

Analysis of a Wi-Fi Hotspot Network

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Abstract

Wireless hotspot networks have become increasingly popular in recent years as a means of providing Internet access in public areas such as restaurants and airports. In this paper we present the first study of such a hotspot network. We examine five weeks of SNMP traces from the Verizon Wi-Fi HotSpot network in Manhattan. We find that far more cards associated to the network than logged into it. Most clients used the network infrequently and visited few APs. AP utilization was uneven and the network displayed some unusual patterns in traffic load. Some characteristics were similar to those previously observed in studies of campus WLANs.

1 Introduction

In recent years, deployment of Wireless Local Area Networks (WLANs) has boomed as demand for wireless Internet access grows and IEEE 802.11 technology matures. 802.11 WLANs can now be found in offices, homes and campuses. One increasingly-popular use for 802.11 networking equipment is to provide wireless ‘hotspots’, that is, providing wireless Internet access in popular public places such as airports, shops and cafés. An understanding of how these hotspot networks are used can guide network design, hotspot deployments, and the development of technologies to be used on WLANs.

In this paper we present one of the first studies of a deployed 802.11 hotspot network. We collected a network activity trace lasting approximately five weeks from the Verizon Wi-Fi HotSpot network. We analyze the network in terms of users, Access Points (APs) and traffic, and compare some of our findings with those for a college campus wireless network and a corporate wireless network.

In the next section, we review related work. In Section 3, we describe the study environment and in Section 4 we describe the tracing methodology. Section 5 presents the most interesting features of the data and compares them to results obtained in previous studies of WLAN usage. In Section 6 we formulate our conclusions.

2 Background and related work

Recent studies have characterized wireless network usage in a variety of environments. Tang and Baker studied a packet radio network composed of nearly 25,000 radios distributed across three major metropolitan areas [10].

Balachandran et al. analyzed WLAN usage over three days in a conference setting [2]. Kotz and Essien examined a college campus wireless network when it was first installed in 2001 [7]. Henderson et al. returned to the same network after it had matured in 2003/2004 [6]. Two other campus WLANs that have been studied include the University of North Carolina [4, 8] and the University of Saskatchewan [9], while Balazinska and Castro analyzed usage of a corporate WLAN [3].

While hotspots are a popular topic in both the business and research worlds, we are unaware of any other papers that examined a deployed hotspot network. Balachandran et al. examined the challenges facing hotspot networks [1], while Verhoosel et al. proposed a generic hotspot business model [11].

3 The Study Environment

Network: The Verizon Wi-Fi HotSpot network (VWHN) consists of 312 APs distributed around the island of Manhattan.¹ APs are installed in the ceilings of Verizon-owned phone booths. Each AP is a Proxim OriNOCO AP-2500 802.11b AP², enclosed within a weatherproof box containing the AP, a DSL modem, a power regulator, and an external antenna. APs are connected to the Internet by a 1.5 Mbps downstream and 768 Kbps upstream ADSL connection. In the weatherproof boxes, the APs have a maximum range of close to 300 feet but in practice, due to environmental interference, an AP’s effective range is approximately 150 feet.

Although all APs share the same SSID, the VWHN does not support roaming between APs. When moving from one AP to another within the network, a user must reauthenticate to obtain Internet access at the new AP.

Users: The VWHN is currently provided solely as an amenity service to Verizon Online (VONL) DSL and dial-up customers. Customers of these services use their VONL username and password to log on to the network. As of December 2004, 10,511 unique VONL accounts had been used to log on to the VWHN.

Test accounts were also distributed to Verizon employees, who routinely access the network for maintenance purposes. Although 30 to 40 of these accounts exist, fewer than ten were in use during the study pe-

¹A full list of available Verizon Wi-Fi HotSpots organized by region is available online at <https://www33.verizon.com/wifi/login/locations/locations-remote.jsp>

²Specifications at <http://www.proxim.com/products/wifi/ap2500/>

riod. Service technicians routinely associate and log into the network for maintenance purposes. Their usage, however, tended to skew the distribution of data and so we eliminated their cards from the study. A company named UDN uses the network to distribute files to electronic signs installed above subway entrances. Usage for UDN users was also atypical and their data have been excluded.

Authentication, Authorization, and Accounting: To obtain Internet access at a Verizon Wi-Fi HotSpot, a user must first log into Hotwire, a proprietary hotspot management system developed within Verizon. To log in, a user first associates to the AP and opens a web browser, which is redirected to a web page requesting a username and password. Access is granted upon submitting a valid username and password. Prior to login, an associated user's Authentication, Authorization, and Accounting (AAA) state is considered *pending* at the AP. After login, it is considered *valid*. A user may also have an *unknown* AAA state before sending any packets to the AP. A user in this state is treated as a pending user because they have similar access privileges [5].

A user may log out by clicking on a logout button provided to them at login or have their session terminated after 15 minutes of inactivity. In addition, Hotwire automatically logs out users logged on for over seven hours whether or not they are still sending or receiving data.

4 Methodology

We used the Simple Network Management Protocol (SNMP) to poll APs every 5 minutes from Nov 15, 2004 to Dec 20, 2004. Polls collected information on users including MAC address, AAA State, and bytes sent and received. Once received, messages were time-stamped using the poller's clock. Traffic counts were not reset by a change in AAA state. A total of 746,397 relevant records were logged.

A 5 minute interval was used to obtain data frequently without affecting AP operations. Moreover, entries in the AP-2500's Current Subscribers table are removed after approximately 10 to 11 minutes of inactivity. A 5 minute poll interval ensures that we observe most users associating to APs. In the results that follow, we round down when calculating session lengths — if a user i is seen at times t_0 , t_1 , but not at t_2 , we assume that their session began at t_0 and ended at t_1 .

During the study period, 282 of the 312 polled APs responded. The remaining 30 APs failed to respond because of technical difficulties.

There are four holes in the data caused by crashes in the data collection process: Nov. 17 to Nov. 19 (41 hours), Nov. 24 to Nov. 29 (118 hours), Dec. 4 to Dec. 5 (43 hours), and Dec. 5 to Dec. 6 (18 hours). In the following results, per-day and per-hour statistics exclude days

and hours for which only partial data is available. To build the most complete picture of the network possible, however, data for these incomplete time periods were taken into account when calculating statistics for the entire trace period. When considering quantities summed over the period of the trace, note that these numbers would be higher if the data were complete.

Users were not informed that the study was being performed. To protect privacy, individual users were not tracked, even though this may have been possible through tracking VONL accounts. To further protect privacy, to be consistent with prior similar studies, and because a VONL account does not necessarily equate with a distinct user, MAC addresses were treated as corresponding to individuals.

4.1 Definitions

AAA State: The Authentication, Authorization, and Accounting state of a card at a given AP. A card may have a *valid*, *pending*, or *unknown* state. A card has an unknown state before sending any packets to the AP [5]. Hereafter, we use the term pending to describe both the pending and unknown states because cards with these states have similar access privileges and we treated them as the same.

Card: A wireless NIC, identified by MAC address.

Valid Card: A card in a valid AAA state during a given time period at a given AP. If no period is specified, the period of the entire trace is implied. Valid cards have unrestricted access to the Internet at the AP where they are valid.

Pending Card: A card in a pending AAA state during a given time period at a given AP. Pending cards have Internet access limited to certain VWHN-related websites. A valid card is not guaranteed to be seen as pending even though it must have been pending at some point prior to login. Note that the set of pending cards is not disjoint from the set of valid cards.

Session: A session begins with the appearance of a card at an AP in a given AAA state (valid or pending), and ends when the card is either no longer at the AP or when the card changes AAA state.

Active AP: An active AP is an AP to which one or more cards are associated (regardless of the cards' AAA state) during a given time period.

Valid AP: An AP at which one or more associated cards was seen with a valid AAA state during a given time period.

Pending Traffic: Traffic generated by pending sessions.

Valid Traffic: Traffic generated by valid sessions.

Inbound: Traffic sent by the AP to the card.

Outbound: Traffic sent by the card to the AP.

5 Results

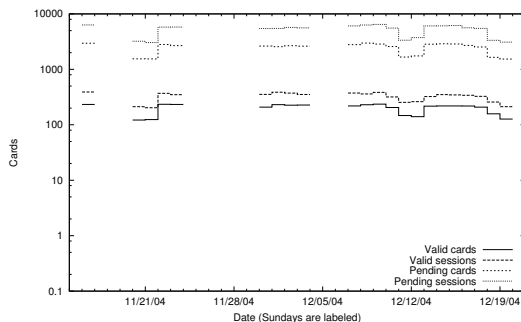
Over the 36-day trace period (which includes 22 complete days of data), we gathered 746,397 SNMP records. We saw 26,925 total cards, of which 1,682 were valid at one point in the trace. We summarize our results in a manner that facilitates comparing the VWHN with WLANs studied in other environments. In addition, we investigate usage characteristics of the VWHN that differ from previously studied networks.

5.1 Users

For a WLAN such as Verizon's, understanding the user is critical to building and maintaining a successful network.

Card Activity: Patterns in the number of valid cards for each day of the study strongly mirror the number of pending cards on the network for each day of the study (Figure 1). Some users have multiple sessions in a day, and so we observe approximately twice as many sessions as cards.

Figure 1: Cards and sessions per day. The cards and sessions for a day appear just to the right of its tic mark. Blank spaces represent holes in the data. Sundays are labeled. The x-axis is on a logscale.



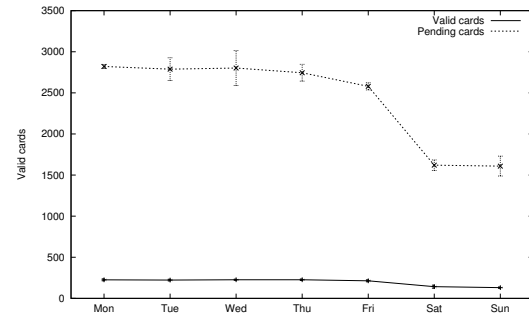
A puzzling question is raised by the small number of valid cards (1,682) in comparison to total cards (26,925) seen during the trace. Why did so many cards associate to Verizon APs but not log in (and attain a valid AAA state)? Perhaps some users are simply curious and select the VWHN SSID when they see it is an available network, or perhaps some clients' wireless networking management utilities chose to automatically associate to the network.

A median of 13% of the valid card population and 10% of the pending card population appear on any given day. A much larger portion of the user population appears daily on college [7,6] and corporate campus WLANs [3]. It appears that the VWHN is made up of many of what Balazinska and Castro term "locations visited occasionally" rather than "primary places of work" [3].

More cards are seen during the work-week than during weekends with the weekly trend for pending cards closely resembling that for valid cards (although Figure 2

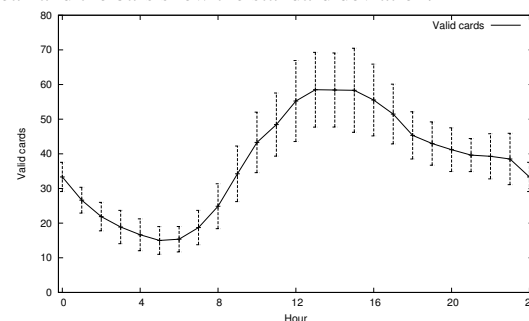
shows both valid and pending cards on the same plot to save space, both valid and pending cards follow similar trends).

Figure 2: Active and pending cards per day of the week. The curve shows the mean and the bars show the standard deviation.



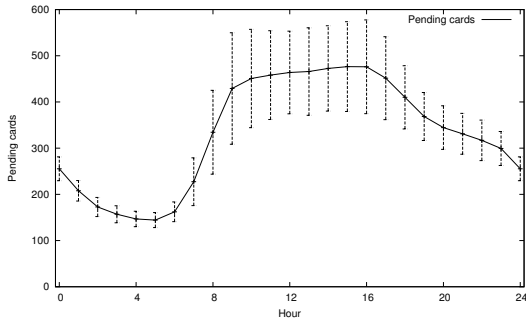
As with other wireless networks studied, Verizon's network displays a strong diurnal usage pattern (Figures 3–4). This is true for both valid and pending cards, though pending cards show greater variation in number during the busiest hours of the day. The higher numbers for pending cards during the morning commuting hours might reflect devices automatically associating as people go to work but before they begin to use the network. The number of pending cards on the network late at night is still much larger than the number of valid cards. This makes it seem unlikely that the large number of pending cards is a result of curious users. It is hard to imagine hundreds of curious users attempting to log onto an unfamiliar network late at night and in the early morning.

Figure 3: Active valid cards per hour. The curve shows the mean and the bars show the standard deviation.



Mobility: A benefit of wireless networking is that it can enable mobility; users are not tied to a particular location by network cabling. But the opportunity for mobility does not necessarily mean that users will move around. Balazinska and Castro [3] define a user's *home location* as the AP at which a user spends more than 50% of his or her total time on the network. Adopting this definition, 95.72% of valid users had a home location, and 98.34% of pending users had a home location.

Figure 4: Active pending cards per hour. The curve shows the mean and the bars show the standard deviation.



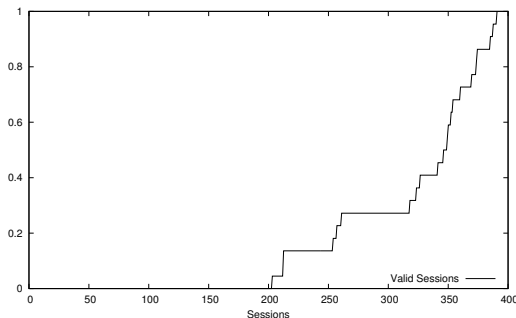
A Wilcoxon Mann-Whitney test on the distributions of time spent at the most visited AP across valid and pending cards is significant at the 1% level: more pending cards spend most of their time at a single AP than do valid cards.

23.66% of valid users and 26.93% of pending users visited more than one AP. Of these users that visited more than one AP, 81.91% of valid users and 93.84% of pending users had home locations.

In terms of home locations, the mobility of users of Verizon’s WLAN more resembles that of users of a college campus WLAN [6] than that of users of a corporate WLAN [3]. APs in the Verizon network, however, are more geographically isolated from the rest of the APs in the network than APs in a campus WLAN. A card at one AP has to travel a long distance to reach another. This distance might be a cause of the high percentage of cards with home locations.

Sessions: The elbows in the distributions of valid and pending sessions (Figures 5–6) reflect the usage drops seen on weekends (Figure 1).

Figure 5: Valid sessions per day, distribution across days. Maximum: 390. Median: 346.



Valid sessions tend to be longer than pending sessions (Figure 7), with 45.74% of valid sessions and 12.09% of pending sessions lasting more than one hour. A log-log CCDF of the valid session durations (Figure 9(a)) indicates that session durations appear to fit a power law or Pareto distribution. The knee in the valid session distri-

Figure 6: Pending sessions per day, distribution across days. Maximum: 6468. Median: 5596.

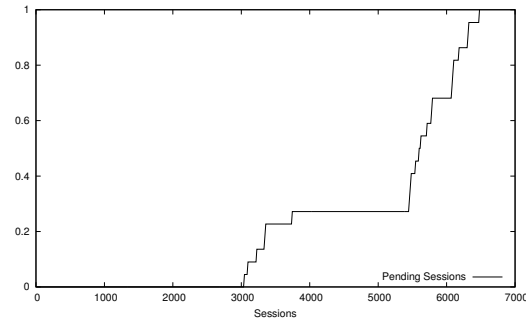
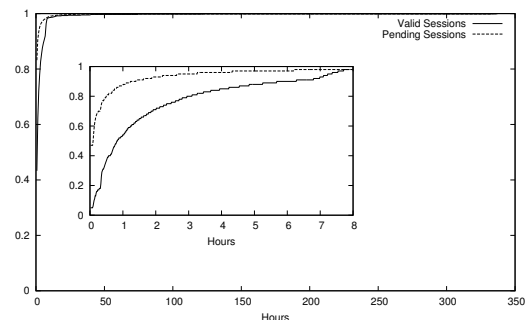


Figure 7: Session durations in hours, distribution across sessions. Maximums: 336 hours (valid), 334 hours (pending). Medians: 49 minutes (valid), 5.6 minutes (pending).



bution is caused by the fact that users are automatically logged out after seven hours (a user might appear to have a session longer than seven hours by quickly logging back in before the next SNMP poll). Considering only those sessions that last longer than seven hours, maximum likelihood estimation finds that they fit a Pareto distribution with a shape parameter $k = 1.42$ (Figure 9(b)). This is remarkably close to the session duration distribution observed on a campus WLAN [8], where a biPareto distribution is found to fit, with the long tail having a shape parameter of 1.37. We do not attempt to fit a bi-Pareto distribution to our data, as it is inaccurate at lower session durations due to the five-minute SNMP poll period, which means that short sessions are omitted from our dataset. We also find that pending session durations fit a Pareto distribution (data not shown here).

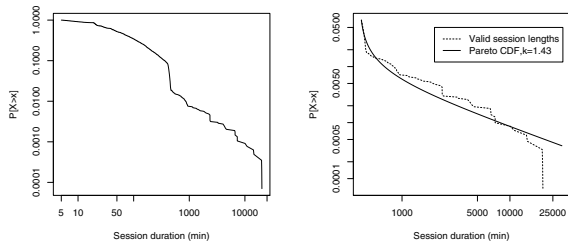
5.2 Access Points

We had 282 APs respond to SNMP polls. We now look in detail at the AP statistics.

Activity: Examining AP activity over the course of the trace, some APs see many cards while others see relatively few (figure not shown).

In testing for linear correlation (Figure 9), the proportion of variation in valid cards that is explained by the linear regression of valid cards on pending cards (r^2) is only 0.391. In other words, a device’s association with Verizon’s WLAN poorly correlates with the likelihood

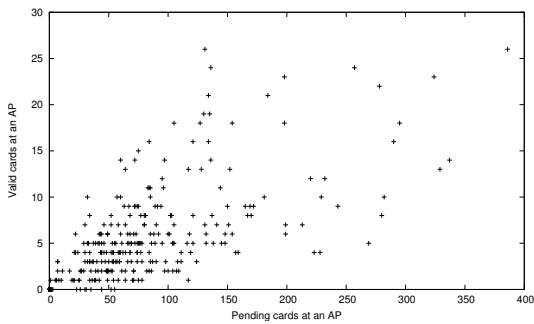
Figure 8: Log-log CCDF (Complementary Cumulative Distribution Function) of valid session durations.



(a) CCDF of all valid session durations. The linear trend shows that the data appears to fit a power law. The knee indicates the 7 hour automatic logout.

(b) CCDF of session durations longer than 7 hours. The solid line shows a fitted Pareto distribution.

Figure 9: Scatterplot of pending cards at an AP and valid cards at an AP.



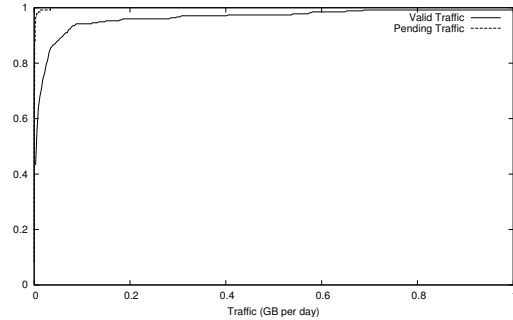
of that device actually using the WLAN. Perhaps this reflects an uneven distribution of VONL customers around the city. Or it might be that an AP's surroundings play a role in determining whether or not someone able to take advantage of the network will do so. Further investigation of the data shows that the greatest number of pending cards was seen at APs in the Midtown area, a mostly business district, while valid cards were heaviest at APs in the Upper West Side, a residential area.

Busiest periods: The hotspot APs were not particularly busy, even during peak usage periods. The greatest number of simultaneous valid sessions ever hosted by an AP was 7, whereas the most cards ever simultaneously associated to an AP was 24. The most valid cards seen by an AP during a day was 10, and the most pending cards ever seen by an AP during a day was 106. On the Dartmouth campus, in contrast, the maximum simultaneous users on one AP is 89, and the maximum cards seen on an AP in a single day is 405.

Traffic: Most APs see little traffic, but several see significant amounts (Figure 10). This pattern is similar to the traffic pattern across APs on a college campus [7, 6]

with APs handling traffic more unevenly than on a corporate WLAN [3].

Figure 10: Average daily traffic (GB), distribution across APs (CDF truncated at 1GB). Maximums: 1.56 GB (valid), 36.5 MB (pending); Medians: 4.6 MB (valid), 0.5 MB (pending).

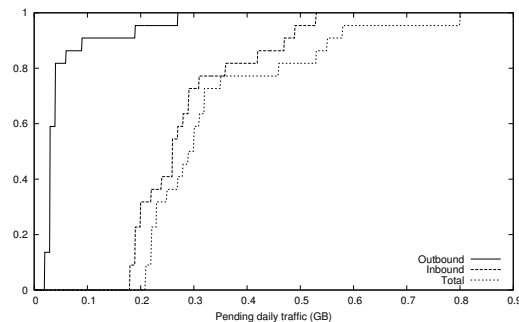


5.3 Traffic

Over the course of the trace, the network handled 281 GB of total traffic, of which 196 GB (69.9%) was inbound and 85 GB (30.1%) was outbound.

Pending Traffic: Pending traffic was mostly inbound (83.23%) although there are high outbound loads on some days (Figure 11). Pending traffic accounted for only 2.07% of total traffic. But this small percentage still totaled a median of 0.29 GB each day, which could become expensive for a hotspot provider who is paying for upstream bandwidth that is being consumed by non-customers (i.e., pending cards). Hotwire access logs show that HTTP requests from automated processes (e.g., Windows Update) being redirected to the Hotwire login page generated much of the pending traffic.

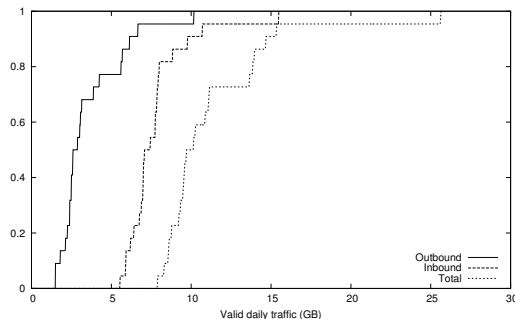
Figure 11: Daily pending traffic (GB), distribution across days. Maximums: (outbound) 0.27, (inbound) 0.53, (total) 0.80; Medians (outbound) 0.03, (inbound) 0.26, (total) 0.29.



Valid Traffic: Valid traffic accounted for the majority of traffic, with 275.42 GB of valid traffic seen during the course of the trace period. Traffic per day varied moderately during days of the trace (Figure 12). The busiest 5% of valid cards accounted for 85.52% of total traffic and 95.08% of outbound traffic. Even on its busiest day

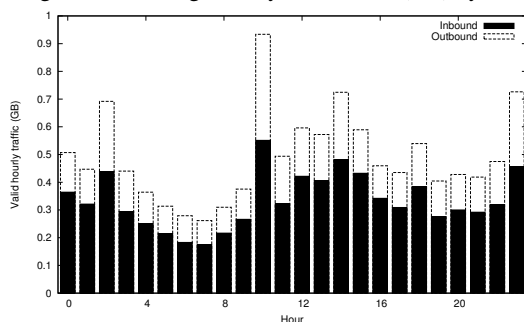
(25.50 GB), the network did not approach the average traffic loads observed on a college campus network (400 GB) [6]. Considering traffic per user, however, the average daily traffic per valid card (62.4 MB) approached that of the Dartmouth network (71.2 MB). This is interesting considering that hotspot users are limited by the capacity of the DSL connections.

Figure 12: Daily valid traffic (GB), distribution across days. Maximums: (outbound) 10.15, (inbound) 15.49, (total) 25.64; Medians (outbound) 2.60, (inbound) 7.06, (total) 9.66.



Examining valid traffic by hour, there are two peaks during the day: one in the early afternoon and one in the late evening (Figure 13). This pattern does not echo the strong diurnal pattern for valid cards shown in Figure 3. Though the midday peak corresponds with that in Figure 3, the high volume of traffic near midnight (particularly the spikes at 11 PM and 2AM) are striking. The spike at 10 AM is also odd, and was caused by an outlier: one user at a single AP on a single day.

Figure 13: Average hourly valid traffic (GB) by hour.



6 Conclusions and Future Work

This paper presents the first analysis of a production 802.11 hotspot network. We examine five weeks of SNMP traces from the Verizon Wi-Fi HotSpot network in Manhattan. We find that most users access the network infrequently, but daily, weekly, and hourly trends still emerge. Far more cards associate to the network than log in, and it is difficult to explain why. The vast

majority of cards spend most of their time at a single AP, and few cards even visit more than one AP.

APs vary widely in their utilization. Most APs were active on any given day, but fewer saw a login. The number of cards that associated to an AP is a poor predictor of the number of users that logged in.

Most network traffic was caused by valid sessions and in particular by fewer than 5% of valid users. Traffic varied across days and exhibited unusual hourly characteristics.

We intend to look further into similarities between the hotspot network data and previously-collected campus datasets. Hotspot data is somewhat harder to obtain than campus WLAN data, and our conclusions in this study we were limited by the absence of data concerning what users were actually doing on the network along with the coarse granularity of SNMP polls. It would be useful to understand what aspects of a hotspot network can be simulated or modeled using campus WLAN data.

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