Understanding the Impact of AP Density on WiFi Performance Through Real-World Deployment

Kaixin Sui, Siqi Sun, Yousef Azzabi, Xiaoping Zhang, Youjian Zhao, Jilong Wang, Zimu Li, Dan Pei*
Tsinghua National Laboratory for Information Science and Technology (TNList), Tsinghua University

***Abstract*—802.11 (WiFi) networks have become increasingly important for our daily lives. However, previous work has shown that enterprise WiFi performance is often unsatisfactory and that over-utilization and interference from rogue APs are the two primary reasons. To address the above problem, this paper proposes to improve the capacity of WiFi infrastructures by increasing the enterprise AP deployment density, as well as disabling the wired Internet access in buildings to eliminate rogue APs and their interference. We deployed several WiFi networks with different AP density and vendors on Tsinghua campus. Based on the measurement results from our real-world deployments, we made three main observations: 1) in general, higher AP density improves WiFi performance; 2) over-dense deployment with unnecessarily high transmission power can worsen WiFi performance. 3) choice of AP vendors also has an impact on WiFi performance.**

I. Introduction

802.11(WiFi) networks have become more and more important in people's daily lives. The number of WiFi devices may rise up to 20 billion in 2018 [15], and the Cisco VNI [1] reports that the Internet traffic generated by WiFi devices was 55% in 2013 and will be 61% by 2018.

Enterprise Wireless LAN (**EWLAN**) is an important infrastructure for public WiFi usage in universities, companies, shopping malls *etc*. However, complaints about the poor performance of EWLAN are not uncommon. There are two primary reasons for that. The first reason is that the continuously increasing traffic demand might have exceeded the designed capacity and the EWLAN, given the limited number of Enterprise APs (**EAP**s for short). The second reason is the chaotic deployment of rogue APs (**RAP**s for short), which are installed onto the wired network by users (as opposed to network administrators) at will [3]. As observed in [12], these RAPs may compete with the EAPs for the limited wireless resources and cause performance degradation such as packet loss, which will be also shown in Section II.

RAPs exist for two main reasons. Firstly, authenticating the RAP only *once* typically allows multiple devices connected to the RAP to access the Internet without the need of authenticating them one by one. Thus, it is more convenient to users who have multiple devices, or several users who share the same RAP. The second reason is often the unsatisfying EWLAN performance provided by the EAPs. On one hand, poor EWLAN performance is due to the fact that each EAP can only support a limited number of clients *nearby* and a limited amount of traffic demand. On the other hand, trying to achieve better WiFi performance by chaotically adding RAPs only makes the situation worse. Therefore, we get into this cyclical problem: the worse the EAP performance gets, the more people would want to use RAPs, which makes EAP performance even worse.

Given that EAP over-utilization and RAP existence are the two culprits, we pose the following question: **what if we increase the EAP deployment density to increase the capacity of the EWLAN infrastructure, and disable users' wired Internet access to eliminate the RAPs?** While this direction is intuitively promising, it is actually challenging to decide the deployment density that works the best for a set of real-world users. First, the deployment should be dense enough such that the user traffic previously carried by Ethernet, RAPs, and EAPs can be carried by EAPs alone. Second, higher density means higher deployment cost. Third, EAPs at the same channel can actually interfere with each other if they are too close to each other, but there are only limited number of orthogonal channels (*e.g.*, three in 802.11 2.4 GHz) without interference.

In general there could be three methods to understand the impact of AP density on EWLAN performance: theoretical analysis, testbed experiment, and real-world deployment. In this paper, we opt for real-world deployment for its larger scale (compared to testbed experiment) and realistic traffic (compared to theoretical analysis and testbed experiment). In our large-scale deployment on Tsinghua campus (Section III), there are six WiFi networks, three types of AP density levels, and four EAP vendors. Each of the networks has more than 100 EAPs. The measurement results based on SNMP data are presented in Section IV, Section V, Section VI.

The contributions of the paper are two-fold:

- To the best of our knowledge, this is the largest real-world deployment to study the impact of EAP density on WiFi performance.
- We make three main observations which can be insightful guidelines for EWLAN planners and operators: 1) in general higher AP density improves WiFi performance; 2) over-dense deployment with unnecessary high transmission power can worsen WiFi performance. 3) choice of AP vendors also has an impact on WiFi performance.

II. Tsinghua WiFi measurements

In this section, we first briefly overview Tsinghua campus EWLAN and then show evidences that over-utilization and

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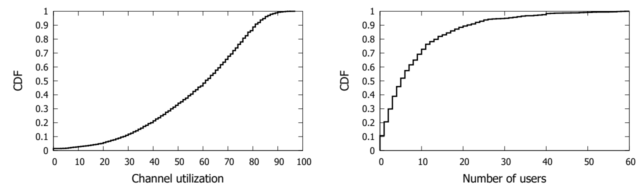
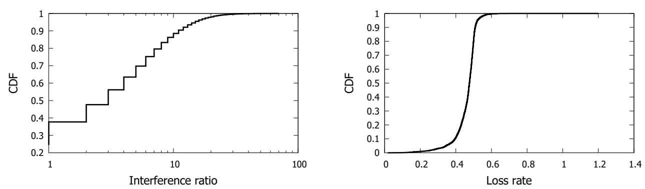
. * Dan Pei is the corresponding author.



(a) Channel utilization. (b) The number of users per EAP.

Fig. 1. Distribution of channel utilization and #users on each EAP during rush hours.



(a) Interference utilization. (b) MAC loss rate.

Fig. 2. Distribution of Interference utilization and MAC loss rate on each EAP during rush hours.

RAP interference are two culprits for unsatisfactory WiFi performance in Tsinghua.

Tsinghua campus covers an area of about 4 km^2, with about 42,000 students, 11,000 faculty and staff members. On this campus there are more than 2,000 EAPs which serve over 50,000 802.11 devices in more than 80 buildings. We collect SNMP data from the above networks. SNMP data is a commonly-used data source for monitoring the performance of large-scale EWLANs and can be easily obtained at the vendor's hardware. We focus on the SNMP objects related to the channel utilization, the interference ratio, the loss rate, and the throughput. Table I summarizes the SNMP objects we used in this paper. We polled these SNMP objects every three minutes to avoid causing overload of the wireless controllers for a period of five days. In this section we only use the objects for Cisco.

According to [12] (which studies the same network) as well as the students in Tsinghua, the WiFi of the campus is of poor performance. There are mainly two reasons for this phenomena.

Over-utilization: We show that both channel utilization and number of connected users during rush hours (defined in [12]) are more than the recommended limit in Tsinghua, deteriorating EAP's performance.

First, the number of users are more than Tsinghua EWLAN's capacity. Previous studies [5, 6] have shown that channel utilization should be kept under 50% for good WiFi performance. However, in Fig. 1(a) we can see that the medians of channel utilization (object 5 in Table I) in Tsinghua are all greater than 50%. Thus EAPs in Tsinghua are significantly over-utilized.

Second, the number of connected users exceeded the number of users which the EAPs are designed for. Previous studies show that 24 connected users [2] per EAP can cause a local contention problem, which decreases the achievable channel utilization [7, 9]. However, as shown in Fig. 1(b), about 15% of APs have more than 24 clients per radio (object 6 in Table I) connected to them, and the number of clients attached to the same AP may rise up to 60 in some extreme cases.

RAPs significantly interfere with EAP's performance: Users install RAPs for convenience and for improving WiFi experience. As a result, the rogue APs outnumber EAPs by about seven times in Tsinghua. [12] shows that the RAPs compete for the same wireless spectrum with the EAPs and have a severe impact on the performance of the EWLAN. Fig. 2(a) shows the interference utilization (object 4 in in Table I) is greater than 5%.

The MAC loss rate can be derived from the frame counters in SNMP data by a method similar to [12]. The computation formula is shown in Equation (1), where $FailCount$, $RetryCount$ and $SuccessCount$ are objects 1, 2 and 3, respectively. The median of the MAC loss rate is greater than 50%, as shown in Fig. 2(b). The channel interference and packet loss rate are high due to the chaotic deployment of the RAPs.

$$LossRate = \frac{FailCount + RetryCount}{FailCount + RetryCount + SuccessCount} \quad (1)$$

III. Deployment Settings

The previous section shows that the over-utilization and interference from RAPs lead to the poor performance of the enterprise WiFi and cause complaints of the users. To address the above problems, one proposal is to increase the EAP deployment density so as to increase the EWLAN infrastructure's capacity, as well as to disable users wired Internet access to get rid of the RAPs. However, for both economical and technical reasons, it is not the case that the higher the density, the better. To study the feasibility of this proposal and choose the appropriate density, we try several network deployment schemes with different density levels and vendors in the real world and collect SNMP data from these networks.

As shown in Table II, about 800 EAPs from four vendors, including Cisco, H3C, Aruba, and Ruckus, are deployed at three density levels on Tsinghua campus. Networks 1, 2, and 3 are at the densest level which have one EAP per room. Networks 4 and 5 are at the less dense level which have one EAP serving two rooms. Networks 1 to 5 are deployed in newly-decorated dormitories where no Ethernet port is available in order to eliminate the RAPs. Networks 1 to 5 have been deployed for more than six months. Network 6 is not a newly deployed network, but is a subset of the original Tsinghua EWLAN. Network 6 is at a relatively sparse level where more than ten rooms share only one EAP and contains a large number of RAPs due to the reasons mentioned in Section I. The overall traffic load for Networks 1, 2, and 3 is similar since they are deployed in similar buildings with the same schedule. Same is the case with Networks 4 and 5.

In the rest of the paper our study focuses on the *2.4 GHz* WiFi performance during the *rush hour*. Although EAPs of

TABLE I
SNMP DATA SET.

Object	Description	Cisco OID	H3C OID	Aruba OID	Ruckus OID
1	This counter shall increment when an MSDU is not transmitted successfully	bsnAPIfDot11-FailedCount	h3cDot11FailedCnt	N/A	ruckusZDWLANAP-RadioStatsTxFail
2	The number of attempts made by the EAP before transmitting the MSDU successfully	bsnAPIfDot11-RetryCount	h3cDot11RetryMSDUCnt	N/A	ruckusZDWLAN-StaRetries
3	This counter shall increment for each successfully transmitted MSDU	bsnAPIfDot11-TransmittedFrameCount	N/A	N/A	N/A
4	Time percentage used by interference from other 802.11 networks on this channel	bsnAPIf-InterferenceUtilization	N/A	wlanAPCh-InterferenceIndex	N/A
5	Time percentage used by all non WiFi and WiFi traffic of current channel	bsnAPIf-LoadChannelUtilization	N/A	wlanAPRadioUtilization	ruckusZDWLANAP-RadioStatsResourceUtil
6	Number of clients associated with this radio	bsnApIfNoOfUsers	h3cDot11AP-UserAuthCurNumber	wlanAPRadio-NumAssociatedClients	ruckusZDWLANAP-RadioStatsNumSta
7	Name assigned to this AP	bsnAPName	h3cDot11CurrAPName	wlanAPName	ruckusZDAP-ConfigDeviceName
8	802.11 MAC address of the AP to which the client is associated	bsnMobileStation-APMacAddr	N/A	N/A	ruckusZDWLAN-StaAPMacAddr
9	The number of bytes sent by this station	bsnMobileStation-BytesSent	h3cDot11Station-TxDataFrameCnt	wlanStaTxBytes	ruckusZDWLAN-StaTxBytes
10	IP Address of the Mobile Station	bsnMobileStation-IpAddress	h3cDot11Station-IPAddress	wlanAPIpAddress	ruckusZDWLAN-StaIPAddr
11	Average packet RSSI for the Mobile Station	bsnMobileStationRSSI	h3cDot11StationRSSI	wlanStaRSSI	ruckusZDWLAN-StaAvgRSSI
12	The difference between signal strength of the client and noise	bsnMobileStationSnr	h3cDot11StationRxSNR	StaSNR	N/A
13	The SSID Advertised by Mobile Station	bsnMobileStationSsid	h3cDot11Station-SSIDName	wlanSta-AccessPointESSID	ruckusZDWLAN-StaSSID
14	The throughput achieved on this channel	N/A	N/A	wlanAPChannel-Throughput	N/A
15	The current power level of the radio	N/A	N/A	wlanAPRadio-TransmitPower	ruckusZDWLANAP-RadioStatsTxPower
16	The number of retry packets as a percentage of the total packets transmitted and received by this station	N/A	N/A	wlanStaFrameRetryRate	ruckusZDWLANAP-RadioStatsFrameRetryRate

TABLE II
NETWORK DEPLOYMENT SCHEMES.

Network	Vendor	Density	Rogue exists?	Total #AP	#Student per room
1	Cisco	One AP per room	No	156	2
2	H3C	One AP per room	No	133	2
3	Aruba	One AP per room	No	124	2
4	Aruba	One AP per two rooms	No	108	3
5	Ruckus	One AP per two rooms	No	170	3
6 (A subset of the original Tsinghua EWLAN)	Cisco	One AP per more than ten rooms (APs deployed in the corridors)	Yes	165	Various but large

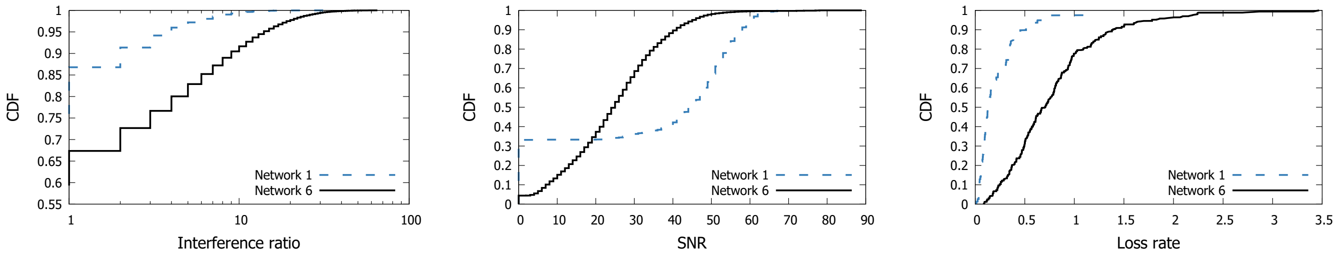
the four vendors support both 2.4 GHz and 5 GHz, the 5 GHz is still largely underutilized because the technology for 5 GHz is relatively new and a 5 GHz wireless card is more expensive and is less common as compared to 2.4 GHz wireless card. Moreover, the user-perceivable performance of 2.4 GHz at rush hour is what we are concerned with the most because the actual traffic and active users of EAPs at rush hour are much more than those at the usual time.

In the following sections, based on the data of a five-day period, we compare different network deployment schemes to show 1) the improvement if we increase the EAP deployment density and eliminate the RAPs in Section IV; 2) the performance of different density levels in Section V; and 3) the difference of AP vendors in Section VI.

IV. DENSE *vs.* SPARSE

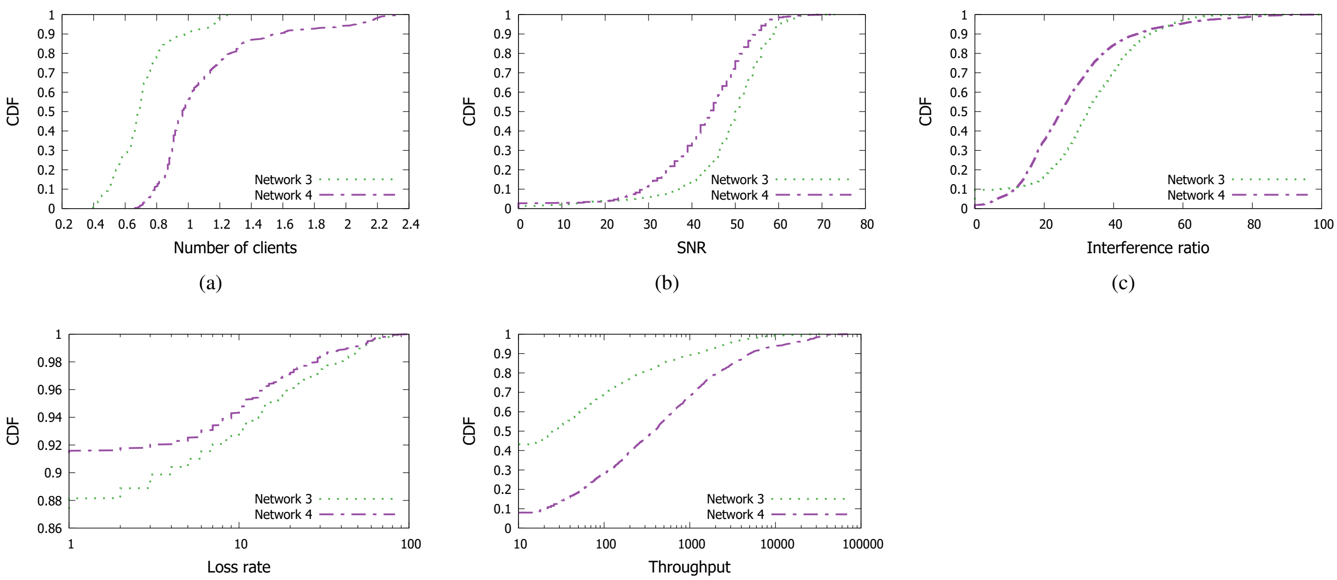
During the operation of the Networks 1 to 5 for more than six months, operators receive much less complains about these dense deployment networks than the original sparse deployment network (Network 6). In order to quantify the advantages of dense deployment, we make a comparison between client SNR, interference ratio, and loss rate of two networks which have similar size, same vendor, but different density: Network 1 (dense, no RAPs, 156 Cisco EAPs) and Network 6 (sparse, lots of RAPs, 165 Cisco EAPs).

Interference ratio (object 4)**:** Fig. 3(a) shows that Network 1 has a much lower interference ratio than Network 6. The interference ratio of Network 1 is below ten in most cases. Users need personal RAPs mainly due to the fact that each EAP can only support a limited number of clients but the



(a) (b) (c)

Fig. 3. Dense *vs.* Sparse.



(a) (b) (c)

(d) (e)

Fig. 4. Denser *vs.* Less dense.

number of clients connected to each EAP is often much more than its designed capacity. Since each EAP of Network 1 only has to serve two users (about six client devices) in one room instead of more than 20 users in more than ten rooms in Network 6, users of Network 1 have less incentives to set up RAPs, which gives operators a chance to disable the Ethernet port entirely to eliminate the interference from the RAPs. The remaining interference in Network 1 in Fig. 3(a) might come from non-WiFi interferences such as microwave ovens and cordless phones.

Client SNR (object 12 in Table I)**:** Fig. 3(b) shows that Network 1 has higher SNR than Network 6 in more than 70% of the cases. This is because of two reasons. First, the signal strength of Network 1 users are higher because of much higher EAP density and the resulting shorter distance between EAPs and users. Second, as previously mentioned, Network 1 (with no RAPs) has much less interference than Network 6 (with a lot of RAPs).

Loss rate: As defined in Equation (1), the MAC loss rate can be derived from objects 1, 2 and 3. Fig. 3(c) shows that Network 1 has lower MAC loss rate than Network 6 due to its higher client SNR and lower interference ratio benefited from dense deployment.

In summary, we make the following observation. **Observation 1: Dense deployment (*i.e.* Network 1) has higher SNR, lower interference, and lower loss rate than sparse deployment (*i.e.* Network 6). In general higher AP density improves WiFi performance.**

V. Denser *vs.* Less Dense

In the previous section, we show that dense deployment performs better than sparse deployment. However, since higher density may introduce more interference between EAPs, it is not the case that the higher the density, the better. In order to figure out which density level has better performance, we make comparisons between client number, client SNR, interference ratio, loss rate, and throughput of the two networks which have similar size, same vendor, but different levels of deployment density: Network 3 (denser, no RAPs, 124 Aruba EAPs) and Network 4 (less dense, no RAPs, 108 Aruba EAPs).

Client number (object 9) **:** Fig. 4(a) shows that ratio of client number of Network 3 to that of Network 4 is roughly proportional to the ratio of user density per AP (two students per AP in Network 3, and six students per AP in Network 4).

Client SNR: Fig. 4(b) shows that Network 3 has a relatively higher SNR than Network 4. Users of Network 3 can receive a relatively stronger signal since Network 3 has a denser deployment than Network 4.

Interference ratio: Fig. 4(c) shows that Network 3 has a higher interference ratio than Network 4. This is the result of the following factors. First, EAPs of both Network 3 and Network 4 are set to the same transmission power (level 7 defined by Aruba), and this is the minimum level that can be configurable in these Aruba APs. Second, there are only three non-overlapping channels in 2.4 GHz. Third, the minimum level of transmission power is still high enough to make EAPs of nearby rooms interfere significantly with each other. Thus, the higher density in Network 3 results in higher interference among EAPs as compared to Network 4 which has a lower density.

Loss rate and **throughput** (object 14) **:** Fig. 4(d) and Fig. 4(e) show that Network 3 has a higher loss rate and lower throughput as compared to Network 4. Although Network 3 has a denser EAP deployment to increase the capacity of WiFi infrastructure (a lesser client number per each EAP and a higher client SNR), it performs worse than Network 4 which has a less dense EAP deployment because over-dense deployment with unnecessary high transmission power (level 7) introduces more interferences (see Fig. 4(c)) between EAPs.

To optimize the WiFi performance in Network 3, operators should cut down the interference ratio. One way is to reduce the transmission power of EAPs in Network 3. The lower the power of an EAP, the fewer the number of nearby EAPs that one EAP can interfere with. However, vendors such as Aruba do not allow operators to configure transmission power to be less than level 7. Another way is to decrease the density level of Network 3 to that of Network 4. We strongly recommend the second way because it is not only feasible since we cannot change the transmission power to be below level 7, but also helps to save costs.

In summary, we make the following observation. **Observation 2: Denser deployment (*i.e.* Network 3) has less client numbers per each EAP, higher client SNR, but higher interference ratio, higher loss rate, and lower throughput than less dense deployment (*i.e.* Network 4). Therefore, over-dense deployment with unnecessarily high transmission power can worsen WiFi performance.**

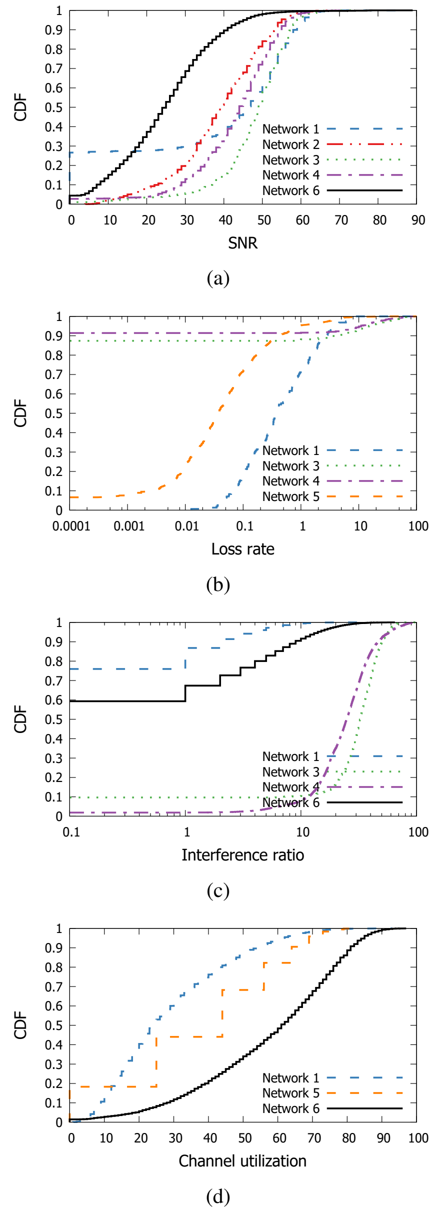


Fig. 5. Different Vendors.

VI. Different Vendors

In the previous sections, we understand the impact of AP density on WiFi performance through real-world deployment. The EWLAN vendor can also affect the WiFi performance, because devices (including EAPs and ACs) of different vendors have different hardware and firmware. For example, in the previous section we have seen that Aruba's minimum level of transmission power significantly affects how AP density impacts WiFi performance. Therefore, we compare the impact of different vendors on WiFi performance in this section.

Note that we have two limitations in this section. First, some objects (those N/A in Table I) are not available from some vendors, therefore we cannot get client SNR from Ruckus, interference ratio from H3C and Ruckus, and throughput from any vendors except for Aruba. Hence, to roughly test the idea about the impact of different vendors, for each specific object, we can only make comparisons among networks who have this object. Second, the technical details of these vendors are not completely available to us, and some similarly-named objects might actually measure slightly different things for different vendors. As such, we cannot offer thorough explanations for some of the observations made in this section. Improvement over these limitations are left as our future work.

Client SNR: Fig. 5(a) shows dense and less dense networks (Network 1 to 4) with different vendors (Cisco, H3C, and Aruba) all having better SNR than sparse Network 1 (Cisco), regardless of their vendors. However, we observe that less dense Network 4 (Aruba) has a better SNR than the dense Network 2 (H3C), and that Network 3 (Aruba) has a better SNR than Network 1 (Cisco) even though they have the same density. This shows that choice of vendors does have an impact on SNR.

Loss rate: The loss rate of Aruba can be directly obtained from the SNMP object 16 in Table I. The formula defined in Equation (1) is used for the loss rate of other vendors. Fig. 5(b) shows that in about 90% of the cases, Networks 4 (Aruba, less dense) and 3 (Aruba, dense) have a better performance than Network 5 (Ruckus, less dense) and 1 (Cisco, dense), showing the impact of vendors. On the other hand, Network 5 (Ruckus, less dense) performs better than Network 1 (Cisco, dense) implies that the density level at one AP per room might indeed be too high for Cisco as well, similar to what we observe in the previous section about Aruba.

Interference ratio: To our surprise, Fig. 5(c) shows that the two Cisco networks (Network 1 for dense and Network 6 for sparse) both perform much better than Aruba networks (Network 3 for dense and Network 4 for less dense). We suspect, however, the reason might be that Cisco and Aruba measure object 4 differently. We contacted the technical supports of both Cisco and Aruba, but was not able to confirm our suspicion. We leave a more in-depth study on the underlying reason for this observation as our future work.

Channel Utilization: Fig. 5(d) shows that Network 1 (Cisco, dense) performs better than Network 5 (Ruckus, less dense), and thus performs better than Network 6 (Cisco, sparse). This is consistent with the fact that the number of users in Network 1 is less than Network 5, which in turn is less than that of Network 6, and is also consistent with our expectation.

In summary, we make the following observation. **Observation 3: The choice of EWLAN vendor also has an impact on the WiFi performance.** Observations 1 and 2 also hold across vendors, with the exception of interference ratio.

VII. Related work

WiFi measurements: Previous studies focuses on WiFi measurement for a single campus network with homogeneous APs and density. For example, [13] uses SNMP data and tcpdump [4] in Stanford. [8] collects syslog, SNMP, and tcpdump in Dartmouth. [12] uses only SNMP data of 2002 APs and over 50,000 users in Tsinghua to measure the rogue AP's impact on WiFi performance. In contrast, this paper measures 6 different networks with multiple density levels and 4 different vendors and studies the impact of density and vendor's impact on WiFi performance.

WiFi optimization: Previous works such as [10, 11, 14, 16] attempts to improve the performance of EWLAN through modifying the AP firmware, client operating system, or the wireless protocol details, which cannot be easily conducted. In contrast, through large scale real-world deployments, this paper shows that our methodology of dense-WiFi deployment with appropriate AP configurations can improve the performance of the WiFi.

VIII. Conclusion

In this paper, we present the first attempt to measure and analyze the impact of AP density on WiFi performance using real-world deployment on Tsinghua campus. Based on the measurement results from our real-world deployment, we make three main observations: 1) in general higher AP density improves WiFi performance; 2) over-dense deployment with unnecessarily high transmission power can worsen WiFi performance due to the minimal transmission power that can be configured by APs. 3) choice of AP vendors also has an impact on WiFi performance. We believe that the observations and insights from the wild will benefit future EWLAN design and deployment around the world.

In our future work, we plan to extend the implementation of APs with appropriate density and configuration all over Tsinghua. We plan to study the impact of other factors such as different AP configurations on WiFi performance, and throughly investigate the underlying reasons for the performance differences of different vendors.

Acknowledgments

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