Should Users Trust Their Android Devices?
An Analysis and Scoring System for Pre-Installed Applications

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Abstract—Most users have no idea that their Android devices are equipped with many pre-installed applications which have the capability of tracking and monitoring them. Although applications coming pre-installed pose a great danger to user security and privacy, they have received little attention so far among researchers in the field. In this study, we collect a dataset comprising such applications and make it publicly available. Using this dataset, we analyze tracker SDKs, manifest files and the use of cloud services and report our results. We also conduct a user survey to understand concerns and perceptions of users. Last but not least, we present a scoring system which assigns scores for smartphones consolidating our findings based on certain criteria. Users could give their own trust decisions based on the available concise information about the security and privacy impacts of applications pre-installed on their devices.

Index Terms—Security, Mobile Security, Privacy, Android, Pre-installed Apps, Scoring System, User Study

I. INTRODUCTION

Android is the most widely used mobile operating system [1] in the world mainly due to two reasons: (i) it is an open-source operating system [2], (ii) Google makes developers and manufacturers’ job of producing new devices and devices much easier if they prefer Android [3]. Not only manufacturers, but also mobile network operators, semiconductor producers and third party companies that assist and collaborate with manufacturers can easily modify and add their own applications to mobile devices with Android.

To audit Android devices, firmware and pre-installed applications, Google provides certification programs. In Android Compatibility Program, device and firmware should be compatible with Android Compatibility Definition Document [4]. These requirements can be checked using Compatibility Test Suite [5]. However, in this program, there is no privacy and security audit applied to an Android device. Google also offers Android Certified Partners Program [6] to device manufacturers. Device manufacturers that want to be a Android Certified Partner [7] have to satisfy this program’s requirements. As part of this program, mobile Built Test Suite (BTS) [8], Security Test Suite (STS) [8] and some other suites are applied. Within BTS, Potential Harmful Applications (PHAs) and other harmful actions are examined. Also, in STS, security patches are checked to verify that pre-installed applications are up-to-date. But, neither Android Compatibility Program nor Android Certified Partners Program guarantees security and privacy of users.

In real life, many pre-installed applications threatening security and privacy of users have been already detected. One of the well-known examples is Adups discovered by Kryptowire [9]. Adups is a Firmware Over The Air (FOTA) application that helps manufacturers to update device firmware remotely. According to the analysis, this application that exists in BLU R1 HD smartphones has the ability to collect Personally Identifiable Information (PII) and run privileged code on user’s devices.

As stated in Google’s Android Security & Privacy 2018 Year In Review [10], Android smartphones could be infected with ease since developers of a PHA only need to deceive OEMs (Original Equipment Manufacturer) or any other company in the supply chain for the installation. There were several PHAs detected in smartphones in big Android markets such as India, USA, Brazil and Indonesia. Furthermore, researchers from Oversecured have found that pre-installed applications on Samsung devices certified in Android Certified Partner Program have multiple dangerous vulnerabilities [11]. We also note that third party applications that are not directly related with OEMs e.g., social networking, search engine, news, telecommunication, etc. may be pre-installed in Android smartphones. For example, as reported by Bloomberg [12], Facebook apps are pre-installed and cannot be deleted from smartphones. These third party applications and their affiliated companies usually cooperate with manufacturers [13].

Until recently, studies on pre-installed application ecosystem analyze only a couple of selected applications and pre-installed applications in mobile devices did not attract much attention from researchers. However, with a comprehensive recent study [14] on pre-installed Android software, the gap has begun to close. In this paper, our aim is to identify and complete the missing spots on this recent work [14]. First of all, because there is no public data set which consists of pre-installed Android applications, our first aim is to make such a dataset available. We believe this dataset could facilitate
further research on this important topic. For this purpose, we implement an Android application and use it to collect data on pre-installed applications from volunteer user’s devices.

Regarding user privacy, using the collected data set, we extract tracker SDKs from applications. Then, we analyze the goals of these trackers which could be analytics, advertisement, location tracking, profiling, identification, etc. Also, we check what kind of applications (OEM, mobile network operator, social networking, etc.) contain these trackers. By this analysis, we discover tracker SDKs ecosystem on pre-installed Android applications and the effects of trackers on user privacy.

From security point of view, we make the first study in literature on critical fields of manifest files in pre-installed applications. Within this scope, we investigate exported application components, shared UIDs, attributes such as `usesCleartextTraffic`, `allowBackup` and `debuggable` in manifest files and find out that if pre-installed applications follow Android security best practices. In addition, we search cloud services that are used by Android pre-installed applications. By doing so, we intend to find out that how securely these apps take advantage of these services.

In addition, we make a survey (with users who download and use our application [15]) to understand their concerns and perceptions regarding security and privacy of pre-installed applications.

Finally, we evaluate pre-installed applications from security and privacy point of view using multiple criteria that are based on our findings and present a device scoring system. These device scores make our findings more understandable for average users of smart phones.

To summarize, with this study we contribute to the young literature of pre-installed mobile applications and their security and privacy implications in following ways:

- We discover tracker SDKs ecosystem that exists in Android pre-installed applications.
- We analyze manifest files of applications to check compliance to security best practices.
- We analyze cloud services that are used by pre-installed applications and check if any misconfiguration exists in these services.
- We report the results of a survey applied to users who install our application [15] to shed light on their concerns and perceptions regarding security and privacy of pre-installed applications.
- We make our preinstalled app dataset publicly available [16].
- We present a scoring system to make the results of our analysis more understandable by average users.
- We publish our analysis results and device scores on a website [17] to inform users and researchers.

The rest of the paper is organized as follows, Section 2 summarizes the results of earlier studies on the topic. Section 3 presents our Android application developed for collecting data on pre-installed apps and provides general information about the dataset made available. Section 4 describes what kind of analyses we perform and what results we obtain. Section 5 contains user survey results and related discussion. Section 6 includes the details of our scoring system and remarks on scores of some devices. Section 7 lists the limitations of this study. Section 8 concludes this paper.

II. RELATED WORK

There were many previous studies on applications from Android Application Markets (e.g., [18], [19], [20], [21], [22]) as opposed to pre-installed applications. A considerable portion of these focused on application permissions since they are important with respect to both privacy and security [23], [24], [25]. Custom permissions were also studied [26]. We note that when applications are pre-installed, users do not have a change to grant or deny dangerous application permissions [27] as they normally can do.

Third-Party Libraries (TPLs) like SDKs are crucial for Android application development as they help developers to expedite application development process. However, these TPLs may contain codes that are related to advertising and tracking services. Earlier studies [28], [29], [30], [31] found out that these services threaten user privacy.

Misconfigurations in Android application manifest files and cloud services used by applications can cause privacy and security issues. Two recent studies [32], [33] which focused on cloud services misconfigurations indicate that unsecured cloud services may expose personal data. In addition, manifest file attributes (e.g., `allowBackup`, `debuggable`, `usesCleartextTraffic`) and shared UIDs should be configured carefully as specified in guidelines [34]. Particularly, intentional or unintentional misuse of shared UIDs’ may lead to over-privileged (e.g., with `android.uid.system` privilege) execution of applications [8]. Additionally, applications that have same shared UIDs and signed with same keys may access each other’s resources. This can lead situations which affect security and privacy of users [35], [36].

As already mentioned, most earlier work cover Android applications from Android Application Markets. Since pre-installed applications come with the devices and require no further installation and most of them have more privileges than the applications installed from application markets, they pose more danger and demand a more elaborate and focused analysis. The effects of so called bloatware applications that come pre-installed and waste system resources like battery, disk space, memory etc. have been investigated in a recent paper [37]. Also, a user study has been conducted to understand users’ knowledge and awareness regarding bloatware applications. But, they mostly focused on application permissions and consequences that stem from these permissions. There is also a study [38] that aims to find privilege escalation vulnerabilities on pre-installed applications. To achieve their goals, the authors mostly make use of taint analysis methods. In another recent study [39], pre-installed OTA applications have been the main concern.

In another recent study [14], a comprehensive analysis of pre-installed applications has been made. Third party libraries,
application permissions (particularly custom permissions), and network traffic of applications have been examined. As stated so far (and summarized in Table I), pre-installed applications and applications from app markets differ substantially, and as mentioned, there are a lot work left to do to have a better understanding of the pre-installed app ecosystem and its security and privacy implications. Our goal in this paper is to contribute in this regard. (Our early results were previously published in Turkish in summarized form [40].)

III. DATASET

In this section, we provide information about the application we develop to collect the dataset and share general statistics and some early analysis results regarding this dataset.

A. Android Application (Pre-App Collector)

Up to our best knowledge, no public dataset that consists of Android pre-installed applications exists. A recent study [14] has created such a dataset, but it is not publicly available. Therefore, we decide to prepare our own dataset and make it publicly available [15]. For this purpose, we implement an Android application to collect the pre-installed app data from user’s devices. Our study was approved by TOBB University of Economics & Technology Human Resource Evaluation Board [41]. We make this application available on Google Play Store [15]. To announce the application, we use e-mail groups from universities, social media groups, and also share it on social media.

The application works as follows. When application starts, we inform users about our study, take their consents to start the data collection and ask a couple of questions as part of our survey to understand their concerns and perceptions regarding security and privacy of pre-installed applications. The data collected about the device includes data of manufacturer, model, product, version, timezone, SIM operator, SIM country. Then, we scan /system, /odm, /oem, /vendor, /product directories recursively to reach firmware files including pre-installed applications. Hash of these files are calculated and sent to our server to check if they already exist in our dataset. The list of files that are not in our dataset is sent to the device so that these files are also transferred to our server. Finally, we show users a summary containing the list of pre-installed applications and statistics about firmware files.

B. General Statistics

We present some useful statistics about our dataset as follows:

- We collect files from 22 different OEMs and 98 different devices.
- We determine using timezone information that users from 14 countries have installed our application.
- In total, we collect 143862 firmware files including 14178 apk files, 418 certificates and 58721 libraries.
- In total, 77 users participate in the survey (excluding survey results that have the answers as default picks or do not have a proper e-mail address).

C. Early Analysis and Its Results

We perform a number of early analysis. First, we use Androguard [42] which is a Python based Android reversing tool to extract certificates that are used to sign the applications [43]. We analyze the so-called Issuer field in application certificates to detect which person or company developed the application. We group these certificates because not always a single certificate is used to sign the applications developed by the same entity. We specify groups considering OEMs, OEM-related, and Third Party information (e.g., Social Networking, Web Browser, Application Marketing, Caller Identification, News, Dictionary, Cloud Service, Telecommunication Companies, Marketing & Advertising Services, etc). In total, we determine 126 certificate groups and applications under these groups.

In addition, we check what portion of determined pre-installed applications exists in Google Play Store [18] using application package name. We find out that only 9% of the applications can be accessible from Google Play. Moreover, while collecting the applications, we also obtain metadata about apps e.g., first install time and last update. The analysis of this metadata shows that 7829 out of 14178 (55%) pre-installed apps were not updated ever since they came with the devices. We note that because most of the pre-installed applications are not third party ones and located in the system partition, they can only be updated by over-the-air update mechanism released by vendors and require smartphones to be restarted. Thus, a pre-installed application cannot be easily updated like the applications from app markets.

IV. ANALYSIS

We analyze pre-installed applications with respect to both security and privacy. In privacy part, we perform a detailed analysis of tracker SDKs and privacy policies. From security point of view, we focus on app manifest best practices and cloud services.

A. Privacy Analysis

Tracker SDKs. Android tracker SDKs collect data about users and how they use applications. They may be embedded to pre-installed applications and have various functionalities like crash reporting, analytics, profiling, identification, advertisement, location tracking. To analyze trackers, we base

| Pre-installed Applications | App Market Applications |
|---------------------------|-------------------------|
| Comes pre-installed on devices. | Installed by the user from App Markets. |
| Runs with more privileges. | User privileges. |
| Mostly cannot be uninstalled, only disabled. | Can be uninstalled. |
| Updated less frequently. | Updated more frequently. |
| Permissions mostly automatically granted without user consent. | User consent required for permissions. |

TABLE I: Comparison of pre-installed and app market applications.
our study on the work by Exodus Privacy [44], a non-profit organization working on Android trackers and their effects on user privacy. We take advantage of their tool named exodus-standalone [45] to detect embedded trackers in pre-installed applications. As a result, we discover tracker ecosystem and their effects to user privacy in pre-installed applications. Our findings could be summarized as follows:

- 85 different trackers installed in 836 different applications were detected.
- We investigated the companies which use the trackers and the affiliated companies. We examined their privacy policies and searched for if they were involved in any privacy incident in the past. We noticed that some companies do not clearly state what kind of information they collect. (Since some companies do not provide multi-language support either in their web sites or privacy policies, we use online translation services to investigate them.)
- In their privacy policy, most trackers have stated that they track sensitive information such as PII, location-related data, log information, user behaviour, device identifiers and advertisement IDs (e.g., Google Advertising ID [46]). This practice threatens user privacy at different levels.
- Most of the trackers have stated that they comply with regulations like GDPR [47] and CCPA [48], but still a few do not mention them in their privacy policies. In addition, according to their privacy policies, trackers tend to collect more data when they are not under these regulations.

Tracker Statistics. As stated above, we detected so many trackers in so many different apps. Some of these trackers are more common than the others in pre-installed applications. In Figure [1] we list the most common trackers that exist in pre-installed applications. It is not surprising to see that big technology companies such as Google, Facebook, Tencent and Amazon are dominant here.

Also, we observe that a number of applications come with excessive number of trackers which makes violation of user privacy inevitable. Figure [2] lists application package names which have the highest number of tracker SDKs (when we detected different versions of applications with different hash values, we collect them under the same app name). Interestingly, most of these applications are third party applications according to our certificate based analysis. Consequently, to work properly, the devices do not actually require them.

In addition, we group trackers based on their companies. Some of the tracking services are offered by companies affiliated with big technology companies. In Table [II] we list some of these companies and the number of tracker-related companies that are affiliated with them.

According to our analysis (see Table [III]), big technology companies acquire tracking services continuously. Once we check companies offering tracking services from Crunchbase [49] which is a website that provides data about companies and the people behind them, we noticed that tracking companies are acquired by either by each other or by other technology companies to grow and expand their market share. However, this situation brings new privacy risks as some tracking services state in their privacy policies that when they are acquired by a different company, user data becomes no longer under their control and is shared with the company which acquired them.

Finally, we have checked the headquarters of these companies from Crunchbase. We note that in some countries like China, companies have the obligation to share any data with intelligence services or the government. Moreover, personal data can be transferred to these countries that are not under regulations (e.g., GDPR, CCPA) protecting user privacy. Table [III] shows the most dominant countries and number of tracking companies located there.

Purpose of Trackers. Tracker SDKs may provide different functionalities as they are designed for different purposes. Hence their impact on user privacy could vary significantly. Exodus Privacy [44] categorizes tracker SDKs in six groups:

- Google Firebase Analytics
- Google AdMob
- Google Analytics
- Google Crashlytics
- Google Tag Manager
- Facebook Login
- Facebook Share
- AutoNavi / Amap
- Facebook Analytics
- Facebook Ads
- Facebook Places
- Inmobi
- Flurry
- HockeyApp
- Sensors Analytics
- Tencent Stats
- Baidu Location
- myTarget
- Adjust
- Amazon Advertisement
- Moat
- Twitter MoPub
- AppMetrica
- Yandex Ad
- Braze (formerly Appboy)
Fig. 2: Applications that contain most tracker SDKs.

TABLE III: Number of tracker companies in different countries.

| Country       | Number of Companies |
|---------------|---------------------|
| United States | 56                  |
| China         | 11                  |
| Russia        | 4                   |
| Germany       | 4                   |
| France        | 3                   |
| India         | 2                   |
| United Kingdom| 1                   |
| Israel        | 1                   |
| Open Source   | 1                   |

- **Crash Reporters**: The goal of these trackers is to notify developers when applications crash.

- **Analytics**: This kind of trackers collect data usage and let developers to get familiar with target users. For example, user’s browsing behaviours are collected.

- **Profiling**: By collecting from users as much data as possible, these trackers try to build virtual profile of users. For this purpose, trackers collect data like browser history, list of installed applications, etc.

- **Identification**: The purpose of these trackers is to specify users’ digital identity. Thus, developers may associate user’s online and offline activities.

- **Advertisement**: The aim of these trackers is to show users targeted advertisements by using users’ digital pro-

files and help developers to monetize their applications.

- **Location**: These trackers are used to locate users by taking advantage of hardware and software features like Bluetooth, GPS antenna, IP address, etc.

We categorize trackers we have detected using these groups since the effects on user privacy varies per group. Figure 3 shows the number of trackers associated with each group. As stated, each tracker group has a different functionality (some trackers perform more than one functionality). On the overall, trackers under analytics, profiling and identification groups highly threaten user privacy since they mostly need to collect personal data to fulfill their functionality. Location trackers collect location data which might also be sensitive for purposes like advertisement, sale, etc. Lastly, advertisement trackers access and collect personal data for a targeted advertisement. However, not all trackers are evil, crash reporters mostly does not threaten user privacy. As mentioned, they are mostly used to report application failures to help developers.

Fig. 3: Number of detected trackers In different tracker groups.

**Privacy Policies.** We investigate tracker companies’ privacy policies and related privacy issues to understand what kind of data is collected, what data is shared with whom and whether or not these companies comply with regulations such as GDPR and CCPA.

As stated in their privacy policies, all of the trackers collect various types of user data. Below, we present interesting points in privacy policies of tracker companies regarding their data collection routines.

First of all, most of the tracking services collect location data in various ways. For instance, nearly all services collect IP address of devices, using this information approximate location of users can be determined. Also, when available, services might access GPS data from the device to locate users. Moreover, a few of the trackers collect nearby Wi-Fi hotspots, cellular and Bluetooth information for location tracking purposes. We observe that a number of trackers take advantage of all these methods to get precise location information.
Secondly, nearly all of the trackers access advertisement IDs like iOS Identifier for Advertising (IDFA) and Google Advertising ID (GAID) to recognize devices for advertisement purposes.

Thirdly, many of the trackers collect network identifiers like IP address, MAC address, connection type (e.g., Wi-Fi, cellular), etc. This information can help location tracking and device identification.

In addition, some tracking services collect device identifiers like IMEI and IMSI numbers. This kind of data cannot be changed by users and can be used to identify the devices. The risk due to IMEI number collection is well-known [50].

Furthermore, to profile users and understand their device or application usage behaviours, a number of tracking services collect information such as browser history, application log, application usage stats, cookies, etc.

Finally, some of these companies collect Personally Identifiable Information (PII) such as name, email address, gender, contact information (e.g., telephone number), etc.

Below, we compile a list of real life examples concerning trackers and their impact on user privacy:

- **Sensor Analytics** whose owner is Sang Wenfeng, former technology manager at Baidu Inc’s big data department, has a partnership with Xiaomi [51] to work on understanding behaviours of users.
- **Citizen Lab** claims that Baidu Mobile Analytics SDK cause sensitive data leak in applications using it [52]. This data include IMEI number, GPS location and nearby wireless access points. In addition, Baidu Map service may collect sensitive data such as IMEI number, IMSI number, MAC address, etc. [53].
- According to a research by Gizmodo, applications that use Bugly crash reporting service collect and send IMEI number and IP address to servers located in China [54].
- As stated in its privacy policy, Chinese tracking service Mintegral may collect IMEI numbers of users. Also, it cooperates with advertisement exchange platform like Google DoubleClick, Inmobi, MoPub, Tencent, Baidu, etc. [55].
- From the applications that embed its tracking code, MoEngage may obtain PII like email address, name and phone number as indicated in its privacy policy [56].
- Applications that use JPush service may send IMEI numbers, MAC addresses, serial numbers, and precise location data to Aurora Mobile’s servers [57].

**Data Sharing.** Analysis of privacy policies shows that tracking services may share data collected from devices. In general, the data may be shared with:

- Affiliates and Subsidiaries,
- Service Providers,
- Law Enforcement Units,
- Business transfers,
- Advertisers,
- Researchers and Academics,
- Publishers,
- Data Partners.

Also, as pointed in a study on tracking ecosystem [28], all of the ten largest tracking organizations could share collected data with third parties and subsidiaries. Because of these sharing routines, opt out chance of users is in danger since different companies have different opt out procedures. Moreover, some tracking companies may share data with each other e.g., MoPub’s partnership with Integral Ad Science, DoubleVerify and Moat [58].

Lastly, to the best of our knowledge, all of the tracking companies share data for legal purposes (e.g., law enforcement requirements). Even if this stems from a good intention to help law enforcement units, it can be abused by some governments [59].

**Compliance with Regulations.** Under the protection of regulations like CCPA, GDPR, and COPPA, users have more control over their data. They can learn what kind of data is collected, with whom their data is shared or to whom it is sold, etc. Our analysis on privacy policies show that when companies are not required to comply with these regulations, they are more likely to ignore privacy rights of users (e.g., without these regulations, as we saw in Mintegral example [55], companies continue to abuse their capabilities). High fines obligate companies to adapt to these regulations and show more respect to data privacy. Therefore we believe these regulations must be universally embraced throughout the world.

**B. Security Analysis**

We analyze security practices in manifest files (Android-Manifest.xml) and cloud service configurations in applications.

**Manifest File Analysis.** We focus on the manifest file which is an XML file that describes application specific essentials [60] containing app’s package name, app components (activity, service, broadcast receiver, content provider), app permissions, app attributes and manifest attributes. We examine attributes such as sharedUserId, allowBackup, usesCleartextTraffic, and debuggable, which are among the most critical fields with respect to user security. Below, we explain the security implications of misconfigurations in these fields together with our findings on the dataset.

**sharedUserId.** In Android, unique user ID values are assigned to each application. However, in some conditions, for instance, when the same developer or company have multiple applications on a smartphone and want to share application resources (e.g., permissions, code) with each other, the same user ID value may be assigned to these applications. For this functionality, sharedUserId attribute is used. But misconfiguration of this attribute may cause security vulnerabilities. Also, adversaries could take advantage of this attribute to hide their malicious codes from users and security analysts. We examined if any third party application has the same shared UID value with a system application but could not find any (because of the risks this attribute brings, it was deprecated in API level 29 by Android).
We also note that pre-installed applications that are signed as system apps with the same certificate can run with system user privileges, one of the most privileged users in Android system. We observed that 3303 out of 14178 pre-installed applications possess "android.uid.system" shared UID value which gives system privileges to applications. Vulnerabilities in these applications may cause adversaries to access devices with the system privileges [61]. Also, malware (e.g., Adups malware [9]) may be embedded with system privileges in devices as we have mentioned. In our analysis, we detected apps that run with system privileges without a real need (e.g., com.caf.fmradio). Clearly, this practice violates the least privilege principle.

**allowBackup.** When this attribute is set in the manifest file and if USB debugging is enabled in an Android device, application data can be backed up by anyone who has physical access to it. Thus, all data in /data/data/package_name can be exported from the smartphone. If any unencrypted sensitive data such as PII, passwords, keys etc. is stored in such a directory, adversaries who has physical access may easily capture it.

We examined if any application has enabled allowBackup attribute. We also analyzed its prevalence in each certificate group. We detected 6847 applications in total that allow backup using adb [62]. In Figure 4, vendors with the most applications in this situation can be seen. The results clearly show that almost all vendors take advantage of allowBackup attribute. We think this practice requires further investigation due to its security implications.

![Fig. 4: Vendors and the number of applications signed by them that allow data backup.](image)

**usesClearTextTraffic.** Applications may use cleartext traffic to connect to remote servers. This can cause private and sensitive data to be eavesdropped by adversaries [63]. With Android 6.0, application developers may prevent their applications to send cleartext data by setting of the usesClearTextTraffic attribute. However, we detected a number of pre-installed applications with the usesClearTextTraffic flag set to "true". 1270 of the apps from our data set may send their data as cleartext to servers. Most of these apps are belong to OEMs and only 37 of them are belong to third parties.

**debuggable.** We also looked at which applications come with debuggable flag. When this flag is set in an application, it may be debugged by users who have physical access to the device with tools like jdb [64]. Using this functionality, classes and functions of apps can be easily read and even manipulated. In addition, it is possible to execute arbitrary code within the permission context of these applications. Thus, it is strongly suggested that to set this flag "false" in production. Fortunately, we only found 5 such applications (three variants of com.sec.android.kiosk com.trendmicro.mars.mda.httpserver and com.huawei.camera2.mode.cosplay). It was surprising for us to see that com.huawei.camera2.mode.cosplay application was signed by Android Debug Certificate [43]. Most app stores does not accept applications that are signed with this certificate (recall the difference between pre-installed and app market applications).

As a conclusion of manifest file analysis, we state that while developers usually follow the best practices regarding the use of sharedUserId and debuggable attributes, we cannot say the same for the allowBackup and usesClearTextTraffic attributes.

**Cloud Services Analysis** Almost all Android applications connect to backend servers to fulfill its functionality. These servers can be used for various purposes such as storing data, querying for information, performing actions for application, etc. Not every developer or company has the resources and time to implement their own server infrastructure. Even when they have enough resources, they might choose not to use their own server because cloud based solutions are easy to manage and provide many other advantages. These solutions offer functionalities such as data storage, notification management, analytics, API based services, etc. Due to their critical role in the mobile app ecosystem, cloud-based solutions need to be managed carefully in terms of security and privacy. Although they may be regarded as secure by default, developers should still be aware of their correct configurations and operation logic before using them. Unfortunately, considerable number of developers overlook the configuration of these solutions, that may affect millions of people.

Some of the popular cloud-based services are Google Firebase [65], Amazon Web Services (AWS) [66], Microsoft Azure [67] and Google Maps API [68]. Pre-installed applications also use these services and we examined cloud services used by these applications and misconfigurations exist in them.

These services require special keys, secrets and URL formats. Disclosure of these values may cause unauthorized access to company resources, sensitive and confidential information leaks, denial of service attacks and waste of company resources. To extract these values, we take advantage of several tools [69], [70], [71], [72] and also write a few custom scripts. We also manually analyzed some of the applications by reverse engineering. As a result, we detected vulnerabilities related to Google Maps API, AWS, Firebase, Slack Webhooks [73], and OAuth [74]. Using custom Python scripts, we test and validate...
our findings. Below, we discuss interesting results with respect to user security and privacy.

**Google Maps API.** Using this API service, developers could search and embed Google Maps Database in their applications. Until 2018, this service was free. However, in June 2018, Google launched the pay-as-you-go pricing model [75]. In this model, the price is determined according to number of request that made to Product Stock-Keeping Unit (SKU). A SKU is a combination of Product API and the service or function called e.g., Place API - Photos Details.

To extract Google Maps API key values, we used a modified version of apkleaks [69], a Python tool that uses special regex patterns for various URIs, endpoints and secrets for mass file scan. We tested the extracted keys using also a modified version of gmapsapiscanner [72] so that unauthorized accesses using these keys can be revealed. We present our results in Table IV that consists of Accesses using these keys can be revealed. We succeeded in automatically. We tested them to see if any of them are still valid and can be used to access S3 buckets. We succeeded in accessing buckets of two different companies. The number of valid key pairs we have found is not many but the impact could be outrageous. Using these keys, we were able to access S3 buckets of companies which reveal not only the application information but also buckets and objects of various other applications and services. This situation clearly violates the principle of least privilege. In addition, we investigated the objects in these buckets and discovered PII, credentials and source code of applications and services. In conclusion, we urge developers to use these keys securely and be aware of impacts of their disclosure.

**Google Firebase Database.** Google offers developers and companies a cloud based database [65] to store their data as JSON. This database, named as Firebase Realtime Database, can be used via SDK and has some key capabilities like real-time synchronization, offline response management, multiple database scalability, direct access from client devices such as mobile device or web browser. To utilize this database, developers should create a database from Firebase console. This database is named as database-name\_firebase\_database\_app. By default, anyone can access it, hence Firebase database should be configured properly to prevent unauthorized read and write accesses.

In our work, using the apkleaks, we detected Firebase URLs in applications with the pattern mentioned above. We found 665 applications using Firebase databases and tested them using a custom Python script. To see if a database is readable by anyone, we simply add ".json" at the end of database URL and check the status code of response which is 200 when readable. In addition, to find the world-readable databases, we send a put request to the database URL with some JSON data and check the status code of response which needs to be 200. As a result, we found two Firebase databases that belongs to two different applications, which everyone may read and write.

**OAuth.** With client\_id and client\_secret values, Android applications generally use OAuth 2.0 to access different APIs or services. These values especially client\_secret should be protected against unauthorized access. For better protection, developers can take advantage of Proof Key for Code Exchange (PKCE) in which the client creates a new secret on each authorization request and uses this secret when exchanging authorization code for an access token [80]. However, in our analysis, we observed applications that store OAuth values belonging to services such as Google, AOL, Outlook, Office 365, Yahoo, Microsoft and mail.ru as cleartext. Thus, attackers can steal these values and use them to access APIs or services. It should be noted that, "PKCE is not a replacement for a client secret, and PKCE is recommended even if a client is using a client secret, since apps with a client secret are still susceptible to authorization code injection attacks" quoted from [80].

V. USER SURVEY

While getting help from users by installing our app for building our dataset [15], we also asked them questions to shed light on their concerns and perceptions about pre-installed applications (Survey questions are provided in APPENDIX [A]). 77 users attended to our survey after elimination of results with answers all as same as the default ones and the results that
have previously used e-mail addresses. At the beginning, we asked questions on demographics. There were 40 participants in 25-34 age range and 19 in 18-24 age. 25 were female with one person chose not to provide gender information. Educational level of participants is at least Bachelor degree (70%). Only 29 of them stated they were professionally interested in cyber/mobile security. Figure 5 shows the profile of survey participants.

With the survey, we try to understand user behaviour and mindset while purchasing and using their devices. While 17 people did not provide any answer, most of the others (51 out of 60) bought their smartphones from online markets, technology shops or MNOs. This shows that people mostly trust big sellers when buying their phones. Arguably, this also makes sense in a privacy and security perspective. Big sellers might help users in this regard. For instance, as stated in The Verge [81], Amazon suspended Blu phones which comes with pre-installed spyware.

According to survey results, only 10% use devices which cost less than $100 US dollars. 44 users prefer $351-$700 devices and 27 prefer those costing $701-$1400. We remind that in general there are more security and privacy risks in less expensive smartphones [82].

We also asked questions to learn how long users have been using their phones and how often they change them. Nearly half of the users (40%) stated that their devices were between 2 and 5 years old. Even worse, a remarkable portion (11.7%) have not change their smartphones for at least 5 years. As most vendors support security updates only in their most recent models (2 years on average [83]), a significant part of users are at great risk for potential security vulnerabilities. We also asked how often users change their smartphones (this is not asking the previous question again because users may have bought their devices recently). Most users (68 out of 77) change their phones after at least 2 years. As already pointed above, this brings considerable risks in Android ecosystem. The survey results about the age of smartphones used by participants can be seen in Figure 6.

In order to learn about the criteria in user choices when purchasing smartphones, we asked another question. As expected, price and model are important for most people. Only 14 claimed they care about privacy and security policies of vendors. 13 users stated that they consider the country of the vendor as part of their purchasing decision. We argue that users should be informed better about the importance of privacy policies.

We also aim at measuring user knowledge on pre-installed applications and their impacts. We observed that the knowledge of users on the number of pre-installed applications on their device is far from the actual numbers. In Figure 7, we present the number of pre-installed applications users thought exist in their phones. Most of their guesses are underestimates (more than half (%55.8) assume only 0-20 pre-installed applications). We note that we calculate the average number of pre-installed applications per device as 294 which is far more than these guesses. In addition, we asked users whether they are informed at any time about pre-installed applications. 31 users (40%) stated that they did not pay any attention to this subject. 27 of them (35%) thought that they were not informed about pre-installed applications.

To understand and compare user behaviour when managing Android permissions, we asked two additional questions. Almost half of them (38 out of 77) stated they checked application permissions before installation. On the other hand, 71% does not bother with periodic regular checks. We remind that even when application permissions are checked by users, permissions given to pre-installed applications cannot be seen.

Do users update applications in their devices when an update is available? Most of them (81%) indicated that they pay attention applications are up-to-date. However, according to our metadata analysis, as previously mentioned, more than half of the pre-installed applications have not been updated since they came with the devices.

Finally, we asked users if they have heard about regulations like GDPR [47] or KVKK [84] (Personal Data Protection Authority in Turkey). Unfortunately, more than half of the

| Vulnerable SKU | Vulnerable Application Count | Impact(s) |
|----------------|-----------------------------|-----------|
| Places Photo API | 199 | $7 per 1000 requests |
| Nearby Search-Places API | 198 | $32 per 1000 requests |
| Text Search-Places API | 198 | $32 per 1000 requests |
| Find Place From Text API | 196 | $17 per 1000 elements |
| Autocomplete API | 196 | $2.83 per 1000 requests, Per Session - $17 per 1000 requests |
| Place Details API | 196 | $17 per 1000 requests |
| Staticmap API | 161 | $2 per 1000 requests |
| Geocode API | 81 | $5 per 1000 requests |
| Geolocation API | 51 | $5 per 1000 requests |
| Timezone API | 36 | $5 per 1000 requests |
| Embed (Basic) API | 26 | Free |
| Elevation API | 16 | $5 per 1000 requests |
| Streetview API | 15 | $7 per 1000 requests |
| Embed (Advanced) API | 12 | Free |
| Directions API | 7 | $5 per 1000 requests, (Advanced) - $10 per 1000 requests |
| Distance Matrix API | 5 | $5 per 1000 elements, (Advanced) - $10 per 1000 elements |
| Nearest Roads API | 4 | $10 per 1000 requests |
| Route to Traveled API | 4 | $10 per 1000 requests |
users did not hear any of these regulations. As we discussed, these regulations have an important role for user privacy. Thus, users should be informed more about these regulations and their importance regarding user privacy.

At the end of our survey, we collect email addresses of users to send our analysis results. In our view, it is clear that users should be notified about pre-installed applications and their impacts on security and privacy.

VI. SCORING SYSTEM

As a result of series of analysis, we obtained various findings regarding pre-installed applications on smart phones that have various effects on security and privacy. However, these findings cannot easily be understood by an average smartphone user especially when they are presented and discussed independently. For this reason, we aim at obtaining a scoring system to provide users information about their devices and pre-installed applications with respect to security and privacy in a more clear and concise way. Although, the scores seem inevitably fraught with issues of subjectivity, we believe the end result is still helpful in a certain extent.

In this context, we evaluate each of our findings from different point of views: how hard is it to exploit, the estimated impact on user security and privacy, and whether the user is aware or not. Considering these three criteria, we grade each finding according to Tables V, VI, VII where relevant subjective coefficients are determined according to our expertise and experience. We multiply the number of applications the concerned finding exists in a particular smart phone with these coefficients. In addition, we multiply the scores by 100 just for aesthetic reasons. Finally, we calculate the sum of these individual scores to obtain the overall device score. We are inspired from the Common Vulnerability Scoring System (CVSS) Score Metrics while building our scoring system. In the CVSS Base Metrics, exploitability, scope and impact elements are considered in the calculation of a vulnerability score [85]. In our analysis, we only consider devices where we could collect more than 50 pre-installed applications (we do not have sufficient data for some devices due to different reasons).

The following equation formalizes the score calculations. In this equation, "a" represents the number of pre-installed applications the concerned finding is present. The values of "b", "c" and "d" respectively represent the coefficients for exploitability, impact and awareness.

**TABLE V: How hard is it to exploit the finding?**

| Criterion                                                                 | Coefficient |
|---------------------------------------------------------------------------|-------------|
| No requirement. (Easy)                                                    | 1.00        |
| One of either physical access, an available vulnerability or user interaction is required. (Medium) | 0.50        |
| Two of physical access, an available vulnerability and user interaction are all required. (Very Hard) | 0.10        |

**TABLE VI: The impact on user security and privacy.**

| Criterion                                                                 | Coefficient |
|---------------------------------------------------------------------------|-------------|
| Affects user privacy or security directly and has very high impact.        | 1.00        |
| Affects user privacy or security directly and has high impact.             | 0.50        |
| Possibly affects user privacy or security with high impact.                | 0.25        |
| Possibly affects user privacy or security with low impact.                 | 0.10        |

**TABLE VII: **

**TABLE VII: **
TABLE VII: Is the user aware of finding and its effects?

| Criterion | Coefficient |
|-----------|-------------|
| The user is unlikely aware of the finding and its effect. (Very Hard) | 1.00 |
| The user is possibly aware of the finding and its effect. (Hard) | 0.50 |
| The user is likely aware of the finding and its effect. (Medium) | 0.25 |
| The user is most likely aware of the finding and its effect. (Easy) | 0.10 |

\[ score_i = a \times b \times c \times d \times 100 \]  
\[ Score = \sum_{i=1}^{10} score_i \]  

Below, all of the ten components of our scoring system are discussed in two groups. First group contains the findings we analyzed and discussed first in this work and the second group is for those that were already analyzed and discussed in previous work (but not put into any scoring system). We provide a short discussion followed by an explanation of “a” and the chosen values of “b”, “c” and “d”.

A. New Findings

System applications. System user is one of most privileged users in Android devices and its use by device manufacturers is common. We detected the applications that run with system user privilege by checking if `sharedUserId` value is "android.uid.system" or not. Even though not directly affecting user privacy and security, unnecessary usage of this privilege definitely opens new attack vectors.

\[ a=Total \text{ number of applications that run with system user privileges on the device} \]  
\[ b=0.25 \text{ (exploitability)} \]  
\[ c=0.25 \text{ (impact)} \]  
\[ d=0.50 \text{ (awareness)} \]

Applications allowBackup flag enabled. In Android applications, `allowBackup` flag is used by applications to allow user to backup application data. However, this feature can be used as a vulnerability by adversaries to reach application data but only if they have physical access.

\[ a=Total \text{ number of applications with the allowBackup flag enabled} \]  
\[ b=0.25 \text{ (exploitability)} \]  
\[ c=0.25 \text{ (impact)} \]  
\[ d=0.25 \text{ (awareness)} \]

Applications not signed by the manufacturer/vendor. We examined application certificates and detected applications not belong to device manufacturers. These applications mostly do not follow security best practices and contain tracker SDKs. Moreover, these applications are not strictly necessary in the operation of the device. The last but not the least, when pre-installed they run with more privileges and permissions as compared to when they are installed from application markets.

\[ a=Total \text{ number of applications that are not signed by manufacturer/vendor} \]  
\[ b=0.50 \text{ (exploitability)} \]  
\[ c=0.25 \text{ (impact)} \]  
\[ d=0.50 \text{ (awareness)} \]

Applications not updated for more than two years. According to our user survey, most of the users state that they have been using their phones more than two years period. Thus, their devices are open to many security vulnerabilities if the pre-installed applications are not updated. We calculate the value of “a” using the last update time of pre-installed applications.

\[ a=Total \text{ number of applications that are not updated for more than two years} \]  
\[ b=0.25 \text{ (exploitability)} \]  
\[ c=0.10 \text{ (impact)} \]  
\[ d=0.50 \text{ (awareness)} \]

Applications usesClearTextTraffic flag enabled. One of the best practices in network communication is the use of TLS protocols. After Android API Level 27, applications are not allowed to make cleartext communication unless they set `usesClearTextTraffic` flag as "true" in their manifest file. However this choice is dangerous since many network attacks such as man-in-the-middle becomes possible.

\[ a=Total \text{ number of applications with usesClearTextTraffic flag enabled} \]  
\[ b=0.50 \text{ (exploitability)} \]  
\[ c=0.25 \text{ (impact)} \]  
\[ d=0.50 \text{ (awareness)} \]

Applications debuggable flag enabled. This flag should only be used by application developers to detect and investigate software bugs. However, usage of this flag in production is extremely dangerous and applications with debuggable flag set are not allowed to upload Google Play Store. When this flag is set, application methods and classes can be listed and application behaviour can be manipulated by adversaries who have physically access to smartphone.

Fig. 7: How many applications were pre-installed you think when you first bought your phone?
\(a=\text{Total number of applications with debuggable flag enabled}\)
\(b=0.25\) (exploitability)
\(c=0.50\) (impact)
\(d=0.25\) (awareness)

**Trackers (excluding crash reporters).** We analyzed trackers in detail earlier. As already stated, tracker SDKs come with pre-installed applications and collect various kinds of user data. Users mostly are not aware of trackers and their activities.

\(a=\text{Total number of trackers (excluding crash reporters)}\)
\(b=1.00\) (exploitability)
\(c=1.00\) (impact)
\(d=1.00\) (awareness)

**Vulnerabilities in cloud services.** As mentioned, we found a number of vulnerabilities on cloud service configurations used by applications.

\(a=\text{Total number of vulnerabilities in Google Maps API}\)
\(b=1.00\) (exploitability)
\(c=0.25\) (impact)
\(d=1.00\) (awareness)

Because of differences with respect to the impact on user security and privacy, we separate Google Maps API from the other cloud services in our evaluation.

\(a=\text{Total number of vulnerabilities in other cloud services}\)
\(b=1.00\) (exploitability)
\(c=1.00\) (impact)
\(d=1.00\) (awareness)

**B. Findings Regarding Earlier Research**

In our scoring system, we also used the results of previous studies. Especially, we took advantage of one of the most comprehensive study [14] on Android pre-installed applications. In this context, we include findings regarding dangerous application permissions and exported application components to the score system. These criteria are analyzed and discussed in previous study [14], thus we only repeated their procedure to obtain our results.

**Exported application components not requiring permission(s).** Exported application components can be used by applications to share data and functionality with other applications that are also installed on the device. But, insecure usage of these components may cause various security vulnerabilities. As a result of our analysis, we detected that many pre-installed applications use exported components without permissions. Although, this does not directly threaten user security and privacy, vulnerabilities that are found in these components still pose a considerable risk for device owners.

\(a=\text{Total number of exported application components that does not require permission(s)}\)
\(b=0.25\) (exploitability)
\(c=0.10\) (impact)
\(d=0.25\) (awareness)

**Dangerous permissions.** In Android, dangerous permissions are those given to perform actions which may affect user security and privacy. After the Android API Level 23, user consent for the permissions applications require is received at runtime. In theory, this is applied to both third-party and pre-installed applications, however vendors can enable exceptions for pre-installed applications. This can be applied by whitelisting dangerous permissions for specific pre-installed applications [86]. Also, privileged applications which are located in /system for Android 8.1 and lower, and /system, /product, /vendor for Android 9.0 and higher can take advantage of privilege permission allowlisting [87]. Moreover, pre-installed apps may expose critical services and data by using custom permissions [14]. This feature allows applications to use runtime permissions without user consent. Thus, users mostly do not have enough information about dangerous permissions that pre-installed applications use.

\(a=\text{Total number of dangerous permissions}\)
\(b=0.25\) (exploitability)
\(c=0.25\) (impact)
\(d=0.25\) (awareness)

**C. Results**

We use 10 different criteria as listed above to calculate the final device score, which is simply the sum of all individual scores. Devices with the highest scores are the worst with respect to security and privacy impacts of pre-installed applications.

We classify final scores using the year of device releases as in Figure 8. The general trend is that newer devices have lower scores than the old ones. Thus, users have yet another reason (privacy and security) to spend money and buy new phones.

We also evaluate devices individually and determine the devices with the highest scores. Our results show that 7 of the 10 highest score phones are Samsung devices. Sony Xperia Z1 is the highest score device in our dataset. In addition, we have Asus and General Mobile devices among the devices with the highest scores. Devices with the highest and lowest scores can be seen in Figure 9 (a). The latest device in our list is Samsung Galaxy A7 which was released in 2018.
We also determine the devices with the lowest scores. As seen in Figure 9 (b), most of these device are released after 2019.

To conclude this section, we note that with our proposed scoring system, users as well as researchers could easily have an opinion and compare devices with respect to pre-installed applications and their effects on user security and privacy.

VII. LIMITATIONS

In this section, we report various limitations of our study as follows:

Scope. Our study involves a dataset comprising 14178 apk files and a user study with 77 participants. These numbers are far from being sufficient to draw ultimate results on pre-installed application ecosystem. Our observation is that most people is reluctant on installing an unknown application to their smartphone even when the application is developed for an ethically approved research study. We encourage researchers to use our Android application [15] to conduct follow-up studies to obtain larger datasets of pre-installed applications.

Analysis. We only analyzed pre-installed applications using static analysis methods, however full functionality of applications cannot be understood only by this method because these applications could take advantage of techniques such as reflection, dynamic code loading, native libraries, obfuscation and encryption. Therefore, future work may focus on developing and adapting dynamic analysis methods and platforms for pre-installed applications.

Scoring System The scoring system is designed using the results obtained from a limited number of devices and pre-installed applications. By adding more criteria the scoring system can be made more comprehensive. While dangerous permissions may sometimes be actually required in applications to fulfill their functionality, some others may use these permissions just to access and leak sensitive user data. These behaviours can be detected with techniques like taint flow analysis. Different findings could be correlated with each other (e.g., tracker SDKs and dangerous permissions) to improve reliability of scores.

VIII. CONCLUSION AND FUTURE WORK

In this work, we presented an Android pre-installed application dataset made publicly available. We analyzed these pre-installed applications in various aspects and developed a scoring system grading the effects on user security and privacy. We also conducted a user study to understand and measure knowledge and perceptions of users about pre-installed applications and their activities.

In our tracker SDK analysis, we observed that most of the tracker SDKs exist in third-party applications. However, users cannot uninstall these applications, they could only deactivate them. Although these applications are not critical for proper device operation, they have serious security and usability impacts. Also, we detected tracker SDKs on vendor pre-installed applications, which confirms that vendors and third-party firms collaborate with each other.

We analyzed critical manifest file attributes and flags such as sharedUserId, allowBackup, debuggable, usesClearTextTraffic and determined various pre-installed applications having critical security vulnerabilities. Vendors are urged to follow security best practices while developing pre-installed applications.

We examined cloud services in pre-installed applications. Unfortunately, we detected various vulnerabilities that affect user security and privacy in different levels. Some of these allow even an unauthorized access to data of other applications and users.

We conducted a user survey to understand knowledge and perception of users about pre-installed applications and observed that most of the participants have limited knowledge about pre-installed applications and their activities. One takeaway is that users should be informed better about pre-installed applications and their effects on user security and privacy. For this purpose, we developed a website [17] and published our analysis results for each device we analyzed.

We developed a scoring system based on three criteria; the difficulty of exploiting, the impact on security and privacy, and the awareness level of users. We evaluated and graded 10 different findings with these criteria. The sum of individual scores gave us a final device score. With this device score, users may easily form an opinion concerning the security and privacy impacts of pre-installed applications.

To sum up, pre-installed applications in Android devices can affect security and privacy of users in multiple ways. However, this topic has not drawn much attention in academic literature. We encourage researchers to take advantage of our available dataset. We believe there are still many aspects of pre-installed applications awaiting to be uncovered.

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1) Please select your age range.
   a. Under 18 years old
   b. 18-24
   c. 25-34
   d. 35-44
   e. 45-64

2) Please select your gender.
   a. Female
   b. Male

3) What is your educational background?
   a. Primary School-Secondary School
   b. High school
   c. Bachelor (BSc)
   d. Master of Science (MSc)
   e. Doctorate (PhD)

4) Are you professionally interested in cyber security / mobile security?
   a. Yes
   b. No

5) Where did you buy your smartphone?
   a. Technology Store, Telecommunication Company, Local Store, 2nd Hand Seller, Online Market etc. (Text Box)

6) How much money did you pay for your smartphone?
   a. Under 130 $  
   b. 131-350 $
   c. 351-700 $
   d. 701-1400 $

APPENDIX
7) How long have you been using your smartphone?
   a. 0-1 Year
   b. 1-2 Years
   c. 2-5 Years
   d. 5 Years and above

8) How often do you change your smartphone?
   a. 0-1 Year
   b. 1-2 Years
   c. 2-5 Years
   d. 5 Years and above

9) How many pre-installed applications (already installed
   on the device when the device came out of the box) do you
   think there are when you first bought your phone?
   a. 0-20
   b. 21-100
   c. 101-200
   d. 201-300
   e. 301-400
   f. 400 and above

10) When purchasing a smartphone, select the factors that
    affect your purchasing decision. (Note: Users can choose
    multiple choices)
    a. Price
    b. Model
    c. Popularity
    d. Country of manufacturer (Samsung South Korea, Huawei
       China etc.)
    e. Security and Privacy Policy of the Manufacturer / Seller
    f. Sold / manufactured by large and well-known companies

11) While setting up your smartphone, have you been
    informed about the pre-installed applications and the
    operations these applications perform and the data they
    collect?
    a. Yes, I have been informed.
    b. No, I haven't been informed.
    c. I did not pay attention / I did not read.

12) Have your permission on these matters been received?
    a. No, it has not been received.
    b. Yes, it has been received.
    c. I did not pay attention / I did not read

13) Do you pay attention to what permissions the apps you
    install on your phone use?
    a. No, I don’t pay attention.
    b. Yes, I pay attention.

14) Do you regularly check these permissions?
    a. Yes, I’m checking.
    b. No, I’m not checking.

15) Do you control that applications on your smartphone
    are up to date?
    a. Yes
    b. No

16) Do you know enough information about General Data
    Protection Regulation (GDPR)?
    a. Yes
    b. No