Hybrid Approach to Distributed Wi-Fi Performance Assessment for Multi-floor Structures

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Abstract—This paper proposes the enhancement of Wi-Fi quality assessment with a hybrid approach, which uses small and low-cost devices like Raspberry Pi, and mobile devices like smart-phones. Existing solutions for Wi-Fi quality assessment are expensive, and guarantee for continuous monitoring is not given. A monitoring device like a spectrum analyzer, needs the user to follow a specified path to cover entire geographical Wi-Fi coverage, for each Wi-Fi quality assessment procedure with the limited number of such monitoring devices. This paper introduces several engineering approaches, including mixture of Raspberry Pi and mobile phones as sensing devices. Taking the advantage of low cost Raspberry Pis and readily available mobile devices, we collect real-world multi-floored building data for Wi-Fi performance information from user's perspective and visualize it as a geographical Wi-Fi signal strength heat map, as well as a geographical end-user network experience. We analyze the result of field trials to understand how small, low-cost devices may contribute as an alternative and efficient solution of Wi-Fi quality assessment.

Index Terms—Wi-Fi Performance Assessment, Network Quality, Low Cost System, Raspberry Pi, Smartphone

I. INTRODUCTION

Wi-Fi has emerged as the primary network choice for enterprise environments, as businesses of all sizes have started to adopt devices like smart-phones, tablets and laptops. With this increment in Wi-Fi consumer usage, it has become increasingly complex to assess and predict the propagation of Wi-Fi signal. Moreover, the fact that the radio waves undergo various degree of attenuation due to physical obstacles like doors, floor and ceiling, walls, people and interferences pose even more challenges in studying the pattern in which Wi-Fi signal propagates.

Over the time, demands on efficient assessment of Wi-Fi network has increased due to the extra costs and human efforts required after it gets setup. Hence, many organizations invest considerably in network assessment to predict the location of Access Points to be installed for best performance. Some tools like, Wi-Spy[6], Ekahau[4], etc. provide all the required information for the network assessment and thereby allowing predictions based upon that. These tools evaluates Wi-Fi quality with a larger investment in terms of dedicated efforts and money.

This paper extends Wi-Pi[1], one of the product which is able to compete with some of the challenges mentioned above in a sustainable fashion. The proposed solution in this paper is evolved from Wi-Pi, by using a hybrid combination of small low-cost processing devices like Raspberry Pi and Android Devices. This hybrid combination of stationary and mobile devices allows the system to integrate the knowledge acquired from data collected through both the mediums, and thereby improving the predictions of attenuation of Wi-Fi signal propagation caused due to physical obstacles, especially from those existing in multi-floor structures which forms the core of this proposed solution.

This approach brings an extra dimension to process of Wi-Fi assessment done by Wi-Pi, by showing user's perspective. Most of the present solutions provides the knowledge understandable to network administrator only, who is then able to interpret it and modify the network (if required). However, the solution presented in this paper, is able to provide understandable knowledge to a novice user, who can interpret the Wi-Fi signal strength at any specific location and hence decide the areas which have a better Wi-Fi connectivity in terms of Wi-Fi signal strength, latency and packet loss.

II. SYSTEM ARCHITECTURE

Hybrid approach mentioned in this paper is a combination of Raspberry Pis and smart-phones which analyze the Wi-Fi performance by collecting Received Signal Strength Indication (RSSI) of channels from the surrounding Access Points and packet loss/latency through the Access Point with which that monitoring device is associated. This information is later processed with location of hybrid nodes and projected on Wi-Fi heat map as well as on a map reflecting user perspective of network access at different locations, which consists of packet loss and latency. The collected information, demonstrates the gap between wireless signal propagation and user network experience. Overall system architecture for this paper is shown in Figure 1, while its details is described in the paper[1].

Accurate location of a monitoring point is an important factor to introduce reliable results of the assessment in a multi-floor environment. However, most of Global Positioning System (GPS) component in smart-phone continuously collaborate only horizontal location. We use Quick Response (QR) code, which contains both vertical and horizontal component of location. If data is collected with the help of a QR code to locate a smart-phone, GPS information will be ignored. Location of stationary device is set to specific location at the time of setup, which can be changed using User-Interface.
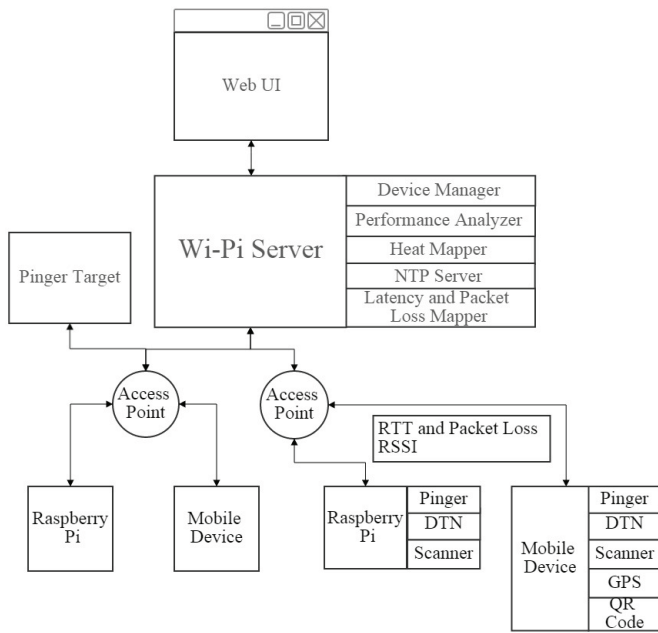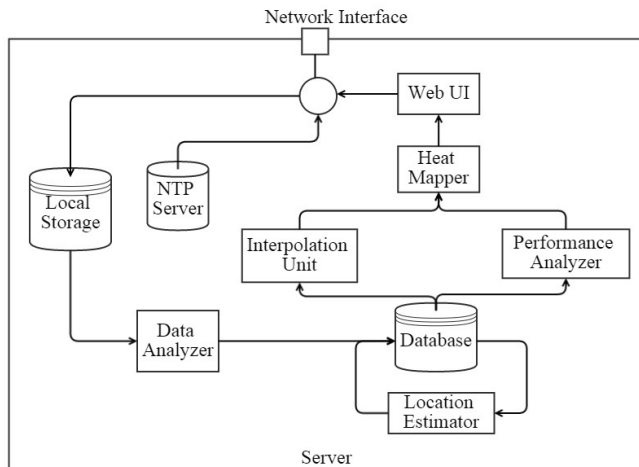
Fig. 1. Overall system architecture

Fig. 2. System Diagram for Server

Fig. 3. Database Schema

A. Data Handling and User Interface for Data Analysis on Server

All the data collected from monitoring devices is stored and processed on a server. This data is then visualized on two separate maps, namely Wi-Fi signal strength heat map and latency and packet loss map for better understanding. Server also acts as a Device Manager which interacts between database and other parts of server. Device manager stores and manages all information related to hybrid nodes of this system in a database table.

Figure 2 represents the system diagram of server. Initially all incoming data is stored in local storage and after analysis by the 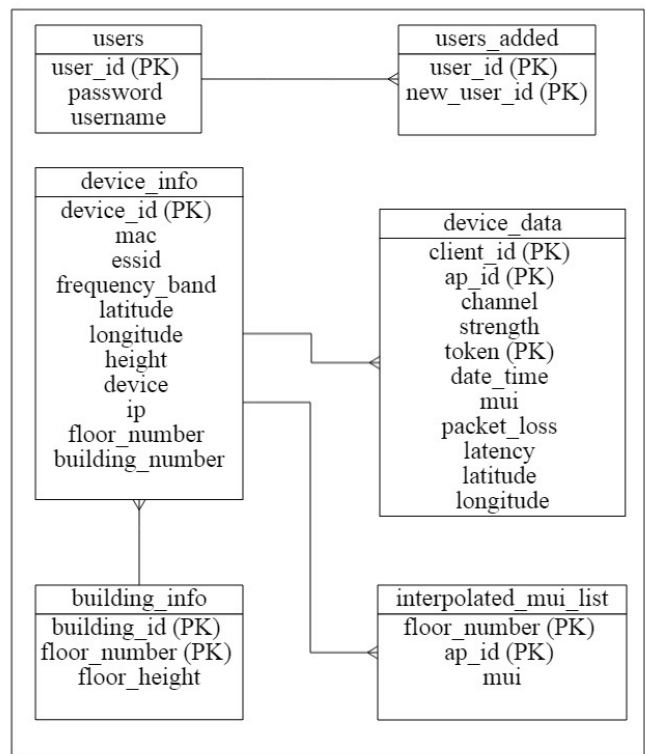'Data Analyzer' module, it is stored in a database. Such data is used by 'Performance Analyzer' to calculate Wi-Fi conductivity factor μ for every Access Point, and also used for interpolation of μ to other floors, if data for other floors are not available. Output by these includes maximum, upper quantile, median, lower quantile and minimum values of data for better understanding the wireless situation. Later this output is taken as input for Heat Mapper, and Packet Loss/Latency Mapper. Heat Mapper visualizes Wi-Fi signal strength, expected to be observed in a geographical location, whereas Latency and Packet Loss Mapper maps the latency and packet loss observed by a user at a particular location. These plots help in visualizing user's perspective in a simpler way. 'Location Estimator' is used for smart-phones, to estimate their vertical location from ground. Work of a Network Time Protocol (NTP) Server is to make sure that all the server and monitoring devices maintain the at same time so that data consistency can be easily achieved.

B. Database Schema

Database schema is shown in Figure 3, containing 6 relations. Relations 'users' and 'users_added' are for the user authentication purpose, containing the information related to users and the new users they add. 'building_info' contains data related to a building, like the number of floors and floor height, which will be used for interpolating the data. All the information related to a device is stored in 'device_info' relation and subsequently collected data in 'device_data' relation, with 'interpolated_mui_list' relation storing the interpolated μ
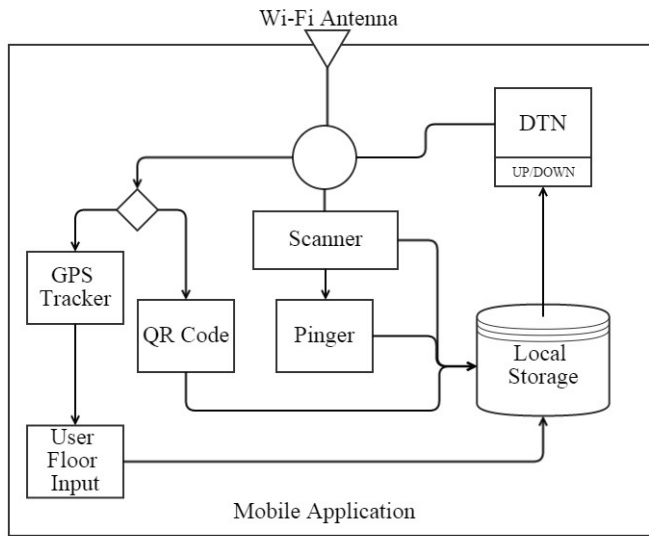
Fig. 4. System Diagram for Mobile Device (Smart-phone)

Fig. 5. User Interface for Mobile device

for an Access Point of floors other than the floor it is located in. These relations plays a major role in performance analysis and storing the following attribute:

• device_info: Horizontal and Vertical location in specific building, Frequency band, Media Access Control (MAC) Address, Internet Protocol (IP) Address, Extended Service Set Identifier (ESSID) and unique device id for each device (covering Raspberry Pi, smart-phone and Access Point)

• device_data: RSSI, Channel, time, conductivity factor μ, location at the point to data collection, packet loss percentage and latency of a particular Access Points detected by client device.

• interpolated_mui_list: Interpolated conductivity factor μ and corresponding floor number of the Access Points.

As shown in Figure 3, '(PK)' represents primary key attributes of relation. In the relation 'device_info', 'device_id' is the primary key, which is a unique id given to all the devices (Access Point, Raspberry Pi and smart-phone) and 'mac' and 'ip' are corresponding MAC Address or Basis Service Set Identification (BSSID) and IP address of the device. Location of device is combination of 'latitude', 'longitude' and 'building_number' indicating the horizontal location and 'floor_number' representing vertical location. 'client_id' and 'ap_id' are foreign keys attributes to 'device_id' attribute of 'device_info' relation and combined with 'token' attributes makes the primary key for 'device_data' relation. 'interpolated_mui_list' has the 'ap_id' and 'floor_number', which is floor number of interpolated floor, together as primary key for the relation.

C. Data collection at Mobile device

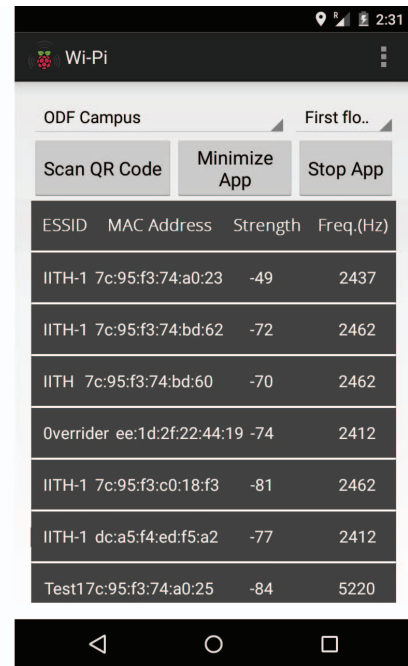As shown in Figure 4, a mobile device includes an additional module for location detection and continuous monitoring of location. Horizontal location of mobile device is detected either by 'GPS Tracker' module or by scanning QR Code with the help of 'QR Code' module. QR code contains additional information of vertical distance from ground, but can taken as input from user in case horizontal location is inputted from 'GPS Tracker'. RSSI scanning, Packet Loss percentage and Latency data collection is same as Raspberry pi by 'Scanner' and 'Pinger' module. All this information collected is stored in local storage and later sent to server, based on network availability by 'DTN' module to handle both connected and disconnected situations.

Figure 5 shows the user interface(UI) for mobile application, with an ease of use to the user. Android application is designed to take the minimal input from the user. QR Code can be directly scanned using this and has height locational reliability. In other case, horizontal location in detected by GPS of mobile, but the vertical floor location is either manually entered by user or automatically detected by triangulation of Wi-Fi signals that are available. In such case the reliability of location is less compared to location from QR Code scanning. User can minimize the application, allowing it to run in background with no user input. This helps to continuously monitor Wi-Fi signals without interrupting user's normal usage.

III. SYSTEM IMPLEMENTATION

A. Processing and Visualizing Data

In order to visualize data in a better fashion, with Packet Loss Rate, Latency and RSSI, continuous location and MAC address of mobile device is stored by the system. Unlike stationary device, registration of mobile device is automatic, and hardware MAC address is used to uniquely recognize the device.
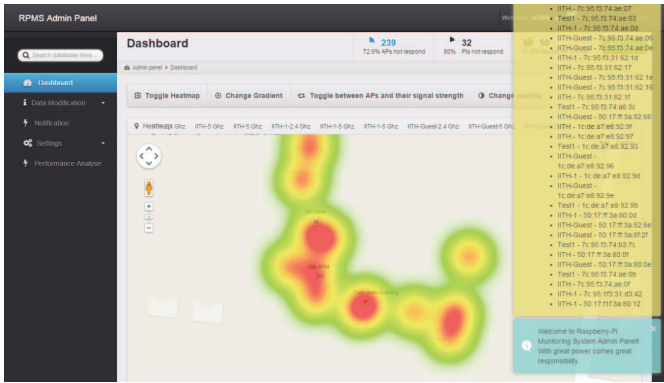
Fig. 6. User Interface for the system, showing Wi-Fi heat map and notifications sidebar
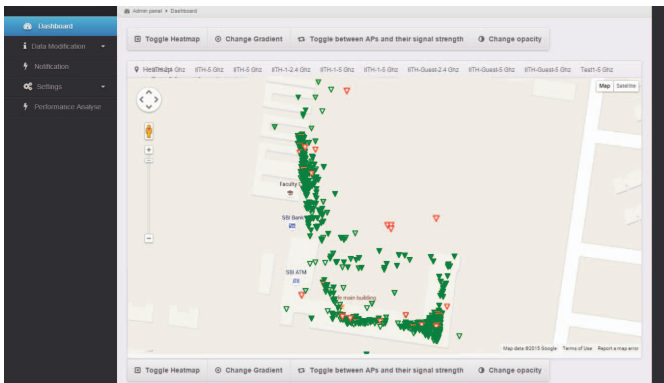

Fig. 7. User's perspective, Packet Loss and Latency mapping

User Interface bridges the gap between real-world data and analysis done by proposed system. This proposed system supports multi-floored architecture and plots a separate map for every floor using Google Map APIv3 [5]. As Figure 6 and 7 show, Wi-Fi signal strength heat map visualizes Wi-Fi signal strength distribution over the geographical area, and Packet Loss percentage and Latency Map plots the observation of real-world user experience.

B. Process of Data Collection

The Android application on smart-phone and Raspberry Pi collect data and send it to the server for processing. The location information for smart-phone is collected on-the-fly and is used for processing. The collected data includes time-stamp, location details, RSSI strength details of various Access Points, latency and packet loss. The frequency of data collection is 10 seconds. Server uses a unique token system to identify the latest file piled up in the server. Figure 8 shows the process of the data collection in both stationary and mobile device.

C. Process of interpreting the collected data

The system is intended for multi-floored structures and thus height in the Free Space Path Loss (FSPL) [7] formula plays a good role in deciding the μ at that floor. FSPL calculates

```
 1: procedure SCANNER
 2:     scan Wi-Fi and list all Access Points available
 3:     get BSSID of best Access Point signal
 4:     ping to server through the best BSSID and record
    result
 5:     while list do
 6:         parse all the data
 7:         write data in file
 8:         List ← List Entry→next
 9:     end while
10: end procedure
```

Fig. 8. SCANNER (for data collection in Raspberry Pi and smart-phone) pseudo code

```
 1: procedure DATA_PROCESSING
 2:     Read the collected data files and update the table
    device_info regarding the Access Point/collection point
    latitude, longitude, heights, strength received and latency.
 3:     distance = (call procedure latitude_longitude_distance(
    ))
 4:     actual_strength = ((strength_collected) - ((reduction in
    conductivity through one floor) * (difference in number of
    floors of Access Point and Point of data collection)))
 5:     μ = (Substitute actual_strength, distance and frequency
    in modified FSPL formula and solve for μ)
 6:     update the table data_data with values like μ, de-
    vice_id
 7: end procedure
```

Fig. 9. DATA_PROCESSING (for interpreting and storing collected data)

the loss in signal propagation through free space. The FSPL formula is

$$L_0 = 20 \log(f_c) + 20 \log(d) + K \qquad (1)$$

where d = distance of the point in interest, f_c is frequency of signal being propagated and K = constant that depends on the units used for d and f_c. In order to identify the decrease in conductivity in real world scenario, we introduced μ, conductivity factor. Modified FSPL formula would be

$$\mu * L_0 = 20 \log(f_c) + 20 \log(d) + K \qquad (2)$$

where μ is the constant for accounting reduction in the signal strength due to various factors, like cemented walls, climate, wind-speed etc.

The collected data is processed as shown in procedure DATA_PROCESSING which is shown in Figure 9. The strength received from the input devices (Raspberry Pi or mobile device) is modified according to Wi-Fi signals absorption occurred while conducting through ceiling between the point used for data collection and Wi-Fi Access Point. As the

```
1: procedure LATITUDE_LONGITUDE_DISTANCE(latitudes,
   longitudes and heights of the two points of interest)
2:     distance due to latitude and longitude difference
   (lat_long_distance) = (substitute latitudes and longitudes
   of the two points in Formula 3 and get distance)
3:     Total distance = √(lat_long_distance² + (h₁ − h₂)²)
   where h₁ and h₂ are height of Access Point and point of
   data collection, respectively.
4: end procedure
```

Fig. 10. LATITUDE_LONGITUDE_DISTANCE (to calculate distance between two latitudes and longitudes)

location of data collection and the Access Point can have a difference in floor number, total distance including the height (apart from the distance due to latitude and longitude) should be taken into consideration. These values are being substituted in the modified FSPL to get the value of μ.

Distance shown in Figure 9 is the diagonal distance between Access Point and point of collection, which is calculated using the following formula.

$$distance = 2 * R * \arctan(\sqrt{a}/\sqrt{1-a}) \qquad (3)$$

where R is Radius of Earth and a is calculated as

$$a = \sin^2((latitude_1 - latitude_2)/2) + \cos(latitude_1) * \cos(latitude_2) * (\sin((longitude_1 - longitude_2)/2))^2) \qquad (4)$$

The procedure LATITUDE_LONGITUDE_DISTANCE shown in Figure 10, computes the total distance between two points having different latitudes, longitudes and heights. The distance between two points given their latitudes and longitudes is given by Formula 4. This distance does not include difference in altitudes of the two points. Total distance is computed by applying Pythagoras theorem on the latitudinal, longitudinal distance and distance due to altitude difference.

D. Process of μ Interpolation

The decrease in Wi-Fi signal strength due to absorption of signals through ceiling is the primary reason to interpolate the μ to floors other than the Access Points' floor. The process is carried out when no information is available about any of the Access Points on a particular level by any of the client devices. Interpolation process requires the building basic structure information like number of floors, height of each floor from the ground etc. to be stored in the database. This process of interpolation has to be done after receiving each data file on server to keep heat map updated. The process is shown in Figure 11 and 12.

The procedure INTERPOLATE_FLOOR calculates the strength of Wi-Fi Access Point at the location exactly above/below in the interpolated_floor. Now modified strength is calculated to account for the blocking of Wi-Fi signals by the ceiling. Now μ is calculated at the interpolated_floor

```
1: procedure INTERPOLATION_PROCESS
2:     Scan the database to the max number of floors in the
   given building
3:     for current_floor : least floor number
   to max floor number do
4:         Get the list of routers which are located in the floor
   current_floor
5:         for router in List of Routers in current_floor do
6:             for floor_number : all floors below cur-
   rent_floor number do
7:                 CALL Interpolate_floor
8:             end for
9:             for floor_number : all floors above cur-
   rent_floor number do
10:                CALL Interpolate_floor
11:            end for
12:        end for
13:    end for
14: end procedure
```

Fig. 11. Pseudo code of INTERPOLATE_PROCESS

```
1: procedure INTERPOLATION_FLOOR(current_floor, inter-
   polated_floor, latitude, longitude, μ)
2:     distance (d) = absolute (current_floor - interpo-
   lated_floor)
3:     strenght_at_d = (substitute values of μ, latitude, longi-
   tude in the modified FSPL formula and solve for strength)
4:     reduce the strength_at_d value by the (signal absorp-
   tion by one floor) * floor difference of current_floor and
   interpolated floor
5:     mui_at_d = (substitute values of strength_at_d, lati-
   tude, longitude in the modified FSPL formula and solve
   for μ) store the value of mui_at_d into the database in
   different table.
6: end procedure
```

Fig. 12. Pseudo code of INTERPOLATE_FLOOR

with this new modified_strength being substituted in the FSPL formula. With this μ the heat map is constructed depicting the Access Points' signal strength variation. The motivation behind this approach is to depict the Access Point's behavior in the interpolated_floor using the data from the current_floor.

E. Setting up the system

The proposed system is an easy to setup system, which is deployed and currently running in IIT Hyderabad on a small scale. Different hardware and software specifications of implementation are shown in Table 1. In order to plot the analyzed data on geographical heat map, Google Maps API [5] is used and HighCharts [2] is used for analyzing packet loss, latency and signal strength by making charts.

TABLE I
IMPLEMENTATION SETUP DETAIL

| Device	Hardware Specifications	Software Requirements
Raspberry Pi	Wi-Fi dongle and compatible drivers OS: Ubuntu 12.04.4 LTS	OS: Raspbian OS (version: July 2014) SSH, SSHPASS, SCREEN and SCP packages Python 2.7
Server	2GB of RAM 10GB of memory space No. of CPUs: Minimum 1 Architecture : x86_64 Network Connection: 1Gbps LAN	OS: Ubuntu 12.04.4 LTS Apache Server Python 2.7 MySQL connector module for python SSH, SCREEN, SCP packages Crontab: to automate the job of backing up the database
Mobile Application	512MB of RAM 2GB of memory space No. of CPUs: Minimum 1 Architecture : x86_64 Network Connection: Wi-Fi 802.11 a/b/g/n	OS: Android 4.0 Barcode Scanner App (by Zxing Team)
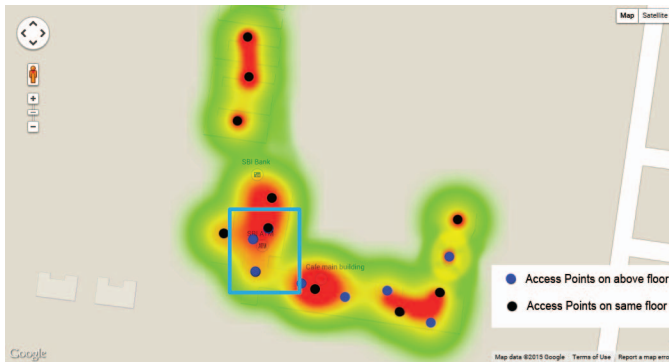
Fig. 13. Wi-Fi signal strength Heat Map. Signal Strength representation variates from red (higher Wi-Fi strength) to green (lesser Wi-Fi strength).
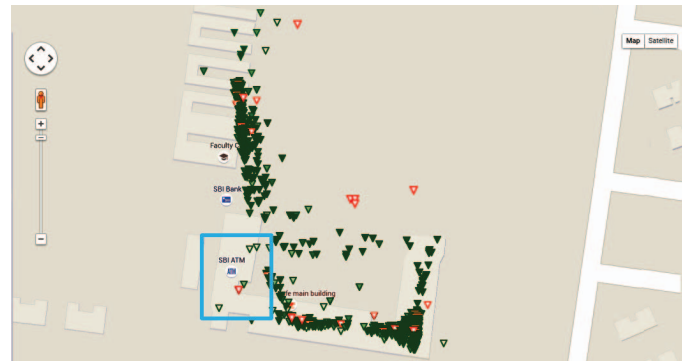

Fig. 14. Wi-Fi Packet Loss and Latency plot, visualizing user's perspective. Border color of triangle represents packet loss percentage (green represents less than 30%, yellow between 30% and 70% and red represents more then 70% packet loss), where as intensity of green color filled in it represents latency (intensity of green color decreases linearly with latency, while white color represents 100% packet loss and time-out for latency).

The setup for mobile device to support this system, would involve installing designed android application [3] and a Barcode Scanner (by Zxing team) [11] on the mobile. This android application runs only when GPS and Wi-Fi for the mobile is enabled, and notifies user if not so. The registration for the mobile user is automatic. The setup for Raspberry Pi includes steps like installing Raspbian OS on Raspberry Pi, get the Wi-Pi code from Git-Hub[3] and registering the device. The required instructions for registration are already mentioned in the manual for deployment at other institutions. Registration of Raspberry Pi can be done on-line from the Web UI and the registration for Access Point is automatic. However the location of any one of the interfaces of Access Points needs to be done manually.

IV. EVALUATION

A. Survey and deployment of the system In IIT Hyderabad

Proposed system has been tested via a field trial in IIT Hyderabad campus with 51 QR codes installed in different locations. For stationary monitoring of Access Points 5 Raspberry Pis had been installed in the building. Figure 13 and 14 show signal strength heat map and Latency and Packet Loss plot that are the aggregated result of the data from the mobile and stationary devices located in the campus. Detailed result regarding the Wi-Fi performance sent by the Raspberry Pis/smart-phones can be available as graph with $\langle pi\_id, ap\_id \rangle$ as key. The server used for processing data is internally accessible in IIT Hyderabad thereby providing administrative control and data visualization. The setup of QR codes and Raspberry Pis was done across different floors to get the visualization in multi floored campus of IIT Hyderabad. The effort for monitoring by Raspberry Pi/smart-phone mainly depends on the number of Access Points in the environment. Typically, 100 Bytes is the size of data sent by monitoring devices per Access Point that had been detected.
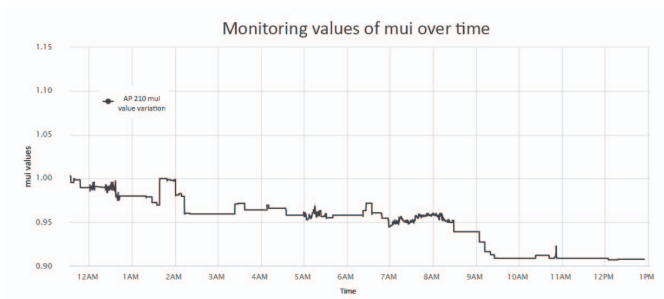
Fig. 15. Variation of value of μ for Access Point ID 210 and floor 1

(a) **Heat map generated by only stationary devices**

(b) **Heat map generated by only mobile devices**

(c) **Users Perspective by using stationary devices only**

(d) **Users Perspective by using mobile devices only**

Fig. 16. Comparison of monitoring results in IIT Hyderabad by using 6 Stationary and 4 Mobile devices.

B. Deployment scenario of Raspberry Pis/mobile devices in IIT Hyderabad

Placement of Raspberry Pis and QR codes plays a huge role in effecting the accuracy, usage of the heat map generated from the proposed system. If the placement of QR codes/Raspberry Pis are distant from Access Points then cold regions could be monitored. However if the placement is near to Access Points then variation of signal strength and latency could be monitored. If in any case, the user wants better accuracy of the heat map, more Raspberry Pis and QR codes can be deployed, as more the Raspberry Pis and smart phones, more accurate the heat map will be. Also for better accuracy, the floor with Access Points should have at-least some Raspberry Pis and QR codes being placed in that floor. Figure 15 represents the convergence of overall μ value of a particular Access Point for a particular floor over the time. Convergence of μ can be observed for each Access Point on all the floors, irrespective of observed μ or interpolated μ

All the situations of the deployment have been tested in IIT Hyderabad campus and the program had been tuned to deliver optimum results from the data that had been collected. Figure 13 and 14 depict Wi-Fi Signal Strength heat map and Latency and Packet Loss plot of results observed in this deployment. Output was compared to that of Wi-spy [6] in Figure 17, which is a proprietary device for data monitoring.

C. Relevance of stationary and mobile device

The heat map to a user serves as a tool to understand the perspective of the Wi-Fi signal distribution over a geographical area. The mobile devices(smart-phones) give a large number of random data collection points wherein the mobile device mimics the mobile Pi behavior. Thus this can be used to detect the points with lower and higher signal strength (Wi-Fi cold and hot regions). With the help of Raspberry Pis, the situation in such regions can be monitored continuously. Thus both stationary and mobile distributions for monitoring the Wi-Fi performance is necessary (to get a better perspective of Wi-Fi quality)as they gives continuous evaluation or geographically wide converge of assessment respectively. The mobile devices use either of QR code or GPS component to detect the location of the data collection. In the former case high accuracy is assured but in later case it is not assured. The influence on the result due to 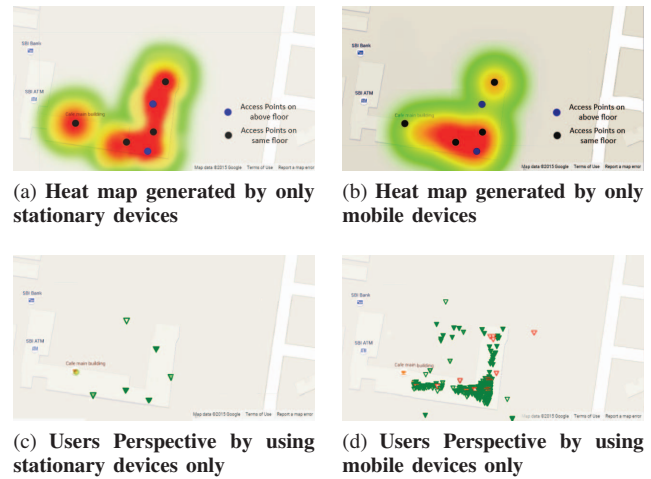such points has been taken in consideration (i.e. more reliability for QR code case and lesser for location GPS component).

Figure 16 (a-d) depicts the Wi-Fi monitoring results of a small deployment in IIT Hyderabad done separately for mobile and stationary devices. Comparison in Figure 16(a) and 16(b) demonstrates the gap in accuracy of mobile and stationary devices, where as Figure 16(c) and 16(d) demonstrates the gap in understanding user's perspective by the results of two different kind of devices. Thus, a better result can be seen from combination of mobile and stationary devices.

D. Relation between Wi-Fi signal strength heat map and Packet-Loss and Latency Map

In most of the cases, heat map gives approximately good picture of the Wi-Fi performance. But in some cases (as represented by blue box in Figures 13 and 14) even though the signal strength was noted to be high, the packet loss and latency was observed to be high. This could be either due to high network usage or unavailability of the pinging server. Also some points do exist with low signal strength but are observed having low packet loss and latency. Thus both the heat map and users perspective should be considered for understanding the Wi-Fi performance in the region.

V. RELATED WORK

The other famous Wi-Fi heat mappers available are Ekahau and Wi-Spy. Most of such methods monitor the Wi-Fi performance but they make use of expensive proprietary hardware. Figure 13 and Figure 17 depicts Wi-Fi signal strength heat map by the proposed system and Wi-Spy software, respectively. Wi-Spy required the user to roam through the building in specific straight paths. The detection of Access Points in the building was automatically done in Wi-Spy however there were errors in the location of the Access Points detected. Overall the results of both the systems were comparable. Few other softwares require the map of the region as an input. Most
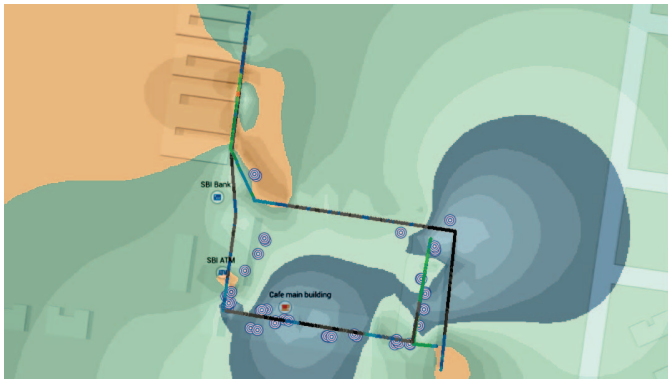
Fig. 17. Wi-Fi signal strength visualization using Wi-Spy

of these softwares account for the obstacles in path of signal propagation and depict the same in the generated heat map.

VI. Conclusion and Future Work

This paper introduced a Hybrid approach using different devices like Raspberry Pis and smart-phones to visualize and analyze the Wi-Fi performance in multi-floored structures. Use of mobile devices in Hybrid mode introduced more detailed result of Wi-Fi network quality which could not be observed by only using Raspberry Pis. Raspberry Pis are used because of their low cost and customization ability to continuously monitor information, like RSSI, location etc. The mobile devices contributes significantly by providing randomized network information of the geographical area, also it is one of the most common device available with people. Medium scaled deployment of the proposed system has been done in IIT Hyderabad campus and Wi-Fi performance has been analyzed using detailed per-device monitoring results including heat map of RSSI, packet loss and latency.

Future plans include further reduction of cost for monitoring by using newer technologies and optimizing the placement of stationary device and QR codes for better assessment of Wi-Fi network. Current system needs user assistance for multi-floored Wi-Fi assessment but later it could be extended to smartly detect the location of mobile devices.
Currently, the FSPL formula being used considers the effect of signal absorption due to ceiling between the Access Point and Raspberry Pi or mobile device. Integration of CAD file for geographical map input can further improve the reliability of assessment to automate the consideration of other obstacles like doors and walls.

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