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Paper

Throughput Characteristics in Densely Deployed Wireless LANs with Various Channel Assignments and Differing Numbers of Terminals

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Abstract Mobile wireless local area networks (WLANs) are becoming popular. Mobile WLANs can be composed of WiFi devices such as portable access points (APs) and portable terminals such as smartphones, tablets and any tethering devices. Several mobile WLANs are densely deployed in a conference room or café. In this case, the WLANs have to share available channels even though they suffer from interference. The interferences coming from the same channel (intra-channel contention) or a different channel (inter-channel interference) reduce the total throughput of the WLANs. This paper investigates the throughput characteristics of several densely deployed WLANs for multimedia communications. For experiments using real machines, for example, 18 sets of WLANs, the relationship among the number of WLANs, distance of WLANs, channel assignment and total throughput was revealed. Moreover, it is shown that the number of terminals in each WLAN substantially affects the total throughput because of the nature of the multi-rate and sending opportunity fairness in CSMA/CA or a *performance anomaly*.

Keywords: Interference, Quality of Service, TCP, wireless LANs, mobile user.

1. Introduction

IEEE 802.11-based wireless local area networks (WLANs) have seen rapid deployment over the last decade and are now a critical part of the wireless infrastructure in both residential and enterprise settings. Buoyed by the increasing base of Wi-Fi-enabled consumer devices and the explosive growth in mobile data demand, there has been a recent emergence of a new form of WLAN in which the access point (AP) itself is a mobile device. These mobile wireless LANs, alternatively termed as mobile hotspot networks, MiFi networks[1), or Wi-Fi tethered networks, are expected to grow over 400% in the next three years[2). WLANs are composed of small form-factor mobile APs (either a stand-alone device or a smartphone or tablet with tethering capability) and a small number of connected client-devices, such as laptops, other smartphones, and wearable Internet devices[3). 3G-, LTE-, or WiMAX-based cellular networks typically provide the backhaul connection from the mobile AP to the Internet.

Because of its small form factor and portability, the wide-scale adoption of WLANs could lead to an extremely dense deployment of APs - a conference with several attendees using MiFi-like devices is a typical example. In these settings, the throughput of the WLANs and thus the quality of service (QoS) delivered to the users who enjoy multimedia communications could be severely degraded because of interference and bandwidth sharing. The extent of degradation would evidently depend on both the physical distance and the density of the WLANs. It is also necessary to consider the throughput characteristics when many densely deployed WLANs use a certain channel combination. There could be several WLANs that use the same channel because the number of WLANs is greater than the number of available channels and because each AP selects a random channel regardless of what the other AP does.

Previous studies[4)-8)] have disclosed the throughput characteristics of two WLANs at different distances from each other. The results indicate some factors that reduce

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the throughput also affect greater than two densely deployed WLANs. Moreover, when the number of terminals that participate in CSMA/CA increases, the probability of contention or collision increases. This would lead to another performance reduction. Specifically, if a terminal uses auto rate fallback (ARF) or adaptive multi-rate, the situation becomes substantially worse because of the nature of the multi-rate and sending opportunity fairness in CSMA/CA or *performance anomaly* that occurs so that the throughputs of all WLANs are forced to decrease. Thus, this paper is devoted to investigating the throughput characteristics of densely deployed WLANs. To capture physical layer factors such as interference (called inter-channel interference) and MAC layer factors such as collision (intra-channel contention), real machines of APs and terminals were used in experiments in which 18 sets of real WLANs are used.

This paper is organized as follows. Section 2 discusses related works and issues to be solved with an explanation of the interference factors. In Section 3, the relation between channel assignments to densely deployed WLANs and the overall throughputs of the WLANs are addressed with inter-channel and intra-channel interference. The number of terminals is revealed to be a dominant factor and causes a *performance anomaly* in terms of the total throughput of all WLANs in Section 4, followed by the conclusion in Section 5.

2. Background

2.1. Related works

Many studies have been conducted for the performance evaluation of WLANs, which are well managed and placed with sophisticated channel usage plans. They, however, do not consider the situation in which several WLANs are densely deployed when personal mobile WLANs such as MiFis or tethering become popular. In this situation, substantially more interference is expected and will affect the throughput characteristics. Channel assignment is more complicated because the number of channels is not sufficient, for example, more than 11 sets of WLANs should be assigned to 11 channels (13 channels in Asia and Europe). Figure 1 shows a 2.4-GHz channel plan and spectrum mask of IEEE 802.11. WLANs that are assigned to the same channel should have contention to receive a sending opportunity. Moreover, because channels in the 2.4 GHz range are overlapped, one can

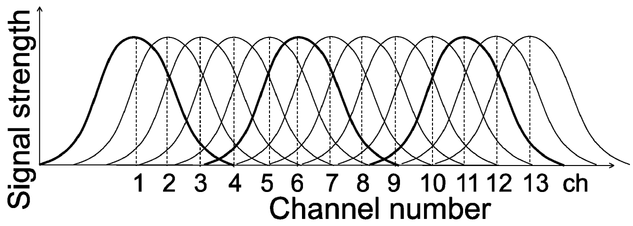


Fig. 1 2.4-GHz channel plan and spectrum mask of IEEE 802.11.

hear carriers from adjacent channels. Studies[9)10)] investigated the interference between very closely located WLANs. Interference is also analyzed for a mobile WLAN which moves in a trajectory with many fixed WLANs[20)]. However, it does not reveal how the throughput characteristics change based on the number of WLANs and number of terminals. As explained in Section 1, the number of WLANs sharing the same CSMA/CA and the number of terminals in a WLAN significantly affect the throughput characteristics.

To effectively utilize 2.4-GHz bandwidth of the IEEE 802.11 WLAN with overlapping channels, several studies have been performed. Several studies have already investigated interference between WLANs. Some of them consider the interferences between channels[16)] and performance anomalies caused by the multi-transmission rate[17)-19)]. These studies revealed that the interference between WLANs reduces the signal-to-interference noise ratio (SINR) and thereby reduces the capacity of the whole WLAN. Because it is assumed that an AP and the associated terminals of a WLAN reside in a shorter range than APs of different WLANs, the capture effects would dominantly affect the QoS, such as throughput. However, previous studies[17)-20)] did not show the capture effect. Reference[21)] used real machines and was supposed to have the capture effect in the results. However, because the configuration of the WLAN is different from the one discussed here, a very small capture effect would be included in the results of the reference. As a minimum, studies[16)22)] consider capture effects. They also show optimal channel assignments with a fixed transmission rate by using computer simulations. In general, a fixed transmission rate is not used, but multiple transmission rates are used by default in nearly all WLAN devices. The rates are adaptively chosen according to the SINR. For example, the auto rate fallback (ARF) is a famous rate adaptation mechanism. The rate adaptation mechanism implemented in a real device is not standardized but is proprietarily implemented by each MAC chip vendor.

Moreover, rate adaptation causes a *performance anomaly*, and it substantially affects the throughput characteristics.

The purpose of this paper is to reveal the characteristics of WLAN throughput with combinations of many factors, such as the capture effect, rate adaptation mechanism and interference. To evaluate the factors, real devices such as mobile APs and smartphones are used in the experiments. Note that real devices have vendor/chip specific characteristics. The devices used in the experiments were popular and were not for a special purpose. The experimental results for those devices could reveal some effective insights on the characteristics of real devices and estimate the characteristics of other real devices.

In this paper, throughput characteristics are investigated based on the number of WLANs, number of terminals in a WLAN with different channel assignments and different distances between WLANs. Interference is, for convenience, divided into two categories; intra-channel contention and inter-channel interference. They will be explained in the following subsections. Because of the nature of the interference, it is very difficult to evaluate the interference by using computer simulations. Thus, real machines such as portable APs and smartphones that are sold in IT shops are used in the experiments. The effectiveness of the ARF is also investigated. The ARF is not standardized but is proprietarily implemented by each MAC chip vendor.

2.2. Inter-channel interference and intra-channel contention

Interference from a wireless LAN and other channel and contention from a wireless LAN of the same channel degrades the throughput performance[11]. The mechanism of degradation regarding this inter-channel interference and intra-channel contention will be explained.

The interference is caused as follows. Radio waves of a wireless LAN overlap radio waves of another wireless LAN of another channel, and then the received radio waves are degraded from the original radio waves. In the 2.4-GHz band allowed in the IEEE 802.11 wireless LAN, if a channel is used, a frequency band practically corresponds to the adjacent channels because the output radio waves spread around the frequency corresponding to the channel. Therefore, if adjacent channels are used, radio waves of the other channel overlap a wireless LAN frame, and the frame might be broken. Alternatively, if the signal is sufficient for receiving, the transmission has to wait because it is regarded as a carrier. However, in the 5-GHz band, no interference generally occurs in adjacent channels.

In a 2.4-GHz band, which is more popular in IEEE 802.11g, there are 13 channels (11 channels in the USA). These are called channel 1 ~ channel 13 from the lower frequency. It is said that the interference does not occur when the channel difference is greater than 5 (for example, between channel 1 and 6) and occurs when the channel difference is less than 4. Additionally, the smaller the channel difference is, the larger the strength of the interference is. However, if the distances of the WLANs are very short, i.e., WLANs are densely deployed, the following sections show that interference does occur. End channels, such as channel 1 and 13, suffer minimal interference because there are few adjacent channels. Generally, both ends of the channel and a middle channel, that is, channel 1, 6, and 11 (or 13 instead of 11) are used by wireless LANs by default to use to the fullest limited channel and to perform a channel assignment, avoiding interference[12)-14)].

The contention comes from frame collisions that also cause quality degradation to occur by a mechanism of random access of CSMA/CA on the same channel and possibly in adjacent channels. When a terminal can hear a carrier from the same channel or another channel, a collision occurs if the contention timer is synchronized in more than two terminals. When a collision occurs, two results are expected. One result is that the collision collapses all the sending frames. The other result is that one or more frames successfully transmit because of the *capture effect*. This is because even the collided frame has a sufficient SINR, can be correctly decoded and is called the capture effect. Thus, in multiple WLAN cases, collision means parallel transmission in the same or adjacent channels regardless of the same CSMA/CA domain.

2.3. Performance anomaly

Even when only one terminal uses a low transmission rate, the throughput of all terminals and APs sharing the bandwidth, i.e., in the same CSMA/CA domain, decrease. This is called a *performance anomaly*. Specifically, the combination of a higher transmission rate and lower transmission rate causes severe throughput degradation for the higher transmission rate terminal. For example, if a WLAN has a 54-Mbps and a 6-Mbps terminal, each throughput is roughly and logically calculated with a harmonic average, 1 / (1/54 +

1/6) = 5.4 Mbps. This means that only 10% of the throughput is obtained from 54 Mbps of the IEEE 802.11g capacity. This is because of the even sending opportunity of the CSMA/CA mechanism and the multi-rate of the transmission rate. Originally, multi-rate was used for improving the probability of successful transmission by adapting any SINR environment, and it was implemented in ARF mechanism. The ARF generally allows the transmission rate to decrease in the case of successive retransmission and to increase in the case of successive success transmission. However, it is difficult for the ARF to differentiate between retransmission by a poor SINR and retransmission by collision. This difficulty may cause an unnecessarily low transmission rate. Collisions are likely to occur when a WLAN has many terminals.

In the case of a densely deployed WLAN, a *performance anomaly* occurs over all WLANs that are sharing the same CSMA/CA domain. In other words, when one terminal allows its transmission rate to decrease, all the terminals that can sense its carrier have to wait to send their frames. This means that if one WLAN is likely to have a significant retransmission rate, other WLANs could suffer from a *performance anomaly*. This is similar to a *performance anomaly* that is propagated over the WLANs.

3. Channel assignment and system total throughput

3.1. Evaluation model

Densely deployed WLAN systems were modeled as follows. The same APs and the same terminals are used to avoid device dependent differences. IEEE 802.11g, which is currently the most popular standard, was employed. The distance between the AP and its terminals is very short (approximately 10 cm). However, the distance between the WLANs varies from 5 cm to 100 cm, roughly called 0 m and 1 m, respectively. For this setting, the capture effect becomes larger as the distance of the WLANs becomes larger. To make the complicated WLAN behavior look simple, functions other than focusing were turned off, such as WMM (802.11e). The portable AP, PLANEX MZK-MF300N with a 566-packet buffer size (measured in the paper[15]) and a smartphone as a terminal, Nexus S and Galaxy S with Android 2.3 were used. Experiments were performed in a room that had a 6 x 7 -m^2 space and concrete walls. The location of those WLAN devices were specified in each experiment and were more than 2 m away from the walls. Very small traffic was detected through the experiment, although the place is not an ideal radio-shutter room and some APs outside of the experiments were found. A throughput of 24 Mbps was measured for one UDP flow from a terminal to its AP.

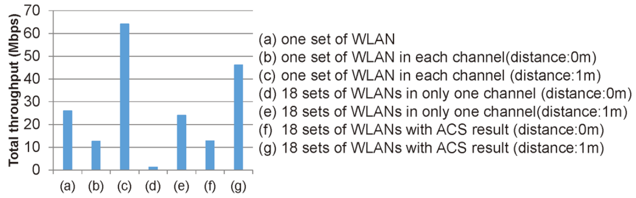


Fig. 2 Throughput with various channel assignments.

3.2. Inter-channel interference

Inter-channel interference was evaluated. The interference became stronger as the distance between the WLANs became weaker. Figure 2 (a), (b) and (c) show the throughput of 1 UDP as measured in the previous subsection (reference throughput) and the total throughput of 13 sets of WLANs at distances of 0 and 1 m. The 13 sets of WLANs correspond to the number of channels from 1 to 13, and each WLAN has only one terminal. Each WLAN is assigned to a different channel. Thus, each channel has only one WLAN. Figure 1 (b) and (c) show that throughput for distance 0 m is substantially smaller than that of 1 m. Compared to the reference throughput of 24 Mbps as shown in (a), the throughput at 0 m has a very poor quality, 12.7 Mbps. For the distance 0~30 cm, even channel 1 and channel 11 were overlapped, i.e., they can hear the carriers of each other. However, the 1-m distance is an acceptable distance even though the WLANs suffer from the interference of each other. A 64.2 Mbps total throughput was obtained.

3.3. Intra-channel contention

The effect of inter-channel contention on throughput depends on the strength of the *capture effect*. Although studies[4,5] investigated the inter-channel contention with two sets of WLANs, the case in which greater than two, for example, 18 sets of WLANs, were measured. As stated before, depending of the distance of WLANs, the strength of the *capture effect* changes. Two distances, 0 m and 1 m, were examined here. Figures 2 (a) and (c) show the results of the total throughput of 18 sets of WLANs in channel 1 for the 0-m and 1-m cases, respectively. They were 1.27 Mbps and 24 Mbps. The throughput of 0 m was quite small. This is because of a lack of capture effect. However, the throughput of 1 m was the same as the reference throughput in Fig. 2 (a).

3.4. Auto channel selection (ACS)

It is important to know the relationship between the channel assignment and throughput characteristics. APs sold in a market have a function to select a good channel called the auto channel selection (ACS). The first investigation was devoted to how the ACS selects channels. Then, the total throughput was measured in the selected channel.

In several trials, ACS did not seem to use non-overlapping channels as shown in Fig. 3. Here, channels 1, 6 and 11 are called the non-overlapping channels. The APs turned on one by one and take sufficient time between the turn-on. The results were nearly the same either with or without traffic. In the case with traffic, a saturated UDP flow was emitted from the terminal to the AP. Although an algorithm for ACS is vendor specific and the algorithm is supposed to increase the total throughput by avoiding inter-channel interferences[7], the APs choose channels such as channels 8 and 9 that cause substantial interferences to channels 6 and 11. Thus, as shown in Figs. 3 (f) and (g), the total throughput of the channel assignment ACS chosen does not seem appropriate.

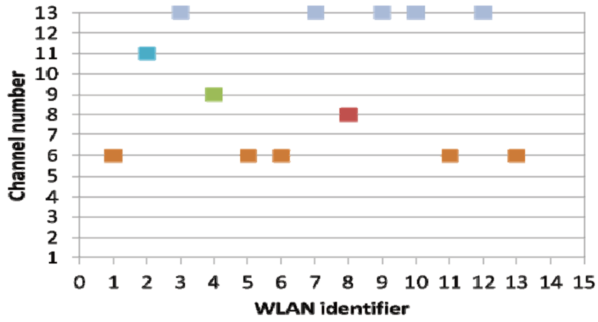


Fig. 3 Auto Channel Selection.

4. Numbers of terminals in a WLAN and the performance anomaly

4.1. Implications of the number of terminals on the frame error rate by collision in ARF

The effect of the number of terminals on the throughput characteristics is investigated here. The *performance anomaly* is caused by a low transmission rate terminal. The rate adaptation mechanism (here called ARF) in a terminal has a transmission rate that moves up/down. The algorithms and detailed behavior of the ARF are not standardized and are implemented proprietarily for MAC chip vendors. Thus, it is impossible to know how the terminal used in the experiment chooses the transmission rate. However, through various experiments of this research, at least, a retransmission epoch plays an important role in choosing transmission rates as many previous studies mention. Figure 4 shows a result from the experiment in which two WLANs with two terminals were placed 1 m from each other. One WLAN was operated with ARF, and the other was operated at a fixed rate of 54 Mbps. From the time of approximately 33 sec to the time of approximately 43 sec, one of the terminals (Terminal-1) of the WLAN with ARF was moved away from its AP. This caused an increase in the frame loss rate at approximately 30 sec. To suppress the increased frame loss rate, the terminals decreased its transmission rate and achieved a slight success in improving the frame loss rate. Therefore, the terminals used in the experiments have an error sensitive ARF.

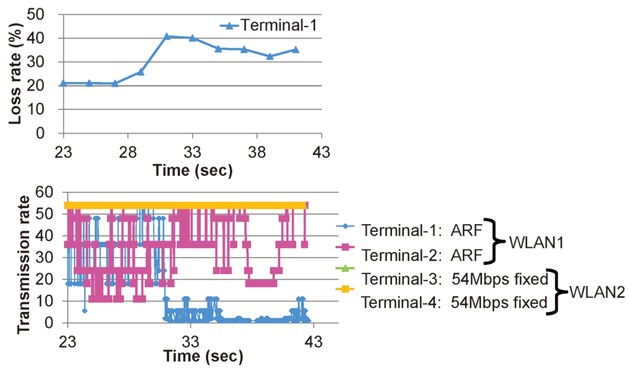


Fig. 4 Frame loss rate and transmission rate with ARF.

By using this error sensitive ARF, the relation between the throughput and number of terminals was investigated. Figure 5 shows the throughput for the number of terminals in a WLAN. Unlike the results frequently observed when using a computer simulation, an increase in the number of terminals causes an increase in collisions and an increase in the loss rate and then leads to a decrease in the transmission rate by ARF. Thus, to keep the throughput high, the number of terminals should be small. In the experiments, greater than three terminals were sufficient to cause a

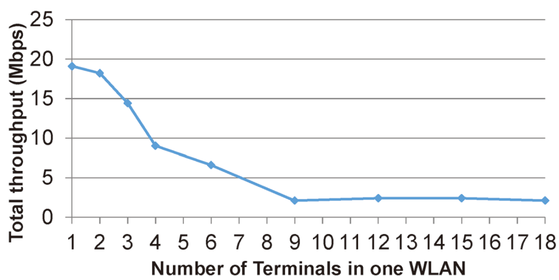


Fig. 5 Throughput for number of terminals in a WLAN.

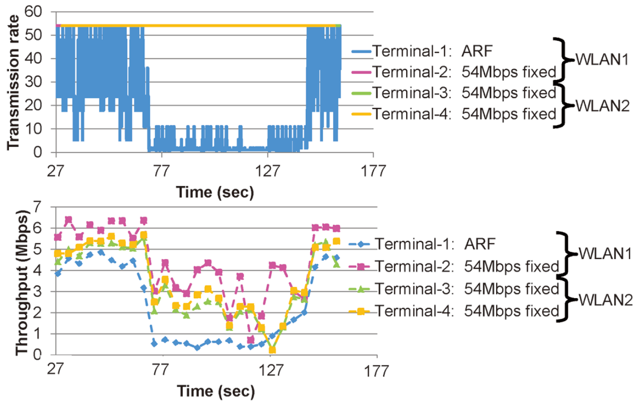


Fig. 6 Throughput and transmission rate with ARF .

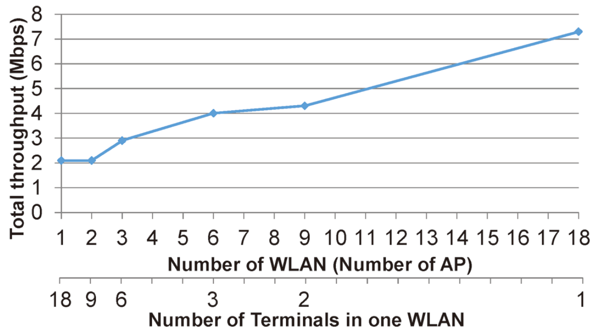


Fig. 7 Throughput for number of terminals (and number of WLANs).

performance anomaly.

Figure 6 reveals that only one ARF terminal caused a *performance anomaly* over all WLANs. In the experiment, two WLANs with two terminals were placed 1 m from each other similar to the previous experiment. However, the ARF was "on" in one of the four terminals and was "off" in the rest of the terminals, and the rates were fixed at 54 Mbps. From the time of approximately 77 sec to the time of approximately 127 sec, one of the terminals (Terminal-1) with ARF was moved away from its AP. This caused an increase in the frame loss rate at the terminal. To suppress the increased frame loss rate, the terminals decreased their transmission rate. By this transmission rate change, all the throughput of the terminals changed even though the transmission rates of the remaining terminals did not change. Note that the WLAN-2, which only had fixed rate terminals, also suffered from the ARF terminals.

4.2. Measured throughput for combinations of the number of terminals

The number of terminals in a WLAN significantly affected the throughput characteristics of all WLANs. In the experiment, various combinations for the number of terminals and number of WLANs were changed so that the total number of terminals, excluding APs, was kept constant at 18 terminals. Figure 7 shows the result of the total throughput for the combination. The experiment showed that the throughput characteristics depend on the distance of the WLANs.

In the case of a 1-m distance, it was better to decrease (increase) the number of terminals (numbers of WLANs) to obtain a higher throughput. This is because the capture effect was effective for small numbers of terminals, and the *performance anomaly* occurred in large numbers of terminals. However, in the case of 0 m, no capture effect was obtained, and the number of WLANs should be smaller. In this case, the number of active terminals including APs is dominant versus other effects. Under the scenario of no capture effect, the *performance anomaly* occurs depending only on the total number of terminals. This means that the *performance anomaly* occurred in all combinations.

4.3. Evaluation for example channel assignment for mitigating performance anomaly

To mitigate the *performance anomaly*, a channel assignment method is proposed here. As stated before, only one low transmission rate terminal causes a *performance anomaly*, and then the overall WLANs and terminals are implicated, resulting in a *performance anomaly*. The terminal is called the designated terminal. A simple idea is to separate the WLANs, including the designated terminals, and to assign them to the same channel. For example, in Fig. 8, there are 12 sets of WLANs. Three sets have 3 terminals (called a large-family) and the rest of the sets have 1 terminal (called small-family) in each WLAN. In this case, a large-family is likely to cause a *performance anomaly*. Because three terminals of the WLAN have very small capture effects, they are likely to cause collision errors. The errors cause retransmission, CW increases and the transmission rate

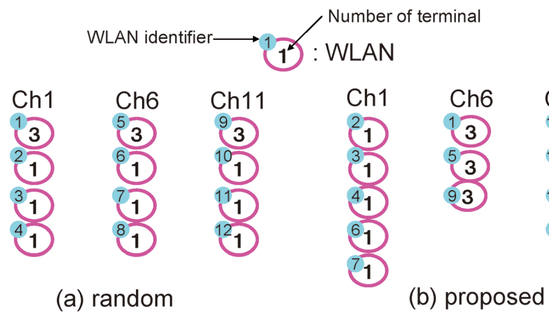


Fig. 8 The proposed channel assignment.

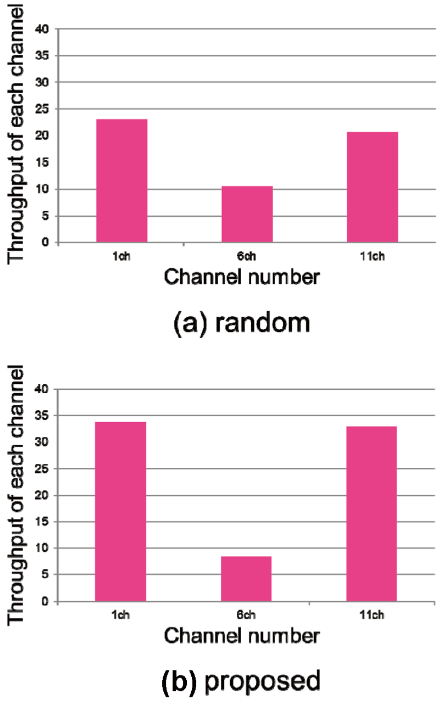


Fig. 9 Total throughput of each channel for random and proposed channel assignment.

decreases. The reduction of the transmission rate would cause a *performance anomaly*. The proposed method assigns the large-families separately to a channel and the small-families to other channels. For example, large-families, WLAN-1, WLAN-5 and WLAN-9, are assigned to channel 6, and the rest of the WLANs are assigned to channel 1 and channel 11. These assignments are not based on transmission rates but on the number of terminals of a WLAN. In the same experiment settings, the proposed assignment is compared with the random assignment. Figure 9 shows the total throughputs of each channel (channels 1, 6 and 11). The total throughputs of the three channels are 51.75 and 75.25 Mbps for (a) random and (b) proposed, respectively. In Fig. 9 (b) compared with (a), channel 6 has a lower throughput, but channels 1 and 11 have substantially higher throughputs. The proposed simple channel assignment is very effective and can improve by 45% for the total throughputs of the three channels.

5. Conclusion

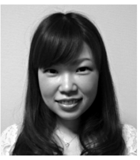
The throughput characteristics are investigated for various channel assignments and for a different number of terminals in densely deployed WLANs. The throughput characteristic results from the inter-channel interference, intra-channel contention (collision), *capture effect* and *Performance Anomaly* are caused by a lower transmission rate because of the auto rate fallback (ARF). Auto channel selection (ACS) does not select the appropriate channels for avoiding either interference or contention even at different distances of WLANs, for example, 0 m (very close) and 1 m. For example, 12.7 Mbps and 64.2 Mbps were measured for 0 m and 1 m. Because of the *capture effect*, contention could be ignored for the 1 m case but not for the 0 m case.

The increase in the number of terminals is likely to cause a *performance anomaly*. The *performance anomaly* results from lower transmission rates are caused by frame loss and collision. Even when only a WLAN causes a *performance anomaly*, all the WLANs cause a *performance anomaly* as if it propagates to one another. The rough calculation shows that a *performance anomaly* can be mitigated by appropriate channel assignments.

References

1) Novatel Wireless: "MiFi Intelligent Mobile Hotspot", http://www.novatelwireless.com/index.php
2) Strategy Analytics Report: "Mobile Hotspot Tethering Handsets to Grow 400% by 2016", http://www.strategyanalytics.com/
3) Roy L. Ashok and Dharma P. Agrawal: "Next-Generation Wearable Networks," Computer, 36, 11, pp.31-39, Nov. 2003, doi:10.1109/MC.2003.1 (2445)
4) Remi Ando, Tutomu Murase, Masato Oguchi: "Characteristics of QoS-Guaranteed TCP on Real Mobile Terminal in Wireless LAN," IEEE Sarnoff Symposium 2012 (May 2012)
5) Remi Ando, Tutomu Murase, Masato Oguchi: "Control Method of Fairness among users in the mobile environment," The 4th Forum on Data Engineering and Information Management (DEIM) 2012, C2-1 (Mar. 2012)
6) Natsumi Kumatani, Tutomu Murase, Masato Oguchi: "Experimental results on quality of services in densely placed APs", Technical Committee on Network System, NS2012-94 (Oct. 2012)
7) Natsumi Kumatani, Mitomo Isomura, Tutomu Murase, Masato Oguchi,: "Optimal channel assignment with considering contention and interference in intra-channel and inter-channel in massive multiple wireless LANs," Technical Committee on Communication Quality, CQ2012-68 (Nov. 2012)
8) Natsumi Kumatani, Mitomo Isomura, Tutomu Murase, Masato Oguchi: "Throughput characteristics of multiple wireless LANs with different traffic directions" The 5th Forum on Data Engineering and Information Management(DEIM)2013, E6-3 (Mar. 2013)
9) Eduard Garcia Villegas, Elena Lopez-Aguilera, Rafael Vidal Josep Paradells: "Effect of adjacent-channel interference in IEEE 802.11 WLANs," Cognitive Radio Oriented Wireless Networks and Communications,2007. CrownCom 2007. 2nd International Conference on, Aug. 2007, pp.118-125
10) Jihoon Choi, Kyubum Lee, Sae Rom Lee, Jay (Jongtae) Ihm: "Channel selection for IEEE 802.11 based wireless LANs using 2.4GHz band," IEICE Electronics Express (ELEX), Vol. 8 (2011) No. 16 P 1275-1280 (2012)
11) Akash Baid, Michael Schapira, Ivan Seskar, Jennifer Rexford Dipankar Raychaudhuri: "Network Cooperation for Client-AP Association Optimization," in Proc. Modeling and Optimization in Mobile, Ad Hoc and Wireless Networks (WiOpt), 2012 10th International Symposium on, pp.431-436 (May 2012)
12) Default channel setting in WiFi access point: http://compnetworking.about.com/od/wifihomenetworking/qt/wifichannel.htm, as of 19

(Sep. 2012)
13) Default channel setting in Netgear WiFi access point: http://documentation.netgear.com/dg834n/enu/202-10197-02/Wireless.4.3.html, as of 19 (Sep. 2012)
14) Recommended channel setting in Netgear WiFi access point: http://documentation.netgear.com/reference/fra/wireless/WirelessNetworkingBasics-3-05.html, as of 19 (Sep. 2012)
15) Ayaka Moriuchi, Remi Ando, Tutomu Murase, Masato Oguchi,: "A study on QoS characteristics for mobile station in wireless LANs," The 4th Forum on Data Engineering and Information Management(DEIM)2012, C2-4 (Mar. 2012)
16) Masashi Iwabuchi, Akira Kishida, Toshiyuki Shintaku, Tkeshi Onizawa, Tetsu Sakata: "A Study on Interference-aware Dynamic Channel Selection in Multi-Channel Transmission", IEICE Technical Report, RCS2013-257 (2014)
17) Takeshi Yamaguchi, Kazuya Tsukamoto, Shigeru Kashihara, Yuji Oie: "Seamless Handover Management avoiding Performance Anomaly in Ubiquitous Wireless LANs", IEICE Technical Report, IN2007-172 (2008)
18) Fumie Miki, Daiki Nobayashi, Yutaka Fukuda, Takeshi Ikenaga: "Performance Evaluation of Multi-Rate communication in Wireless LANs", IEICE Technical Report, NS2008-230 (2009)
19) Fumie Miki, Daiki Nobayashi, Yutaka Fukuda, Takeshi Ikenaga: "AP Selection Scheme with Expected Performance in Wireless Mesh Network", IEICE Technical Report, IN2009-158 (2010)
20) Shweta Sagari, Akash Baid, Ivan Seskar, Tutomu Murase, Masato Oguchi, Dipankar Raychaudhuri, "Performance evaluation of mobile hotspots in densely deployed WLAN environments," IEEE PIMRC 2013, pp.2935-2939 (2013)
21) Tadayuki Fukuhara, Kanshiro Kashiki, Akira Yamaguchi, Toshinori Suzuki: "Experimental Studies concerning Channel Occupancy Ratio and Delay Performances of Wireless LAN", IEICE Technical Report, RCS2009-320 (2010)
22) Masashi Iwabuchi, Akira Kishida, Toshiyuki Shintaku, Tetsu Sakata: "A Study on Autonomous Matching Method for Distributed Cooperative Meduim Access Control", IEICE Technical Report, RCS2013-8 (2013)



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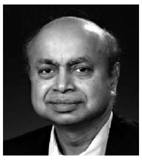

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