What Where Wi:
An Analysis of Millions of Wi-Fi Access Points

Kipp Jones, Ling Liu
College of Computing, Computing Science and Systems Division
Georgia Institute of Technology, Atlanta, GA, USA
{kippster, lingliu}@cc.gatech.edu

Abstract— **With the growing demand for wireless Internet access and increasing maturity of IEEE 802.11 technologies, wireless networks have sprung up by the millions throughout the world as a popular means for Internet access. An increasingly popular use of Wi-Fi networking equipment is to provide wireless 'hotspots' as the wireless access points (APs) to the Internet. These APs are installed and managed by individuals and businesses in an unregulated manner – allowing anyone to install and operate one of these devices using unlicensed radio spectrum. This has allowed literally millions of these APs to become available and 'visible' to any interested party who happens to be within range of the radio waves emitted from the device. As the density of these APs increases, these 'beacons' can be put into multiple uses. From home networking to wireless positioning to mesh networks, there are more alternative ways for connecting wirelessly as newer, longer-range technologies come to market.**

This paper reports an initial study that examines a database of over 5 million wireless access points collected through systematic wardriving by Skyhook Wireless. By performing the analytical study of this data including the default naming behavior, movement of access points over time, and density of access points, we found that the AP data, coupled with location information, can provide a fertile ground for understanding the "What, Where and Why" of Wi-Fi access points. More importantly, the analysis and mining of this vast and growing collection of AP data can yield important technological, social and economical results.

Keywords: Wi-Fi; Wireless Networks; Access Points; Location Based Services

I. INTRODUCTION

Wireless networks have become increasingly popular in recent years as a means of providing Internet access and 'last meter' connectivity within homes and businesses. These networks allow limited movement within a designated area such as a home or an office while maintaining connectivity to the Internet. This use of 'tails' through the Wi-Fi connectivity to the wired network is the dominant model of wireless Internet access today. We continue to see new methods of using Wi-Fi emerge – mobile Voice over IP (VoIP), location based services, mobile emergency services – based on a growing array of applications, portable devices [1] and readily available Wi-Fi connectivity.

Commercial hotspots – Wi-Fi enabled zones – have sprouted in many places. These access points, located in the ubiquitous coffee shop, in airports, in bookstores, are currently providing Internet access to the public. Many of these APs require subscription and payment for the service, while others provide Internet access as some benefit to the public. According to Broadband Wireless Exchange[1], the top hotspot providers now have over 40,000 hotspots worldwide.

The wave of municipal wireless networks like those being rolled out in cities around the country offer another motivation for this study. Public enterprise has become extremely interested in the value that a city-wide wireless infrastructure could provide both for the efficiency and the capabilities of the public servants, as well as for the universal access that such an infrastructure could provide to help bridge the digital divide.

Some look at the sea of access points and find commercial value. Companies such as FON[2] and WiFiTastic[3] are out to help individuals monetize their Wi-Fi access points by providing authentication and billing infrastructure that turns ordinary access points into commercial endeavors. In fact, a cottage industry has sprung up dedicated to providing aftermarket modifications to standard access points[4] in order to facilitate the use for commercial or group access.

Others such as Place Lab [8] and UCSD [2] have shown that the access points need not provide active connectivity to provide value. By using the signal and identity of the myriad access points, value can be obtained by providing services such as positioning information to stationary and mobile users. And unlike systems such as GPS where the location of the beacons are known, the location and signal propagation of these access points can be learned over time and need not be complete to provide adequate location information.

Developing the understanding of how these wireless networks are being used can guide not only how to carry out more efficient hotspot deployments and network design [7], but also on how to proceed and leverage the existing investment [4]. Some representative questions include:

- How many access points are present and what are their characteristics?
- How to conduct a taxonomic analysis of network properties?
- What types of wireless networks can be designed for legitimate public use and what will their performance be?
- What should be considered as non-legitimate use of the network and how can we prevent the networks from misuse or abuse?
- How to assess the saturation of the spectrum?

In this paper, we report our initial analysis of over 5 million geolocated access points and the scanning logs associated with these

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[1] List of top hot spot providers: http://www.bbwexchange.com/top10_wi-fi_hotspot_operators.asp
[2] FON web site: http://www.fon.com/
[3] WiFiTastic web site: http://www.wifitastic.com/
[4] Companies such as Sveasoft (http://www.sveasoft.com/) provide firmware upgrades for standard access points.

access points, addressing some of the questions listed above. Our statistical analysis shows that there is significant information contained in such a large collection of APs, and the AP data can be linked with other information sources to create additional value towards developing the understanding of the many characteristics of wireless networks in general. We conjecture that the knowledge of the current infrastructure and the improvement of our network models will help increase the effective use of the networks.

The rest of the paper proceeds as follows. We first provide an overview of the dataset and the process that was used to gather this data. Then we describe the analytical results of the study, focusing on a taxonomic analysis of a selection of network properties. We also provide a short discussion on the related work before concluding the paper.

II. Approach

To conduct this study, we acquired the rights to analyze a dataset provided by Skyhook Wireless. A fleet of drivers that systematically drive urban areas to scan for 802.11 Wi-Fi access points collects this data. Skyhook Wireless gathered the current dataset during the time between April 2004 and December 2005. This data corresponds to the systematic scanning in some 75 cities throughout the United States.

The process of gathering this data is often referred to as 'wardriving', a term derived from wardialing which was popularized by the movie WarGames[5]. Wardriving is the act of locating wireless access points through the use of wireless scanning equipment within a moving vehicle.

Traditional wardriving is ad-hoc and resultant datasets are composed of numerous passes by many drivers. In these instances, the decision of which routes to drive is often made with respect to the types of roads – major roads are driven more often than minor roads. When this data is used to calculate the location of the access point, it is common to see the 'weight' of the major roads unduly influence the derived location of the access point. This effect is referred to as 'arterial bias' and is represented in Fig. 1.

However, routes for Skyhook Wireless drivers are determined such that this arterial bias is virtually eliminated, increasing the accuracy of the resultant location estimation.

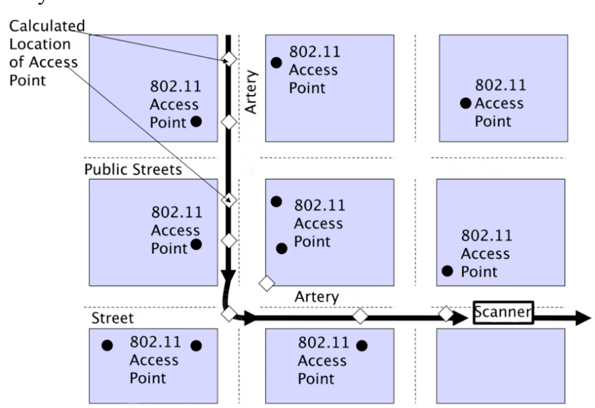

Figure 1. The effect of arterial bias on location estimation.

Efficient routing for obtaining the data can be modeled as a Chinese Postman problem. The Chinese Postman problem is defined as finding the shortest route in a network that traverses each edge. In this case, the network is the road system and we desire to find the most efficient route that traverses each segment of the roadway. While this problem has been shown to be NP-complete [10], Fredrickson [5] analyzes several approximation algorithms that provide worst-case bounds as low as $\frac{3}{2}$. By ensuring that readings are gathered from as many angles as possible, a more accurate estimation of the source can be calculated. This effect is illustrated in Fig. 2.

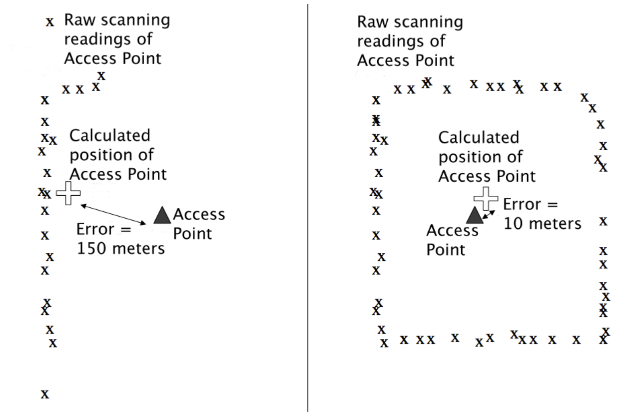

Figure 2. Reducing arterial bias by traversing all roads.

The data is logged using a proprietary scanning software package from Skyhook Wireless. The software runs on custom configured mobile devices connected to a standard GPS device via serial or Bluetooth communications. During scanning, no connections are established to the access points.

The software utilizes commercial access points to automate the upload of scanned data to a central server. Upon upload, the scanning data is processed to produce the correlation of each access point with its GPS location and signal strength information. The specifics of the algorithm for this calculation is beyond the scope of this paper; however, a number of methods and algorithms have been developed ranging from simple triangulation of signals to more complex hierarchical Bayesian sensor models [9].

The system measures the signal strength and gathers access point information from the radio signal produced by each AP. For each access point, this includes multiple records that include its name or Service Set Identifier (SSID), the Media Access Control (MAC) address and the timestamp when the AP was scanned. Unfortunately, the dataset does not include channel or security setting information that would be useful for a number of studies.

Concurrent with the logging of this data, the geolocation in the form of latitude, longitude, number of satellites, and error is captured using GPS.

The system also tracks the 'movement' or change in calculated location for each access point. For purposes of this study, the resulting processed dataset as well as the movement dataset were analyzed at two different points in time. This data was stored in a standard relational database. Table 1 describes the available tables and the relevant fields within each table.

III. Results

The results from this study include a set of statistical measures as well as a set of tools, which we will use to continue the analysis and mining of the growing amount of AP data collected by Skyhook Wireless on the subject. Results were calculated using a number of

[5] For further information on wardriving see Wikipedia, http://en.wikipedia.org/wiki/Wardriving

methods including database queries, java programs, spreadsheets, GIS tools, and mash-ups with Google Maps.

Table 1. Data tables and relevant fields.

Table Name	Fields
Main AP table	MAC, SSID, Latitude, Longitude, Date, Scanner Key
Location adjustments	MAC, Date, Previous Latitude / Longitude, New Latitude / Longitude, Distance
AP scan records	MAC, Date, Latitude, Longitude, Signal Strength, Scanner Key
GPS Logs	Scanner Key, Latitude, Longitude, Satellites, Date

During the analysis two different datasets were used based on snapshots of the data at a particular time. The first dataset included 3,571,212 access points (Dataset 1) while the second included 5,660,428 access points (Dataset 2).

It is estimated that there are in over 40 million access points deployed in the United States. Assuming this estimate is correct, the data sets would represent approximately 9% and 14% of the deployed access points respectively.

A. Access Point Naming and Default Settings

Access point naming analysis aims at understanding and identifying the different behaviors in the method that users name their access points. Through examining both datasets, we observe that approximately 44% of the studied access points retain their default factory names. Fig. 3 below is an example of the naming statistics showing the top 25 names by frequency.

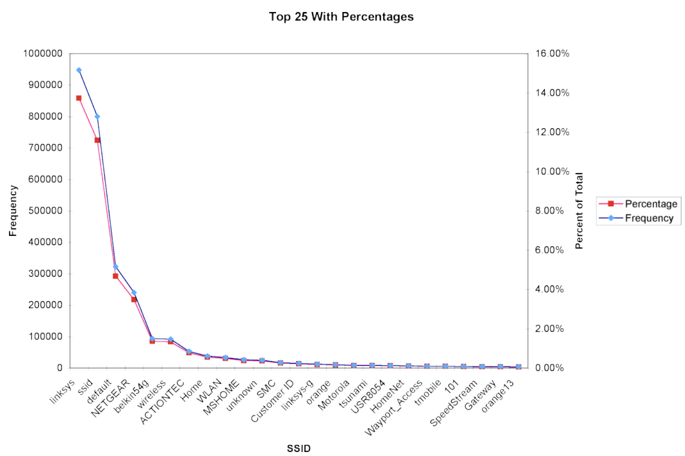

Figure 3. Top SSID frequency and percentage of total

Fig. 4 provides a visualization of over 100,000 scanned access points in the North Atlanta region, nearly blanketing certain areas of the city. This image provides a visceral 'sense' of how thoroughly wireless networks have penetrated our urban and suburban society. Fig. 5 provides a view of the same area as shown in Fig. 4 but includes only those access points which retained the default 'Linksys' SSID configuration. Clearly there is a reduction in total number of access points, but there remains a substantial installed base of access points with default configurations.

The use of default settings has been noted in other studies such as those produced by Bychkovsky et al in [3] where nearly 75% of the APs had default security settings (not secured) while nearly 50% had default SSID names. Our current dataset does not provide specific information on the security settings of the access points scanned, but we can infer the possible default security settings based on default SSID names. If we were to use the same ratio as previous studies have uncovered, it may indicate that as many as 66% of the access points remain unsecured. This information indicates that manufacturers would do well to ensure that sufficient security and privacy is provided as a default configuration.

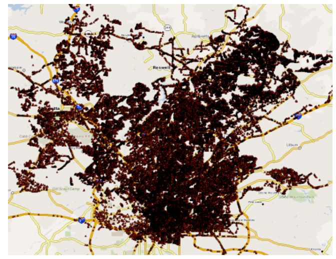

Figure 4. All access points in North Atlanta region.

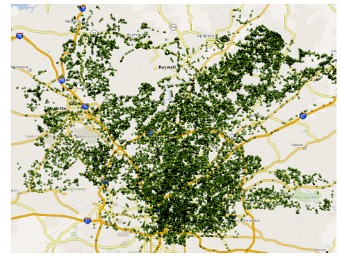

Figure 5. Access points with Linksys default settings.

B. Manufacturer Information

Manufacturer information regarding the deployed APs was analyzed using two measures. First, the default naming characteristics provides a baseline measure that indicates the relative number of access points that maintain their default settings. Second, an analysis of the MAC address was performed to correlate these assigned addresses with the manufacturer information. The results, shown in Fig. 6, indicate the market leadership of Linksys (a Division of Cisco Systems, Inc.) in the Wi-Fi marketplace. Of the 5,660,428 access points in Dataset 2, we found 38% of them belonged to Linksys. In addition, the top 20 manufacturers represent 96% of the access points in the database.

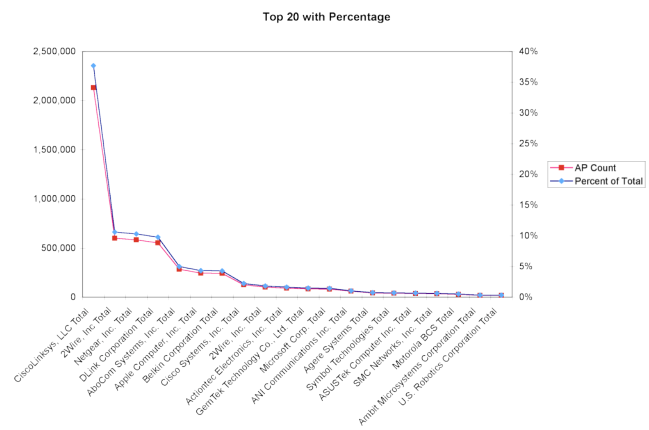

Figure 6. Manufacturer based on MAC address.

Note that Fig. 3 and Fig. 6 are closely related as would be expected based on the manufacturer and the default SSIDs for the access points.

C. Access Point Stability

One unforeseen use for which the growing Wi-Fi infrastructure is being used is to provide a location service similar to GPS. Skyhook Wireless provides such a service. Based on the location of the access points a user with a Wi-Fi enabled device can determine their location via the Wireless Positioning Service (WPS).

One key measure that is important for the performance guarantee of the WPS system in general is the stability of the access points. In the cases where access points were actively being moved (i.e., person moving across town or elsewhere), the WPS system could be at risk of providing faulty or degraded information.

Any solution for measuring movement of access points must solve several issues:

1. Account for lack of signal on rescan
2. Account for new access points
3. Account for changes due to improved estimation techniques
4. Isolate areas in which valid organized rescans have taken place
5. Eliminate issues with duplicate MAC addresses
6. Eliminate issues with traveling/mobile access points.

Preliminary results from isolating these elements are insufficient to accurately predict the overall motion of access points. This is primarily due to the lack of repeated scans of geographic regions. As more longitudinal data is gathered we expect to complete more thorough analysis of this problem.

While the initial findings are encouraging, systems should also rely on signals from more than one access point to reduce the effect of access point motion.

D. Access Point Density

In this section we explore the density of access points, aiming at better understanding of the current state of wireless deployment and exploring what the future wireless landscape will look like.

In particular, the density of access points can play an important role in how or whether individual access points can cooperate with each other. In certain scenarios, it has been suggested that access points, even those owned by individuals, could cooperate in a mesh network in which they use each other as a blanket of connectivity rather than relying solely on the individual Internet connections for each and every access point. For this to work there must be sufficient density of access points such that the majority of APs are able to not just 'see' several other access points, but must have sufficient signal strength to perform reliable connectivity between them [5].

It should be noted that there is a difference between being able to detect the radio signal from an access point and the ability to actually perform the network connection necessary to transport data. Certain services may be performed without the need for actual connectivity and thus can deal with a lower density of access points. For example, the Wireless Positioning Service does not require connectivity, providing a nominal coverage of 200 meters radius for each access point[6].

The signal propagation depends on a large variety of variables from building material, antennas, power, and other obstacles that may attenuate the signal [9]. In addition, newer wireless standards such as 802.11n and WiMax (802.16) have the ability to travel much farther and still maintain their ability to provide connectivity. Nevertheless, we focus on standard 802.11b/g (standard Wi-Fi) due to the proliferation of already deployed devices[7].

We assume that the nominal range for standard 802.11b/g is 100 meters[8] for full data connectivity. For simplicity, we use a basic calculation, and assume uniform circular coverage for each AP, noting that each square kilometer of area would require approximately 33 access points. This is quite different than the purpose built networks being constructed for metro-scale Wi-Fi networks which utilize specialized radio and antenna equipment to reduce the hardware requirements.

Using the database linked with Google Maps we can quickly determine the access point density of any particular area. Table 1 provides a sample of these density measurements based on rough bounding boxes of a given area.

Table 2. Access Point Density

Region	Area (km^2)	Access Points	Density (APs/km^2)
U.S.	9,166,600	5,615,451	0.6
Las Vegas	240	26,069	109
Kansas City	270	29,438	109
Atlanta	460	65,364	142
San Francisco	213	69,502	326
Seattle	165	64,923	395
Boston	225	164,072	729
Manhattan	105	194,651	1,854

As observed in the density statistic analysis, major metropolitan areas are well above the 33 AP/km^2 that we noted above. This is especially true as you focus on high-density population areas, with Manhattan, for example, having a density of over 1,800 access points per square kilometer.

Given these sample points, there are numerous areas in the U.S. that would be able to support new models of use for the already deployed access points.

E. Demographics

Once the access points are geographically mapped they can be combined with demographic information. For example, we can examine the density of access points within census tracts and compare this with the population or household income. This may help city planners in understanding and planning deployment of municipal wireless networks.

Through the use of MapServer[9] combined with the TIGER (Topologically Integrated Geographic Encoding and Referencing system) data provided by the US Census Bureau[10] we are able to visualize the density of access points in particular regions.

Table 3 shows three areas in the Atlanta region examined for understanding of the correlation between AP density and demographics. For each area, a representative census tract was examined and included in the table. Red triangles in the images depict the estimated location of specific access points. Population and household income relate to specific sample census tracts within the area depicted and do not relate to the total area shown.

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[6] Personal communication with Farshid Alizadeh, VP of Technology Development and Research for Skyhook Wireless.

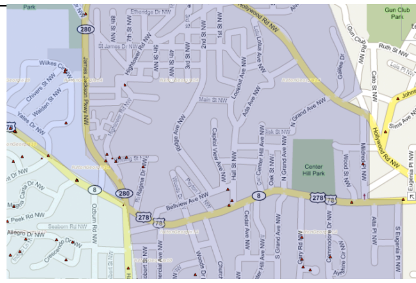
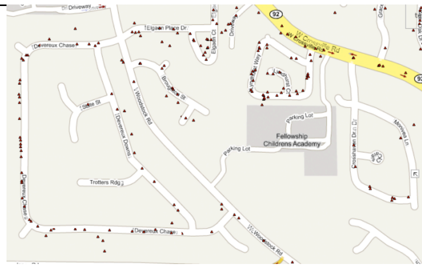
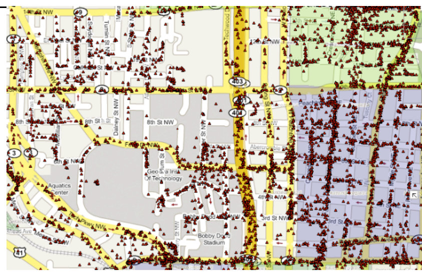
[7] For more on the 802 series of standards, see: http://grouper.ieee.org/groups/802/

[8] Based on numerous sources including: http://www.designnews.com/article/CA272261.html

[9] Open source GIS tools http://ka-map.maptools.org/ and http://mapserver.gis.umn.edu/

[10] U.S. Census Bureau Geography: http://www.census.gov/geo/www/

Table 3. Access Points and Demographics

Region	Grove Park	
APs	46	
Sample Tract	86.01	
Population	5,811	
Household Income[11]	$18,051	
Region	Roswell	
APs	176	
Sample Tract	114.07	
Population	9,456	
Household Income	$79,364	
Region	Midtown	
APs	2780	
Sample Tract	12	
Population	4,216	
Household Income	$40,654	

As one would expect, we see a higher density of access points in areas of higher household income, presumably the constituents have more money available to spend on computing equipment and services.

We also note the heavy density in areas such as Midtown Atlanta. This is likely due to a number of factors including the age of the residents, proximity to Georgia Tech, proclivity to use technology and the density of businesses in the region.

It is important to note that these are preliminary results. There are many other demographic parameters that could be studied relative to the location and density of access points to better understand the adoption of wireless technologies and to guide the design of next generation of wireless networks..

IV. CONCLUSIONS

This study is the first to look at the information available from a large-scale database of geolocated access points, and provides a glimpse into the value of the data. Our initial analytical results show that statistical mining of this data and the information revealed by this data (such as the default naming behavior, movement of access points over time, and density of access points) can yield important technological, social and economical results. Concretely, the findings of this analysis can provide technological guidelines for the design of wireless network systems that are more efficient, more scalable, and more reliable. The results have also suggested both social and economical benefits of open networks. For example, the data set has provided a glimpse into the market dynamics by examining the actual statistics of manufacturer data of the access points that have been deployed as well as their location of deployment. Further, the behaviors of the people who install the access points (whether business or individual) can yield some interesting results, including the default configuration habits of those users. In addition, we show that the geographic information can be exploited to understand the wireless infrastructure at large by exploring network characteristics such as access point density, demographic propensities, and signal propagation behavior. We believe that many areas in the U.S. would be able to support new models of use for the already deployed wireless access points.

Our research will continue along several dimensions, aiming at continuing to improve our understanding of this rapidly growing and changing infrastructure of wireless networks and the applications that it can support.

Due to space limitations the security and privacy section as well as the future directions section were removed. Additional information can be found online at www.whatwherewi.com.

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