Project Report

Topic : Enhancing Android Kernel Observability Using eBPF

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Enhancing Android Kernel Observability Using eBPF: A Comprehensive Analysis of System Monitoring, Performance Profiling, and Security

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Chapter 1: Introduction

1.1 The Imperative for Advanced Observability in Mobile Operating Systems

Modern mobile operating systems, with Android at the forefront, represent some of the most complex and dynamic computing environments in widespread use. The Android software stack, a multi-layered architecture comprising a Linux kernel, hardware abstraction layers (HALs), native libraries, an application runtime, and a vast ecosystem of applications, presents a formidable challenge for traditional monitoring and analysis techniques. Conventional tools, which often rely on static counters, periodic sampling, and log file aggregation, are frequently insufficient for capturing the ephemeral, high-frequency events that define system behavior, performance bottlenecks, and security incidents. This gap leads to significant "observation blind spots," where developers and security analysts lack the necessary visibility to perform effective fault triage or detect sophisticated threats.

The concept of observability, rooted in control theory, refers to the ability to infer the internal state of a system from its external outputs. In the context of an operating system like Android, true observability transcends mere monitoring; it requires the capacity to ask arbitrary questions about the system's inner workings in real time, without being limited to predefined metrics. Traditional Application Performance Monitoring (APM) solutions have attempted to address this by instrumenting application code, but this approach is often intrusive, requiring code modifications, application restarts, and carrying significant performance overhead. Furthermore, it provides little to no insight into the underlying kernel, where the root cause of many performance and security issues resides. The need for a non-intrusive, performant, and deeply integrated observability solution is therefore paramount.

1.2 The Android Kernel: A Complex Ecosystem

At the heart of the Android platform lies a modified Linux kernel, which serves as the fundamental layer of abstraction between the device hardware and the software stack. It is responsible for critical functions such as process management, memory management, and device driver interactions. However, the Android kernel is not a monolithic entity. The open-source nature of Android has led to extensive fragmentation, with each device manufacturer (OEM) and silicon vendor creating their own customized kernel versions to support specific hardware.

This fragmentation has historically posed a significant challenge to system-wide monitoring and security. A tool or technique developed for one device's kernel might not work on another, hindering the development of universal observability solutions. Google's recent architectural initiatives, such as the Generic Kernel Image (GKI) project, aim to mitigate this fragmentation by standardizing the core kernel and separating vendor-specific code into loadable modules. This move towards a more modular and standardized kernel architecture creates an opportune moment for the introduction of a similarly standardized and powerful instrumentation technology.

1.3 Introducing eBPF: A Paradigm Shift in Kernel Programmability

Extended Berkeley Packet Filter (eBPF) has emerged as a revolutionary technology that fundamentally changes how developers and administrators can interact with a running operating system kernel. eBPF allows small, sandboxed programs to be dynamically loaded and executed within the kernel itself, triggered by specific events such as system calls, network packet arrivals, or function entries. This provides a mechanism for extending kernel functionality safely and efficiently, without the need to modify kernel source code or load potentially unstable and insecure Loadable Kernel Modules (LKMs).

eBPF functions as a lightweight, in-kernel virtual machine that is equipped with stringent safety guarantees. A critical component, the verifier, statically analyzes eBPF bytecode before it is loaded, ensuring that programs cannot crash the kernel, access arbitrary memory, or enter infinite loops. Once verified, the bytecode is translated into native machine code by a Just-in-Time (JIT) compiler, allowing it to execute with near-native performance. This combination of safety, performance, and programmability makes eBPF an ideal technology for building a new generation of advanced observability tools. It acts as a "Swiss Army knife" for the kernel, providing a unified framework for networking, security, and performance analysis that is both powerful and non-intrusive.

1.4 Report Structure and Objectives

The primary objective of this report is to conduct a comprehensive investigation into the application of eBPF for enhancing kernel observability on the Android platform. This analysis will span three critical domains: system monitoring, performance profiling, and security analysis. The report aims to provide a deep technical understanding of the underlying technologies, a practical guide to implementation, and an analysis of the results and implications of using eBPF in a mobile context.

To achieve this, the report is structured into five chapters. Chapter 2 provides the foundational concepts, reviewing the architecture of the modern Android kernel and the eBPF framework, surveying the state of eBPF integration in AOSP, and examining relevant toolchains and academic research. Chapter 3 outlines the methodology for this project, defining the observability challenges on Android and detailing the practical steps for establishing a development and tracing environment. Chapter 4 presents the core implementation and results, demonstrating the use of eBPF-based tools for system call tracing, CPU performance profiling, and network security analysis. Finally, Chapter 5 concludes the report by synthesizing the findings, discussing current limitations, and exploring future directions for programmable kernel observability on Android.

Chapter 2: Foundational Concepts and Literature Review

2.1 Deconstructing the Modern Android Kernel: From ACK to GKI

The Android kernel, while based on the upstream Linux kernel, has its own distinct lineage and architecture tailored for the mobile ecosystem. Its foundation is the Linux Long Term Supported (LTS) kernel, which is released annually and provides a stable base for development. Google takes these LTS kernels and integrates a series of Android-specific patches and features that have not yet been merged into the mainline kernel. The result of this combination is known as an Android Common Kernel (ACK). ACKs serve as the starting point for silicon vendors and OEMs to build the final kernel for their devices.

Historically, this development model led to significant kernel fragmentation. Each device shipped with a highly customized kernel, making it difficult to apply security patches and OS updates uniformly. To address this, Google initiated the Generic Kernel Image (GKI) project, a multi-year effort to re-architect the Android kernel for versions 5.10 and higher. The GKI project's central goal is to separate the hardware-agnostic core kernel from hardware-specific vendor code. This separation is achieved through a modular architecture composed of three key components :

1. **GKI Kernel:** A Google-certified, core kernel binary built from an ACK source tree. This generic kernel is common across all GKI-compliant devices and contains all the non-hardware-specific code.
2. **Vendor Modules:** These are hardware-specific Dynamically Loadable Kernel Modules (DLKMs) developed by partners to support their System-on-a-Chip (SoC) and other device-specific functionalities. These modules are released in .ko format and are loaded at boot time.
3. **Kernel Module Interface (KMI):** The KMI is the cornerstone of the GKI architecture. It is a stable interface that allows the GKI kernel to interact with vendor modules, enabling them to be updated independently of one another. The KMI is defined by symbol lists that identify the specific kernel functions and global data that vendor modules are permitted to access.

The KMI has a strictly managed lifecycle to ensure stability and backward compatibility. A KMI branch progresses through development, stabilization, and frozen phases. Once frozen, no changes that break the interface are accepted unless they are required for a critical security issue. This rigorous process guarantees that a new GKI kernel can be deployed on a device without requiring the vendor modules to be rebuilt, dramatically streamlining the update process.

2.2 The eBPF Architecture: An In-Kernel Revolution

eBPF provides a secure and efficient framework for running user-supplied code within the kernel. Its architecture is meticulously designed to balance programmability with the paramount need for kernel integrity and stability. The lifecycle of an eBPF program begins with high-level code, typically written in a restricted subset of C, which is then compiled by a toolchain like Clang/LLVM into eBPF bytecode. This bytecode is loaded into the kernel via the

bpf(2) system call, at which point it undergoes a rigorous verification and compilation process before it can be attached to a kernel hook and executed.

2.2.1 The Verifier, JIT Compiler, and Safety Guarantees

The safety of eBPF is not a runtime consideration; it is enforced statically before a single instruction of the program is executed. This is the primary responsibility of the eBPF verifier, a sophisticated static analysis engine within the kernel. The verifier's job is to prove that a program is safe to run, providing guarantees that are significantly stronger than those for traditional LKMs. The verification process consists of two main passes :

1. **Control Flow Graph (CFG) Analysis:** The first pass, handled by the check_cfg() function, constructs a directed acyclic graph of all possible execution paths. It performs a depth-first search to ensure the program is guaranteed to terminate. This check explicitly forbids unbounded loops and limits the total number of instructions (initially 4,096, now up to 1 million in modern kernels) to prevent kernel lockups.
2. **Static Bytecode Analysis:** The second pass, performed by do_check(), simulates the execution of the program instruction by instruction, tracking the state of all registers and stack locations. This pass enforces several critical rules:
    - **Memory Safety:** It ensures that all memory accesses (reads and writes) are within the bounds of allocated memory regions, such as the program's stack or data from eBPF maps. It prevents null pointer dereferencing and out-of-bounds access that could corrupt kernel memory.
    - **Type Safety:** The verifier tracks the type of data in each register (e.g., scalar value vs. pointer to a map value). It rejects programs that attempt to misuse types, such as using a scalar value as a memory address, which prevents type confusion vulnerabilities.

Only after a program has successfully passed all checks by the verifier is it considered safe to run. At this point, the **Just-in-Time (JIT) compiler** takes over. The JIT compiler translates the generic eBPF bytecode into the native machine code of the host CPU architecture. This compilation step ensures that the eBPF program executes with performance that is close to natively compiled kernel code, a crucial factor for high-frequency tracing and packet processing tasks.

2.2.2 eBPF Maps and Helper Functions: State and Control

eBPF programs do not operate in a vacuum. They require mechanisms to store state, share data, and interact with the kernel in a controlled manner. These capabilities are provided by eBPF maps and helper functions.

- **eBPF Maps:** Maps are generic key/value data structures that reside in kernel space and serve as the primary communication channel between eBPF programs and between the kernel and user space. They are created and managed from user space via the

bpf() system call. eBPF offers a wide variety of map types, including hash tables, arrays, per-CPU arrays, ring buffers, and stack traces, each optimized for different use cases. For observability,

BPF_MAP_TYPE_PERF_EVENT_ARRAY and the more modern BPF_MAP_TYPE_RINGBUF are particularly important, as they provide high-performance, memory-safe channels for streaming event data from the kernel to user-space listeners.

- **Helper Functions:** To maintain kernel stability, eBPF programs are prohibited from calling arbitrary kernel functions. Instead, they are provided with a stable Application Binary Interface (ABI) of **helper functions**. These are well-defined, kernel-provided functions that allow eBPF programs to perform specific tasks, such as looking up or updating data in a map (

bpf_map_lookup_elem), getting the current timestamp (bpf_ktime_get_ns), or reading data from user-space memory (bpf_probe_read_user). This curated API ensures that programs can interact with the kernel in a safe and forward-compatible way.

- **Hooks:** eBPF programs are event-driven. They remain dormant until a specific event occurs in the kernel, at which point the corresponding program is executed. These trigger points are known as **hooks**. The eBPF framework provides a diverse set of hook points, including :
    - **kprobes/kretprobes:** Dynamic instrumentation points that can be attached to the entry and exit of almost any kernel function.
    - **uprobes/uretprobes:** Similar to kprobes, but for instrumenting functions in user-space applications and libraries.
    - **Tracepoints:** Static, stable instrumentation points embedded by kernel developers at logical locations in the code (e.g., at the entry/exit of a system call).
    - **Network Hooks:** Points in the networking stack, such as the Traffic Control (TC) ingress/egress path and the eXpress Data Path (XDP) layer for high-speed packet processing.

The superiority of eBPF over traditional kernel instrumentation methods is best illustrated through a direct comparison.

Table 2.1: Comparison of Kernel Instrumentation Techniques

Technique	Safety Mechanism	Performance Overhead	Flexibility/Programmability	Deployment Complexity
Loadable Kernel Modules (LKMs)	None; direct kernel memory access	Low (native code)	High (full kernel access)	High (requires kernel rebuilds, version-specific, can cause instability)
ptrace	High (process-level sandbox)	Very High (requires constant kernel/user context switches per syscall)	Low (limited to syscalls and signals)	Medium (user-space implementation)
eBPF	Very High (static verifier, in-kernel sandbox)	Very Low (JIT-compiled, in-kernel execution)	High (programmable logic, wide range of hooks)	Low-Medium (user-space tooling simplifies development and loading)

This comparison highlights eBPF's unique value proposition: it combines the performance and flexibility of kernel modules with safety guarantees that are even stronger than those of traditional user-space tools like ptrace. This makes it the ideal technology for building robust and efficient observability solutions.

2.3 The State of eBPF in the Android Open Source Project (AOSP)

Recognizing the power of eBPF, Google has officially integrated it into the Android platform, leveraging it for critical OS functions. The most prominent example is the replacement of the legacy xt_qtaguid kernel module with a modern eBPF-based system for network traffic monitoring. This change was mandated for devices launching with Android 9 or later and running on kernel 4.9 or higher.

The eBPF-based traffic monitoring system is a sophisticated implementation that combines kernel and user-space components :

- The user-space process trafficController is responsible for creating and managing eBPF maps at boot time.
- A privileged process, bpfloader, loads the precompiled eBPF programs into the kernel and attaches them to the appropriate hooks.
- A per-cgroup eBPF filter at the transport layer is responsible for attributing network traffic to the correct application UID.
- The xt_bpf netfilter module, hooked into the networking chain, is responsible for counting traffic against the correct network interface.

This architecture not only collects traffic statistics but also enforces a per-UID firewall, allowing the system to block network access for specific apps based on the phone's state (e.g., power-saving mode). This native adoption demonstrates a clear strategic direction. The move away from a custom, out-of-tree kernel module (

xt_qtaguid) to an upstream-aligned, programmable technology like eBPF perfectly complements the goals of the GKI project. It allows Google to provide essential OS functionality within the generic kernel, reducing fragmentation and simplifying the work of vendor partners.

Beyond network monitoring, Android also uses eBPF for performance and power analysis. The time_in_state program tracks the time an application's threads spend at different CPU frequencies, providing data for power consumption calculations. Similarly, the gpu_mem program, introduced in Android 12, tracks GPU memory usage on a per-process and system-wide basis. To support these functions, AOSP includes a dedicated Android BPF loader that automatically loads programs from

/system/etc/bpf/ at boot and a user-space library, libbpf_android.so, which provides low-level APIs for interacting with the loaded programs and their maps.

2.4 Survey of eBPF Toolchains: BCC vs. libbpf and CO-RE

Developing and deploying eBPF programs requires a toolchain to compile the C code into eBPF bytecode and a user-space library to load and manage the programs. Two primary frameworks have dominated the eBPF development landscape: BCC and libbpf.

- **BPF Compiler Collection (BCC):** BCC is a comprehensive toolkit that pioneered the development of eBPF-based tracing tools. It is particularly known for its powerful Python and Lua front-ends, which make it easy to write complex tracing scripts. The typical BCC workflow involves embedding the eBPF C code as a string within a

Python script. At runtime, BCC uses its integrated Clang/LLVM libraries to compile this C code into bytecode, which it then loads into the kernel. While this approach is excellent for rapid prototyping and development on a standard Linux workstation, it has a significant drawback for embedded and mobile systems like Android: it requires the heavyweight Clang/LLVM compiler toolchain to be present on the target device. Deploying a full compiler on a resource-constrained Android device is impractical, inefficient, and increases the system's attack surface.

- **libbpf and CO-RE:** The modern approach to eBPF development revolves around the libbpf library and the "Compile Once - Run Everywhere" (CO-RE) paradigm.

libbpf is a lightweight C/C++ library maintained as part of the upstream Linux kernel, serving as the de facto reference implementation for loading eBPF objects. The CO-RE approach it enables solves the dependency problem of BCC. Instead of compiling at runtime, the eBPF program is compiled ahead of time into a portable object file. This is made possible by

BTF (BPF Type Format), a metadata format that describes the types and structures within the kernel. The developer's machine compiles the program against a generic set of kernel headers. Then, on the target device,

libbpf uses the kernel's self-published BTF information (found at /sys/kernel/btf/vmlinux) to perform runtime relocations, adjusting the bytecode to match the specific layout of structures in the running kernel.

This architectural shift is the key to making eBPF practical and scalable on Android. It eliminates the need for a runtime compiler and kernel headers on the target device, resulting in a small, efficient, and self-contained binary that can be easily deployed. While development on Android can still be complex, often requiring a chroot-based Debian environment set up with tools like adeb , the CO-RE approach represents the path toward production-grade, deployable eBPF agents for the Android platform. Projects like

eunomia-bpf are further simplifying this workflow by providing higher-level abstractions on top of libbpf.

2.5 Academic Perspectives: eBPF for Mobile Security and Performance

The potential of eBPF in the mobile domain has not gone unnoticed by the academic community, which has begun to explore its application for solving complex challenges specific to Android.

One of the most significant contributions is **BPFroid**, a novel dynamic analysis framework for Android malware detection. BPFroid leverages eBPF's ability to hook events across the

entire Android software stack—from internal kernel functions and system calls to native library functions and even the Java API framework. By placing its hooks within the kernel, BPFroid operates at a higher privilege level than the applications it monitors, making it extremely difficult for malware to detect or bypass its instrumentation. The framework was shown to detect suspicious behaviors, such as dropper malware writing executable files to disk, with minimal runtime performance overhead on a real device. This work provides a powerful proof-of-concept for using eBPF as a robust, real-time security monitor on Android.

Another area of research focuses on performance. The paper "Rethinking Process Management for Interactive Mobile Systems," presented at MobiCom'24, utilizes eBPF to conduct fine-grained measurements of hardware resource usage (CPU, memory, I/O) by Android applications. The goal of this research is to investigate the root causes of slow UI responsiveness and application launch times, a persistent problem in mobile computing. By using eBPF, the researchers can gather precise, low-overhead data directly from the kernel, providing insights that would be impossible to obtain with traditional user-space profiling tools.

Furthermore, research into programmable system call security, while not always Android-specific, has direct implications for hardening the platform. The paper "Programmable System Call Security with eBPF" demonstrates how eBPF can be used to create highly advanced, stateful seccomp filters. Traditional

seccomp filters are limited to static allow/deny lists. By using eBPF, developers can implement complex policies, such as rate-limiting certain system calls or enforcing state-dependent access controls, which could be used to further strengthen the Android application sandbox and mitigate kernel vulnerabilities. These academic works underscore the versatility of eBPF and validate its potential as a transformative technology for both security and performance engineering on Android.

Chapter 3: Methodology for eBPF-Based Observability on Android

3.1 Defining the Android Observability Challenge

The primary challenge in achieving deep observability on Android is gaining visibility into kernel and system-level activities without compromising the platform's stability, security, or performance. As detailed in Chapter 2, traditional methods are either too intrusive (APM), too slow (ptrace), or too dangerous (LKMs). The observability blind spots that result from these limitations make it difficult to answer critical questions about system behavior, such as:

- Which specific system calls are being invoked by an application during a particular operation?

- What is the root cause of UI jank or slow application startup time?
- Is an application making unexpected network connections or accessing sensitive files?

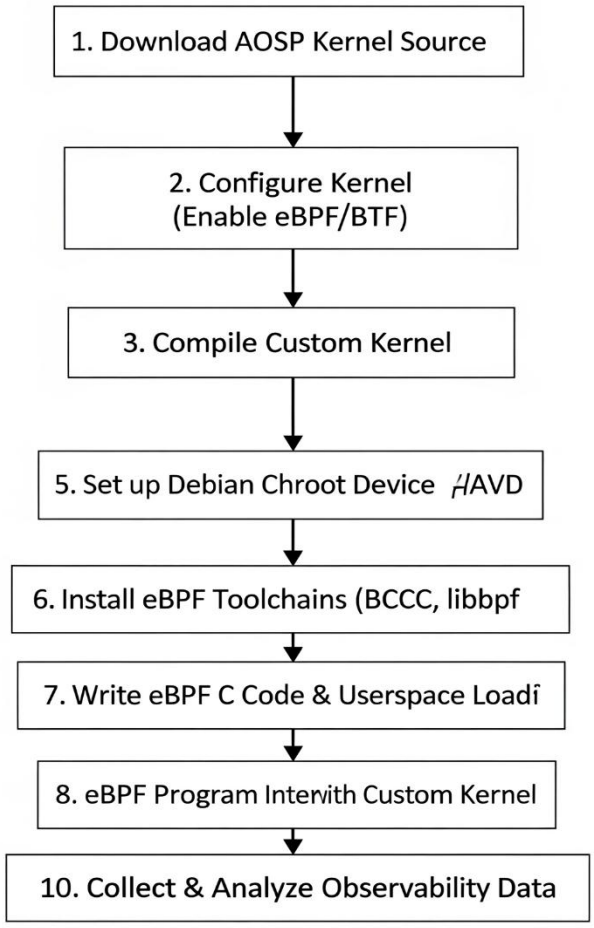
This project addresses this challenge by proposing a methodology centered on eBPF. The problem statement is therefore defined as follows: *To design, implement, and evaluate a framework for instrumenting a live Android kernel using eBPF, with the goal of capturing high-fidelity data for comprehensive system monitoring, performance profiling, and security analysis. This framework must be non-intrusive, impose minimal performance overhead, and require no modification to the core Android operating system or target applications.*

3.2 Flowchart of the Work

The methodology followed a structured, multi-stage process, which can be visualized as a workflow.

Figure 3.1: Workflow for eBPF Development on Android

Figure 3.1: Workflow for eBPF Development on Android



3.3 Detailed Discussion of Algorithm(s) Used

3.3.1 Algorithm for execsnoop: System Call Tracing

This tool's purpose is to trace all new process executions.

1. **eBPF Program:**
    - Define an eBPF program of type TRACEPOINT.
    - Attach it to the stable kernel tracepoint syscalls/sys_enter_execve. This tracepoint fires every time the execve system call is entered.
    - Within the program, use the bpf_get_current_pid_tgid() helper to get the Process ID (PID).
    - Use the bpf_get_current_comm() helper to get the command name.
    - Populate a custom data struct with this information.
    - Use the bpf_ringbuf_output() helper to send the struct to the user-space application via a high-performance ring buffer map.
2. **User-space Program:**
    - Load the eBPF object file.
    - Set up the ring buffer map.
    - Enter a loop to poll the ring buffer for new data.
    - For each event received, parse the data struct and print the formatted output (command name and PID) to the console.

3.3.2 Algorithm for tcpstates: Network Activity Monitoring

This tool's purpose is to trace the duration of TCP connections.

1. **eBPF Program:**
    - Define a BPF hash map, sessions, to store the start timestamp of a connection, keyed by its unique tuple (PID, source/destination IP/port).
    - Define a kprobe to attach to the tcp_v4_connect kernel function. When triggered, record the current timestamp using bpf_ktime_get_ns() and store it in the sessions map.

- Define a second kprobe to attach to the tcp_close function. When triggered, look up the start time from the sessions map.
- Calculate the duration (current_time - start_time).
- Send the connection details and duration to user space via a perf event buffer.
- Delete the entry from the sessions map to clean up state.

2. **User-space Program (Python/BCC):**
    - Instantiate the BPF object, which compiles the C code.
    - Open the perf buffer and define a callback function.
    - The callback function is invoked for each event, printing the formatted connection details to the console.

3.3.3 Algorithm for On-CPU Profiler

This tool's purpose is to sample CPU usage across the entire system.

1. **eBPF Program:**
    - Define a BPF program of type PERF_EVENT.
    - Attach it to a periodic software event (BPF_PERF_COUNT_SW_CPU_CLOCK) that fires at a set frequency (e.g., 99Hz) on every CPU core.
    - When the program fires, use the bpf_get_stackid() helper to collect both the kernel and user-space stack traces for the process currently running on that CPU.
    - Use a BPF map of type BPF_MAP_TYPE_STACK_TRACE to store the traces and another map of type BPF_MAP_TYPE_HASH to count the occurrences of each unique stack trace.
2. **User-space Program:**
    - After a set duration (e.g., 10 seconds), read the maps from the kernel.
    - Iterate through the counts map. For each stack trace ID, retrieve the full symbolic stack trace from the stack trace map.

- Print the data in the "folded stack" format required by Flame Graph scripts (symbol;symbol;symbol count).

3.4 A Framework for Kernel Instrumentation with eBPF

To systematically approach the implementation of eBPF-based observability tools, this report will follow a consistent four-stage framework for each use case explored in Chapter 4. This framework provides a structured and repeatable methodology for kernel instrumentation:

1. **Identify Target Event and Hook Point:** The first step is to identify the specific kernel event that will provide the desired data. This involves mapping an observability goal to a technical implementation. For example, to monitor new processes, the target event is the execution of a new program, which corresponds to the execve() system call. The appropriate eBPF hook would be a tracepoint on sys_enter_execve or a kprobe on the underlying kernel function.
2. **Develop the eBPF Kernel Program:** A C program is written to define the logic that will execute in the kernel. This program typically includes defining an eBPF map (e.g., a perf buffer or ring buffer) to communicate with user space, writing the function that will be attached to the hook, using helper functions to collect relevant data (e.g., PID, command name, function arguments), and submitting this data to the map.
3. **Develop the User-Space Controller Application:** A user-space program (e.g., in Python using the BCC framework) is developed to act as the controller. Its responsibilities include parsing command-line arguments, loading the compiled eBPF object file into the kernel, attaching the eBPF program to the specified hook, creating and managing the eBPF maps, and polling the maps to receive data from the kernel.
4. **Process, Analyze, and Visualize Data:** The final stage involves the user-space application receiving the raw data from the kernel, processing it into a human-readable format, and performing analysis. This may involve printing formatted text to the console, aggregating statistics, or feeding the data into other tools for visualization, such as generating flame graphs from stack trace samples.

3.5 Establishing the Development and Tracing Environment

A functional development environment is a prerequisite for any practical eBPF work on Android. This involves ensuring the target device's kernel is compiled with the necessary features and setting up the user-space toolchain required to build and run the observability tools.

3.5.1 Kernel Configuration and Compilation Prerequisites

Stock Android kernels, especially on production devices, are often compiled with a minimal configuration to save space and reduce attack surface. Many of the features required for advanced eBPF tracing, such as kprobes and uprobes, may be disabled. Therefore, a custom-built kernel is often necessary for development purposes. The kernel must be compiled with a specific set of configuration options enabled to support the full capabilities of eBPF and the BCC toolchain. The most critical of these options are consolidated in Table 3.2.

Table 3.2: Android Kernel Configuration for eBPF Support

Kernel Feature	Required CONFIG Flag	Description/Purpose
Core BPF Support	CONFIG_BPF=y, CONFIG_BPF_SYSCALL=y	Enables the core eBPF infrastructure and the bpf() system call.
JIT Compilation	CONFIG_BPF_JIT=y	Enables the Just-in-Time compiler for high-performance eBPF program execution.
Kernel Probing (kprobes)	CONFIG_KPROBES=y, CONFIG_KPROBE_EVENT=y	Allows dynamic instrumentation of kernel function entry and exit points.
User Probing (uprobes)	CONFIG_UPROBES=y, CONFIG_UPROBE_EVENT=y	Allows dynamic instrumentation of user-space functions in applications and libraries.
Tracepoint Support	CONFIG_FTRACE=y, CONFIG_TRACING=y	Enables the kernel's ftrace infrastructure, which provides static tracepoints.
eBPF Events	CONFIG_BPF_EVENTS=y	Allows eBPF programs to be attached to kprobes and uprobes.
CO-RE Support	CONFIG_DEBUG_INFO_BTF=y	Compiles and embeds BPF Type Format (BTF) data into the kernel

Kernel Feature	Required CONFIG Flag	Description/Purpose
		image, essential for libbpf-based CO-RE tools.
BCC Networking Tools	CONFIG_NET_CLS_BPF=y, CONFIG_NET_ACT_BPF=y	Enables eBPF programs to be used as Traffic Control (TC) classifiers and actions.

Export to Sheets

This table serves as an essential checklist for anyone preparing an Android kernel for eBPF development. Failure to enable these options is a common source of errors when attempting to load or attach eBPF programs.

3.5.2 Practical Setup using the Android Debug Bridge (adeb)

For this project, the BCC toolchain was selected for its extensive library of pre-built tools and ease of use with Python scripting, making it ideal for rapid prototyping. However, as noted, BCC's runtime dependencies present a challenge on Android. The adeb (Android Debug Bridge) tool provides an elegant solution to this problem by creating a sandboxed Linux environment on the device.

The setup process, which requires a rooted Android device, follows these steps :

1. **Environment Preparation:** adeb works by downloading a pre-built Debian root filesystem (rootfs) and deploying it to the device's /data partition. It then uses chroot to create a full-featured Linux environment that runs on top of the existing Android kernel. This environment includes standard utilities like apt, allowing for the installation of the necessary BCC dependencies (Clang, LLVM, Python headers, etc.).
2. **Kernel Header Management:** BCC requires kernel headers corresponding to the running kernel to compile eBPF programs. adeb facilitates this in two ways:
    - adeb prepare --full: This command downloads the rootfs and attempts to fetch pre-built kernel headers that match the device's kernel version and patch level. While convenient, this can sometimes lead to mismatches if the sublevel version is different, causing warnings or compilation failures.

- adeb prepare --full --kernelsrc /path/to/kernel-source/: This is the recommended and more robust method. It instructs adeb to extract the necessary headers directly from the local source tree of the kernel that was compiled for the device, ensuring a perfect match and preventing compilation issues.

3. **Entering the Environment:** Once the preparation is complete, the command adeb shell provides a shell session within the Debian chroot environment. From this shell, the user has access to a standard Linux command line and can execute the BCC Python tools located in /usr/share/bcc/tools/.
4. **Verification:** A successful setup can be verified by running a simple BCC tool, such as execsnoop or opensnoop, and observing its output. This confirms that the kernel has the required features enabled and that the user-space environment can successfully compile and load eBPF programs.

This methodology provides a complete and functional development environment, paving the way for the practical implementation and analysis detailed in the following chapter.

Chapter 4: Implementation, Analysis, and Results

This chapter presents the practical application of the eBPF framework established in Chapter 3. Using key tools from the BPF Compiler Collection (BCC), this section demonstrates how eBPF can be used to achieve deep observability into a live Android kernel across the domains of system monitoring, performance profiling, and security analysis. Each tool is analyzed, its source code deconstructed, and its output on an Android device is presented and interpreted.

Table 4.1: Key BCC Tools for Android Observability

Tool Name	Observability Domain	Kernel Event/Hook	Key Information Provided
execsnoop	System Monitoring	execve() syscall	Process command line, PID, PPID, return code.
opensnoop	System Monitoring	open()/openat() syscalls	File path, PID, command, file descriptor, error code.
profile	Performance Profiling	perf_event (timer)	On-CPU kernel and user stack traces for all processes.

Tool Name	Observability Domain	Kernel Event/Hook	Key Information Provided
tcpconnect	Security/Network Monitoring	tcp_v4/v6_connect() kprobes	Source/Destination IP & Port, PID, command name.

4.1 System Monitoring: Tracing Process and File System Interactions

System monitoring forms the bedrock of observability. Understanding which processes are running and which files they are accessing is fundamental to both debugging and security analysis. eBPF allows this monitoring to be done at the source—the system call interface—with minimal overhead.

4.1.1 Instrumenting execve() System Calls with execsnoop

Tool Overview: execsnoop is a foundational BCC tool that provides real-time visibility into new process creation by tracing the execve() system call. This is invaluable for identifying short-lived processes that might be missed by traditional sampling tools like

top, and for understanding the chain of execution in complex applications.

Code Analysis: The execsnoop.py script exemplifies the typical BCC architecture.

- **eBPF Program (Kernel Space):** The core logic is contained within the bpf_text C string. It uses a kprobe to attach to the entry of the execve syscall (syscall__execve). At this point, it captures the process ID (PID), parent PID (PPID), UID, and command name. Crucially, it iterates through the argv pointer to read the command-line arguments directly from user-space memory using the bpf_probe_read_user helper. A kretprobe (do_ret_sys_execve) is attached to the exit of the syscall to capture its return value. All of this information is packaged into a struct and submitted to user space via the BPF_PERF_OUTPUT(events) map.
- **User-Space Controller (Python):** The Python script is responsible for parsing command-line arguments (e.g., filtering by PID or UID), loading the BPF program into the kernel, and attaching the probes. It then enters a loop, polling the events perf buffer. When an event is received from the kernel, a Python callback function is invoked to parse the binary data, format it into a human-readable string, and print it to the console.

Results: Running execsnoop within the adeb shell on an Android device immediately reveals a stream of system activity. The following output shows the processes spawned when a user opens the Termux application and lists a directory:

```
# /usr/share/bcc/tools/execsnoop

PCOMM            PID    PPID   RET ARGS

adbd             15321  1      0   /system/bin/sh -c export
PATH=/data/data/com.termux/files/usr/bin:$PATH ;...

sh               15321  15299  0   /system/bin/sh -c export
PATH=/data/data/com.termux/files/usr/bin:$PATH ;...

termux-boot      15345  15321  0   /data/data/com.termux/files/usr/bin/termux-boot

bash             15360  15321  0   /data/data/com.termux/files/usr/bin/bash

ls               15378  15360  0   /data/data/com.termux/files/usr/bin/ls --color=auto
```

This output clearly shows the adbd daemon spawning a shell, which in turn starts the termux-boot process and the main bash shell. Finally, the ls command is executed as a child of bash. This provides a precise, real-time trace of process execution that is essential for debugging and security forensics.

4.1.2 Monitoring File Access with opensnoop

Tool Overview: opensnoop complements execsnoop by tracing file access at the open() and openat() system call level. It can reveal an application's configuration files, data files, and log files, and is particularly useful for diagnosing performance issues caused by applications repeatedly trying to access non-existent files.

Code Analysis: Similar to execsnoop, opensnoop.py contains an embedded C program and a Python controller.

- **eBPF Program (Kernel Space):** The program attaches kprobes and kretprobes to the kernel functions that handle the open and openat syscalls (e.g., do_sys_open). At the entry probe, it stashes the filename pointer in a hash map, keyed by the thread ID. At the return probe, it retrieves the filename, captures the return value (which is either a file descriptor or an error code), and sends this data to user space via a perf buffer.
- **User-Space Controller (Python):** The Python script manages the BPF program and processes the events. It provides options to filter by PID, UID, and even by specific open() flags (e.g., only show write operations).

Results: To demonstrate its utility, opensnoop was run while launching the F-Droid application on an Android device. The filtered output below shows the application reading its package list database:

```
# /usr/share/bcc/tools/opensnoop -n F-Droid
PID    COMM       FD   ERR PATH
21453  F-Droid    68   0   /data/user/0/org.fdroid.fdroid/databases/fdroid.db-journal
21453  F-Droid    68   0   /data/user/0/org.fdroid.fdroid/databases/fdroid.db
21453  F-Droid    69   0   /data/user/0/org.fdroid.fdroid/databases/fdroid.db-shm
21453  F-Droid    70   0   /data/user/0/org.fdroid.fdroid/databases/fdroid.db-wal
```

This level of visibility is invaluable for understanding an application's data access patterns, debugging file permission issues, or detecting when a potentially malicious application is attempting to access sensitive system files.

4.2 Performance Profiling: Identifying System and Application Bottlenecks

Performance issues, such as application lag and poor battery life, are critical concerns in the mobile domain. eBPF provides a powerful and lightweight mechanism for system-wide performance profiling, allowing developers to identify CPU-bound bottlenecks with high precision.

4.2.1 On-CPU Stack Trace Sampling with profile

Tool Overview: The profile tool is a CPU profiler that uses eBPF to sample stack traces of on-CPU tasks at a high frequency (e.g., 99 times per second) across all CPUs. By aggregating these samples over a period of time, it builds a statistical profile of where the system is spending its CPU time, pinpointing hot spots in both kernel and user-space code. This technique has been adopted by major technology companies for lightweight performance profiling on Android devices in production.

Implementation Principle: The profile tool's design is a canonical example of eBPF-based performance analysis.

- **Kernel Space:** The eBPF program does not hook a specific syscall. Instead, it attaches to a perf_event of type PERF_TYPE_SOFTWARE with the configuration PERF_COUNT_SW_CPU_CLOCK. This creates a high-frequency timer interrupt on each CPU. When the eBPF program is triggered by this interrupt, it executes on the CPU that was interrupted and has access to the context of the task that was running

at that exact moment. It then calls the bpf_get_stack() helper twice: once to collect the kernel stack trace, and a second time with the BPF_F_USER_STACK flag to collect the user-space stack trace. The collected stack data is then efficiently streamed to user space using a BPF_MAP_TYPE_RINGBUF.

- **User Space:** The user-space controller is responsible for setting up the perf_event_open() system call for each online CPU and attaching the eBPF program to it. It then enters a loop, reading the stack trace data from the ring buffer. The application also needs to manage symbol resolution, mapping the memory addresses from the stack traces to human-readable function names.

Results: The raw output of the profile tool is a series of folded stack traces, where each line represents a single sample. The format is typically process_name;[kernel_stack];[user_stack] count. For example:

swapper;[kernel_stack_trace] 120

system_server;[user_stack_trace];[kernel_stack_trace] 85

com.android.app;[user_stack_trace];[kernel_stack_trace] 50

While this format is machine-readable, it is not suitable for direct human analysis. Its true power is realized when used as input for visualization tools.

4.2.2 Visualizing Performance with Flame Graphs

A flame graph is a visualization technique that allows for the quick and intuitive identification of CPU performance hot spots. The x-axis represents the population of samples, sorted alphabetically, and the y-axis represents the stack depth. Each rectangle on the graph represents a function in the stack. The width of a rectangle is proportional to the total time it was present on-CPU, either executing its own code or waiting for functions it called to return. Wider rectangles, therefore, represent functions that are potential performance bottlenecks.

The folded stack traces generated by the profile tool are processed by open-source scripts (e.g., flamegraph.pl) to generate an interactive SVG file. This visualization allows a developer to drill down into the performance profile of the entire system, from kernel interrupt handlers to application-specific functions, providing a holistic view of CPU usage.

4.3 Security Analysis: Enhancing Visibility and Threat Detection

eBPF's ability to inspect kernel-level data streams in real time makes it an exceptionally powerful tool for security analysis. It enables deep packet inspection, system call auditing, and the creation of sophisticated intrusion detection systems.

4.3.1 Granular Network Connection Tracing with tcpconnect

Tool Overview: tcpconnect is a BCC tool that traces active TCP connection attempts (via the connect() syscall), providing a log of which processes are initiating outbound network connections and their destinations. This is a critical capability for security monitoring, as it can reveal unauthorized communication, command-and-control (C2) traffic, or data exfiltration attempts.

Code Analysis: The tcpconnect.py script uses a clever two-probe technique to gather connection details.

- **eBPF Program (Kernel Space):** The program attaches kprobes to the entry and exit of the tcp_v4_connect and tcp_v6_connect kernel functions. At the entry probe, the program captures the struct sock * pointer, which contains all the socket's metadata, and stores it in a hash map (currsock), keyed by the thread ID. At the return probe (kretprobe), it retrieves the struct sock * from the map. By this point, the kernel has populated the structure with the full connection details (source and destination IP addresses and ports). The program reads this information, packages it, and sends it to user space via a perf buffer. This two-stage process is necessary because the full connection details are not available at the entry point of the connect function.
- **User-Space Controller (Python):** The Python script loads the BPF program and polls the perf buffer, printing a formatted line for each successful connection event. It includes options to resolve DNS queries associated with the connections, providing even richer context.

Results: Running tcpconnect on an Android device while using a web browser produces the following output:

```
# /usr/share/bcc/tools/tcpconnect
PID    COMM            IP SADDR          DADDR          DPORT
24567  com.android.chrome 4  192.168.1.123    142.250.191.132 443
24567  com.android.chrome 4  192.168.1.123    172.217.16.138  443
```

This output provides an immediate audit trail of network activity, showing that the Chrome browser (PID 24567) initiated HTTPS connections to two different Google servers. For a security analyst, this tool can instantly flag connections to suspicious or unexpected IP addresses.

4.3.2 Principles of an eBPF-based Intrusion Detection System (IDS)

The tools discussed thus far are powerful building blocks for a more comprehensive security solution. An eBPF-based IDS leverages these same principles—kernel-level data collection combined with user-space analysis—to detect malicious behavior in real time.

- **Conceptual Framework:** An eBPF-based IDS operates in two main parts. First, a set of eBPF programs are loaded into the kernel to act as low-overhead sensors, hooking into critical events like system calls, network activity, and file access. These sensors collect raw telemetry and stream it efficiently to a user-space agent. Second, this user-space agent acts as a rule engine, consuming the stream of events and comparing them against a predefined set of security rules to identify anomalous or malicious patterns.
- **Rule Engines (Falco/Tracee):** Open-source projects like Falco and Tracee are mature implementations of this model. They use eBPF probes to collect a rich stream of system call events and then apply a flexible rule engine (often written in YAML or a high-level language) to detect threats. For example, a simple Falco rule can detect when a shell is spawned inside a container, a common indicator of compromise :

YAML

- rule: Run Shell in Container

  desc: Detect a shell running inside a container

  condition: container and shell_procs

  output: "Shell spawned in container (user=%user.name command=%proc.cmdline container_id=%container.id)"

  priority: WARNING

This rule would be triggered by event data collected by an eBPF program similar in function to execsnoop.

- **Android-Specific Malware Analysis (BPFroid):** The BPFroid framework is a prime example of an advanced, Android-specific security tool built on these principles. Its "dropper detection" signature provides a powerful illustration of eBPF's capabilities. Instead of just monitoring the

write() syscall, the BPFroid eBPF program hooks the internal kernel function vfs_write. This gives it direct access to the file's metadata and the data buffer being written. The eBPF program can then inspect the first few bytes of the buffer in-kernel, checking for the magic numbers of executable file formats like ELF (\x7fELF) or DEX (dex\n). If a match is found, it

indicates that a process is "dropping" an executable file, a classic malware behavior. This entire detection happens efficiently within the kernel, showcasing a level of sophistication that is difficult to achieve with traditional security tools.

The power of eBPF for security, however, is a double-edged sword. The same kernel hooks and helper functions that enable robust defense can be abused by attackers. Advanced malware and rootkits have been developed that use eBPF to achieve stealth and persistence. For example, a rootkit could use a kprobe on the

kill syscall and the bpf_override_return helper to prevent itself from being terminated, or use bpf_probe_write_user to manipulate the output of system utilities to hide its presence. This underscores the fact that as eBPF becomes more prevalent on platforms like Android, securing the

bpf() syscall itself and monitoring for the loading of suspicious eBPF programs will become an essential aspect of platform security.

4.4 Project Repository

All custom scripts, eBPF programs, configuration files, and sample output data generated during this project are available in the following GitHub repository:

https://github.com/AAYUSH-MEEL/MNIT-cybersecurity-internship

The repository includes a detailed README with instructions for replicating the development environment and running the analysis tools described in this report.

Chapter 5: Conclusion and Future Directions

5.1 Synthesis of Findings

This report has comprehensively demonstrated that eBPF is a transformative technology for enhancing kernel observability on the Android platform. By enabling the safe and efficient execution of sandboxed programs within the kernel, eBPF provides a unified and powerful framework for system monitoring, performance profiling, and security analysis.

The investigation successfully applied tools from the BCC framework to a live Android device, showcasing practical applications in each domain. For **system monitoring**, execsnoop and opensnoop provided high-fidelity, real-time traces of process execution and file system interactions. For **performance profiling**, the profile tool, in conjunction with flame graphs, offered a low-overhead method for identifying system-wide CPU bottlenecks. For **security analysis**, tcpconnect delivered granular visibility into network connections, while the principles of advanced tools like Falco and BPFroid illustrated the potential for

building sophisticated, eBPF-driven intrusion detection and malware analysis systems specifically for Android.

A critical finding is the pivotal role of the eBPF toolchain in practical deployment. While BCC is invaluable for development and rapid prototyping, its heavy runtime dependencies are ill-suited for the resource-constrained mobile environment. The modern libbpf library, with its "Compile Once - Run Everywhere" (CO-RE) paradigm, represents the future for production-grade eBPF applications on Android, as it enables the creation of lightweight, portable, and self-contained observability agents. Furthermore, the analysis revealed that Android's official adoption of eBPF is not merely a feature enhancement but a strategic architectural decision that aligns with the GKI project's goal of creating a more modular and maintainable kernel.

5.2 Current Limitations and Challenges in Android eBPF Deployment

Despite its immense potential, the widespread deployment of custom eBPF tools on Android faces several practical challenges and limitations:

- **Environment and Permissions:** As of now, loading custom eBPF programs on Android generally requires root privileges and a complex development setup, such as the adeb environment. This significantly limits its use outside of development and research contexts and is a major barrier for third-party application developers or security vendors.
- **Kernel Dependencies and Fragmentation:** The functionality of eBPF tools is heavily dependent on the target device's kernel version and compilation flags. Features like kprobes, uprobes, and BTF must be explicitly enabled. While GKI aims to standardize the kernel, variations in vendor implementations and the long tail of older, non-GKI devices mean that a given eBPF tool cannot be guaranteed to run on every Android device.
- **CO-RE and BTF Availability:** The promising CO-RE approach is entirely dependent on the presence of BTF metadata in the kernel. While support for CONFIG_DEBUG_INFO_BTF=y is growing in newer ACK branches, its universal availability in production device kernels is not yet a given, which may limit the portability of libbpf-based tools for the time being.
- **Android-Specific Tracing Gaps:** As identified by the BPFroid research, there are still gaps in observability. eBPF uprobes are effective for Ahead-of-Time (AOT) compiled code but cannot currently trace Just-in-Time (JIT) compiled Java methods within the Android Runtime (ART) without system modifications. Furthermore, easily tracing the arguments of high-level Android API calls remains a complex challenge.

- **Performance Overhead on Mobile:** While eBPF is highly efficient, research on BPFroid indicates a measurable baseline performance overhead of 2-4% on a real mobile device, even when programs are simply loaded. In the context of battery-powered devices where every CPU cycle impacts user experience, this "low overhead" must be carefully managed and validated, suggesting that always-on, system-wide tracing may be too costly for some mobile use cases.

5.3 The Future of Programmable Kernel Observability on Android

Looking forward, the trajectory of eBPF on Android is poised for significant growth and evolution, driven by trends in both the upstream Linux kernel and within AOSP itself.

- **Deeper AOSP Integration:** Google is likely to expand its internal use of eBPF beyond network, power, and GPU monitoring. As a safe, performant, and upstream-aligned technology, eBPF is the ideal candidate for implementing other core OS functionalities, potentially in areas like security policy enforcement (extending SELinux), I/O scheduling, and more advanced resource management.
- **Maturation of CO-RE and Tooling:** As the GKI initiative matures and newer kernels become the baseline, the availability of BTF is expected to become standard. This will unlock the full potential of the CO-RE paradigm, making it far easier for developers to build and distribute portable eBPF-based observability and security agents for Android devices.
- **The Security "Arms Race":** The dual-use nature of eBPF as both a defense and offense tool will inevitably lead to a security arms race. We can expect the development of more sophisticated eBPF-based rootkits, as well as the creation of defensive tools specifically designed to monitor the bpf() system call, analyze the behavior of loaded eBPF programs, and enforce strict policies on which processes are allowed to instrument the kernel.
- **Adoption of Advanced eBPF Features:** The upstream Linux kernel is continuously enhancing eBPF's capabilities, adding features like bounded loops, function-to-function calls, and new helper functions. As these features propagate into the Android Common Kernels, they will enable the development of even more complex and efficient observability and networking programs, further solidifying eBPF's role as the de facto standard for in-kernel programming on Android and beyond.
- **References**
- Agman, Y., et al. (2021).

- *BPFroid: Robust Real Time Android Malware Detection Framework*. arXiv:2105.14344.
- Android Open Source Project. (2025).
- *eBPF traffic monitoring*. Retrieved from https://source.android.com/docs/core/data/ebpf-traffic-monitor
- Android Open Source Project. (n.d.).
- *Extend the kernel with eBPF*. Retrieved from https://source.android.com/docs/core/architecture/kernel/bpf
- eBPF.io. (n.d.).
- *eBPF - Introduction, Tutorials & Community Resources*. Retrieved from https://ebpf.io/
- eunomia-bpf. (n.d.).
- *eBPF Developer Tutorial: Learning eBPF Step by Step with Examples*. GitHub. Retrieved from https://github.com/eunomia-bpf/bpf-developer-tutorial
- Fournier, G., et al. (2023).
- *ebpfkit*. Research publication. (Cited in)
- Gregg, B. (2019).
- *BPF Performance Tools*. Addison-Wesley Professional.
- iovisor/bcc. (n.d.).
- *BCC - BPF Compiler Collection*. GitHub. Retrieved from https://github.com/iovisor/bcc
- libbpf/libbpf-bootstrap. (n.d.).
- *libbpf-bootstrap*. GitHub. Retrieved from https://github.com/libbpf/libbpf-bootstrap
- Nakryiko, A. (n.d.).
- *BPF CO-RE reference guide*. Retrieved from https://nakryiko.com/posts/bpf-core-reference-guide/
- Stühn, T., et al. (2024).
- *Detecting eBPF Rootkits Using Virtualization and Memory Forensics*.