A Channel Selection Strategy for WLAN in Urban Areas by Regression Analysis

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Abstract—**This paper presents a strategy to choose WiFi channels in urban areas. We consider (i) inter-channel interference where adjacent channels interfere with each other in WiFi systems and (ii) urban situations where many APs in different systems are deployed in an uncoordinated way. As it is often hard to identify the channel with less interference in such a situation, we present a channel scoring function that estimates the performance level of each channel. To build the scoring function, we have conducted exhaustive simulations with a large number of scenarios, and multiple regression analysis has been applied where channel occupancy patterns, traffic volumes and RSS in those channels are used as explanatory variables. To evaluate our method, this scoring function was examined in a realistic scenario where several APs interfere with the AP of interest. We have confirmed that the scores and the actual performance are well-matched where the Spearman's rank correlation coefficient was sufficiently high and can identify the top-ranked channel as well.**

I. Introduction

Cellular networks have been successful to cover worldwide locations. Besides high speed 3G or 4G like LTE that widely cover both urban and rural areas, a number of short range wireless stations are covering urban areas to provide high-speed Internet services. For instance, outdoor public Wi-Fi access points (APs) have been deployed by AT&T, Time Warner Cable etc. to offload smartphone 3G or 4G traffic in large cities of US. In addition, not only WiFi devices but also no-WiFi devices and machines such as handy phones, microwaves and medical devices use the same frequency band. For vehicular networks, Audi has developed a vehicular WiFi system called Audi Connect and the other companies are now focusing on on-board WiFi devices for intra-vehicle communication. This tread will promote WiFi-based inter-vehicle communications (V2V) and vehicle-to-roadside (V2R), and can be extended in future to pedestrians-to-X (P2R or P2V) due to its low-cost and high-penetration features.

As seen, unlicensed band becomes more congested particularly in urban areas. In order to assure a certain level of communication quality even in such circumstances, intelligent WiFi channel selection is simple but promising technology. A naive but straightforward approach is to directly examine the performance by active probing of each channel. However, it needs the target system to be tuned into each channel and run probing, which is a time-consuming task. Another possibility is (passive) traffic monitoring of channels. We may estimate the quality of channels based on the traffic information monitored in each channel. However, considering WiFi-specific features, real performance is not easily estimated only from the monitored traffic in each channel. This is mainly because there are several factors that cause interference and noise. Not only noise from non-WiFi systems, WiFi traffic in adjacent channels may become noise signals like non-WiFi devices since WiFi channels are not completely separated in terms of the spectrum they use, particularly in 2.4GHz band (IEEE802.11b/g). Therefore, IEEE802.11 frames in one channel may be noise for another channel. We call it *inter-channel interference problem*, which is referred to as *ICI* problem hereafter. This is very significant in such a situation like urban areas where many WiFi systems use different channels. Additionally, traffic and RSS diversity within each channel makes the ICI problem more complex. More concretely, it is not easy to assess the impact of both signal strength and traffic volume in the same channel or in a different channel on the performance of the target system.

This paper presents a strategy to choose WiFi channels in urban areas. As stated earlier, adjacent channels interfere with each other in the current WiFi systems. This often makes it very complex to estimate the performance of the target system in presence with other WiFi systems at different locations, which use different channels with different traffic volume. In our method, we build a function to predict how much the target system is affected by interference from the other systems, by taking inter-channel distance, RSS levels and traffic volumes into account. This function is built based on a number of data with different parameter values, and the dataset has been obtained by exhaustive simulations using realistic network simulator called *Scenargie* 1.7 [1], which can simulate the complete protocol stack from the PHY level (OFDM subchannel spectrum spread) to the application layer, as well as the IEEE802.11 family. Finally, multiple regression analysis is employed to represent the performance metrics (throughput and delay) by the observed values.

To evaluate our method, this scoring function was examined in a realistic scenario where several APs interfere with the AP of interest in a 150m $\times$ 150m region. We have confirmed that the scores and the actual performance are well-matched where the Spearman's rank correlation coefficient was sufficiently high and can identify the top-ranked channel as well.

II. Related Work

To avoid interference in cellular networks, inter-cell interference avoidance has been well-investigated. For example, Fractional Frequency Reuse (FFR), which allocates different frequencies to users around cell boundaries and the same frequency to those near base stations, has been developed so far [2]. Cooperative network control mechanisms such as cell clustering are also effective for such (closed) cellular networks [3], [4], but cannot be applied directly to uncontrolled WiFi systems. Ref. [5] presents various analysis of resources and performance with time, frequency and spatial-division multiplexing. Ref. [6] presents an autonomous power and resource control mechanism for efficient spatial reuse.

Frequency Hopping (FH) is another approach to mitigate interference effect. Many FH systems like Bluetooth use static subchannel hopping sequences and they continue hopping along the sequences. However, FH systems move over subchannels regardless of subchannel status, and this often causes serious performance degradation in a new subchannel. Moreover, it causes a certain overhead in hopping, and in particular, WiFi system is not designed for frequent hopping among channels due to its association overhead between APs and clients. Although some work like Ref. [7] considers dynamic channel sequences, it needs channel status estimation by monitoring or some other techniques.

RSS monitoring is often utilized for channel quality estimation and its merits and demerits have been discussed in the past. For example, [8] has pointed out SNR and RSS do not provide sufficient information to estimate L2 performance, but recent work [9] presents a novel method to accurately identify the presence of non-WiFi machines using information obtained through off-the-shelf WiFi cards. This is done by machine learning where RSS variation is modeled as pulse waves. In addition, Ref. [10] presents an approach of estimating frame collision and loss rates in IEEE802.11MAC. It employs probabilistic models to infer backoff occurrence due to carrier-sense operations.

Besides channel selection techniques, adaptive carrier sense threshold control and transmission rate control have been considered for densely-deployed WiFi APs. Interestingly, from the research results in [11], Ref. [12] addresses the fact that the transmission power of most WiFi APs are configured to maximum in the factory settings, which often induces unnecessary interference, but self-control of transmission power by APs may cause unidirectional links. Therefore, cross-layer control is recommended where the carrier-sense threshold is coordinately controlled with transmission power and the transmission power of APs with heavy traffic load should be larger. Ref. [13] presents a distributed channel selection algorithm and an AP selection strategy for clients. However, the goal of this approach is fairness among clients while ours is selection of a channel with least interference effect. It is worth noting that both [12], [13] predict performance by the Gibbs sampling method and this principle can be used for online learning and building of our function.

Compared with the previous approaches, we focus on (i) inter-channel interference where adjacent channels interfere with each other in WiFi systems and (ii) urban situations where many APs in different systems are deployed in an uncoordinated way. To cope with the problem, our approach derives *relative indicator* of channel quality based on realistic, observable parameters like inter-channel distance, RSS and traffic volume. We do not predict absolute throughput and latency, but we do predict how each channel is affected by interference compared with the other channels for channel selection. We monitor the IEEE802.11 control and data frames in each channel, which can be obtained by the off-the-shelf devices with low-cost. As the relative indicator, we have built a function that anticipates the performance level in each channel from the given a set of traffic and RSS information in the channels, and for this, we have conducted exhaustive simulations and multiple regression analysis. This is a unique approach to the urban WiFi problem, and as far as we know, this is the first approach to ranking channel quality based on simple measurement of inter-channel distance, RSS and traffic.

III. Approach Overview

We consider a target system is an IEEE802.11g AP with clients (the AP is referred to as *target AP* in this paper) and propose a method to rate its performance (L2 delay simply called *delay* and L2 frame delivery ratio (we use the term *throughput* to refer to the ratio without confusion) for each channel as a channel selection algorithm. Basically we assume urban situation where a number of APs and their clients of different systems or mobile routers exist among the target AP. In indoor environment, building administrators constitute operational policy of utilization of WiFi channels and in such a coordinated environment, static allocation is much better. Instead, in urban outdoor, a number of public APs are deployed each of which is not under control, *i.e.* highly uncoordinated situation needs to be considered. Our collaborator Sumitomo Electric Industries LTD. is now investigating possibilities to exploit 2.4GHz ISM band devices for ITS roadside units for V2R and P2R communication. A typical scenario is that roadside CCTVs and IR-beacon transmitters detect vehicles driving through the streets, and these information is aggregated to the AP at the intersection.

We assume that target APs have an IEEE802.11MAC monitoring function as well as RSS detection. It is worth noting that IEEE MAC level information is easy to be captured using off-the-shelf devices and tuned drivers. For example, using Atheros WLAN chips, such information is available in promiscuous mode.

As we have discussed earlier, it is not easy to estimate interference effect in a "chaos" environment like urban areas. As an example, we will show in the experiment section the following scenarios where channels 1, 7 and 11 have been used by IEEE802.11g APs of different systems. In this case, it is not easy to assess which channels are better than others due to the ICI problem and due to different traffic volume and RSS from those APs. The detailed results will be presented later in Section V, but channel 1 is the best in the case. We design the rating function that determines the levels of channel status for given information about traffic and RSS in each channel.

IV. Design Details

A. Channel Monitoring and Explanatory Parameters Definition

We denote the set of all APs and their clients (except the target AP and its clients) that use a channel k as $I(k)$. Each AP or client in $I(k)$ is called *interference source*. For each channel k, we obtain the following information about interference sources by IEEE802.11MAC frame monitoring and some additional information.

a) Normalized received interference signal strength: This is called *RSS indicator* of channel k and denoted as $s(k)$. We define $s(k)$ as the normalized averaged RSS (SS_{ave}) of data-frames transmitted by interference sources in $I(k)$ as follows.

$$s(k) = \frac{SS_{ave} - \theta_{min}}{\theta_{max} - \theta_{min}} \tag{1}$$

where θ_{min} and θ_{max} represent the minimum RSS threshold of data frame reception (-90dBm in IEEE802.11g) and expected maximum RSS (usually -50dBm or around), respectively.

b) Normalized traffic volume: This is called *traffic indicator* of channel k and denoted as $t(k)$. We define $t(k)$ as the normalized data bytes transmitted by interference sources in $I(k)$ as follows.

$$t(k) = \frac{8 \cdot d}{b} \tag{2}$$

where d is the byte amount of data frames per second and b is the transmission rate of IEEE802.11b/g.

c) Inter-channel distance: This is called *inter-channel distance indicator* and denoted as $c(k)$. We define $c(k)$ as the normalized inter-channel distance between the channel h of the target AP and channel k used by at least one interference source;

$$c(k) = \frac{|h-k|}{c_{max}} \tag{3}$$

where c_{max} is the maximum channel distance within which two nodes interfere. From our preliminary experiments, two nodes with inter-channel distance larger than 3 do not significantly interfere with each other with any RSS and traffic. Therefore, we set $c_{max} = 3$ and interference source with $|h-k| > c_{max}$ is ignored.

As briefly stated earlier, *averagedSS* and *bitrate* are parameters from the PHY layer, but off-the-shelf WLAN devices (*e.g.* those using Atheros chips) can obtain this information through normally-provided drivers. For example, the above information can be displayed by *iwconfig* command.

B. Building a Rating Function by Multiple Regression Analysis

1) Basic Strategy: In order to estimate the performance of the target AP in each channel, it is required to understand how RSS, traffic and inter-channel distance indicators affect the performance. Furthermore, usually multiple channels are occupied by interference sources. For example, let us consider a scenario; the target AP scanned all the channels and observed that (a) some APs use channels 2 and 8 with heavy traffic and weak RSS and (b) some others use channels 5 and 11 with marginal traffic and strong RSS. The question is which channel is the best for the target AP, and a naive answer is to choose one without any APs (such as channel 3, 4, 6, 7 ...). However, traffic from channels 2 and 8 may become noise signal in those channels and it is not easy to estimate their effect. Therefore, we conducted exhaustive simulations to obtain the model to estimate the interference effect.

Before addressing exhaustive simulations and multiple regression analysis, we investigate the number of cases that we need for the exhaustive simulations. We let n_s and n_t denote the number of "levels" that are contained in $s(k)$ and $t(k)$, respectively. We also let K denote the set of all the possible channel occupation patterns. In order to completely explore all the possible cases, we need

$$\sum_{h \in 0..c_{max}} \left\{ {}_{(c_{max}+1)}\mathrm{C}_h \cdot (n_s \cdot n_t)^h \right\} \tag{4}$$

cases where C denotes a combination. In the above, ${}_{(c_{max}+1)}\mathrm{C}_h$ denotes the number of occupancy patterns of h channels, $(n_s \cdot n_t)^h$ denotes the number of RSS and traffic patterns for each occupancy pattern of h channels. For example, in case that $n_{rs} = n_{tr} = 30$ and $c_{max} = 3$ (the settings used later), totally we need 659,020,863,604 (about 6.6×10^{11}) cases. As this number is not realistic even in an offline process, we try to reduce the number of combinations by taking the following strategy. (i) For each $c(k)$, we conduct simulations for all the combinations of $s(k)$ and $t(k)$. (ii) We apply linear regression analysis to obtain the regression model of the performance for given $s(k)$ and $t(k)$. This is called *single ICI model* (ICI denotes inter-channel interference) and denoted as $f_{single}(k)$. This represents how RSS and traffic affect the performance if only channel k is occupied by interference sources. (iii) For each set $\{k_1, k_2, ..., k_L\} \in K$ of channels occupied by interference sources, we conduct simulations for limited combinations of $s(k_1)$, $t(k_1)$, $s(k_2)$, $t(k_2)$, ... , $s(k_L)$ and $t(k_L)$. (iv) We apply linear regression analysis to obtain the regression model of the performance for given $f_{single}(k_1)$, $f_{single}(k_2)$, ... and $f_{single}(k_L)$ as well as $c(k_1)$, $c(k_2)$, ... and $c(k_L)$ to obtain the final function for given RSS, traffic and inter-channel distance indicator values. This is called *complete ICI model* and denoted as f_{multi}. Our channel selection algorithm uses f_{multi} to choose a channel.

2) Single ICI Model: We have built the single-ICI model by analysis of simulation results. Simulation settings are defined by generalizing the situation of Section III.The client uploads obtained information to the AP periodically, and the physical distance between them is set to 100m. The interference sources are a pair of AP and its client, and traffic between them is created by iperf implemented on the Scenargie simulator [1] with changing the parameter *iperf-udp-rate-bps*, in order to arrange different $t(k)$ values. For different $s(k)$ values, the distance between the target AP and interference source AP is changed from 10m to 300m with step 10m. We have measured (i) the frame delivery ratio (which we call *throughput*) from the client to the target AP and (ii) the MAC layer transmission duration (which we call *delay*) which is obtained as time duration from the moment that a frame is queued at the client till the moment that the frame is queued at the target AP. The simulation scenario is illustrated in Fig. 1.

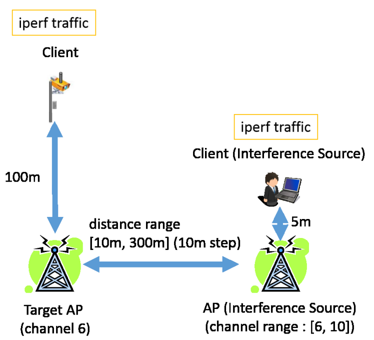

Fig. 1. Simulation Scenario for Single ICI Model

In this scenario, we have 30 $s(k)$ values and 30 $t(k)$ values ($n_s = n_t = 30$). In addition, we have 4 $c(k)$ ($= c_{max} + 1$) values for an interference source pair of AP and client. Therefore, we have 3600 simulation cases as a total. Each case was simulated for 30 seconds.

We have used the following linear function for regression analysis.

$$f_{single}(k) = c_1 + c_2 \cdot s(k) + c_3 \cdot t(k) + c_4 \cdot s(k) \cdot t(k) \quad (5)$$

The result of the analysis is summarized in Tables I and II.

With $c(k) = 0$, the target AP and interference sources reside in the same channel. In this case, the target AP can hear the preamble of the other APs' frame transmission, which may explicitly prevent the target AP's frame transmission. Therefore, $t(k)$ is more significant than $s(k)$. Meanwhile, with $c(k) = 1/3$ or larger, $s(k)$ as well as $t(k)$ also affects the performance since the traffic from the interference sources becomes "noise" for the target AP, which affects the AP's carrier-sense behavior and SNR (this causes frame error, *i.e.*, FCS is likely to be false). It seems that $s(k)$ is more tightly related with the performance than $t(k)$, which supports our hypothesis. As a total, the adjusted R^2 is mostly above 0.8 in all the cases except $c(k) = 3/3$, and around 0.75 even in case of $c(k) = 3/3$. This shows that our linear regression successfully represents the effects of $s(k)$ and $t(k)$ for each inter-channel distance (0, 1, 2 and 3). Based on this result, we move to the step (iii) to analyze the effect of multiple k's.

3) Complete ICI Model: Based on the strategy in the Basic Strategy section, we prepare the following regression function f_{multi}. For simplicity, we have dealt with the case that the number of occupied channels is 2 in this paper.

$$\begin{aligned} f_{multi} \\ = \quad & d_1 + d_2 \cdot c(k_1) + d_3 \cdot f_{single}(k_1) \\ & + d_4 \cdot c(k_2) + d_5 \cdot f_{single}(k_2) \\ & + d_6 \cdot c(k_1) \cdot f_{single}(k_1) \\ & + d_7 \cdot c(k_2) \cdot f_{single}(k_2) \quad (6) \end{aligned}$$

Then using the scenario of Fig. 2, we have conducted 1134 simulations where we have 7 $c(k_1)$ values[1], 54 $f_{single}(k_1)$, 7 $c(k_2)$ values and 54 $f_{single}(k_2)$. The results are shown in Tables III . Similarly with the single ICI cases, the adjusted R^2 is above 0.8, and for the case of delay, it is close to 0.85. Therefore, we can say that the linear function f_{multi} successfully models the delay and throughput performance with derived coefficients.

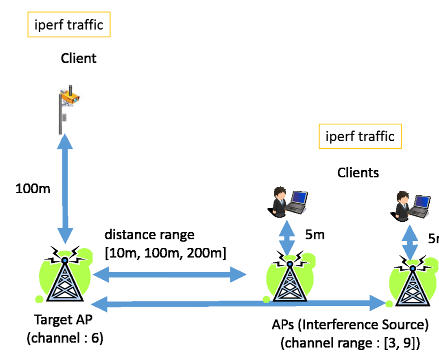

Fig. 2. Simulation Scenario for Complete ICI Model

We note that for reference, we have plotted the values of delay and throughput indicators obtained by the models and simulations in Figures 3 and 4. The 1134 cases are sorted along X-axis by the simulation values. We can confirm that the models well-represent the treads of the values by simulations.

In the next section, we conducted experiments to confirm that our complete ICI model can be used for general scenarios.

V. Performance Analysis

We have examined using more general scenarios the ability of f_{multi} to find out the "best" channel in terms of expected delay and throughput. In particular, when the currently-chosen channel does not provide expected quality due to traffic situation changes, our rating scheme provides

[1]In case of multiple channel occupancy, two sides should be taken into account, *i.e.* $7 = 1 + 2 * c_{max}$.

TABLE I. REGRESSION ANALYSIS FOR SINGLE ICI MODEL (DELAY)

$c(k)$	Coefficient				adjusted R^2
	c_1	c_2	c_3	c_4	(delay)
0	-0.38498	-0.86602	5.89684	1.27298	0.905
1/3	1.3917	-3.7342	-12.7026	35.1980	0.9029
2/3	1.5988	-3.8891	-16.6614	40.9565	0.8895
3/3	0.4015	-0.9238	-11.2069	25.4772	0.7379

TABLE II. REGRESSION ANALYSIS FOR SINGLE ICI MODEL (THROUGHPUT)

$c(k)$	Coefficient				adjusted R^2
	c_1	c_2	c_3	c_4	(Throughput)
0	0.86200	0.17056	-0.51439	-0.48568	0.8413
1/3	0.80081	0.14843	0.94830	-2.86823	0.8223
2/3	0.81915	0.07458	1.12194	-2.93707	0.8339
3/3	0.81033	0.05432	1.06558	-2.44258	0.7635

TABLE III. REGRESSION ANALYSIS FOR COMPLETE ICI MODEL

	Coefficient							adjusted R^2
	d_1	d_2	d_3	d_4	d_5	d_6	d_7	
delay	2.24359	-1.10688	0.70291	-2.66502	0.05354	0.54053	1.63336	0.8685
Throughput	-0.09109	-0.29729	0.44932	-0.34902	0.34982	0.48801	0.56516	0.8064

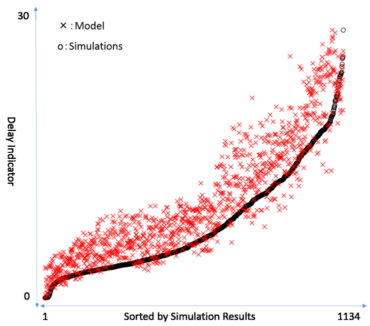

Fig. 3. Delay Indicator Values (Y-axis) by Model and Simulations

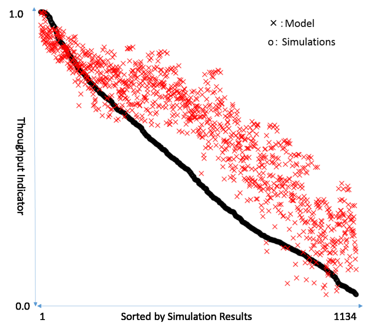

Fig. 4. Throughput Indicator Values (Y-axis) by Model and Simulations

TABLE IV. NODE LOCATIONS AND CHANNELS

Node	Coords.	Channel
Target AP	(75.000, 25.000)	to be determined
Target Client	(75.000,125.000)	to be determined
Interference AP 1	(87.220,105.632)	1
Interference AP 2	(148.151, 14.946)	7
Interference AP 3	(18.433, 20.508)	7
Interference AP 4	(139.297, 85.083)	11

useful information for the target AP to move to another channel (the target AP may examine one by one from the top-ranked channel to the bottom, which extensively reduce the overhead of channel selection in dynamic situations).

For the target AP and its client, we have deployed four AP-client pairs as interference sources in a 150m $\times$ 150 area with crossed roads (Fig. 5). We assume that the target AP-client pairs is in an ITS roadside unit system that generates *iperf-udp-rate-bps* with 5Mbps. Interference sources are those in a convenience store (AP1), public WiFi AP (AP2) and APs in office buildings (AP3 and AP4). Each client is at 5m north from the location of its associated AP, and their rates are 1.5Mbps, 3Mbps 2Mbps and 3Mbps, respectively. They employ BPSK 3/4 (thus $bitrate = 9Mbps$). Table IV shows the coordinates of those interference sources. The target AP monitors the 13 channels for 30 seconds each. We have compared the ranking of f_{multi} values by the proposed models and that of the real performance metrics by the simulations to examine the accuracy of rating. In order to see the performance in each channel, we have run simulations changing the target AP's channels from 1 to 13.

We have summarized the results in Figs. 6 and 7 and

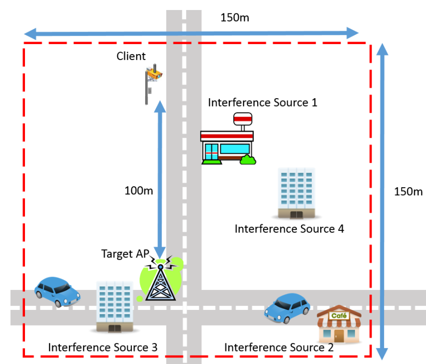

Fig. 5. Simulation Settings

in Tables V and VI. From the figures, the treads of f_{multi} values over 13 channels well-match the act;ually simulated performance. The tables show the ranking results. In both cases, the Spearman's rank correlations are 0.965035 (delay) and 0.9352028 (throughput), which mean very high correlation between the models and the real performance. Therefore, we confirmed that our model could estimate the top-ranked channel and the whole ranking with reasonable accuracy.

VI. CONCLUSION

This paper presents a strategy to choose WiFi channels in urban areas and we have studied the effect of interference in 2.4GHz WLAN. In particular, we consider (i) inter-channel interference where adjacent channels interfere with each other in WiFi systems and (ii) urban situations where

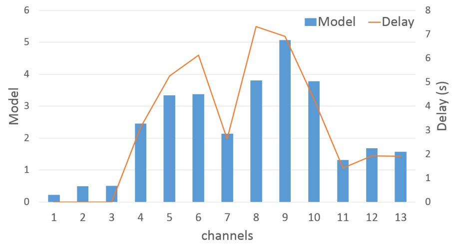

Fig. 6. f_{multi} Values (Y1-axis with Boxes) and Simulated Delay (Y2-axis with Lines) over 13 Channels

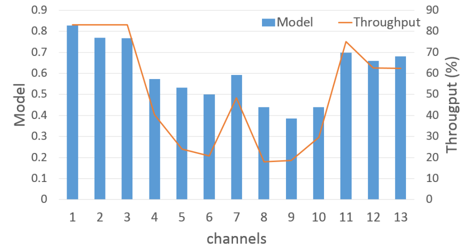

Fig. 7. f_{multi} Values (Y1-axis with Boxes) and Simulated Throughput (Y2-axis with Lines) over 13 Channels

TABLE V. EXPERIMENTAL RESULTS (DELAY)

Channel	Model		Simulation	
ID	Indicator	Ranking	Delay (s)	Ranking
1	0.221914	1	0.002356	1
2	0.501899	2	0.002854	2
3	0.512307	3	0.003902	3
11	1.314429	4	1.414476	4
13	1.574846	5	1.916814	6
12	1.683511	6	1.922286	5
7	2.141591	7	2.62581	7
4	2.463841	8	3.129002	8
5	3.337122	9	5.267372	10
6	3.380002	10	6.132739	11
10	3.789207	11	4.306259	9
8	3.808662	12	7.328154	13
9	5.076176	13	6.919489	12

TABLE VI. EXPERIMENTAL RESULTS (THROUGHPUT)

Channel	Model		Simulation	
ID	Indicator	Ranking	Throughput (%)	Ranking
1	0.827794	1	83.08427	1
2	0.769155	2	83.08427	1
3	0.767343	3	83.06915	3
11	0.69729	4	75.08957	4
13	0.680698	5	62.3103	6
12	0.659767	6	62.61121	5
7	0.593243	7	48.34523	7
4	0.57273	8	40.40192	8
5	0.532401	9	23.92966	10
6	0.500817	10	20.76474	11
8	0.439509	11	18.02075	13
10	0.438814	12	29.57189	9
9	0.385057	13	18.61199	12

many APs in different systems are deployed in an uncoordinated way. It seems that WiFi channel selection issues have been well-investigated, but it has not been discussed how the inter-channel interference affects the performance, how it is closely related with RSS and traffic volume, and how we should choose a channel in an open, uncoordinated situation. Relying on exhaustive simulations but with a reduced number of simulation cases, our model built by regression analysis achieves sufficient accuracy to estimate better WiFi channels.

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