Platform-Centric Android Monitoring—Modular and Efficient

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Abstract

We present an add-on for the Android platform, capable of intercepting nearly all interactions between apps or apps with the platform, including arguments of method invocations in a human-readable format. A preliminary performance evaluation shows that the performance penalty of our solution is roughly comparable with similar tools in that area. The advantage of our solution, however, is that it is truly modular in the sense that we do not actually modify the Android platform itself, and can include it even with an already running system. Possible uses of such an add-on are manifold; we discuss one from the area of runtime verification that aims at improving system security.

1 Introduction

In a nutshell, monitoring a system means gaining state information while it executes, for example, for the purpose of profiling (cf. [14]) or security hardening (cf. [5, 13, 1]), the latter being also our motivation although our technical contribution is entirely application-agnostic. For Android, efficient monitoring relies on having access to low-level (and under normal circumstances inaccessible) system events, such as Linux system calls, for example, that are generated by the running apps. Existing monitoring approaches are roughly distinguishable as being either app- or platform-centric: while the former basically rewrite and repackage apps under scrutiny in order to intercept the relevant events and app interactions, the latter are usually known to rely on modifications to some key system components of the Android platform, such as its API, virtual machine (Dalvik VM), the various system services, C/C++ libraries, the OS kernel, and whatever else is needed for an application at hand. In this paper, we present a monitoring add-on for Android, which is platform-centric, yet does not require such comprehensive system modifications.

As app-centric monitoring does not even require root access to the Android platform, it, arguably, has an edge over the platform-centric approaches described in the literature, as far as usability goes. For example, AppGuard [1], which manages the modification and repackaging process of untrusted apps entirely on a user’s “off the shelf” phone has been downloaded more than one million times, hinting at the fact that it is not just used by a select group of domain experts—on the contrary [1]. However, the ease in usability comes at the expense of some inherent vulnerabilities, namely that the added security controls and event interception code are actually being executed within the very same (Java) app they are meant to keep an eye on. AppGuard redirects method calls in the Java layer by altering method references in the Dalvik VM, but cannot take note of system calls that are happening deeper down the stack. Aurasium [13], another app-centric monitoring tool, works by redirecting low-level function pointers away from an app’s dynamically linked Bionic C library to a security monitor, which only gives users the desired security benefits if the modified app does not provide its own C library—for whatever reason. Besides, decompiling and changing third-party apps usually violates the licence agreement and destroys their original signatures and therefore the ability to automatically update in the future. However, AppGuard solves this particular problem by also taking control over updates for the “patched” apps.

The platform-centric approaches described in the literature (cf. [5, 8, 3, 10, 11]) generally tie deeper into the platform, and so they need to find ways to cope with the extensive market fragmentation surrounding the Android platform (cf. [9]); that is, they have to make sure that their changes are ported to various versions of the OS as well as to different hardware platforms, some of which do not lend themselves well to running custom-built Android versions, due to closed-source device drivers, for example. TaintDroid [8] is a pioneering platform-centric tool for taint flow analysis, which requires modifica-
trons beginning from the OS kernel all the way up to the Dalvik VM. Although it is being actively ported to newer versions of Android since its inception, users of vendor-specific Android releases may find it difficult to use, unless they are sufficiently experienced to not only compile their own version of Android, including the TaintDroid changes, but also to make it work on a hardware platform of their choice. On the other hand, these deep ties into the platform enable analyses that go beyond what is possible with app-centric tools, since information can be tracked down to the OS kernel level as is needed for taint flow analysis.

Our approach, conceptually, is a combination of the advantages of app- and platform-centric monitoring: that is, to offer a software add-on that can be loaded even into a currently running Android system, yet is able to trace app interactions all the way down to the OS kernel level. Technically, this functionality is mostly provided by an OS kernel module, which uses Linux’ own kernel debugging facility (called kprobes) to intercept system calls (see also §3). As such, our approach is strictly platform-centric and does not just apply to specifically prepared apps, but everything that is executed on the system. In fact, we are able to intercept Android’s own inter process communication (IPC) mechanism called Binder and can therefore gather information on almost all possible interactions between apps and the Android platform or via the platform. However, as platform-centric approach, we too require root privileges, if only to load the module. This may seem restrictive, but one should keep in mind that it has become somewhat common practice to obtain root privileges on unlocked devices in order to use custom ROMs like CyanogenMod etc., to check if an app eventually reads from (or writes to) a file on the SD card, we break into the system call `sys_open()` and check if its argument, filename, which always holds the full path of a file to open, contains the sub-string “sdcard”. Similarly, we can track down every internet connection established by an app, independent of the API version in use, by checking in `sys_connect()` if the socket address family is of type AF_INET (resp. AF_INET6), and so forth.

Alternatively, we could have placed hooks directly into the high-level service handlers or the various system services of the platform, like [8, 3, 10, 11] do, in order to be notified when relevant events take place. Although this is possible and sometimes unavoidable, as in the case of TaintDroid, since taint flow analysis requires seamless tracking of control and data flows, this has the disadvantage that such hooks are specific to particular platform releases and, generally, not portable. Besides, the functionality provided by our kernel module can be entirely switched on or off without rebooting or modifying the system.

Binder Interception Binder is Android’s main communication infrastructure between apps and system services and it implements the popular remote method invocation (RMI) scheme. Essentially it lets an object running in one Dalvik VM invoke methods on an object running in another Dalvik VM. This communication is exemplified in Fig. 1. It shows an app that attempts to send an SMS by using methods provided by the class SmsManager. This class, however, is more of an interface rather than the actual implementation of the service which does the sending. What is actually happening is that the SmsManager invokes a so called proxy which compactly encodes arguments and data types of SmsManager::sendTextMessage(), for efficient transmission via the Binder kernel driver. The class android.os.Parcel is the corresponding container for this data, also providing the required encoding and decoding methods. The parcel is then received by com.android.internal.telephony.ISms.Stub, which is the counterpart of the proxy and which takes care of the de-

2 How It All Works

In a nutshell, our add-on implements two different but complementary means of event monitoring: firstly, it directly intercepts relevant Linux system calls and secondly, it intercepts IPC calls via Android’s internal communication infrastructure called Binder (see below).

System Call Interception Normally, Android apps, which are executed on a Java virtual machine and without root privileges, do not directly trigger system calls. Instead they request via a Java API that some service be used, or some resource be allocated. These high-level requests eventually translate into a sequence of system calls that ultimately make the kernel open a file, send something to a (virtual) device, etc. Our kernel module contains handler methods that get invoked by small bits of code (so called probes) that are dynamically inserted by kprobes at almost arbitrary kernel addresses, corresponding to the respective system calls. For example, to check if an app eventually reads from (or writes to) a file on the SD card, we break into the system call `sys_open()` and check if its argument, filename, which always holds the full path of a file to open, contains the sub-string “sdcard”. Similarly, we can track down every internet connection established by an app, independent of the API version in use, by checking in `sys_connect()` if the socket address family is of type AF_INET (resp. AF_INET6), and so forth.

In the remainder, we will shed some light on Droid-Tracer’s internals ([2], how it may be put to good use ([3], and discuss its performance overhead ([4]. Some conclusions are given in [5].

1 https://www.kernel.org/doc/Documentation/kprobes.txt
2 http://developer.android.com/reference/android/os/Binder.html
3 http://www.cyanogenmod.org

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coding. The stub, in turn, invokes IccSmsInterfaceManagerProxy::sendText() with the arguments originally intended for sendTextMessage() to tell the GSM driver (not depicted) to do the physical transmission of said message.

The communication with Binder basically follows a stringent communication protocol between sender and target. By hooking into the function binder_thread_write() of its kernel driver, we are able to tell when a new communication session commences; that is, when a sender has triggered the transmission of the BC_TRANSACTION signal. Specifically, this signal (defined inside binder.h along with other protocol signals) indicates that the custom C structure, binder_transaction_data (also defined inside binder.h), has been initialized at a set address in memory. It contains, amongst others, information on the sender, method arguments, and the method name—although compactly and not human-readable encoded (see paragraph on data extraction below). We read this information from the structure before the kernel copies it into the address space of the target process.

Naturally, one can also intercept system events and messages later in the control flow; for example, when the IccSmsInterfaceManagerProxy communicates with the kernel driver of the radio device. At this late stage, however, one would lose the information about the original sender app of an SMS, since its Linux User ID (UID), which uniquely identifies an app on the Android platform, is not passed to the kernel. In other words, we would see that an SMS is being sent, but not by whom. As system services check the permission of the client based on its UID, Android uses Binder to communicate said UID directly to the service (by writing the field sender_euid inside binder_transaction_data). Via this indirect, it is not possible for a rogue process to directly query a service, using a fake UID, for example. These observations suggest to us that there are no real alternatives to intercepting system events and communication at the level of Binder, if one is interested not only in the occurrence of certain events, but also in the associated metadata.

Data Extraction Our interception of Binder lets us monitor every API method invocation, but name, types and data of arguments as well as caller and callee are either dropped or compactly encoded (i.e., marshalled) in terms of abstract IDs for efficiency reasons. Therefore, we also need to concern ourselves with unmarshalling the data once intercepted; that is, determine which process/app tries to send an SMS, what its content is, who the recipient is, etc.

To that end, we have realised DroidTracerService (see right upper corner of Fig. 1), a user space app without its own GUI. It serves mainly two purposes: On the one hand, it acts as an interface between the kernel module and Android’s “unmarshalling algorithms, on the other hand, it is able to pass the intercepted system events on to
a client app (cf. [3] for an example). As such it is similar to a classical system library, which provides an API for third-party apps to use rather than a dedicated GUI.

Unmarshalling Binder communication, however, is not something that is typically done by apps. In fact, there is no public API for this task nor any complete documentation on the marshalling algorithms that would allow users to devise their own implementations easily. Hence, we reverse engineered this whole process to some extent, to be able to use the official unmarshalling methods of Android’s android.os.Parcel. This has the advantage that our solution ends up using the same methods that are being used by the Binder communication anyways, and is therefore not specific to particular versions of the Android OS.

We discovered that android.os.Parcel provides a method to fill its internal data structure from a byte array. Thus, we can create a Parcel object directly from the intercepted field buffer inside binder_transaction_data, to apply the Android specific unmarshalling methods to it, namely, readString(), readInt(), readFloat(), etc. However, we cannot access arguments easily, as a Parcel object for efficiency is missing the information about the order in which they appear; that is, we have to invoke the unmarshalling methods in the right order to read the encoded arguments from it correctly. In the official unmarshalling process, the stub knows how its proxy has encoded the arguments using the counterpart methods writeString(), writeInt(), writeFloat(), etc. By examining several proxy classes, we then observed they usually marshall the method arguments in the same order they appear in the corresponding method’s signature. We can access the signature and with it the ordering and the types of the arguments via reflection, but only under the prerequisite of having the called interface and method name revealed and at hand first. For our example in Fig. 1 this information is com.android.internal.telephony.ISms and sendText(). We found out that the interface name is always encoded first (before the method arguments) in a Parcel object; this is, for the stub to read and ensure that the proxy called its correct counterpart. We can access it by applying writeString(). In terms of decoding the called method name, binder_transaction_data leaves us with an integer, called code. A closer look at several stub classes reveals that the mapping of code to its according method name is, in fact, defined there. For example, in com.android.internal.telephony.ISms.Stub the method sendText(), is encoded in terms of a variable static final int TRANSACTION_sendText = 5. If the according proxy class sends this code through Binder, the stub uses it to first trigger the correct unmarshalling and second, the execution of sendText(). As the suffix of TRANSACTION_sendText equals the method name, we are able to use reflection to extract it.

Marshalling methods exist only for Java primitives, and some other types, such as Binder references, primitive arrays, etc. But more complex objects can be sent through Binder, too; that is, if they implement the method createFromParcel() of the interface Parcelable to define how they can be encoded using Parcel’s standard marshalling methods. We can invoke createFromParcel() via reflection in most cases, and are thus able to cover most argument types appearing in method calls. This is crucial, as once we miss unmarshalling one argument for a method call, we cannot access remaining arguments in the rest of Parcel object’s byte array.

Kernel/User-Space Communication As event interception takes place solely inside the kernel space and unmarshalling relies on Android’s Java API, we need a mechanism that allows us to pass data from inside the kernel space up to an app. Moreover, we need some means to let the user control the kernel module for even the most basic tasks, for example, to switch event interception on or off from an app. However, Android has no built-in way to serve as a solution, but we were able to use netlink[5] which is a socket based mechanism of the Linux kernel that can bidirectionally communicate with user space. We placed the implementation of the communication endpoints into our kernel module and into our app, and thus, leave the Android framework as such completely unmodified. As the Android API does not offer netlink support, we had to build a custom netlink endpoint for our app, using the Netlink Protocol Library Suite (libnl[4]). It runs as a shared C++-library, droidtracer.so (see Fig. 1), in the same process as our app. We had to extract the core functionality for netlink from libnl and recompile it for Android devices using Android’s Native Developer Kit (NDK). Netlink allows to declare a callback method to receive kernel data, so that droidtracer.so does not have to poll our kernel module for events. As the ultimate goal is to transmit them all the way to DroidTracerService we use reflection and Java Native Interface (JNI) to register a method in Java that is automatically triggered if we forward data received from netlink to it.

3 Use Cases—Runtime Verification

As already pointed out in [3] there is a myriad of reasons why users may want to closely monitor their mobile devices. Although our add-on is application-agnostic, our motivation is to bring techniques developed in the area of runtime verification (cf. [4, 2]) closer to Android. In

4http://www.linuxfoundation.org/collaborate/workgroups/networking/generic_netlink_howto
5http://www.carisma.slowglass.com/tgp/libnl/
a nutshell, runtime verification subsumes tools and techniques that aim at checking that a system’s actual behaviour agrees to a (formal) specification of pre-defined behaviour. For example, one could specify that “no installed app should ever send an SMS to a phone number, which is not stored in the user’s contacts list,” using a dedicated temporal logic, for example. Arguably, a major focus in runtime verification research right now is to be able to monitor not just reactive, but also data-intensive systems, where one not only needs to know that a message was sent, but also by who and to whom (cf. keynote speech “Runtime Verification with Data” by M. Leucker at the Runtime Verification conference 2013, Rennes, France). Temporal logics and regular expressions, traditionally used in that domain are typically not sufficient to express such parameterised behavioural policies, and if they are (cf. [4]), there is usually no tool support for the domain that concerns us.

A recent paper [2], introduces a general purpose monitoring algorithm for a parameterised logic, which we have implemented as a client that directly utilises the API of the DroidTracer add-on. The above policy can be formalised in this logic and be applied to any app installed on the phone. To that end, our client provides a graphical front-end that lists all the installed apps of a device and users can choose which ones are being monitored simply by clicking on its name in a list.

Although our approach is platform-centric, we give users the possibility to exempt certain apps from being monitored, mainly for two reasons: firstly, to avoid false negatives in case certain apps are more trustworthy than others, and secondly, for performance reasons, since our runtime verification client, internally, instantiates one runtime verification monitor per app and policy [6]. Therefore, the fewer apps are being monitored, the less overhead and disruption for the rest of the system.

Note that, in an abstract sense, the aforementioned tools such as AppGuard are also runtime verification tools. However, rather than employing tools and techniques developed in the area of runtime verification directly, they use alternative means to define security policies (in case of AppGuard, for example, security automata that have been introduced by Schneider [12]). Also, off the shelf security automata are not suitable as a fully declarative policy specification language over potentially infinite data domains (e.g., set of all IPs, email addresses, etc.).

4 Performance Overhead

When our add-on is being executed with our runtime verification client on, the average performance overhead is 38.6%. This was determined on a Nexus 7 (1st generation) tablet with a quad-core CPU and 1 GB RAM running Android OS 4.3. We used seven test apps, specifically written for our purpose, i.e., each of the apps was designed to generate 100 runs of up to 10,000 events of the following sorts: 1. access the device ID (IMEI), 2. read the SIM card serial number, 3. request location, 4. send SMS, 5. look up list of installed apps, 6. access connection status about all network types, and 7. read file from SD card. Besides monitoring the policy introduced in [4] namely that no app shall send a text message to a number not recorded in the user’s contacts list, we have instantiated the policies used in [2] to cover a somewhat broader range of possible applications. However, as the results of these test runs are specific only to our implementation of runtime verification, we also need to measure the performance overhead of our “bare bones” add-on when no further analysis is undertaken. Table 1 shows the execution time when intercepting the API method calls of the above eight events in three different modes of operation: First, we ran the test apps without our add-on enabled to get a reference execution time for the unmodified system. Second, we enabled only the event interception part of our add-on but no further analysis is undertaken. Table 1 shows the execution time when intercepting the API method calls of the above eight events in three different modes of operation: First, we ran the test apps without our add-on enabled to get a reference execution time for the unmodified system. Second, we enabled only the event interception part of our add-on but no further analysis is undertaken. Table 1 shows the execution time when intercepting the API method calls of the above eight events in three different modes of operation: First, we ran the test apps without our add-on enabled to get a reference execution time for the unmodified system. Second, we enabled only the event interception part of our add-on but no further analysis is undertaken. Table 1 shows the execution time when intercepting the API method calls of the above eight events in three different modes of operation: First, we ran the test apps without our add-on enabled to get a reference execution time for the unmodified system. Second, we enabled only the event interception part of our add-on but no further analysis is undertaken. Table 1 shows the execution time when intercepting the API method calls of the above eight events in three different modes of operation: First, we ran the test apps without our add-on enabled to get a reference execution time for the unmodified system. Second, we enabled only the event interception part of our add-on but no further analysis is undertaken. Table 1 shows the execution time when intercepting the API method calls of the above eight events in three different modes of operation: First, we ran the test apps without our add-on enabled to get a reference execution time for the unmodified system. Second, we enabled only the event interception part of our add-on but no further analysis is undertaken.
Table 1: Execution of Android API method calls (each up to 10,000 times) with and without DroidTracer. The margin of error is given for the 95% confidence interval.

| Interface                  | Method                  | Android (in ms) | Kprobes (in ms) | Add-on (in ms) | Kprobes (Overhead in %) | Add-on (Overhead in %) |
|----------------------------|-------------------------|-----------------|-----------------|----------------|-------------------------|-------------------------|
| TelephonyManager           | getDeviceId             | 5309 ± 15       | 5517 ± 18       | 5811 ± 11      | 3.92                    | 9.46                    |
| TelephonyManager           | getSimSerialNumber      | 5346 ± 16       | 5524 ± 16       | 5817 ± 7       | 8.81                    |                         |
| LocationManager            | getLastKnownLocation    | 3516 ± 13       | 3562 ± 13       | 4126 ± 5       | 17.35                   |                         |
| SmsManager                 | sendTextMessage()       | 9166 ± 13       | 9396 ± 13       | 10216 ± 10     | 2.51                    | 11.46                   |
| PackageManager             | getInstalledApplications| 15730 ± 204     | 15514 ± 202     | 15422 ± 172    |                         |                         |
| ConnectivityManager        | getAllNetworkInfo       | 5769 ± 53       | 5841 ± 60       | 5671 ± 7       |                         |                         |
| BufferedReader             | readLine                | 15360 ± 72      | 15531 ± 67      | 15455 ± 38     |                         |                         |

through Binder. As sendTextMessage() contains only Java primitives as arguments, its unmarshalling overhead is slightly lower.

5 Conclusions and Future Work

Our benchmarks suggest that we sit comfortably between the competition. For example, Aurasium’s interception of getDeviceId() has a 35% and getLastLocation() a 34% performance overhead [13], whereas AppGuard’s benchmarks range between 0.8 and 21.4% overhead. TaintDroid, although more of a taint flow analysis rather than a pure monitoring tool, has a performance overhead of up to 29%, which is in the range of our measurements of 38.6% average overhead with the runtime verification client enabled. However, one should keep in mind that unlike the other solutions, DroidTracer does not rely on app or system modifications and therefore has limited potential for optimisation. The fact that, in particular, our kernel module performs well under these constraints, is somewhat surprising but largely due to our ability to intercept all the relevant data at a single point of entry, i.e., the Binder. More so, we have shown that detailed systems monitoring on Android is possible even without any modifications to the platform itself.

However, this is preliminary work, a proof of concept. While we are content with the event interception part of our work and already offer an API, such that others can use and benefit from it as is, we have yet to substantiate our claim that runtime verification as outlined in particular in §3 really is beneficial to system security. Works that analyse current threats and security trends in that area (cf. [15, 21, 6]) seem to suggest that the total number of Android attacks is on the rise, but that most of the threats follow only a handful of different patterns. Our working hypothesis is that these patterns can and should be translated into (temporal logic) policies, which then in turn are monitored by our tool. The essential ingredients for this undertaking were presented in this paper and shown to work.

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