Throughput Improvement by using Dynamic Channel Selection in 2.4GHz Band of IEEE 802.11 WLAN

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***Abstract*—IEEE 802.11 WLAN Access Points(APs) are configured in the 2.4GHz band extensively to cater for the needs of all WiFi-enabled devices. In densely populated areas this causes considerable interference amongst the APs since there are only three orthogonal channels. Downlink data throughput reduces due to co-channel and overlapping channel interference. Efficient channel selection is a significant problem due to the dynamic wireless environment. Our proposed Dynamic Channel Selection(DCS) algorithm selects the optimal channel based on the periodic scan of the environment by a co-located monitoring radio unit. Frequent switching of channels is also reduced to maintain the AP's performance and stability. It is an innovative solution, readily applicable to the existing WLAN standard not necessitating any change in IEEE 802.11 MAC Layer. Our results show an improvement of up to 35% in the data throughput in six different real-time network scenarios.**

***Index Terms*—Access Point(AP), Co-channel interference, Dynamic Channel Selection, IEEE 802.11, Overlapping channel interference, WiFi**

I. Introduction

IEEE 802.11 WLAN deployment is widespread due to the availability of free unlicensed band, low-cost Access Points(APs) and enormous data demand. Infrastructure WiFi has become popular with public hotspots providing a free connection to the users and personal/enterprise networks being easily accessible in urban areas. The trend of offloading high bandwidth data from the 3G/4G network to WiFi network is also growing. However, like any other popular technology, WLAN has an unforeseen limitation triggered by the large-scale usage in an area.

IEEE 802.11 networks operate in 5GHz(.11a) and 2.4GHz(.11b/g) frequency bands. There are 23 orthogonal channels in the 5GHz band and only 3 in the 2.4GHz band [7]. The 5GHz band is less crowded and free of interference. However, WiFi-enabled devices compatible with the 5GHz band are less. So, in real-life scenarios, APs are generally configured in the 2.4GHz band. Due to the limited number of channels in this band as shown in Fig.1, new APs coming up in a locality have to coexist in a channel already occupied by other APs. This causes co-channel interference in that channel and overlapping interference with adjacent channels. A considerable interference among neighboring APs can cause degradation in downlink data throughput. This makes dynamic channel allocation crucial for designing 2.4GHz wireless networks.

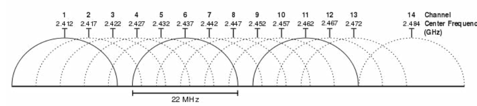

Fig. 1: IEEE 802.11 WLAN channels in 2.4GHz band

In [1], the authors suggested the use of an extra control bit in the MAC header of a control packet transmitted from interference prone station to AP, to avoid co-channel interference. In [2], the authors proposed channel utilization factor by quantifying adjacent channel interference in IEEE 802.11b/g network only. In [3], radio features are measured by all stations and reported to AP using IEEE 802.11k standard to optimize co-channel interference, but this causes some overhead and inaccuracy of measurements due to the non-centralized scan. Overlapping channel interference is considered in [4] to design an algorithm that calculates distance, transmit(Tx) power, loss and interference of nearby APs to find possible optimal channels. Network throughput improvement in [5] is observed by considering AP as well as client interference, although it is not feasible to implement practically. In [6], the authors provided an algorithm for transmission power adjustment of APs by using the concept of cognitive radio. It eventually helps in minimizing co-channel interference, although adjacent channel interference is ignored.

In this paper, we consider both co-channel and overlapping channel interference in 2.4GHz IEEE 802.11 WLAN. We propose a simple linear algorithm that assigns the best channel based on the scan results provided by a monitoring radio present in our AP. It ensures that there is an adequate number of channel switches to maintain stability and throughput, irrespective of the environment. The underlying principle of our algorithm is attributed to the variance in channel power across the spectrum, with or without interference. The IEEE 802.11 MAC layer is unaltered in our work and hence it can be practically deployed in the existing WLAN standard. We have tested our algorithm in six real-time scenarios and observed an improvement in data throughput up to 35%.

This paper is divided into five sections. Section II discusses system architecture of our AP. Section III describes our proposed Dynamic Channel Selection(DCS) algorithm in detail with spectrum scan, channel selection, and channel switching decision. Performance evaluation in the real-time network along with results are available in section IV. Finally, the conclusion is available in section V.

II. System Architecture

The architecture of our AP is shown in Fig. 2. We propose two co-located radio units to be used with one host processing platform in the AP. WiFi Radio-1 is configured in *Master* mode to give network access to the clients while WiFi Radio-2 is configured in the *Monitor* mode to scan the 2.4GHz band. Both the WiFi Radios should have RF antennas with same characteristics so that their coverage areas superimpose. Our DCS algorithm is executed on the host processor. WiFi Radio-2 scans the 2.4GHz band passively at regular intervals. It provides scan results to the host processor, where our DCS algorithm selects the optimal channel and takes the decision of channel switch of WiFi Radio-1.

WiFi Radio-2 does accurate channel scanning and power measurement of interfering APs since the channel characteristics remain same for both the co-located radios. It does passive scanning without affecting the processing of WiFi Radio-1. Popular mechanisms scan through clients or any reference AP and send the measurements to the AP. Messages exchanged in the wireless network may suffer from path loss apart from causing additional overhead. MAC changes are suggested to exchange these messages, but our algorithm does not need any such change by the usage of WiFi Radio-2.

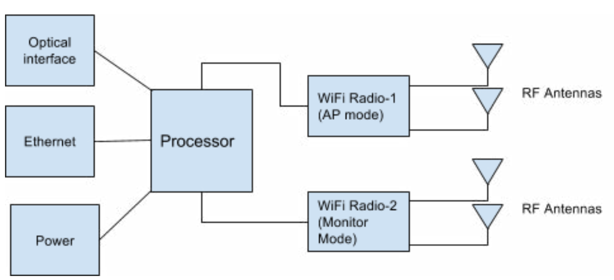

Fig. 2: System architecture of access point

III. Proposed Algorithm

Our DCS algorithm is designed as a continuous cycle of three primary actions: *Spectrum Scan*, *Channel Selection*, and *Channel Switch Decision*. Passive scanning of the spectrum is done by WiFi Radio-2 as discussed in section II. Beacon packets of neighboring APs in the 2.4GHz band only need to be considered. Received Signal Strength Indication (RSSI) value, which signifies the power level, is determined for each of these packets. The cumulation of these power levels in a particular channel *i*, gives a clear picture of that channel's interference and noise levels. This information is utilized to select the optimum channel i_{opt}. At the start of each cycle, the current configured channel number of the AP, i_{curr}, is retrieved. The channel switch decision is made by comparing the difference in power of i_{opt} and i_{curr} along with other factors to maintain stability and consistent throughput. The following parameters are given as input to start this algorithm:

- Scan Time: T_{Sc} is the time interval for *Spectrum Scan*.
- Sleep Time: T_s is the time interval between two cycles.
- Stability Factor: α is the percentage change in channel power of i_{curr} and i_{opt}.

The algorithm has following steps:

1) Extract the initial configuration of AP and Virtual APs(VAPs) if any(SSIDs, mode, channel bandwidth).
2) Start timer T_{Sc}.
3) Initialize channel power array with zeros P_i = 0, where channel number $i = \{1,2,...11\}$.
4) Read the RSSI value for each AP present in i except our own AP and VAPs, if any. Convert it from dBm to mW and add it to P_i to get the aggregate channel power of i.
5) Repeat step 3 till timer T_{Sc} expires.
6) Calculate the weighted channel power P_{wi} as per the mathematical channel power model, given in subsection B.
7) If $P_{wi_{curr}}$ = 0, then retain AP operation on i_{curr}. Go to step 12.
8) Find the channel with minimum power level or interference-free channel(if available).
9) Select the optimal channel number i_{opt} on the basis of *Channel Selection*, given in subsection B.
10) Extract i_{curr}.
11) Find output of *Channel Switch Decision*, given in subsection C. If affirmative, switch the channel to i_{opt}, retaining the configuration obtained in step 1.
12) Sleep for T_s and repeat from step 2.

A. Spectrum Scan

In infrastructure WLAN, beacon frames are periodically broadcasted in the network. When WiFi Radio-2 receives a beacon frame, its wireless driver determines the RSSI and provides this information to the application layer via netlink. These values are processed by our algorithm to update P_i. Beacon frames of our AP and VAPs are discarded to ensure correctness of interference level with respect to our AP. T_{Sc} depends on the speed of the host processor and environment. T_{Sc} has to be chosen such that the beacons of APs present in channel 1 to 11 should be captured only once, and the number of channel switches should be reasonable. T_s should be decided as per the desirable frequency of spectrum scan.

B. Channel Selection

The Channel Selection principle is the unique and innovative solution to the *optimization problem* of determining the best channel in any dynamic environment. The cumulative channel power P_i captured on each channel i per cycle of scanning time, T_{Sc} by the monitoring station is dependent on the interference in the environment. Thus a weighted sum function on P_i is implemented to compute the effect of co-channel interference and overlapping channel interference. One of the following weight function models can be used to generate the weighted channel power P_{wi}.

1) Weight Function 1:

$$P_{wi} = \sum_{j=-1}^{1} (\delta_j \times P_{i+j}) \tag{1}$$

where δ_j is the interference factor and is defined as:

$$\delta_j = \begin{cases} 0.5, & \mid j \mid = 1 \\ 1, & j = 0 \end{cases} \tag{2}$$

2) Weight Function 2:

$$P_{wi} = \sum_{j=-2}^{2} (\delta_j \times P_{i+j}) \tag{3}$$

where δ_j is the interference factor and is defined as:

$$\delta_j = \begin{cases} 0.25, & \mid j \mid = 2 \\ 0.5, & \mid j \mid = 1 \\ 1, & j = 0 \end{cases} \tag{4}$$

Both the models consider co-channel interference by a factor of one and adjacent channel interference by a factor of half. The primary difference between them is the number of adjacent channels deemed to cause interference. While the first model accounts for interference only in the immediately adjacent channels, the second model considers interference of two channels on either side of the center frequency. In the first model, the variation in channel power is less whereas the second model is highly sensitive to change in the environment which may cause toggling of i_{opt}. The former has better performance in a crowded environment, but the latter is preferred in a sparsely populated environment. The weighting model can be chosen depending on the deployment scenario. In our work, we have considered the first design of weighted sum function.

P_{wi} of every channel *i* is compared to detect free channels. A free channel is the channel where interfering APs do not exist or may be present at a distance such that they cause negligible deterioration of our AP's performance. It is mathematically defined as

$$P_{wi} \leq 0.00001mW \tag{5}$$

A set of such adjacent free channels is called a *span* of continuous free channels. Optimal channel selection is based on the following algorithm.

1) Find the *span* with the maximum number of free channels.
2) If free channels are available then select i_{opt} as follows:
   a) If edge channels (1 or 11) are included in the *span*, then this edge channel is selected. This implicitly gives priority to the orthogonal channels.

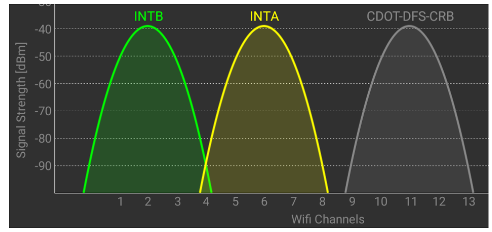

Fig. 3: Edge free channel

   b) If the number of free channels is more than two, then the middle channel in the *span* is selected.

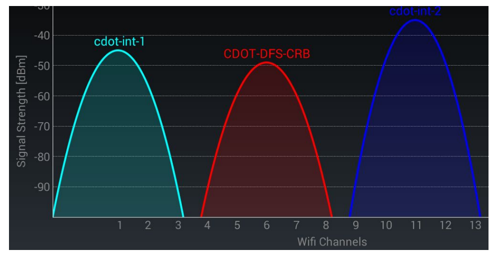

Fig. 4: Middle orthogonal free channel

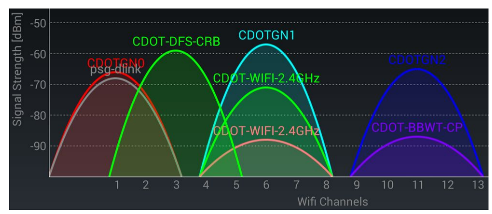

Fig. 5: Middle free channel

   c) If there is only a single free channel, then this channel is selected.

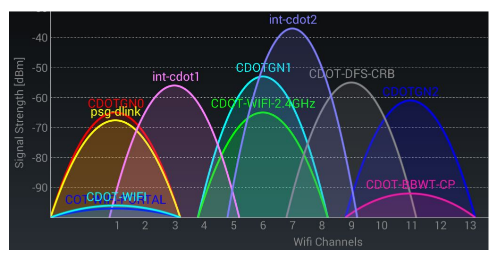

Fig. 6: Single free channel

3) If no free channels are available, then the channel with minimum power is selected.

The above figures are captured using WiFi Analyzer v3.11.2 Android application in real-life scenarios. "CDOT-DFS-CRB" is our AP which is operational in the optimal channel i_{opt}.

C. Channel Switch Decision

The Channel Switch Decision is the proposed solution for the *decision problem* of whether our AP should be switched

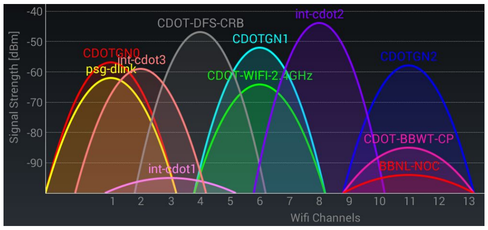

Fig. 7: No free channel

to i_{opt}, the output of the previous section. It is essentially based on the user-desired stability factor α, which implies the tolerance of interference by the AP. The value of α is inversely proportional to the number of channel switches. A lower value makes the AP switch to i_{opt} more often. In real-life deployment, due to this continuous toggling of the AP, total packets dropped while switching increases drastically. On the contrary, a higher value will fix our AP on a channel which may suffer from co-channel interference. It will also reduce the AP's sensitivity to the dynamic environment. Thus, α should be optimized with respect to the tolerance of AP for the best performance of this algorithm. DCS algorithm takes this α value as input in the beginning and decides to switch as follows:

1) Compute cumulative channel power difference ΔP.

$$\Delta P = \frac{P_{wi_{curr}} - P_{wi_{opt}}}{P_{wi_{curr}}} \times 100 \qquad (6)$$

2) Decide channel switching as per the truth value of following compound statement:-
"Change in channel power is greater than α, or the current channel is not orthogonal and free channels are available"

This decision statement is defined in propositional logic as

$$S : P \vee (\neg Q \wedge R) \qquad (7)$$

where the propositions are

P : Change in channel power is greater than α
Q : Current channel is orthogonal
R : Free channels are available

TABLE I: Truth table for decision statement

	P	¬Q	R	S
i)	T	X	X	T
ii)	F	T	T	T
iii)	F	F	T	F
iv)	F	X	F	F

i) If $\Delta P > \alpha$, then decide to switch channel irrespective of other conditions.
ii) Even if $\Delta P < \alpha$, but $i_{curr} \notin$ {1,6,11} and $P_{wi_{opt}}$ = 0, then decide to switch channel. Free or clean channel is given priority in this condition.
iii) Even if $P_{wi_{opt}}$ = 0, but $\Delta P < \alpha$ and $i_{curr} \in$ {1,6,11} then decide not to switch channel. Orthogonal channel is given priority in this condition.
iv) If $\Delta P < \alpha$ and $P_{wi_{opt}} \neq 0$, then decide not to switch channel.

IV. Performance Evaluations

Our AP uses Atheros-based WLM200N2-26 IEEE 802.11 b/g/n radio as WiFi Radio-1 and WiFi Radio-2 with open source Ath9k driver. Freescale QorIQ T1024 processor is used as processing platform with Ethernet backhaul of 1Gbps as shown in Fig. 2. hostapd and hostapd_cli v2.5 are used for enabling AP and channel switching operation respectively. DCS algorithm is embedded in the open source application, horst v4.2 which is initially designed for band sniffing only.

Test Setup: Our AP is configured in IEEE802.11n mode with Tx power of 20dBm and 20MHz bandwidth on i_{curr} as shown in Table II. A controlled environment is created inside a Radio Frequency(RF) enclosure for conducting throughput test for our AP in cases 1, 2 and 3. AP-Client data transfer of 20Mb is also generated on the interfering APs to replicate the effect of real-time data load. Test cases 4, 5 and 6 are conducted in an instance of the dynamic wireless environment of laboratory(20x20m) with around 10 interfering APs as illustrated in Fig. 7. Random real-time data transfer is present in these interfering APs. The six test scenarios are described below:

TABLE II: Test scenarios

Case No.	Environment	i_{curr}	i_{opt}	Interference Type	Complexity
1	-	X	i_{curr}	None	O(1)
2	Fig.3	1	11	Overlapping	O(11)
3	Fig.4	11	6	Co-channel	
4	Fig.5	6	4	Co-channel	
5	Fig.6	6	9	Both	
6	Fig.7	1	X	Both	

Best Scenario
Case 1: No interfering APs are present in i_{curr}

Average Scenario
Case 2: Interfering APs present in channels 2 & 6
Case 3: Interfering APs present in channels 1 & 11
Case 4: Interfering APs present in all orthogonal channels 1, 6 & 11

Worst Scenario
Case 5: Interfering APs present in all the channels except channel 9
Case 6: Interfering APs present in all the channels

Throughput improvement is observed in all the above cases. The effective implementation of the DCS algorithm depends on two input parameters: Scan Time, T_{Sc} and Stability Factor, α. The optimal value of these conditional parameters are derived in the following section, and the increment in throughput is also depicted.

A. Scan Time

Scan Time is the input parameter that depends on the host processor and environment. As discussed in section III, T_{Sc} is selected such that the WiFi Radio-2 can capture the beacons across the spectrum accurately. It is evaluated by rigorously testing the behavior of the DCS algorithm on increasing the scan time and observing the number of channel switches caused thereof. This experiment is conducted for our AP over a period of 24 hours in an uncontrolled environment of Case 6. T_{Sc} is varied from 1 to 15 seconds. DCS is initiated with α value fixed at 10% to ensure sensitivity to the unpredictable environment. T_s is taken as thrice the value of T_{Sc}.

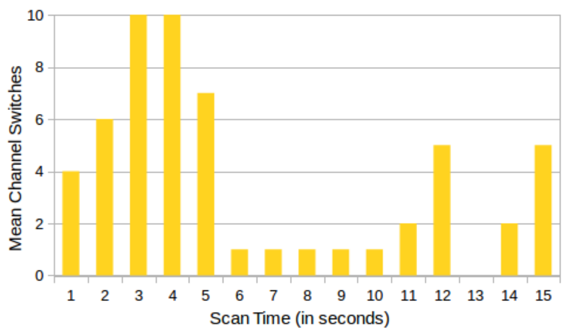

Fig. 8: Mean channel switches for varying T_{Sc}

In Fig. 8, the mean channel switches are calculated for 10 iterations of a particular scan time T_{Sc}. When T_{Sc} ranges from 1 to 5s, it is observed that our AP switches to i_{opt} very frequently. T_{Sc} of up to 5 seconds is not enough to capture all the beacons due to which some part of the spectrum is falsely identified to be unoccupied. Our DCS gives priority to these free channels and switches accordingly. For T_{Sc} >10s, beacons of the same AP may be captured more than once which may make $\Delta P > \alpha$ and thus cause an erroneous channel switch. Our AP exhibits a reasonable number of channel switches with T_{Sc} value from 6 to 10s. Thus, T_{Sc} of 8 seconds and T_s of 24 seconds is considered for further testing.

B. Stability Factor

The value of α is the stability factor of our system which defines the sensitivity towards interference in the environment as discussed in section III. In general, it can be chosen from the range of 20 to 35% as shown in the figure below.

α for our AP is chosen to be 20%, by observing the mean channel switches of 100 runs over α varying from 5 to 50%. Cases 4 & 6 are considered as they represent real-time network deployments. The optimum value of α is finalized to be 20% since there is the same number of mean channel switches for both the cases as shown in Fig. 9. For α <20%, more than one channel switch occurs which can incur higher overhead and less throughput improvement. With α value above 20%, channel switching reduces further, thus making the system insensitive to changes in the dynamic environment. As a result,

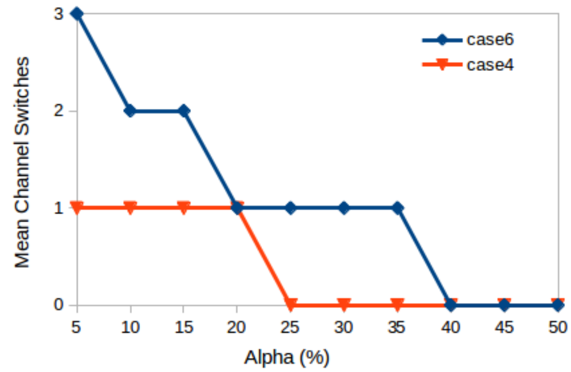

Fig. 9: Mean channel switches for varying α

throughput testing for our AP proceeded with α value fixed to 20%.

C. Data Throughput

A comparative study of the performance of our AP with and without the DCS algorithm implementation shows better throughput in the former case. Ideal throughput for IEEE 802.11n mode of operation for our AP is ≈100Mbps over the association rate of 130Mbps. Mean throughput is taken from 10 iterations of 100Mb data transfer between our AP and Client for 5 minutes. Comprehensive testing in all the six test cases listed above has been carried out, and the result has been plotted as shown in Fig. 10.

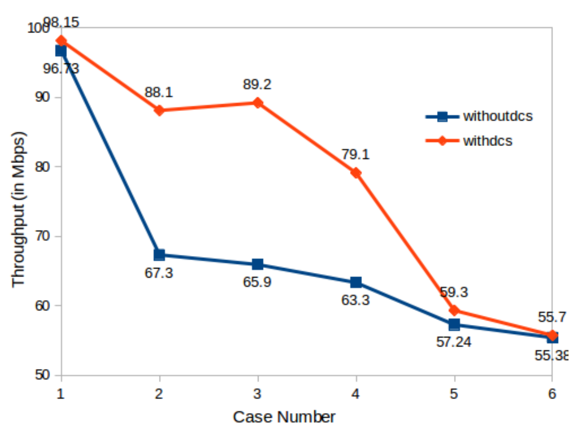

Fig. 10: Data throughput in different test cases

The best environment for deploying an AP is having no kind of interference in its operating channel. In Case 1 which complies with this scenario, it is evident that data throughput results for AP running with or without DCS are comparable. Here the throughput is 98.15Mbps since there is no channel switch. Other cases which undergo channel switch achieve slightly lesser throughput than the ideal value due to the overhead associated with channel switching. Case 2 addresses the impact of overlapping channel interference only. As shown in Fig. 3, if there are neighboring APs in channels 2 & 6, our AP which is initially operating in channel 1 experiences overlapping channel interference. In this case, DCS algorithm shifts it to channel 11 due to which throughput increases by nearly 31%. In the third case, co-channel interference is caused by interfering AP present in channel 11 where our AP is currently residing. By switching our AP operation to channel 6, throughput immensely improves by 35.6%. Case 4 also shows a similar co-channel interference scenario although the improvement in throughput is lesser(≈25%) than the previous case. This is expected since i_{opt} still suffers from overlapping channel interference as shown in Fig 5. The worst case scenarios are depicted in the last two cases where the environment is overcrowded. There is no interference-free channel across the whole spectrum in Case 6. Although in Case 5, i_{opt} has no interference at its center frequency, there is considerable interference in the side sub-carriers. Hence the throughput improvement is negligible.

Fig. 11 shows a statistical comparison of the throughput obtained in various operational channels in the real-time environment shown in Fig. 5. Several interfering APs are present in channel 1, 6 and 11. “CDOTGN0” and “CDOTGN2” are two APs introduced to create active sessions of 20Mb data transfer in channel 1 and 11 respectively. “CDOTGN1” has one active session of 10Mb in channel 6. Under this condition, DCS switches our AP, “CDOT-DFS-CRB” to i_{opt} i.e. channel 4. To study the performance of our AP in some other channel instead of i_{opt}, we configured our AP in each of the 11 channels in this environment. Throughput is measured by transferring data of 100Mb for 5 minutes between our AP and Client.

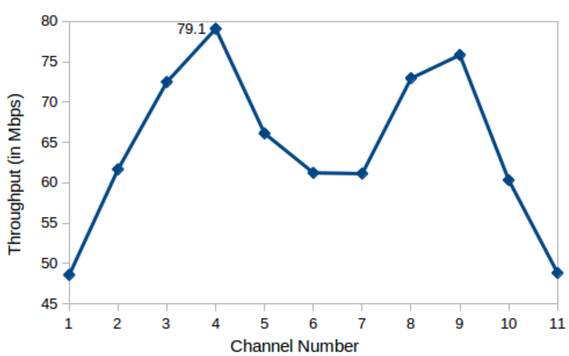

Fig. 11: Throughput comparison between i_{opt} and other channels in Case 4

It is seen that maximum throughput is achieved in i_{opt}. Due to the higher load and co-channel interference in channels 1 and 11, the throughput is remarkably low. Channel 6 suffers from a slightly lesser load which improves the throughput. Overlapping channel interference in the channels 2, 5, 7 and 10 hampers the performance also. Better throughput(>70Mbps) can be expected in the clear channels 3, 4, 8 and 9 which can be seen in Fig. 11. This result verifies that the optimal channel selected by our DCS algorithm is indeed the best channel under the given circumstances.

V. Conclusion

In our proposed algorithm, co-channel and overlapping channel interference detection is achieved by a co-located monitoring WiFi radio which passively scans the spectrum over a period. To avoid interference, two mathematical models have been designed to compute the cumulative channel power of the spectrum. Channel selection is an optimization problem since the deployment environment can be highly turbulent and unpredictable. The channel selected by our DCS mechanism is proven to be the best in six such real-time test cases. Channel switching is a decision problem and is solved by considering the stability factor and giving priority to the orthogonal channels as well as free channels. Considerable improvement of throughput is observed on using DCS algorithm in our AP. This algorithm is easily implementable and can be used on any generic processor platform. It works with existing IEEE 802.11 MAC and does not require any modification. It can cope with the interference caused by any neighboring IEEE 802.11 compliant AP and selects the optimal channel for better throughput. We have practically implemented this algorithm on our AP deployed in several real-time IEEE 802.11n networks.

Channel congestion or load is another parameter to estimate the efficiency of a channel for throughput improvement. Our future work will consider this parameter along with received signal strength for optimal channel selection in IEEE 802.11 WLANs.

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