Measurement Study of Adjacent Channel Interference in Mobile WLANs

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Abstract—**Over the last few years, mobile wireless LANs (m-WLANs), which are characterized by portable access points (APs) and a small number of connected clients, are becoming popular. When a large number of such personal mobile APs operate close to each other, for example in crowded urban areas and conference venues, the quality of service (QoS) of the connected clients can be severely degraded due to co-channel and adjacent-channel interference. While there exists a large pool of literature on interference management techniques for fixed WLANs, the small form-factor mobile APs present new challenges in terms of high-density deployments and mobility-induced dynamic interference relations. The importance of minimizing interference in m-WLANs is additionally motivated from an energy-efficiency point of view. Since mobile APs rely on limited battery power, packet collisions and retransmissions have a direct impact on the on-time of the APs. In this paper, we present results from a detailed measurement study based on commercially-available m-WLAN devices – two brands of mobile APs and smartphone based clients. While the QoS characteristics of m-WLANs operating on the same channel have been investigated in prior work, we believe this is the first study of adjacent-channel interference using real-world mobile APs. Our experiments reveal the relationship between the distance between m-WLANs and the total throughput of each m-WLAN in various combinations of channels used. Further, we outline how the results can be used for designing optimal channel allocations in dense m-WLAN settings.**

Keywords-Wireless LAN, mobile access point, interference

I. 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. Such mobile wireless LANs (m-WLANs), alternative 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]. m-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.

Due to its small form factor and portability, wide-scale adoption of m-WLANs could lead to extremely dense deployment of APs – a conference with several attendees using MiFi like devices being a typical example. In such settings, the throughput of the m-WLANs, and thus the quality of service (QoS) delivered to the users could be severely degraded due to interference and bandwidth sharing. The extent of degradation would evidently depend on both the physical distance and the channel distance between co-located m-WLANs. In addition to the degradation in QoS, interference in m-WLANs leads to another important problem – that of energy wastage. Since mobile APs rely on limited battery power, transmission collisions and subsequent retransmissions could lead to rapid depletion of the stored energy. In comparison to fixed WLANs, interference management in m-WLANs is thus even more important due to combination of high density of APs, and energy constraints per AP.

In this paper, we study the effects of physical and channel distance on QoS characteristics of m-WLANs using commercial mobile APs and clients. Our work is informed by the large pool of existing literature on fixed WLAN systems, and we contribute towards extending the findings in the m-WLAN environment. m-WLANs differ from fixed WLANs in terms of two key characteristics: (i) m-WLANs typically consist of a small number of clients (between 1 and 5) which are located very close to the mobile AP; (ii) m-WLANs exhibit a much more dynamic nature of interference due to the mobility of the AP. Moving APs might go in and out of range of multiple fixed APs or other moving APs. In contrast, enterprise/hotspot management techniques have to typically deal with a large number of spread out clients, and the dynamism is largely due to changes in load rather than movement of APs.

In terms of sharing the same channel, i.e., channel distance of 0, the QoS characteristics of m-WLANs have been investigated in a few recent works [4], [5], [6], [7]. These studies have revealed relationships between the geometric distance between m-WLANs and the total throughput of each m-WLAN. References [4] and [5] use real machines for evaluations while [6] and [7] are based on simulation studies. Previous results also show that the conventional wisdom of sticking to the three orthogonal channels – 1, 6, and 11 in the 2.4 GHz band leads to the least amount of interference in m-WLANs. Sticking to this arrangement, however, would be inefficient in high density cases where each mobile AP could be in range of 10-50 other APs. Thus it is important to find the impact of adjacent channel interference and to determine the cases under which using adjacent channels should be preferred.

Although there have been a few experimental studies on the range, capacity, and same-channel sharing in the m-WLAN environment, to the best of our knowledge, there have been no prior studies on the QoS characteristics of m-WLANs in terms of both the geometric distance and the channel distance using real machines. Moreover since several works (such as [8], [9]) have pointed to the inaccuracy of computer simulation models in reflecting the true nature of interference effects in WLANs, we believe that our study using commercial m-WLAN devices would form a concrete basis for designing optimal channel assignment strategies for densely deployed m-WLANs.

This paper is organized as follows. Section II discusses related works and issues to be solved. In Section III, the QoS characteristics of m-WLANs in adjacent channels, in terms of geometric distance and channel distance, are presented. Experimental results obtained using real machines are outlined in Section IV. Discussions on optimal channel assignment are presented in Section V, followed by the conclusion in Section VI.

II. BACKGROUND

A. Related works

Several studies over the last decade have been devoted to solving interference problems among access points (APs) in a variety of different settings, for example, in multi-hop networks [10], and in the context of handovers [11], [12]. These studies have presented models and methods for locating the optimal point where the best throughput can be obtained, in consideration of the interference from each AP. As mentioned in Sec. I, m-WLANs present a few unique characteristics that make the interference problem even more challenging than in fixed WLANs. Power control has also been shown to be an effective solution for interference mitigation in traditional fixed WLANs [13]. However, it is difficult for power control to be applied to mobile APs because it is assumed that such mobile APs move frequently and that the associated terminals also move with it. For example, if a person is carrying a mobile hotspot device in his pocket while walking/running, the AP and the connected client devices, such as body sensors, smart-shoes, etc. all move together.

Thus in order to ensure continued adoption of m-WLANs, further studies which specifically work in the mobile environment are critical. References [6], [14] have already investigated the capacity characteristics of m-WLANs by theoretical analysis and simulation when multiple m-WLANs come close together. These investigations indicate that capacity decreases as the distances between m-WLANs decrease. However, in these studies, the investigated characteristics are only for the system capacity level. On the other hand, studies [4], [5] have focused on the flow level characteristics. The flow level characteristics are useful for application designs or QoS controls for delay/throughput sensitive applications.

These works have analyzed m-WLANs and shown that the QoS characteristics when using TCP as compared to UDP are different due to the behavior of the TCP congestion control algorithm. In particular, individual m-WLANs that have different numbers of terminals and flows indicate unfairness in terms of the total throughput of each m-WLAN. However, these results are only applicable to situations in which competing m-WLANs use the same channel.

Evidently, in a dense setting, QoS characteristics vary between different m-WLANs, and QoS degradation is exacerbated when multiple m-WLANs use different overlapping channels. This is caused by interferences resulting from cross-talk between channels when m-WLANs in different channels transmit at the same time. Therefore, the QoS characteristics of m-WLANs which use different channels were investigated in [8]. An analytical model for the interference, methods for finding the interference estimates, and corresponding numerical results were presented in [8]. It well explains the relationship between geometric distance and the amount of interference, i.e., the estimated throughput as a function of the physical distance. From a practical point of view, experiments under real conditions are desired to both validate and extend this analysis. On a general level, interference results in bit errors in received signals and affects several important factors, such as device performance, multi-path characteristics, and equalizer performance. A pure simulation based approach to capture the complex nature of such interference is difficult. Empirical studies on real machines are required. Therefore, this paper is devoted to the investigation of QoS characteristics on real m-WLAN devices in terms of the measured throughput when multiple m-WLANs use different channels at different geometric distances.

B. Qos characteristics in the same channel

There are three interference-states that a system of m-WLANs can be in, depending on the geometric distance d between multiple m-WLANs operating on the same channel.

They are called State-1, State-2 and State-3 and are illustrated in Figure 1. In State-1, each m-WLAN is located sufficiently far away from all other m-WLANs and experiences no interferences from other m-WLANs. Each m-WLAN behaves as if it exists alone. In State-2, the m-WLANs are close enough to interfere with each other. The interferences may be recognized as noise or carrier busy signals, depending on the strength of the interference signals. In this state, the throughput of the m-WLANs decreases as the geometric distance between the m-WLANs decreases. In State-3, the m-WLANs completely share the channel bandwidth because they work together based on CSMA/CA on the same channel.

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Figure 2 shows the QoS characteristics of multiple m-WLANs as a function of geometric distance.

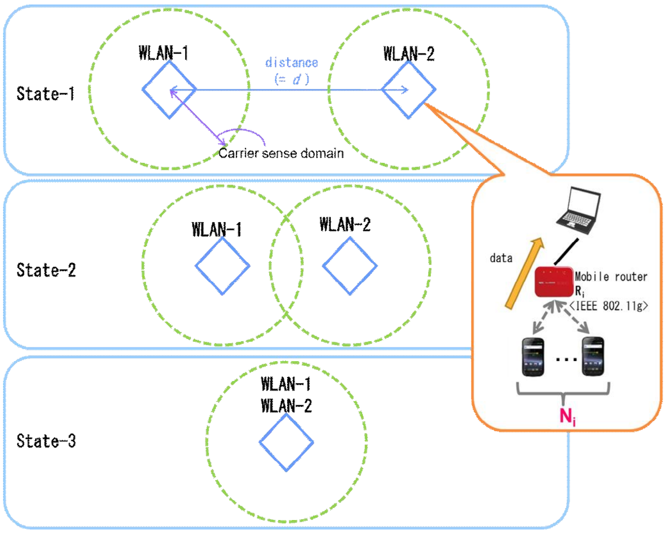

Figure 1. Relation between the distance between interfering m-WLANs and the three states

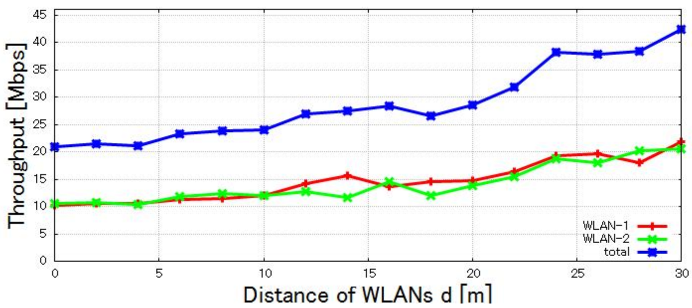

Figure 2. Throughput of co-channel m-WLANs as a function of distance

III. QOS CHARACTERISTICS IN DIFFERENT CHANNEL

A. Channel distance and geometric distance

The throughput characteristics of m-WLANs in different channels have already been investigated through simulations in [8]. The channel distance (ChD) between two m-WLANs is defined as the difference in channel number between the two networks. For example, the ChD between channel 1 and channel 3 is 2. In general, ChD N causes stronger interference than ChD N+1. If N is larger than 4, there is no interference between the two networks in the 2.4 GHz spectrum. This is due to the nature of the spectral density mask of the IEEE 802.11 physical layer specification. In this paper, we only focus on the 2.4 GHz spectrum. For a designated channel, a channel is called an adjacent channel when it is within ChD $N <= 5$ of the designated channel.

In addition to channel distance, the amount of interference also depends on the geometric distance between m-WLANs. As shown in Section II B, the geometric distance (hereafter simply called distance) determines which of the three states a m-WLAN system adopts.

B. Evaluation model

Here we describe the model used to evaluate the throughput characteristics under different interference scenarios. A m-WLAN consists of an AP and one or more terminals. The AP and terminals are placed very close to each other, e.g. 10 cm, because it is assumed that mobile users tether their smartphones to close-by devices such as laptop PCs or other smartphones. Thus, when m-WLANs move, the distance between the AP and the terminals remains the same and very short. Either UDP or TCP traffic is used to fill channel capacity. UDP throughput is a good estimate of channel capacity, whereas TCP shows lower throughput due to its ACK overhead and congestion control mechanism. Because the throughput of UDP and TCP were almost the same in the experiments described in the next section, only the results for UDP are discussed in the following sections. Adjacent channels, channels with ChD N ranging from 0 to 5, were examined.

C. Experimental settings

Consumer devices were used in the experiments. For APs, a portable AP and a mobile AP were chosen. Planex MZK-MF300N [15] and NEC AtermWM3500R [16], which are both pocket-size APs but have almost full functions, were used in the experiments. IEEE802.11g (2.4 GHz) was specified as the mode. These APs, which are commercially available in Japan, have channels ranging from 1 to 13. Only channels from 1 to 11 were used in the experiments. Smartphones were used to emulate client devices. Although typically, smartphones may have 3G/LTE/WiMAX access directly, the demand for traffic off-loading or bit-by-bit charge requires smartphones to connect to nearby IEEE802.11 public APs or other tethering smartphones. The smartphones used were Nexus S phones [17] on which the Android 2.3.7 operating system is running. The Nexus S smartphone is a popular consumer device and offers flexibility in kernel and application programming. Several other brands of smartphones have nearly the same specifications in terms of CPU and wireless chip functions. As shown in Figure 3, two Nexus S terminals were associated with an AP in each m-WLAN and UDP traffic measuring 1500 bytes in length was transmitted from the two smartphones to a receiving terminal via the AP. Throughput measurements were done using the iperf tool [18].

The experiments were performed in a building of Ochanomizu University in Japan. A conference room that has a size of 20 meters in length was used. In general, the room had a favorable radio environment in terms of outside interferences, although some external APs were detected but they were nearly idle. To validate the experimental space, the channel capacity was measured by using UDP traffic; the measured capacity was 26 Mbps, which is a commonly observed value. Therefore, the space was determined to have no serious interferences outside of the experimental system. The emission power of the Nexus S was reduced to 15% of the maximum value to sufficiently diminish the radio signals within the limited experimental space. This means that the experimental models are scaled-down versions of real communications systems.

IV. MESURED THROUGHPUT UNDER DIFFERENT CHANNEL CONFIGURATIONS

Figure 4 shows the measured throughput of the m-WLANs in different channels with varying distance of the m-WLANs and ChD *N*. In these experiments, the Planex device mentioned earlier was used as an AP. Each point in the plot is averaged several experimental recordings.

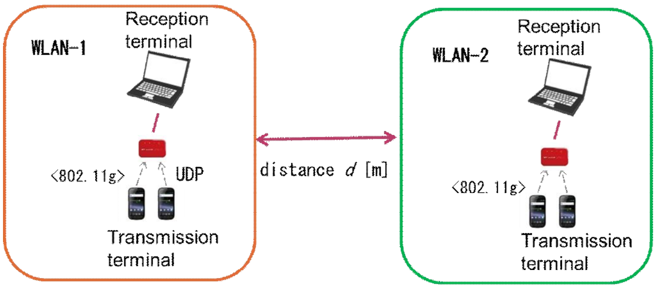

Figure 3. Experimental configuration

In this experiment, for ChD *N* equal to 1, 2, and 3, the throughput degradation in the real machines was the same as that observed in the simulation [8]. For ChD *N* equal to 4 and 5, however, the throughput degradation was unlike that observed in the simulation. Regarding distance, as in the case of *N*=0 in [4] and [5], State-1, State-2 and State-3 were observed. In State-3, nearly the same throughput measured for ChD *N*=1 and *N*=2 was obtained, while *N*=3 shows different throughput from others. However, in State-2, all the throughput characteristics at different values of ChD *N* were different related to the distance.

The value of *N* that gives the best throughput value varies related to the distance between m-WLANs. Unlike that obtained from the simulation, throughput degradation observed in the experiments was affected not only by interference but also by other factors because a smaller *N* did not produce a large decrease in the throughput. Furthermore, almost the same result was obtained when the transmission terminals are changed.

To analyze the difference between the simulated and experimental results, different APs were used. Instead of the Planex, NEC AP was used, as shown in Figure 5. The curves in the figure show characteristics similar to those obtained using the Planex AP, as shown in Figure 4. The slight differences may be due to factors affecting receiver performance, such as the equalizers or filters of radio signals. In the experiments, traffic was sent from terminals to an AP. The AP only contributes to the receiving performance. The precise analysis of overall performance is left for further study. In summary, real machines are expected to have different QoS characteristics from those indicated by simulation models.

V. NUMERICAL EXAMPLE OF OPTIMAL CHANNEL ASSIGNMENT

Since throughput characteristics were shown to depend on both the distance between m-WLANs and the channel distance, the optimal channel assignment must be determined by considering the interference due to channel distance. For example, if the set of available channels is restricted to Channel 1 to Channel 5 and there are three m-WLANs, an intuitive assignment would be: (WLAN-1, WLAN-2, WLAN-3) = Channel (1, 3, 5).

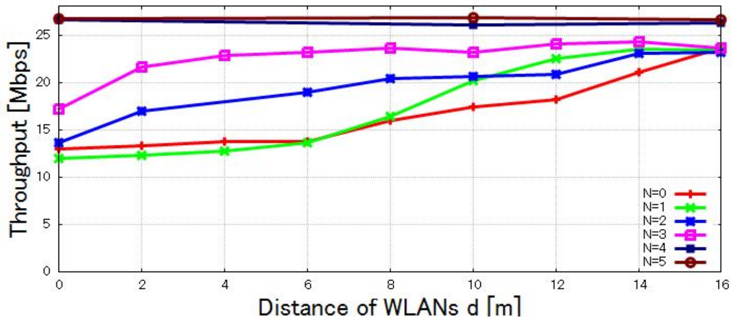

Figure 4. Distance and throughput in various channel distances(Planex router)

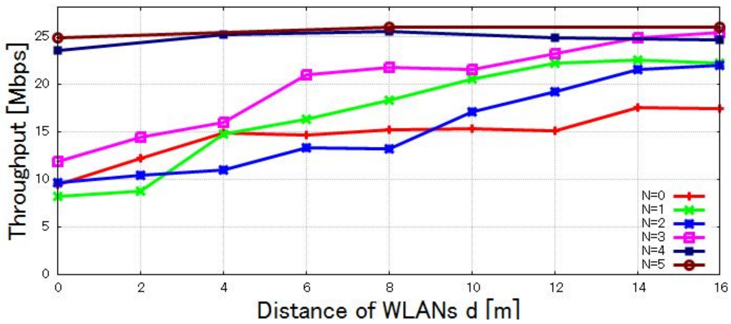

Figure 5. Distance and throughput in various channel distances(NEC router)

However, from the experiments in the previous section, the optimal channel assignment could be (1, 1, 5) because ChD N 4 does not generate much interference. However, this result is expected to vary with the distance between m-WLANs. Therefore, the total throughput (i.e, the sum of throughputs of all flows) of the channel assignments (1, 1, 5), (1, 2, 5), and (1, 3, 5) were compared. Figure 6 shows the channel assignments.

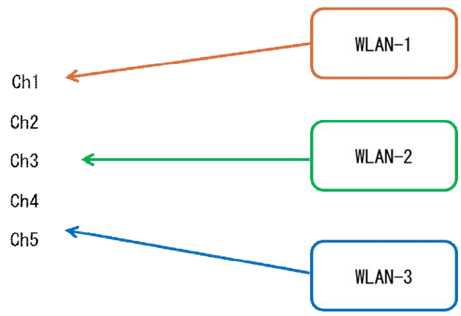

Figure 6. Image of channel assignment

An evaluation was performed experimentally also by using real machines. Figure 7 shows the experimental set-up, where *d* is 0 m or 12 m. WLAN-1, WLAN-2 and WLAN-3 were set *d* m apart. The channel assignment (1, 1, 5), (1, 2, 5), and (1, 3, 5) and the total throughputs of all m-WLANs were compared.

All other settings were similar to those in the experimental environment Figure 3. Distances of 0 m and 12 m were chosen because the total throughputs of three m-WLANs as a function of channel distance, as shown in Figure 4, varied between these two distances. In other words, the optimal channel assignment between these two conditions varied.

The results showed that the channel assignment (1, 1, 5) provided the highest throughput at a distance of 0 m, while the channel assignment (1, 2, 5) provided the highest throughput at a distance of 12 m. At 0 m, the difference between the highest and lowest throughput was over 38%. As a conclusion, because the throughput characteristics vary both with geometric distance and channel distance, the optimal channel assignment also varies.

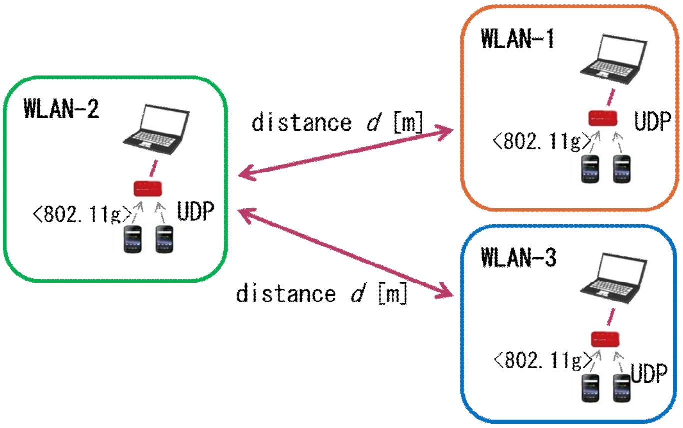

Figure 7. Experimental configuration for channnel assignment

VI. CONCLUSION

In this paper, we investigate the QoS characteristics of interfering mobile WLANs for different settings of physical and channel distances. Interference mitigation in m-WLANs is critical not only to ensure consistent QoS experience to the users but also from an energy management point of view. Since mobile APs are typically battery-powered, wasted retransmissions have a direct impact on their on-time. Experiments using real machines have been performed because the characteristics are affected not only by the interference between channels but also many other device-specific factors. The effect of the channel distance on the throughput is non-uniform in nature, with some distances resulting in more than expected interference. In particular, we show that previous simulation results do not match the experimental results from commercial-devices, suggesting the need for capturing real-world effects into future simulations.

The results obtained are used to present the outline of an optimal channel assignment procedure in densely deployed m-WLANs environments. The optimal assignment of channel usage varies with geometric distance. For example, if channels 1 to 5 are available in a three m-WLANs setting, the channel assignment (1, 1, 5) provides the highest throughput at a distance of 0 m, though an intuitive best assignment would be (1, 3, 5). Further, a (1, 2, 5) assignment provided the highest throughput at a distance of 12 m.

We plan to extend our analysis through more experiments using various types of devices such as iPhones, laptop PCs, game devices and sensors.

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