# MobiScope: A Practical Platform to Monitor Mobile Internet Traffic

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## ABSTRACT

Existing platforms to monitor mobile Internet traffic fall short of being practical because they fail to be either portable, pervasive, passive, or deployable. In this paper, we present *MobiScope*, a practical VPN based platform solutions to monitor mobile Internet traffic. We posit that *MobiScope* can be used to monitor the mobile Internet traffic regardless of the mobile operating system, source of the mobile application, access technologies, and ISPs serving the mobile device. *MobiScope*'s practicality is powered by some novel functionality provided by Mobile OSes to manage VPN tunnels, namely, *VPN On-Demand* by iOS and [**TBD: ...**] by Android.

We use *MobiScope* to detail the characteristics of iOS Push Notifications, compare the behavior of popular social networking apps across Android and iOS, and study the [**TBD:** ] populars in the Apps in the Android and [**TBD:** ] number popular apps in the iOS market. In our experiments and measurement studies we observe [**TBD:** ] ...

## 1. INTRODUCTION

Our contributions are as follows

- We posit that VPNs can be used build a practical platform to monitor mobile Internet traffic regardless of the mobile operating system, device type, access technologies, and service provider.
- We present *MobiScope*, a practical platform for comprehensive monitoring of mobile Internet traffic. *MobiScope* builds on existing functionality provided by Mobile OSes to manage VPN tunnels.
- We use *MobiScope* to compare the behavior of popular mobile applications over Android and iOS. We observe [**TBD: values come here**]. We also compare the behavior of these application over Wifi and 3G.
- [**TBD: Results based on Amy work**].
- [**TBD: Results from an on going IRB based study of 30 users. We use these results to compare our observations from exisiting studies. The key take home is that these measurements were did not require custom OSes, ISP support, or support from marketplaces, warranty voiding of devices.**]

[**TBD: Things to highlight in Intro**
**Tools**
**Techniques**
**Methodology**
**Insights**]

## 2. MOTIVATION

The current mobile ecosystem is very opaque and it offers researchers a limited view into how mobile devices and the installed apps generate network traffic. This lack of transparency is currently being addressed by either instrumenting the mobile operating system (OS), instrumenting the binaries, static analysis of app binaries, or relying on ISP traces. In this section, we discuss each of these techniques and use their shortcomings to motivate the need for *MobiScope*, a VPN based platform to monitor mobile Internet traffic.

Instrumenting a mobile OS system using tools such as Taintdroid [5] and AppFence [8] provides researchers a fine grained view of the apps and OS in action. For example, Hornyack *et al.* [8] use AppFence to detail the internals of the 1100 most popular Android apps. The major shortcomings of instrumenting OSes is that it can result in warranty voiding of the device and that the measurement results are limited to a specific OS version and apps written for that OS version. Longitudinal studies that detail the impact of OS code changes and app code changes cannot be performed by instru-

menting OSes. Furthermore, because the app code is tightly coupled to the API provided by the underlying OS, the results obtained by instrumenting one mobile OS cannot be extrapolated to other mobile OSes. Instrumenting an OS also results in a high barrier to entry for practical studies that require participation of end users who may be unwilling to modify the underlying OS and void the warranty of their devices. [**TBD: The tone should move towards network monitoring and that OS instrumentation is an overkill for network measurements.**]

Instrumenting app binaries at predefined code points can be used to detail the behavior of a specific set of apps. One of the biggest advantages of instrumenting apps is its low barrier to entry because it does not require an OS modifications. This low barrier to entry was one the key motivations for the development of AppInsight [11]. Indeed AppInsight can provide a detail analysis of apps, however, in terms of the network footprint of the app, the scope of AppInsight is limited to the instrumented apps, the marketplaces from where the apps are downloaded, and the OS version for which the app was instrumented. Furthermore, each new version of the app needs to be instrumented.

Static analysis of the app code is used to study apps when the apps and the underlying OS are secured to avoid being tampered. For example, PiOS [4] was used to perform static analysis of 1400 IOS apps by static analysis. The authors of PiOS observe that the unique ID of the device is leaked by more than half of the apps they analyzed. A shortcoming of this study is that the PiOS can access the app binaries only after the iOS device is jail-broken, thus voiding the warranty of the device. Furthermore, like AppInsight [11], the results of PiOS are limited to the iOS operating system. [**TBD: Text for SPARTA project at UW.**]

ISP traces are useful to study mobile devices in the wild. Viallina-Rodriguez *et al.* [16] use an ISP trace of 3 million subscribers to detail the impact of ads and analytics on the mobile data and energy consumption. Similarly, Maier *et al.* [10] study the mobile traffic by looking at the DSL traces from a popular European ISP. However, these studies cannot provide a comprehensive view of the traffic from mobile devices because users can access the Internet using different ISPs depending on their location and the access technology used to connect to the Internet. For example, the home wi-fi and office wi-fi may be served from ISPs that are different from the ISP used for cellular data traffic.

In summary, existing solutions to measure the network characteristics of mobile network traffic fall short of being either portable, pervasive, passive, or deployable. In the next section we show that a VPN based platform can address these issues to get a network perspective of mobile devices.

[**TBD: Discuss new OSes coming out. .. Ubuntu, Firefox OS, etc**].

# 3. VPN BASED MOBILE MEASUREMENT PLATFORM

In this section, we begin by enumerating the goals for a practical mobile measurement platform. We then show how VPNs can be used to achieve the described goals, and present empirical results that demonstrate the feasibility of *MobiScope*, a VPN based platform to monitor mobile Internet traffic.

## 3.1 Goals

Our primary goal was to built a practical platform that can provide comprehensive visibility into the Internet traffic from mobile devices. To meet this goal, we further identify the following sub-goals we believe are important to make the platform practical.

1. *Portable.* We want our platform to work regardless of operating system, access technology, and service provider. Portability ensures that the measurement studies can performed to compare different OSes, access technologies, and service providers in action.
2. *Pervasive.* For maximum transparency, our platform should provide seamless visibility into all network traffic generated by devices. Pervasiveness ensures that the measurement results are realistic and can be used to study real users including those that use mobile devices "on the move."
3. *Passive.* For comprehensive measurements that are independent of user triggers, we want our platform to passively perform measurements. Passiveness also ensures that the system is capable of capture the network traffic even when the devices are *idle*.
4. *Deployable.* Our platform should be easy to use, immediately deployable, and have a low barrier to entry. A deployable platform implies that real end users can take part in measurement studies.

In summary, we use portability, pervasiveness, passiveness, and deployablity as the building blocks to define a practical platform to monitor mobile Internet traffic.

## 3.2 Description

We posit that VPNs can be used to build a platform to attain our goals. Our motivation was the use of VPNs by corporate executives "on the move" to securely connect to corporate servers with their mobile device. The use of VPNs by corporate clients gave us hints towards the portability and deployability of VPNs. Further investigation showed us that Mobile OSes expose features that can make them pervasive and suitable for passive monitoring of mobile Internet traffic.

### *3.2.1 Mobile Devices*

VPNs are deployable and portable because Android, BlackBerry, Bada, and iOS all support VPNs tunnels over Wi-Fi and the cellular interface. We now provide an overview of the features that make them pervasive.

All iOS devices (version 3.0 and above) come with a feature called "VPN On-Demand". *VPN On-Demand* forces the iOS device to use VPN tunnels when connecting to a specified set of domains. Using trial-and-error, we discovered that VPN On-Demand uses suffix matching to determine which domains require a VPN connection. We extend this feature to ensure that a VPN tunnel is used when an iOS device connects to the Internet.

Android version 4.0 and above comes with native VPN support. Unlike iOS, Android does not offer an equivalent of *VPN On-Demand*; however, Android provides an API that allows an user space app to manage VPN connections. We modify the open source StrongSwan VPN client [13] to ensure that the VPN reconnects each time the preferred network changes (*e.g.*, when a device switches from cellular to Wi-Fi). As of Android 4.2, Android supports "Always On" VPN connections that uses VPNs to tunnel all the data traffic. [**TBD: text on Always ON**].

#### 3.2.2 VPN Server

We believe that any practical platform should be based on *off-the-shelf* hardware using open source software. Open source VPN solutions to manage VPN tunnels include Strongswan, Openswan, and OpenVPN. *MobiScope* uses Strongswan [12] because it is the only open source solution that can use the IPsec services of the Linux kernel *without any kernel modifications*. We emphasize on VPN tunnels created using IPsec, though PPTP and L2TP can be used to create VPNs tunnels, because the *VPN On-Demand* feature of iOS is supported only for VPN tunnels that use IPsec. Furthermore, Strongswan also supports IKEv2 [9] protocol used by Android clients and the IKEv1 [7] protocol used by iOS devices. Thus Strongswan, which is used the IPsec services of the Linux kernel ensures that VPN tunnels can be managed using *off-the-shelf* hardware and open source software.

#### 3.2.3 Measurement Platform

As shown in Figure 1 mobile devices tunnel all their Internet traffic through *MobiScope* using VPN tunnels that are managed by Strongswan. The Android users need to install a certificate and fill our five fields while iOS users need to install a configuration file. This step, performed only once, is required to configure the key exchange algorithms that drive the VPN tunnels. After this installation step, all Internet traffic from the mobile device flows through *MobiScope*. This simplicity is important for practical and realistic measurement studies

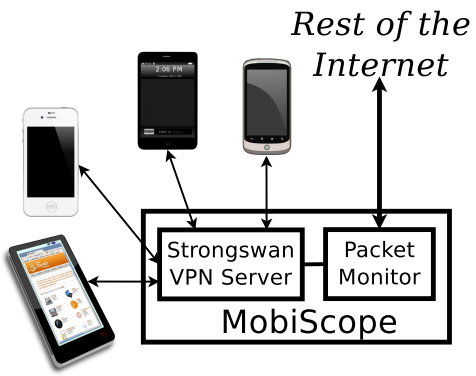


Figure 1: *MobiScope* description. Mobile clients use VPNs to tunnel their data traffic through *MobiScope*.

with end users.

We now present the technique we used to monitor the traffic. *MobiScope* uses NAT to divert the packets encapsulated in the VPN tunnels to Internet. In the ideal scenario, the encapsulated packets from the mobile device would be tunneled to *MobiScope*. On *MobiScope*, these packets would be decapsulated and the packets would then undergo NAT before leaving for their intended destination. The packets from the mobile clients to the Internet could be monitored before they undergo NAT. However, due to the existing network stack implementation, the packets from the Internet that are destined to the mobile clients undergo NAT and IPSec encapsulation take place in one step. The inter-dependencies between these various modules responsible for routing, NAT, and IPSec make it difficult segregate and monitor the packets. We address this issue by looping the packets through a virtual (*tun/tap*) device. The looping of packets through a virtual device allows us to monitor the packets when they are outside the VPN tunnels and have not undergone NAT. We use tcpdump to monitor the packets that flowing through *MobiScope*.

In summary, mobile VPNs are portable and deployable because they are natively supported by popular mobile operating systems. We build on existing features provided by iOS and Android to make sure that the VPN tunnels are pervasive and are created passively. We rely on the open source Strongswan VPN daemon to manage VPN tunnels which makes *MobiScope* deployable. We plan to release the source code to segregate and monitor the packets that flow through *MobiScope*.

### 3.3 Feasibility

By using *MobiScope*, all the mobile Internet traffic shall flow through the VPN server. The redirection when using *MobiScope* implies that all services that of-

fer features based on IP address of their clients shall react according to the IP address of the server rather than the IP address of the mobile client. Furthermore, some ISPs are known to block VPNs. During our measurement we observed one such ISP that blocked VPN tunnel creation requests from one of our clients. Redirection also implies an increase in latency. We now show that the cost of tunnel traffic in terms of latency, data consumption, and power is sufficiently low.

#### 3.3.1 *Latency Overheads*

The iOS devices use IKEv1 to manage the VPN tunnels while Android devices support both IKEv1 and IKEv2. To establish the VPN tunnel, IKEv1 requires a total 16 packets to be exchanged between the mobile client and the VPN server while IKEv2 requires 4 packets. We use IKEv2 for our Android devices while IKEv1 is used for the iOS devices.

We performed controlled experiments using one Android device and an iPhone 5 to measure the time required to establish a VPN tunnel. We performed this test from two different locations and performed **!number!** of connections over **!!** hours. These two locations were based in the same city in which the server was deployed. For the Android device, we observe a median connection establishment time of **!0.62!** seconds from both locations when using Wi-Fi with a maximum of **!0.81!** seconds. The median connection establishment time was **!0.81!** seconds with a maximum of **!1.59!** seconds from both locations when the Android device used cellular networks to establish the tunnel. Compared to the Android device, the iOS devices required a larger amount of time to establish the connection. We observed a median connection establishment time of **!1.60!** seconds and **!1.34!** seconds with a maximum of **!2.0!** seconds and **!1.48!** seconds respectively from the two Wi-Fi networks; in the case of cellular networks we observed a median of **!1.80!** seconds and **!1.65!** seconds with a maximum of **!2.18!** seconds and **!1.87!** seconds respectively.

#### 3.3.2 *Data Consumption*

IPSec encapsulation slightly inflates packet sizes, in addition to preventing carrier middleboxes from applying their own compression. We measured the overhead of the tunnel in terms of data overhead from IPsec headers and keep-alive messages, finding that it ranges from **!8–12.8!**%.

For our measurements, we capture the encrypted packets exchanged by our *MobiScope* servers and the mobile clients that use *MobiScope*. We performed the packet capture for **!30!** days during which **!25!** devices tunneled their traffic via *MobiScope*. During this time interval we also capture the packets that were encapsulated in the IPsec packets. We use these samples to compute the increase in the amount of bytes transferred due to encapsulation and the keep-alive messages. During the **!30!** day period we observe that the median of the increase to be **!8.31%!**, with a maximum increase of **!12.8%!**.

#### 3.3.3 *Power Overheads*

[**TBD: Daves results**]

[**TBD: In summary, we show *MobiScope* is feasible to build and deploy**]

### 3.4 Discussion

In this section we show that VPNs can be used for comprehensive monitoring of mobile Internet traffic. Our *MobiScope*, a VPN based platform, has a low barrier to entry and can be built using *off-the-shelf* hardware and open source software. We show that *MobiScope* is feasible. [**TBD: We now do ...**]

## 4. CONCLUSION

Placeholder

## 5. ALL PLACHOLDER SECTIONS COME HERE

## 6. DATASET DESCRIPTION

In this section, we describe the three datasets: *mobAll*, *mobCompare*, and *mobileExpt*. We use these datasets in our studies that we present in the subsequent sections.

[**TBD: Run genDataSetDescription.R to get these numbers**] The *mobAll* dataset consists of mobile data traffic traces from **!25!** devices that belong to **!19!** users who are volunteers of an IRB approved study. This dataset consists of **!9!** iPhones, **!4!** iPads, **!1!** iPodTouch, **!10!** of Android phones, and **!1!** of Android tablet. Though *tablets* can access the Internet via a cellular data connections, we consider tablets to be devices that only use Wi-Fi to access the Internet. The Android devices in this dataset include the Nexus, Sony, Samsung, and Gsmart brands. The users of the 25 devices are spread across France and USA. This dataset consists of **!176!** days of data that flowed through our VPN servers; the number days for each user varies from **!5!** to **!176!** with a median of **!32!** days.

[**TBD: we need some wording and consitency for the usage of ISP – for example ATT can provide cellular and DSL. Also mobile data cannot be used and we need some word for cellular data and wifi data and this must be defined in the dataset description.**] The *mobAll* dataset consists of data traffic from **!54!** distinct ISPs, of which **!10!** provided cellular services. Of the 19 devices that used cellular data, we observed that 16 devices restricted their cellular data traffic to one ISP each; the other three

users used four, two, and two ISPs respectively. The number of Wi-Fi ISPs per device was larger, the median number of ISPs observed was 4 with a maximum of 24 for one user. The user who contributed 24 distinct ISPs used *MobiScope* when traveling across 6 different countries. This implies *MobiScope* was able to capture traffic of users "on the move." Campus wide studies such as [**TBD:** ], studies on DSL networks [10], and studies limited to traces from one specific ISP [16] are not able to capture this behavior.

The *mobCompare* dataset consists of data from two users who had three and two devices respectively. The three devices that belong to one of the two users consists of a two smart phones and a tablet, while one smartphone and a tablet belong to the second user. We use this dataset to compare the behavior of popular apps and to detail the behavior of devices when the device is kept idle. The data set consists of **!number!** of days of data from each device and [**TBD: number**] of days for which data traffic was seen for all the 24 hours.

The *mobileExpt* dataset contains the traffic traces from an Android device and an iOS device that were used to perform a controlled experiment on popular application. We tested **!number!** of Android applications and **!number!** of iOS application for this study. [**TBD: How we decided this list**]. [**TBD: How we performed the test**] [**TBD: other attributes of this dataset**].

## 7. MEASUREMENT RESULTS

[**TBD: In this section we ...** ]

### 7.1 Descriptive Statistics

We now use several descriptive statistics to summarize our *mobAll* dataset. We use these descriptions to support our claim that *MobiScope* can be used as a portable, pervasive, and deployable platform for passive measurements of mobile network traffic.

#### *7.1.1 Comparison of Devices*

One advantage of using *MobiScope* is that we can detail and compare the behavior of mobile devices regardless of the underlying operating system. We now use Table 1 to directly compare Android and iOS, focusing on the key protocols used by the devices.

Our first key observation is that HTTP is responsible for the majority TCP traffic volume in bytes, **!63.13%!** for Android and **!80.28%!** for iOS. This observation is inline with previous results that report HTTP to be the dominant protocol used by mobile devices [6, 10]. We also observe that the majority of TCP flows are sent over SSL, **!43.77%!** of total flows for Android and **!32.18%!** of total flows for iOS . We believe this occurs across platforms because the majority of flows come from e-mail, messaging and social networking, all

| Protocol | Service | Android | | iOS | |
|---|---|---|---|---|---|
| | | Flows | Bytes | Flows | Bytes |
| TCP | HTTP | 13.55 | 63.13 | 14.64 | 80.28 |
| TCP | SSL | 43.77 | 31.36 | 32.18 | 18.98 |
| UDP | - | 37.23 | 1.09 | 47.32 | 0.55 |
| TCP | other | 2.24 | 4.30 | 1.55 | 0.15 |
| Other | - | 3.19 | 0.10 | 4.03 | 0.01 |
| *total* | | 100.00 | 100.00 | 100.00 | 100.00 |

Table 1: Percentage of flows and bytes from iOS and Android devices. [**TBD: Verify total 100 for final results**] *SSL is responsible for the majority of TCP flows from iOS and Android devices.*

of which use secure channels regardless of the OS. We discuss some of these popular application in [**TBD: section**].

For the Android devices in the *mobAll* dataset, **!96.45%!** of the UDP flows that account for **!70.92%!** of the UDP bytes are due to DNS request. The rest of the traffic is due to other applications such as Skype. Similarly, **!80.98%!** of UDP flows that account for **!66.29%!** of UDP bytes from iOS devices are due to DNS requests.

We observe 0.1% of the traffic volume was classified as *other* for Android device which is larger than the 0.01% observed for iOS. This is because the Android users in our dataset tend troubleshoot network connectivity issues using applications that perform pings and traceroutes.

On balance the number of bytes transferred per unit time in Android, and the number of flows, is larger than the same for iOS. We found that iOS devices generated about **!number!** of traffic per hour while Android devices generated about[**TBD: number**] MB/hr, and increase of **!number%!**. Further, Android devices contributed more flows (**!number!** per hour vs. **!number!** per hour), an increase of **!40%!**. It is difficult to account for the impact of user behavior on device-generated traffic; that aside, one explanation is that Android devices generate more bytes and flows due to the relatively permissive API for running code in the background on Android. In contrast, iOS quickly kills processes that are in the background, preventing them from generating network traffic after only a few seconds of losing the foreground. We discuss this [**TBD: section**]

[**TBD: In summary,** ]

#### *7.1.2 Comparison of Access Technology*

*MobiScope* allows us to passively monitor traffic regardless of the access technology used by the mobile device. We use this feature of *MobiScope* to provide a direct comparison of how the different access technologies are used by our users.

In Figure 2 we present the share of Wi-Fi as a fraction of the total traffic generated by the user. The devices

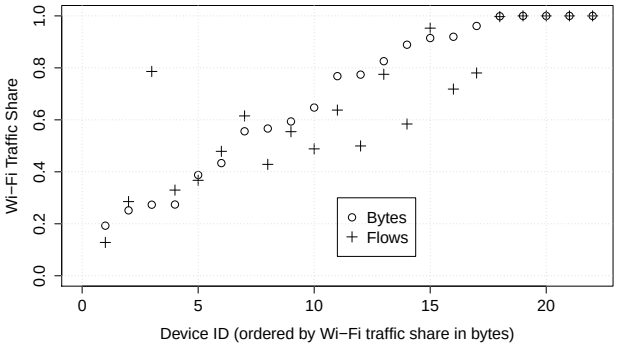


Figure 2: Traffic share of Wi-Fi as a fraction of total traffic from a device.

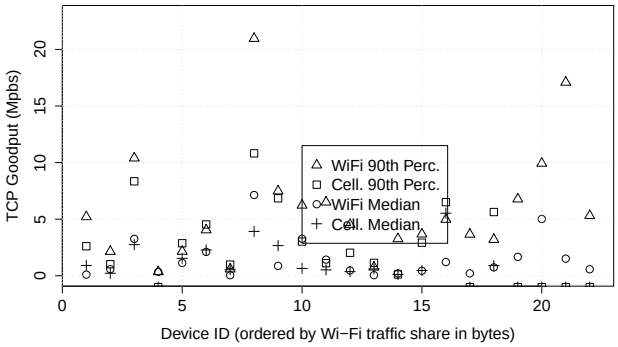


Figure 3: Goodput of TCP flows over Wi-Fi and cellular networks.

| Protocol | Service | Wi-Fi | | Cellular | |
|---|---|---|---|---|---|
| | | Flows | Bytes | Flows | Bytes |
| TCP | HTTP | 16.14 | 81.59 | 10.99 | 57.08 |
| TCP | SSL | 32.56 | 16.97 | 43.99 | 39.59 |
| UDP | - | 46.29 | 0.52 | 38.56 | 1.25 |
| TCP | other | 1.43 | 0.89 | 2.46 | 1.97 |
| Other | - | 3.55 | 0.02 | 3.96 | 0.09 |
| *total* | | 100.00 | 100.00 | 100.00 | 100.00 |

Table 2: Percentage of flows and bytes using Wi-Fi and Cellular as access technology. [**TBD: Verify total 100 for final results**] *The share of SSL traffic over Cellular networks is larger than its share over Wi-Fi in terms of bytes and flows*

are sorted according to the share of Wi-Fi traffic as a fraction of the total traffic from the device. The devices with device IDs from **!18!** to **!23!** are devices that do not have a cellular data plan associated with them device: **!3!** iPads, **!1!** iPodTouch, and **!1!** Android tablet. The diversity in Wi-Fi traffic share in terms of flows and bytes indicates the diversity of mobile device usage. For example, device ID **!3!** is used by a user who prefers to use cellular network to listen to music, watch videos, and troubleshoot the cellular network connectivity issues using tools such as speedtest; the primary use of the device is used to read emails and access social networks when on Wi-Fi. Media content such as music and videos have a higher share of traffic volume per flow, therefore the share of cellular traffic in higher for device ID **!3!**. Similarly, device ID **!1!** is used by a user who prefers to use cellular networks.

In Table 2 we further classify the protocols and services that are responsible for Wi-Fi and cellular data traffic with the help of the techniques used to generate Table 1. The first key observation is that the portion of HTTP bytes sent over Wi-Fi and cellular are significantly different. Upon further inspection, we found that Wi-Fi is the preferred medium to transfer media content, which generates relatively large flows. For example, apps such as Google Plus image backup on Android allow users to upload their images only over Wi-Fi. In line with the difference in HTTP traffic ratios, we note that SSL flows are dominant type in cellular connections. We also observe a smaller number of UDP flows for cellular networks. [**TBD: Why do we observe less??**].

In Figure 3, we present the 90th percentile and median TCP goodput of flows that exchanged more than 512 kB of data. [**TBD: cite [2] if needed for 256 kB**]. We use the goodput because it a good estimate of how the applications perceive the quality of the network. The devices are sorted according to the same technique used to sort the devices in 2. For device 16 we observe higher goodput for cellular compared to Wi-Fi while for device 6 we observe similar values for the TCP goodput; this highlights opportunities for proposals such as 3G onloading [15]. Across all users we observe that ratio of median goodput over Wi-Fi to the median goodput over cellular varies from ! ! to ! ! with a median of !!.

[**TBD: In summary,** ]

### 7.2 Case Studies

### 7.3 Controlled Experiments

### 7.4 Discussion

## 8. RELATED WORK

Placeholder for the papers. [14]
[3]
[16]
[6]
Bro port based classification of HTTP, SSL, other, and so on.

## 9. CLASSIFICATION OF APPLICATION

*MobiScope* enables us to monitor the data being exchanged by the mobile device. However, it does not provide any details of the source of the data. We use the following technique to estimate the source of the mobile data traffic. In 1 and 2 we observe that TCP is responsible for the majority of the traffic volume from iOS and Android devices regardless of the access technology used. We therefore focus on associating TCP flows to the applications for our analysis. From our analysis we were able to classify !x%! of the TCP traffic volume and !y%! of the TCP flows to the applications.

### 9.1 Methodology

### 9.2 Results

User Agent based classification flows per user with a blank user agent. flows per user with a default user agent flows with application in user agent

SSL certificate based classification flows to dedicated hosts flows to cdns

### 9.3 Discussion

## 10. SPECIFIC APPLICATION BEHAVIOR

## 11. ADS AND ANALYTICS

Ads and Analytic sites have received considerable attention. The reason for the attention being the intrusiveness exhibited by the ads and analytics sites in tracking personal information. [16] show that ! ! of data traffic volume observed from a Cellular ISP is because of mobile ads. In our traces we use the classification of [16] and [1] to classify flows as ads flows.

## 12. DISCUSSION ON PLATFORM

IPv6 support of VPNs

ISP support of VPNs. One ISP blocked VPN access.

Open source ??

Releasing datasets ??

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