Wi-Fi Coverage in Indian Homes

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***Abstract*—We seek to study Wi-Fi coverage and performance in typical Indian homes, and appreciate infrastructure deployment strategies for whole home coverage with throughput guarantees. We prefer experiments in real homes for performance evaluation, and measured coverage and throughput performance in homes of different sizes and types, in 2.4 GHz and 5 GHz band, and with 1x1 and 2x2 client devices of different make and price range. The measurements allowed us to characterize coverage as a function of the size of the home and the band of operation, and characterize throughput as a function of signal strength, bandwidth of operation and radio capability of the devices. We also validated the observations with limited experiments in a static channel. Finally, based on our measurements, we make recommendations on network architecture, AP placement and radio configuration for whole home coverage with 100 Mbps guaranteed throughput.**

***Index Terms*—IEEE 802.11 WLANs, Home Wi-Fi networks,**

I. Introduction

Wi-Fi technology is extremely popular for access, especially in indoor environments, due to its support for high data rates (IEEE 802.11ac/ax standards supports PHY rates greater than 1 Gbps), low cost, easy deployment and operation. Wi-Fi technology is now common in homes with a multitude of household devices such as computers, tablets, video and audio systems, and surveillance and security systems using it for data access. The number of networked devices and connections per person, and per household has only been increasing (see e.g., [1]). Recently, Covid-19 has forced the world to adopt new normal ways of work and life from home. Daily activities now include office meetings and classes via the Internet (in addition to the usual browsing and video streaming applications such as Netflix), applications that demand stringent QoS from the access network. As global trends for remote work continue to rise, home Wi-Fi network has once again become an exciting paradigm with focus on whole home coverage, QoS and security.

A number of works have focussed on coverage and propagation modeling in 2.4 GHz and in 5 GHz bands for Wi-Fi applications (see e.g., [3], [4], [5]). The works have used WLAN network interface cards as well as spectrum analyzers to measure signal strength and to characterize path loss. In [4], Hemant et al., propose an India specific indoor path loss model, T-IPLM, for Wi-Fi operations in 2.4 GHz band. We also appreciate that the indoor path loss models proposed for western countries may not be accurate in Indian scenarios due to differences in construction material, dimensions of the house and household appliances. In our work, we seek to study coverage and its relation to link rates and network performance, not studied in the above works. In [6], Toni Adame, et al., propose a path loss model for 5 GHz indoor Wi-Fi scenarios and also discuss the empirical relationship between RSSI, MCS and spatial streams. We present a similar discussion for both 2.4 GHz and 5 GHz band, and also characterize performance as a function of type and size of homes.

IEEE 802.11 WLANs operate in unlicensed bands, and often with limited or no network management. Characterization of Wi-Fi link and network performance in real deployments requires knowledge of wireless channel, mobility behaviour, traffic characteristics and interference (both Wi-Fi and non Wi-Fi). A number of works have sought measurement based characterization of Wi-Fi link and network performance in enterprises, campuses and homes (see e.g., [9], [10], [11], [12], [13], [15]). In [10], Mishra, et al., review usage and adoption of features such as MIMO and aggregation in real deployments including hotspots. In [11], Sanjit, et al., report real-world data on network utilization, link quality, delivery rates, and co-channel interference measured by tens of thousands of (Meraki) access points deployed across the globe. In a recent work [15], Pefkianakis, et al., report observations on traffic activity, coverage, interference and Wi-Fi link performance, made from live access points at 167 homes. The above works seek to study usage pattern in real deployments, while we seek to appreciate bandwidth and throughput achievable in such scenarios (especially, homes). In [12], Papagiannaki, et al., report measurements from Wi-Fi testbeds in six homes and examine the quality of Wi-Fi links in home wireless networks as a function of transmission power, node location, type of house and 802.11 technology. The authors note via empirical evidence that home wireless networks can be unpredictable despite their limited size, and remark that creating an infrastructure WLAN with ubiquitous coverage and guaranteed throughput is challenging. In [13], Ashish, et al., use OpenWrt-based access points installed in 30 homes to measure link performance, and also develop a metric to estimate likely TCP throughput based on current channel and environmental conditions. We do a similar exercise for the recent standards and also make recommendations for ubiquitous coverage with minimum guaranteed throughput.

A. Outline of the paper

In this work, we seek to measure Wi-Fi coverage and network performance in a variety of network and radio configurations, to understand WLAN performance and operations and to make recommendations for home Wi-Fi network deployments. In Section II, we state our objectives and discuss the experimental setup for the measurements and evaluation. In Section III, we review coverage and throughput performance in real homes, in a variety of network and radio configurations. In Section IV, we report experiments conducted in a controlled environment to validate our observations from real home experiments. In Section V, we make recommendations for Wi-Fi deployment in Indian homes based on our experiments and measurements. We conclude our work in Section VI.

II. Problem Statement

We seek to study Wi-Fi coverage and performance in typical Indian homes, and appreciate infrastructure deployment strategies for whole home coverage with throughput guarantees. Coverage and performance of IEEE 802.11 WLANs critically depends on a number of factors including IEEE 802.11 standards and radio capabilities of the AP and client devices, radio configuration including the band and bandwidth of operation, wireless channel quality and interference (both Wi-Fi and non Wi-Fi). In addition, quality of hardware (e.g., processor), software (e.g., link adaptation algorithms) and design (e.g., antenna and RF design) are known to significantly affect the performance of the Wi-Fi link and the network. So, for our study, we preferred in-site measurements (for performance evaluation) with a mix of client devices, in a variety of network, channel and propagation environments. We measured coverage and throughput performance in homes of different sizes and types (1/2/3/4 BHK and duplex homes), in 2.4 GHz (11n) and 5 GHz (11ac) band, and with 1x1 and 2x2 client devices of different make and price range. We used these measurements to characterize Wi-Fi performance in a variety of network and channel configurations, and to make recommendations on network architecture, AP placement and radio configuration for 100 Mbps coverage in Indian homes. In this work, we have restricted to IEEE 802.11n/ac standards for performance evaluation. We will not review the performance of IEEE 802.11ax radios (see [2]) due to its limited proliferation in the market and in Indian homes. We expect to review the impact and performance of IEEE 802.11n/ac/ax BSS in a future work.

A. Experiment and Measurements Methodology

We conducted Wi-Fi experiments in 25 different homes, comprising of equal number of 1/2/3/4 BHK homes and duplex homes, in the Indian states of Tamilnadu and Kerala. The network setup considered for measurements is illustrated in Figure 1, and the details are listed in Table I. The network comprises of an access point, a Wi-Fi client and a server (connected to the access point with a 1 Gbps Ethernet link). We used TP-Link Archer C7 V5 AC1750, a dual-band gigabit router with support for 3 spatial streams, for the access point.

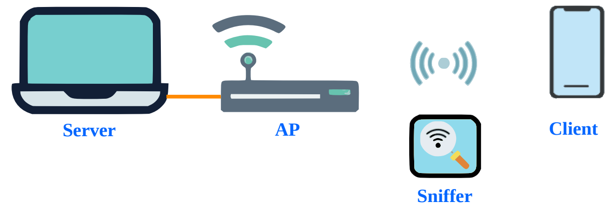


Fig. 1: Network setup

Hardware Specifications	
Access point	TP-Link Archer C7 AC1750 V5
Client devices	IPhone XR, Samsung S10e, Oneplus 7T, Redmi Note 8 Pro and Moto G8 Plus
Sniffer	Macbook Pro 2019
Server	Dell Latitude E5400
AP-server link	Gigabit Ethernet
Radio Configuration	
Standard	11n and 11ac
Band	2.4 GHz (11n) and 5 GHz (11ac)
Bandwidth	20 MHz (11n, 2.4 GHz) and 80 MHz (11ac, 5 GHz)
Aggregation	A-MPDU and A-MSDU enabled
RTS/CTS	Disabled
Tx power (AP)	High
Security	Open
Software Specifications	
Application	Iperf3
Transport layer	TCP
Direction	Downlink and Uplink
Duration	30 seconds

TABLE I: Detailed Network Parameters.

In our experiments, we restricted to mobile phones for client devices as they constitute a major fraction in terms of use, especially in Indian contexts (see e.g., [1]). We conducted both downlink and uplink file transfers between the server and the client device (one flow at a time) using TCP (with the iPerf3 application). In this setup, we evaluated the throughput performance in 2.4 GHz (11n, 20 MHz bandwidth) and in 5 GHz (11ac, 80 MHz bandwidth) bands, and with 1x1 and 2x2 client devices. The access point was placed in the usual/prefered location in the home, and we placed the client device in key locations in each room, approximately two locations per room (see e.g., Figure 2). The mobile phone was held in hand and was subjected to limited mobility, typical of mobile phone usage. Channel quality was measured in terms of average beacon RSSI, and was recorded using a wireless sniffer (Macbook Pro with 3x3 support) at the same sites of throughput measurement.

The following remarks should elaborate and also motivate our choices regarding the network and radio configurations.

- We used commercially available devices for AP and clients, with a decent mix in terms of price and radio capabilities. This should permit us to study average performance in Indian households.
- We considered a live environment (no changes to the radio environment and neighbourhood were made) to evaluate typical performances experienced everyday by users.
- We consider a setup where a single client is associated

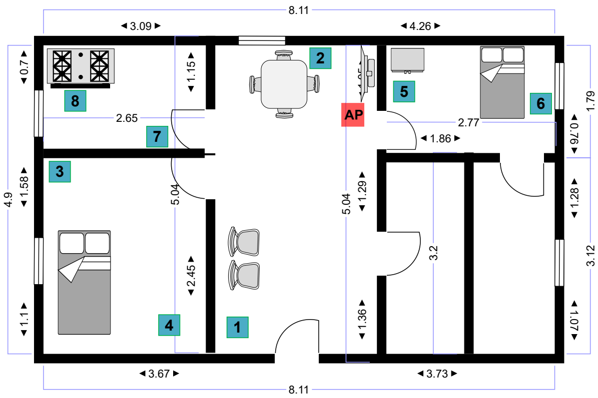


Fig. 2: Floor plan and measurement sites in a 2 BHK home. The red box indicates the location of the AP and the blue boxes indicate the different sites where client device was placed.

with the access point at any time. The basic configuration will permit us to study Wi-Fi link performance less ambiguously. The configuration will also permit us to understand network performance when there are multiple clients.

- We consider 20 MHz bandwidth in 2.4 GHz band and 80 MHz bandwidth in 5 GHz band. The choices are comparable (in deployment scenarios) as we have sufficient number of non-overlapping channels with the above configurations.
- We study TCP throughput (instead of UDP) as most applications use TCP or similar protocol for data transfer.
- We study both downlink traffic and uplink traffic. This should permit us to understand any differences in the performances due to the radio capabilities of the access point and the clients.
- We measure coverage, in terms of average beacon RSSI, with a common wireless sniffer instead of using the client device. A common sniffer allows us to compare performances of devices of different make and radio capabilities.

III. Data and Observations

At every site of measurement, we recorded average TCP throughput of a flow with a 1x1 and a 2x2 client device, in 2.4 GHz band and in 5 GHz band, and with uplink and downlink traffic. At the site of measurement, we also recorded the average beacon RSSI in 2.4 GHz and 5 GHz band, and the average distance from the access point (including the number of walls and floors between them). The measurements from the 200+ sites ($\approx$ 25 homes $\times$ 8 sites per home) allowed us to review coverage and performance as a function of a variety of network and channel parameters. In the following subsections, we will review (i) coverage as a function of the size of the home and the band of operation, and (ii) throughput as a function of signal strength, bandwidth of operation and the radio capability of the client device.

A. Coverage

In Figures 3 and 4, we report coverage, measured in terms of average RSSI of beacon frames, for different types of homes and band of operation. In Figures 3a and 3b, we report the cumulative distribution function (CDF) of average beacon RSSI of the different types of homes for 2.4 GHz and 5 GHz, respectively. In Figures 4a and 4b, we report the CDF of average beacon RSSI as a function of distance of client device from the access point (distance measured in terms of the number of walls separating the client and the AP). From the figures, we can infer the following about coverage in Indian homes.

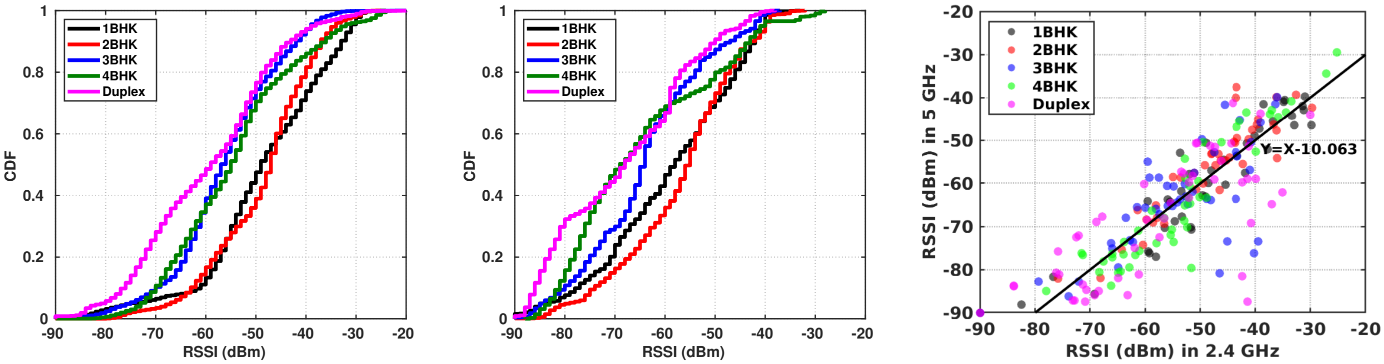
- The average RSSI is typically between -30 dBm and -70 dBm in 2.4 GHz band, and is between -40 dBm and -80 dBm in 5 GHz band.
- Average RSSI in 5 GHz is lower than in 2.4 GHz (see e.g., [12]). In Figure 3c, we compare the average beacon RSSI measured in 2.4 GHz band and in 5 GHz band at every site. We note that average beacon RSSI in 5 GHz band is typically 10 dB less in comparison with the average beacon RSSI in 2.4 GHz band.
- In Figure 4c), we plot average beacon RSSI (and standard deviation) as a function of distance between the AP and the client (in meters). The data lets us fit a path loss model and compute path loss exponent and wall losses in 2.4 GHz and 5 GHz band (see e.g., [6], [8]).

$$\text{RSSI(2.4 GHz)} = -37.2 - 11\ \log(d) - 7.3\ \#\text{walls} \quad (1)$$
$$\text{RSSI(5 GHz)} = -43.1 - 14.5\ \log(d) - 9.4\ \#\text{walls} \quad (2)$$

  In the above expression, RSSI is measured in dBm, d (the distance between the AP and client location) is in meters, and #walls includes both walls and floor. RMSE for our model is below 10 dB and is comparable with models reported in [6] and [7].
- The coverage is poorer in 4 BHK and duplex homes (both in 2.4 GHz and 5 GHz band). This may be attributed to high wall losses as observed in Figures 4a and 4b, and reported in (1) and (2).
- In Figure 4c, we also report standard deviation of the beacon RSSI at the site of measurement. We observed high variance (due to mobility) when there was a line-of-sight path between the AP and the client device.

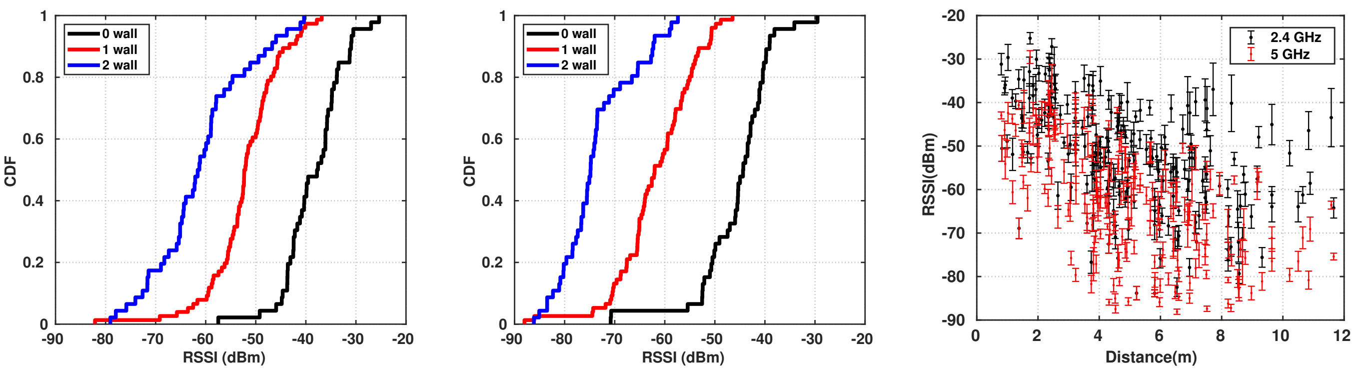
B. TCP Throughput

In Figures 5, 6, 7 and 8, we report average TCP throughput measured in different types of homes, for different client device configurations and band of operation. In Figures 5a, 6a, 7a and 8a, we report the CDF of average TCP throughput (averaged over downlink and uplink) for different types of homes, and in Figures 5b, 6b, 7b and 8b, we report the CDF of average TCP throughput as a function of distance of client device from the access point (measured in terms of the number of walls separating the client device and the AP). From the figures, we can infer the following about throughput performance in Indian homes.



(a) 2.4 GHz (b) 5 GHz (c) 2.4 GHz vs 5 GHz

Fig. 3: Coverage in terms of average beacon RSSI. We report CDF of average beacon RSSI of 1/2/3/4 BHK and duplex homes in 2.4 GHz and 5 GHz band in (a) and (b), respectively. We compare average beacon RSSI in 2.4 GHz and 5 GHz band in a location in (c).



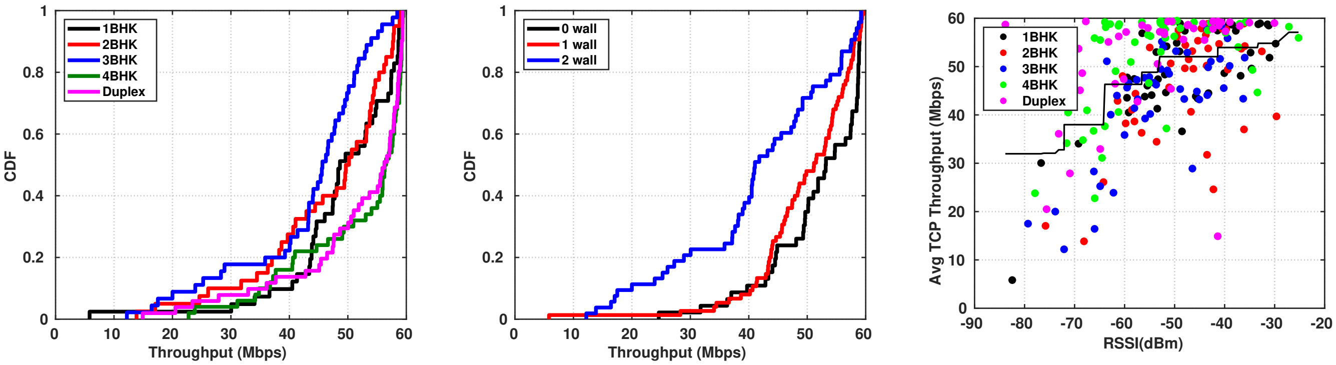
(a) 2.4 GHz (b) 5 GHz (c) path loss model

Fig. 4: We report CDF of average beacon RSSI as a function of distance between the client device and the access point (measured in number of walls) in 2.4 GHz and 5 GHz band in (a) and (b), respectively. We report average beacon RSSI and the standard deviation as a function of distance (in metres) between the AP and the site of measurement, in 2.4 GHz and 5 GHz in (c).

- The average TCP throughput achievable in Indian homes in 2.4 GHz band (and 20 MHz bandwidth) is typically between 30 Mbps and 60 Mbps with 1x1 client device, and is between 40 Mbps and 100 Mbps with 2x2 client devices. The average TCP throughput achievable in 5 GHz band (and 80 MHz bandwidth) is typically between 30 Mbps and 250 Mbps with 1x1 client device, and is between 30 Mbps and 450 Mbps with 2x2 client devices.
- Throughput is poorer in 4 BHK and in duplex homes (especially, in 5 GHz). This may be attributed to poor throughputs beyond walls (see Figures 5b, 6b, 7b and 8b).
- In Figures 5c, 6c, 7c and 8c, we study the correlation between average TCP throughput and average beacon RSSI, for different client device configurations and band of operation. We note that throughput performance in 2.4 GHz is fairly constant throughout the home, while 5 GHz reports rapid deterioration of throughput as RSSI decreases. We see poor throughput beyond 2 walls (see Figure 7b and 8b) where the coverage is typically below -75 dBm (see Figure 4b).

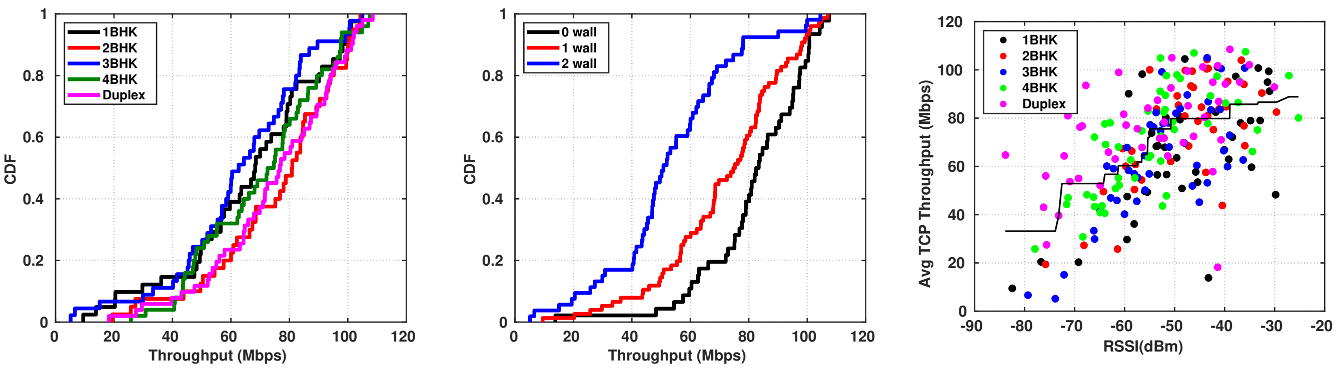
In Figures 9a, 9b and 9c, we compare throughput as a function of direction of traffic, client specification and band of operation, i.e., downlink vs uplink, 1x1 vs 2x2, and 2.4 GHz vs 5 GHz band of operation. The comparisons throw interesting information about the network performance.

- The downlink and uplink performances are nearly equal with better uplink performance in poorer channel conditions.
- The throughput performance with a 2x2 radio is better than with 1x1 radio. However, the benefits are marginal under poor channel conditions.
- The measured performance of the radios in 5 GHz band is significantly higher than in 2.4 GHz band. Once again, the benefits are marginal under poor channel conditions and in some cases (when the RSSI in 5 GHz is below



(a) (b) (c)

Fig. 5: Throughput of 1x1 client devices in 2.4 GHz band. We report CDF of average TCP throughput for 1/2/3/4 BHK and duplex homes with 1x1 client devices in 2.4 GHz in (a). We report the CDF of average TCP throughput as a function of distance (number of walls) from the access point in (b) and report average TCP throughput as a function of average beacon RSSI in (c).



(a) (b) (c)

Fig. 6: Throughput of 2x2 client devices in 2.4 GHz band. We report CDF of average TCP throughput for 1/2/3/4 BHK and duplex homes with 2x2 client devices in 2.4 GHz in (a). We report the CDF of average TCP throughput as a function of distance (number of walls) from the access point in (b) and report average TCP throughput as a function of average beacon RSSI in (c).

-75 dBm), the performance in 2.4 GHz is better.

- The deterioration of performance in 5 GHz is drastic with RSSI in comparison with 2.4 GHz (a similar remark on the sensitivity of IEEE 802.11ac links is reported in [14]).

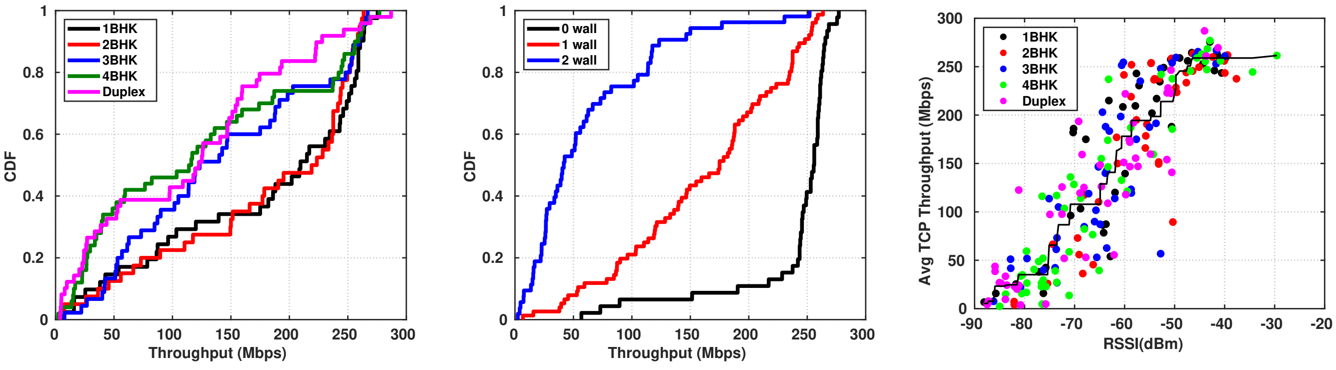
A detailed review of the rate adaptation algorithms is necessary to understand and improve link performance in poor channel conditions.

C. Additional Remarks

- TCP throughput was measured at server and at clients. Wireless sniffer was not able to capture all frames on air (especially, frames transmitted at high PHY rates).
- We observed less and weak interference in 5 GHz band in comparison with 2.4 GHz band. This may be attributed to higher wall losses in 5 GHz band.
- We expect the single link performance to guide home Wi-Fi network design very well, especially in 5 GHz band, with a decent number of non-overlapping channels. In this regard, the role of channel and bandwidth selection is crucial in efficient operation of home Wi-Fi networks.

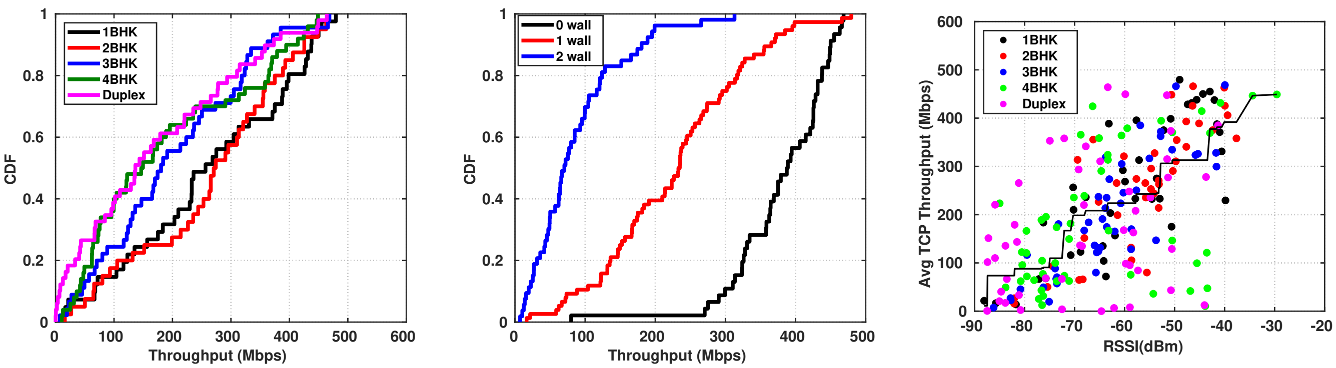
IV. Data Validation

TCP throughput reported in Section III is affected by a number of variables including movement of client device, movement in the environment, rate adaptation algorithms (implemented in the AP and the client device), and even the flavor of TCP. This makes data validation difficult. So, we propose to eliminate some of these factors and repeat the experiments to seek a reliable characterization of link performance, that can also validate the real-world measurements reported in Section III. In this section, we will repeat the same set of experiments in a static channel setup, where the channel between the AP and the client is unaffected during the duration of the experiment. The exercise should allow us to characterize



(a) (b) (c)

Fig. 7: Throughput of 1x1 client devices in 5 GHz band. We report CDF of average TCP throughput for 1/2/3/4 BHK and duplex homes with 1x1 client devices in 5 GHz in (a). We report the CDF of average TCP throughput as a function of distance (number of walls) from the access point in (b) and report average TCP throughput as a function of average beacon RSSI in (c).



(a) (b) (c)

Fig. 8: Throughput of 2x2 client devices in 5 GHz band. We report CDF of average TCP throughput for 1/2/3/4 BHK and duplex homes with 2x2 client devices in 5 GHz in (a). We report the CDF of average TCP throughput as a function of distance (number of walls) from the access point in (b) and report average TCP throughput as a function of average beacon RSSI in (c).

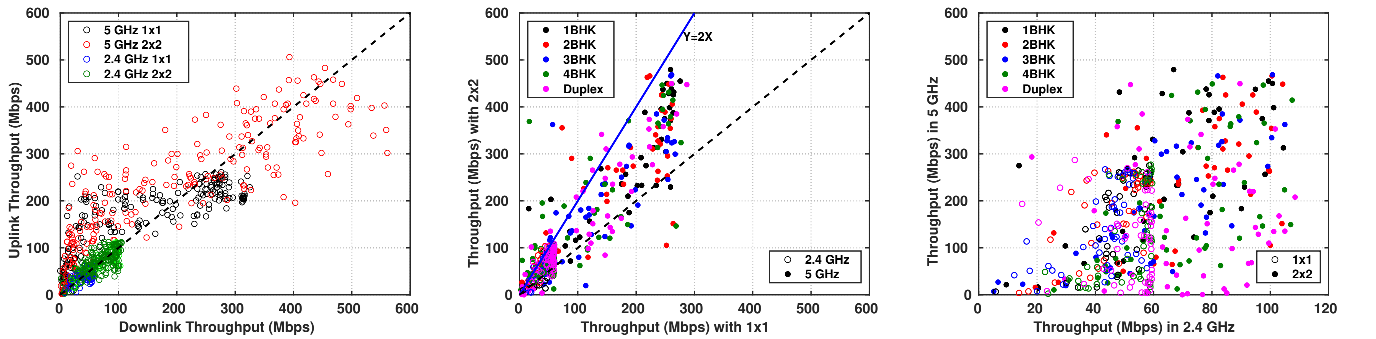
link performance better, and also to bound the results reported in Section III.

In Figures 10a, 10b and 10c, we report average TCP throughput as a function of average beacon RSSI, correlation between average TCP throughput and average PHY rates of data communication, and MAC frame retransmission rates in the static environment, respectively. We can infer the following from the figures.

- The trends in throughput performance in Figure 10a are similar to the real-home experiments. The throughputs are fairly constant in 2.4 GHz band whereas the throughput falls drastically when the signal strengths are poor (average RSSI below -80 dBm). The exercise validates the observations reported in Section III.
- The throughput performance reported in the static environment is better than the throughputs reported in the real-home scenarios. This may be attributed to the dynamic channel conditions prevalent in real-home scenarios.
- The predictable relation between TCP throughput and PHY rates (see Figure 10b) implies that TCP throughput is a good indicator of link behaviour.
- We note that there is a lot of variation in TCP throughput even in the static environment (see Figure 10a). This may have correlation with the MAC retransmission rates reported in Figure 10c. In our view, a thorough understanding of MAC frame error rates (and rate adaptation algorithms) as a function of channel parameters may be critical to appreciate Wi-Fi link performance.

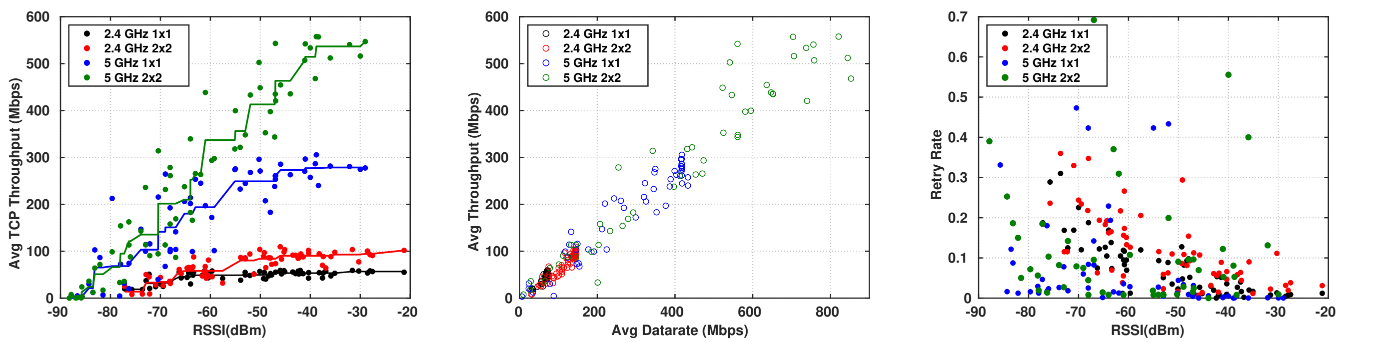
V. Recommendations for 100 Mbps Coverage

In this section, we present our recommendations for whole-home coverage with minimum throughput guarantees, based on our observations from real-home measurements reported in



(a) (b) (c)

Fig. 9: We compare downlink and uplink TCP throughputs, average TCP throughput with 1x1 and 2x2 client devices, and average TCP throughput in 2.4 GHz and 5 GHz band, in (a), (b) and (c) respectively.



(a) (b) (c)

Fig. 10: We report average TCP throughput in a static environment, as a function of average beacon RSSI in (a). We report correlation between average TCP throughput and PHY rates in (b), and we report MAC frame retransmission rate as a function of average beacon RSSI in (c).

Section III. For the exercise, we will assume that the ISP/user seeks ubiquitous coverage with 100 Mbps throughput, and will present our recommendations on network architecture, AP placement and radio configuration.

- The throughput requirements necessitates us to use 5 GHz for Wi-Fi operations (see Figure 10a).
- From Figures 7c, 8c and 10a, we recommend a minimum of -65 dBm or higher at every location in the house. The margin should protect the link from unexpected channel conditions (including due to mobility) and co-channel interference (leading to lesser time share of the wireless channel).
- All locations in the house must be at most one wall away from the AP (see Figures 4b, 7b and 8b). In cases where this is not possible, we may need more than one access point (in a mesh or multi-AP architecture).
- We must place the access point such that propagation losses are minimum (e.g., we may place the AP at a reasonable height to avoid losses due to furnitures). Household items such as furnitures, wardrobes, electronic devices (such as Fridge, TV) and kitchen utensils are common causes of large propagation losses in Indian homes.
- We prefer 2x2 client devices to 1x1 client devices, and we prefer access points with 3x3 support (for added reliability).
- Radio resource management techniques such as transmit power control and channel selection will help avoid coverage holes and mitigate interference. So, we recommend that the access points support such RRM strategies.

VI. Conclusion

In this work, we sought a simple characterization of 11n/ac Wi-Fi link performance as a function of signal strength and radio capabilities. The study allowed us to make recommendations on network architecture, AP placement and radio configuration for home Wi-Fi networks. We expect the single link performance to guide home Wi-Fi network design very well, especially in 5 GHz band, with a decent number of non-overlapping channels. In the future, we seek to study performance with 11n/ac/ax standards as well. In addition to network planning, continuous monitoring of link performance, interference and good radio resource management strategies are key for efficient WLAN operations and management. We expect cloud-based network intelligence to manage home Wi-Fi networks of today and tomorrow.

Acknowledgment

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