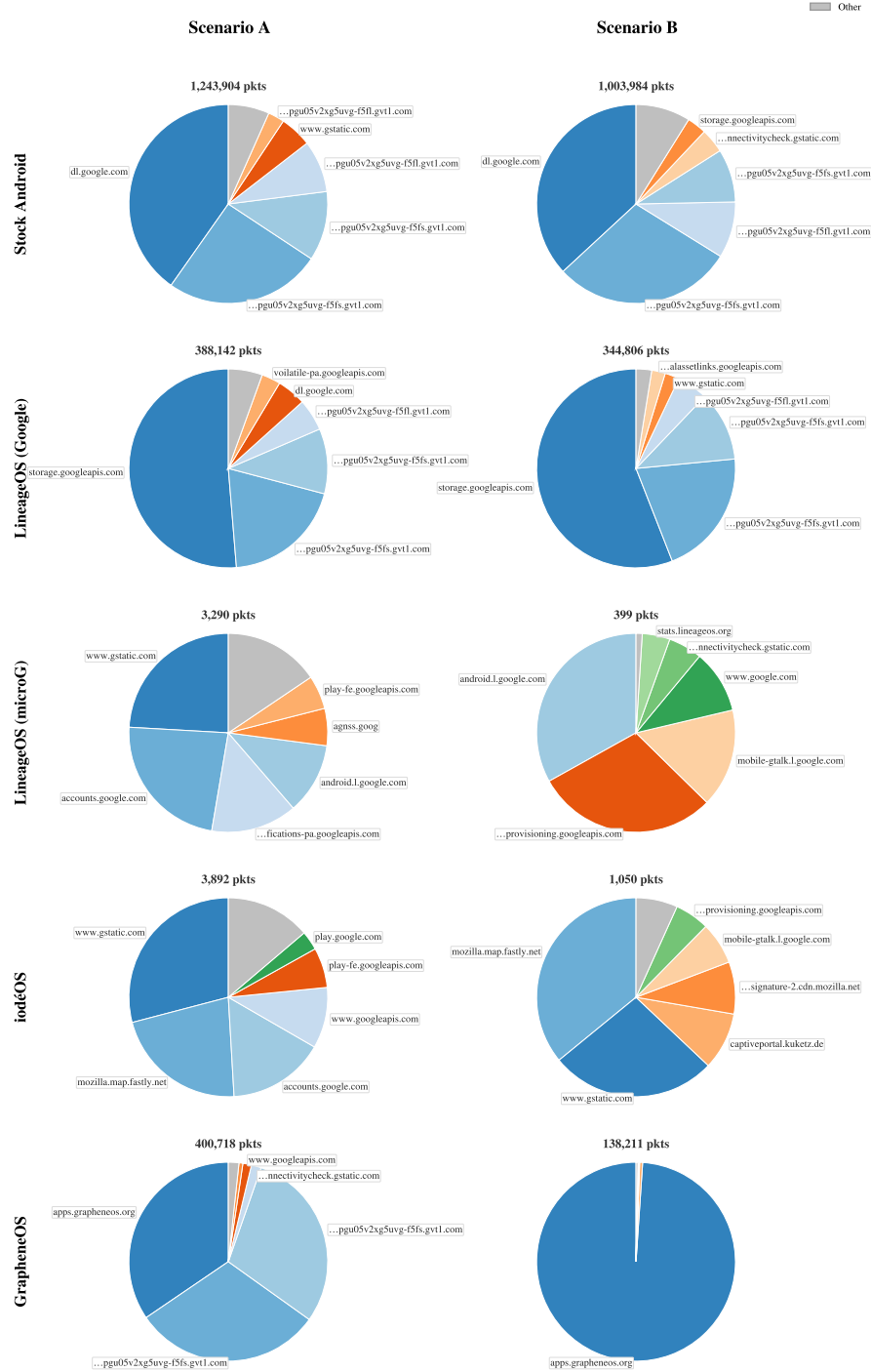


Fig. 5. Domain-level distribution of network packets for scenarios A (with Google account) and B (without Google account, but Google Services present), aggregated over all tasks. Each pie shows the top domains by packet count for a given operating system and scenario.

Table 1. Domains observed for connectivity check, remote provisioning, and location assistance.

System	Connectivity check	Remote provisioning	Location assistance
Stock Android	connectivitycheck.gstatic.com	–	supl.google.com agnss.goog
LineageOS	connectivitycheck.gstatic.com	remoteprovisioning.googleapis.com	supl.google.com agnss.goog
iodeOS	captiveportal.kuketz.de	remoteprovisioning.googleapis.com	supl.google.com
GrapheneOS	connectivitycheck.grapheneos.network	remoteprovisioning.grapheneos.org	gs-loc.apple.grapheneos.org

gathered earlier on Android 14 and could not be reconfirmed on Android 16, as the Frida-based method we employed became unsuccessful, though we expect the general patterns to persist. GrapheneOS blocked all our instrumentation attempts, so we cannot verify what data these requests contained. However, the substantially lower request volume suggests sandboxed Google Play Services likely transmit less complete or authentic information.

Android’s checkin mechanism transmits device identifiers to Google infrastructure. On stock systems, this includes the real IMEI and hardware serial number. In contrast, microG employs a privacy-preserving approach by generating randomized, rotating identifiers including fake IMEIs (consistently prefixed with 35503104), MAC addresses (with OUI b4:07:f9), and a synthetic serial key displayed in microG settings. The Android ID field in microG requests is frequently empty or zeroed. However, microG still transmits authentic device characteristics including model, Android version, and timezone, enabling functional compatibility while obscuring persistent hardware identifiers.

We observed requests to `app-measurement.com` on systems with Google services present, most on stock Android. These transmissions contained application package names, installation sources (Google Play, Aurora Store, manual), app versions and system theme preference. Information about installed applications was transmitted even for apps that were never launched.

The Google Advertising ID (ADID) was observed in multiple requests on stock Android, formatted as a UUID. This value remained constant across different requests, confirming its persistence as a cross-app tracking mechanism. After manual reset in system settings, the ADID was transmitted as zeros, indicating the identifier was actually cleared rather than regenerated immediately.

When enabled by the user, microG performs network geolocation without Google infrastructure by querying a selected provider, in our case `api.position.xyz`. The request transmits nearby cell tower data and returns approximate coordinates. Location fixes were obtained almost immediately after enabling this feature, compared to substantially slower determination prior to activation.

We compared Google Play Store with Aurora Store, a popular application source in alternative Android distributions, by downloading the same application from both stores. Both retrieved identical packages from the same Google CDN infrastructure. However, the Play Store generated 106 requests while Aurora Store produced 93 requests, omitting Google telemetry connections, but adding lookups to Exodus Privacy and Plexus databases for tracker analysis and compatibility ratings. Aurora achieves functional equivalence by mimicking

Play Store user agents and headers, though with shared anonymous credentials rather than personal account.

4.4 Google Takeout

Following testing scenarios where we logged into a Google account, we submitted Google Takeout requests and analyzed the Android device data. Our selection covered four distinct Google service configurations: Stock Android as a baseline, LineageOS with GMS as alternative system incorporating official Google services, LineageOS with microG as an open source reimplementation (IodéOS includes an identical microG version), and GrapheneOS as a representative of sandboxed Google Play. For every logged in system, an entry appeared in `devices.json` containing device model, OS version, country, language, registration timestamp, and last activity time. However, the depth of telemetry varied considerably across configurations, as summarized in Table 2.

Both systems using official Google services reported a large list of installed apps. GrapheneOS reported only four preinstalled applications, two of which were GrapheneOS specific. In contrast, microG did not create any app-related entry. Additionally, Stock Android and LineageOS with GMS both transmitted authentic hardware identifiers including IMEI and serial number. GrapheneOS submitted a falsified serial number and omitted IMEI entirely. Again, microG did not create additional device-related entry, so these identifiers were not present. A Pixel specific telemetry directory, present only for Stock Android and LineageOS with GMS, contained extensive hardware monitoring data including power measurements, Wi-Fi signal logs, battery capacity readings, thermal samples, and battery cycle entries. LineageOS reported less granular telemetry than Stock Android, indicating that while basic Pixel telemetry infrastructure remains functional, the depth of hardware monitoring is reduced compared to the proprietary stock implementation.

Table 2. Comparison of Google Takeout data across Android configurations.

System	Device identifiers	Installed apps	Pixel telemetry
Stock Android	IMEI, serial number	Extensive list	Full (power, Wi-Fi, battery, thermal)
LineageOS (GMS)	IMEI, serial number	Extensive list	Reduced
LineageOS (microG)	—	—	—
GrapheneOS	Falsified serial number	Minimal (4 apps)	—

5 Discussion

Our measurements reveal a clear hierarchy in how different Android configurations handle user data and privacy. The most fundamental finding is that adjusting privacy settings on stock Android, while beneficial, cannot achieve the same

protection as switching to an alternative distribution. On system running proprietary Google services, privacy adjusted scenarios showed modest data transmission reductions compared to default setup. Their underlying architecture tightly integrates Google Mobile Services into core OS and persists background activity. Substantial data flows to Google infrastructure continued regardless of user-facing privacy toggles.

Alternative distributions shift the privacy posture by making Google communication user-initiated rather than ambient. All privacy-focused systems generated orders of magnitude less network traffic with Google. Some of them are utilizing their own or third-party privacy-focused infrastructure to replace Google's. LineageOS with GMS was an exception, while more minimal, by having official Google services preinstalled, it does not differ much from stock Android in terms of privacy. Among other configurations enabling basic Google functionality, microG represents the most privacy-preserving approach, though this comes with potential security trade-offs (e.g. signature spoofing). Our measurements show microG transmits the least data to Google infrastructure while maintaining basic service compatibility. It achieves this through identifier randomization rather than exposing authentic hardware identifiers, similar to GrapheneOS. Our observations illustrate the fundamental difference: microG optimizes for privacy, while GrapheneOS prioritizes platform security, while still delivering great privacy, substantially improved over stock systems.

Alternative distributions also improve user control through minimal base systems and enhanced permission granularity. All tested alternatives ship without forced user agreements during initial setup, unlike stock Android's mandatory terms requiring data collection. One privacy-friendly feature we found in all cases is network permission controls that stock lacks, allowing users to deny Internet access to specific apps. Aurora Store demonstrates that app sourcing from official repositories remains viable without direct Google infrastructure interaction, retrieving identical packages from the same CDN endpoints while generating fewer requests and adding privacy-focused metadata lookups. Updates on alternative systems are typically smaller, more transparent, and user-controlled rather than automatic and opaque.

Several limitations qualify these findings. Our measurements capture specific time-bounded scenarios rather than universal behavior. Traffic patterns likely vary with extended use and evolving service configurations. The TLS interception approach, while revealing substantial information, remains incomplete due to certificate pinning, anti-tamper mechanisms, and protocol evolution. GrapheneOS's resistance to our instrumentation, while security-advantageous, means we cannot closely verify what data sandboxed services transmit. These constraints mean our findings indicate general trends and architectural differences rather than definitive absolute measurements.

In summary, privacy-focused Android distributions deliver measurable, substantial improvements in user control and data exposure reduction. By separating essential functionality from integrated proprietary services, these systems transform Google communication from ambient background activity into user-

initiated interactions The choice between approaches (microG or GrapheneOS sandbox) depends on individual threat models and functional requirements, but all represent meaningful advances in user control and privacy over stock Android.

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