Fine-Grained Radio Resource Management to Control Interference in Dense Wi-Fi Networks

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***Abstract*—In spite of the enormous popularity of Wi-Fi-enabled devices, the utilization of Wi-Fi radio resources (e.g. RF spectrum and transmission power levels) at Access Points (APs) is degraded in current decentralized Radio Resource Management (RRM) schemes. Most state of the art central control solutions apply configurations in which the network-wide impacts of the involved parameters and their mutual relationships are ignored. In this paper, we propose an algorithm for jointly adjusting the transmission power levels and optimizing the RF channel assignment of APs by taking into account the flows' required qualities while minimizing their interference impacts throughout the network. The proposed solution is tailored for an operator-agnostic and Software Defined Wireless Networking (SDWN)-based centralised RRM in dense Wi-Fi networks. Our extensive simulation results validate the performance improvement of the proposed algorithm compared to the main state of the art alternative by showing more than 25% higher spectrum efficiency, satisfying the users' demands and further mitigating the network-wide interference through a flow-based and quality-oriented power level adjustment.**

Keywords—Wireless LAN; Radio Resource Management; RF Channel Assignment; Transmission Power Control; SDWN

I. Introduction

The last few years have witnessed a massive increase in the popularity of portable devices, such as smartphones and tablets, thanks to their functionality, user-friendly interface, and affordable price. This situation has created a growing demand on the wireless spectrum in general, but more specifically on Wi-Fi. Due to its utilisation of non-licensed frequency bands, Wi-Fi is now facing significant spectrum efficiency issues especially in dense areas, such as apartment blocks and shopping malls, where neighbouring Wi-Fi Access Points (APs) interfere with each other while competing for the spectrum. This interference between Wi-Fi networks can negatively affect users' experience, resulting in lower throughput and poor quality connections.

Radio interference in wireless networks has long been a major research challenge that has been studied extensively in the literature [1]-[8]. Certain contributions have adopted a per-cell approach that addressed the interference problem through dynamic channel assignment. In [1] for example, the authors proposed an approach where an AP can select a suitable channel based on the channel monitoring and traffic status obtained locally and decided centrally for each AP. In [2], the authors proposed a heuristic algorithm that assigns a channel to an AP by analysing the effect of partially overlapping channels on the Wi-Fi network throughput. In [3], the authors formulated the optimisation of channel assignment as a graph colouring problem. However, these solutions do not consider other performance related measurements at the AP such as Signal to Interference plus Noise Ratio (SINR) and interference levels. Although these network-side measurements have been considered in the contributions presented in [4] and [5], the impact of these measurements on the performance of the solutions proposed is limited as they are taken locally and not across all of the interference environment.

Other contributions have adopted a per-client approach by focusing on adjusting the transmission power of the communication link between the wireless station (STA) and the AP. In Wi-Fi networks, STAs typically transmit at an output power level which is adopted and decided locally given their required quality. This potentially generates an unwanted level of interference on the corresponding channel. In [6], the authors considered a combination of power level control and rate adjustment for meeting the link quality requirements. Rate selection is determined by an estimation of the channel conditions including packet loss, delivery ratio, throughput, or SINR estimation. Moreover, in [7], the authors investigate the probability distribution of users' optimal power levels and exploit this for defining and broadcasting the desired power levels to the user. This approach, however, requires the users' involvement in the process. In [8] the authors consider the minimization of the interference level when different APs and WLANs are working in the same area, while not affecting the performance perceived by the client. However this approach needs GPS synchronization, which is an important weakness for indoor deployments.

Software-Defined Networking (SDN) [9] has emerged as an efficient and flexible network management approach for large networks. By decoupling the control plane from the data plane, SDN can centralise the network management operations in a single entity, often referred to as a Controller. This centralised management approach allows us to remotely programme large networks through the OpenFlow protocol [9]. These features have recently attracted the attention of the wireless communication research community, who have launched a range of initiatives to develop open source Software Defined Wireless Networking (SDWN) frameworks to manage Wi-Fi networks such as EmPOWER [10], Odin [11], and Wi-5 [12]-[13] which all aim to extend Openflow to support Wi-Fi network management operations and radio configuration primitives.

In this paper, we propose a fine-grained Radio Resource Management (RRM) algorithm that focuses on Wi-Fi APs, and exploits the programmability and centralized management capabilities offered by SDWN to dynamically configure these devices. The proposed algorithm is based on a per-flow approach that takes into account the application flow Quality of Service (QoS) requirements, as well as the effect of the radio configuration of the Wi-Fi APs, on the rest of the network. To the best of our knowledge there have been no previous contributions that combine dynamic channel assignment and transmit power control, and takes QoS into account to mitigate the network-wide interference in dense Wi-Fi networks.

The rest of this paper is structured as follows. Our SDWN-based Wi-Fi management framework and design assumptions are presented in Section II. In Section III, we introduce a quantity which represents the impact of each source of interference in our proposed channel assignment optimization problem and also provides a network-wide benchmark for interference evaluation. In Section IV we highlight certain considerations toward the fine-grained RRM algorithm and explain the details of the proposed heuristic. In Section V we assess our proposed algorithm and illustrate the obtained results. Finally our conclusion is presented in Section VI.

II. SDWN-based Wi-Fi Management Framework

The algorithm in this paper represents part of the work carried out in the H2020 funded Wi-5 project, which aims to address spectrum congestion in Wi-Fi networks. The project proposes an architecture [12] that acknowledges the heterogeneity of Wi-Fi networks operators and uses SDWN to provide a coordination platform among operators that could be used to implement cooperative spectrum management algorithms [14], [15], as illustrated in Fig. 1. The choice of SDWN to build a cooperative Wi-Fi network management platform is justified by the centralised nature of this concept which offers the operators and any entity that manages a Wi-Fi AP, including households, an interface through which a cooperative spectrum utilisation policy could be agreed. Moreover, SDWN offers flexibility and cross-layer management, as the central controller is able to obtain monitoring information about the status of the network and execute the cooperative algorithms to react accordingly while respecting the requirements of the wireless users, such as the solution presented in [14]. It is worth mentioning that Wi-5 is currently developing a SDWN framework that extends the capabilities of OpenFlow to support the monitoring of Wi-Fi networks, the QoS requirements of wireless applications, and the configuration of Wi-APs [13].

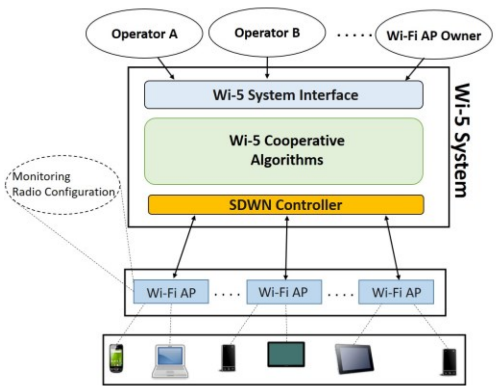


Fig. 1: Wi-Fi network management architecture in Wi-5 project

In addition to the distinct advantages of a SDWN-based RRM approach for Wi-Fi networks, the corresponding algorithm, as presented in this paper, provides the capabilities which are required in a multi-operator, dynamic and partially controllable network. These, as will be modelled in the next section, comprise: 1) a practical way to include/exclude any network element of interest from the real-time process, 2) representing the included APs and their mutual impacts through a network-wide quality metric, 3) capturing the mutual relationship between radio resource parameters and the APs distribution throughout the network, and 4) taking into account the correlation between the employed network-wide quality metric and the per-user's quality demand.

III. Network-wide Interference Analysis

In this section we first revisit our channel assignment optimization problem, which has preliminarily been introduced in [15]. We then extend the analysis of its interference-related quantity, *interference impact*, as a basis for providing a network-wide quality indicator from the perspective of interference. This will later be merged with a flow-based and quality-oriented power adjustment mechanism to establish our proposed RRM algorithm. For the rest of the paper, the following network arrangement is assumed:

- We consider N Wi-Fi APs, based on the IEEE 802.11 standard, that operate on F RF channels including F_{non} of them not-overlapping each other.
- We assume $N > F_{non}$, i.e. there is channel overlapping and therefore an interference problem in the network. An example is $F = 11$ and $F_{non} = 3$ in the IEEE 802.11 2.4 GHz band where $N \geq 4$ is the starting point of channel overlapping and the densification problem.
- We assume that APs are the only elements transacting with the information required at the central controller. APs are the sensing points and measurement agents for the central controller throughout the network and the ultimate configuration is applied to APs via the downlink.

A. Channel Assignment Optimisation

In [15] the channel assignment optimisation problem is defined as follows:

$$A^{*} = \min_{A} \sum_{i\leq N} \sum_{f\leq F} G \times A^{T}.I \qquad (1)$$

where $G^{N\times N}$ is defined as the network topology matrix $G \in \{0,1\}^{N\times N}$, where:

$$g_{ij} = \begin{cases} 1, & average\ power\ strength\ of\ AP_i\ around\ AP_j \\ & exceeds\ a\ given\ threshold \\ 0, & otherwise \end{cases} \qquad (2)$$

and $A^{F\times N}$ as the channel assignment matrix $A \in \{0,1\}^{F\times N}$, where:

$$a_{ij} = \begin{cases} 1, & if\ channel\ i\ is\ assigned\ to\ AP_j \\ 0, & otherwise \end{cases} \qquad (3)$$

$I \in \mathbb{R}^{N \times F}$ is defined as the matrix of the *interference impacts* for N APs and F available channels, where each $I_{i,f}$ element as an *interference impact,* is the summation of the signals corresponding to channel f when it is assigned to AP_i and detected at other APs' locations. The *interference impact* for AP_i and its corresponding channel f can be expressed as follows:

$$I_{i,f} = \sum_{k \le N, k \ne i} P_{i,k}(f) = \sum_{k \le N, k \ne i} P_i^t \gamma_{i,k}(f) \theta_{i,k}(f)$$
$$= P_i^t \sum_{k \le N, k \ne i} \gamma_{i,k}(f) \theta_{i,k}(f) \qquad (4)$$

Where $1 \le f \le F$, $1 \le i, k \le N$, $P_{i,k}$ is the average power strength of the RF channel assigned to AP_i and sensed at close proximity of AP_k. P_i^t is the transmission power level at AP_i, $\gamma_{i,k}$ is the channel gain between AP_i and AP_k, and $\theta_{i,k}$ are coefficients varying from 0 to 1 representing the overlap between the channels assigned to AP_i and AP_k. This coefficient will be zero for non-overlapping channels. An example of such overlap is provided in [3]. Both $\gamma_{i,k}$ and $\theta_{i,k}$ are, obviously, dependent on f. All values are estimated and updated in real-time and are dependent on the actual characteristics of the employed RF channels as well as the arrangement of the network.

The matrix I reflects the interference impacts of APs' transmission powers in the objective function of (1) considering the overlap and orthogonality of the RF channels. The resulting optimised channel assignment, A^*, is supposed to minimise the summation of these impacts throughout the network. More details about the employed binary Integer Linear Programing (ILP) approach to solve (1) and the exact ILP coefficients can be found in [15].

B. The Network-wide Interference Impact Quantity

To examine the optimality of the solution provided in (1), we need to show that the experienced interference in the network with the channel assignment based on A^*, is lower than the interference by any other channel assignment combination. Let I_{acc} be the accumulation of the interferences which can be experienced at all the APs' locations. We aim to use this later in the proposed algorithm to represent the network-wide quality. This, by definition, is actually the summation of the signals detectable at an AP's location and originated from all other APs:

$$I_{acc} = \sum_{i=1}^{N} \sum_{k \le N, k \ne i}^{N} P_k^t \gamma_{k,i} \theta_{k,i} \qquad (5)$$

P_i^t, $\gamma_{i,k}$ and $\theta_{i,k}$ are the same as in (4) and we drop symbol f to avoid notation clutter. Given the resemblance between i and k's range of values in (5) and comparing with the indexes in (4), their recast yields:

$$I_{acc} = \sum_{i=1}^{N} \sum_{k \le N, k \ne i}^{N} P_k^t \gamma_{k,i} \theta_{k,i} = \sum_{i=1}^{N} \sum_{k \le N, k \ne i}^{N} P_i^t \gamma_{i,k} \theta_{i,k}$$
$$= \sum_{i=1}^{N} I_{i,f_i} \qquad (6)$$

Where f_i denotes the instance of f which corresponds to AP_i. Since the linear summation with positive integer coefficients of all $I_{i,f}$ in (1) has already been shown to be optimal for A^*, for any linear summation with unit coefficients we have:

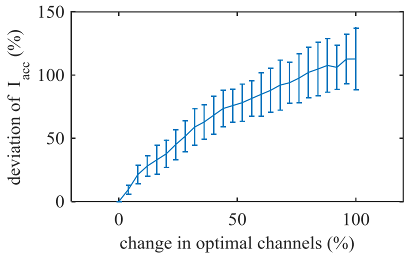


Fig. 2: deviation of the accumulated interference when the optimised channels are changing

$$\sum_{i=1}^{N} I_{i,f_i} \Big|_{A=A^*} \le \sum_{i=1}^{N} I_{i,f_i} \Big|_{A=A'} \qquad (7)$$

Where A' refers to any channel assignment with at least one allocated channel different from A^* and all $I_{i,f}$ are positive and greater than the threshold in (2). Applying (7) to (6) means that:

$$I_{acc}|_{A=A^*} \le I_{acc}|_{A=A'} \qquad (8)$$

This shows that the status of the interference throughout the network and measured from APs point of view will be in its optimal situation immediately after applying the channel assignment A^*. We take this as a reference point for our algorithm in Section IV. Fig. 2 depicts an example of deviation from the optimal I_{acc} when the assigned channels are different from the optimal assignment. The illustrated result shows a positive and increasing trend of deviation from the optimal interference value for more changes compared to the APs optimal channel assignment. This is the validation of the optimality of A^*. A threshold, denoted as δ, for acceptable deviation from the optimal interference value will be used, beyond which the channel assignment process will be triggered or the intended change will be denied.

IV. Fine-Grain Radio Resource Management Algorithm

The network-wide interference quantity defined in (6) results in a direct relationship between the *accumulated interference*, I_{acc}, discussed in Section III-B and the transmission power levels of the APs. Fig. 3 shows an example of the correlation between the AP transmission power levels and I_{acc}. Color-coded values are depicted at the locations of the APs with each colour representing the assigned RF channel to that AP. The value represents the correlation between the transmission power level of that AP and I_{acc}. The correlation values are all positive and close to 1, which highlight a strong direct relationship. However, the impacts of the APs vary based on their locations and/or their assigned channels. For instance, channel 1 assigned to the central location denoted as 0.98/1-red has a correlation value of 0.98. This is higher than the correlation shown for its neighbouring AP (denoted as 0.72/4 green) because they are on different channels. The same central AP has a higher correlation compared to its co-channel AP at the upper left-side of the network (denoted as 0.79/1 red) because of their different locations. These variations highlight the importance of capturing the mutual relationship between radio resource parameters and the APs distribution throughout the network in our proposed approach.

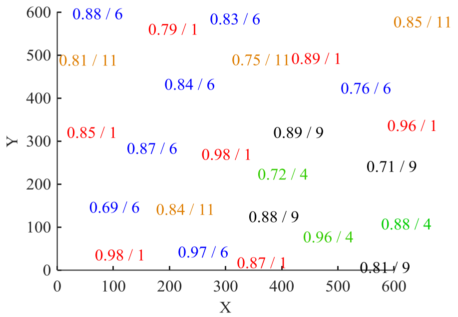


Fig. 3: correlation between the power level and accumulated interference under impacts of locations and assigned channels

The transmission power levels of APs are also positively affecting the transmission rates of their corresponding downlink flows, which in turn affects the provided Quality of Service (QoS). This opposing impact of the transmission power level over the flow-based served quality, compared to their impact over the network-wide interference, needs to be addressed in a joint quality-oriented and flow-based power adjustment scheme alongside network-wide interference control. Assuming that the QoS requirements of the flows are known, the controller needs to adjust the transmission power of the APs such that the QoS requirements are satisfied and the level of interference in the network is maintained close to its optimal value.

Fig. 4 depicts the block diagram of our RRM strategy implemented on top of the SDWN controller, which can maintain the trade-off between the interference status in a dense Wi-Fi network and the satisfactory power levels for all of the flows joining the APs. The main tasks designed for the proposed algorithm are as follows:

J0: optimising the AP's assigned channel given the latest status of the network and setting a reference value for the optimal network-wide interference status. This is based on the optimisation model in (1). J1: estimating the flow's achievable rates in all available APs for a desired range of transmission power levels. This is conducted considering the provided service for other flows already associated with the APs, the estimation of the flow's channel status and the employed OFDM modulations and code rates. J2: taking the flow's required quality into account and assessing the impact on the network-wide interference. J3: assessing the impact of the setting for a new flow over currently active flows in the network, and selecting the most suitable AP for the service.

Algorithm 1 depicts the running sequence of these jobs in the implemented algorithm for the SDWN controller. First, the controller acquires all the measurements from the APs (line 1 in Algorithm 1) and then executes step J0 making use of (1) (line 2 in Algorithm 1). For each new flow connecting to the network, the controller assesses all the available APs that can be associated to the flow based on their Received Signal Strengths (RSS) (lines 3 and 4 in Algorithm 1). It then executes steps J1 and J2 for each AP (lines 5-11 in Algorithm 1). The controller then executes step J3 to select an AP for association (lines 12-13 in Algorithm 1) and finally runs J0 if flagged for the selected AP (lines 14 in Algorithm 1). Given *N*, the number of APs and *M*, the number of discrete applicable power levels, the main 'for loop' (lines 4-11) is called *N* times therein lines 6 and 7 are repeated at most *M* times. Therefore, the time complexity of each run of the setting adjustment for each flow will be *O(MN)*.

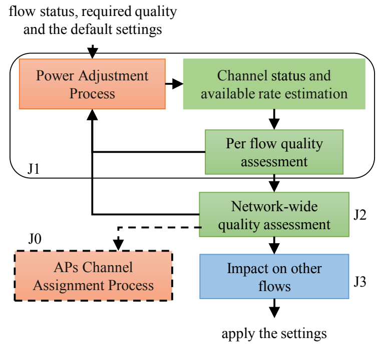


Fig. 4: joint power adjustment and channel assignment

Algorithm 1 – Power level adjustment joint with the channel assignment process

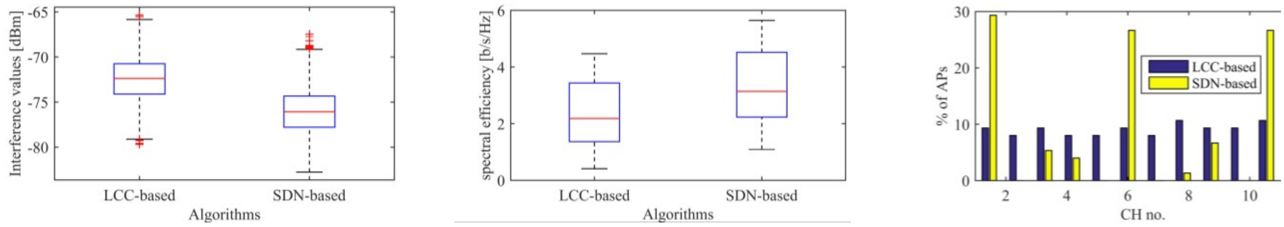
1: get network status
2: run J0: optimize the channels for all involved APs and set a threshold (i.e. δ) for acceptable deviation from optimal accumulated interference, I_{acc}
3: get new flow
4: **find** all APs available for association
5: for all involved APs
6: **run J1:** estimate the achievable rate for a set of power levels
7: **run J2:** evaluate the achievable quality of the flow and the impact on the network-wide interference
8: **if** deviation of I_{acc} is more than δ
9: **flag J0** to be run later if AP selected
10: **end if**
11: end for
12: run J3: evaluate the impact of the rate for other flows in the APs passed through J1 and J2
13: associate the flow to the AP with the minimum impact
14: run J0: if it is flagged for the selected AP

V. Evaluation Scenarios and Simulation Results

A. Simulation Setup and Evaluation Strategy

To evaluate our proposed RRM algorithm, we use MATLAB to simulate the SDWN-based controller in a dense Wi-Fi environment that consists of 25 fixed Wi-Fi APs randomly deployed in an area of 300m×300m at a minimum distance of 50m from each other. The APs transmit power varies from 0dBm to 40dBm and is dynamically adjusted during the simulation process. User stations are deployed randomly at a minimum distance of 1m from each other and from the APs. We adopted a large scale path loss model with the path loss exponent set to 2.5, a fixed noise level at -99dBm and the threshold in (4) is set to -80dBm.

In our evaluation, we first compare the RRM algorithm without transmit power adjustment (i.e. channel assignment only) against the Least Congested Channel algorithm (LCC) [16]. In LCC, each AP acquires a suitable channel based on the neighbouring APs' channels (this can also be implemented based on the contention and retransmission statistics evaluated at the MAC layer). LCC represents the basis for the majority of state of the art commercial channel assignment solutions employed in local or central RF channel management. We then



(a) (b) (c)

Fig. 5: the proposed channel assignment process performance

compare the results of the channel assignment only algorithm against the combined RRM algorithm, which includes both channel assignment and transmit power adjustment. We also show the possibility of setting a desired threshold to the interference variation as a consequence of power adjustment, beyond which the channel assignment procedure will be triggered, or the intended change will be denied. This is also necessary for reducing traffic interruption due to frequent execution of the RF channel reassignment process.

B. Simulation Results Analysis

For the first evaluation, we compared the average interference level throughout the network based on LCC and our SDWN-based approach in Fig. 5-(a). The upper and lower edges of the plotted boxes are the 25th and 75th percentile of the values and the median values are indicated by the central red lines. The values which we considered as outliers are indicated by red symbols in each case. The results show more than 3 dB improvement which is reflected in the achievable SINR and subsequently the higher spectral efficiency as shown in Fig. 5-(b). An extra 0.8 b/s/Hz improvement with the proposed centralized channel assignment leads to 16Mb/s extra capacity achievable at the physical layer and for each employed RF channel throughout the network. This is 25% of a standard IEEE 802.11g-SISO capacity per channel. Fig. 5-(c) shows the combination of the channels which has been assigned through LCC and our proposed approach. The non-overlapping channels 1, 6 and 11 have been used more frequently in our centralized model alongside a limited number of overlapping channels 3, 4, 8 and 9. This combination of overlapping and non-overlapping channels provides the optimal trade-off between co-channel and adjacent-channel interference impacts, given the exemplified network status.

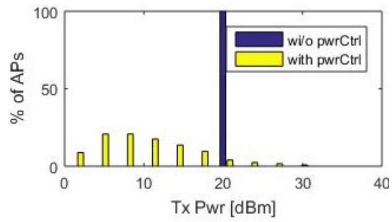
For the second evaluation, we assume two scenarios. In Scenario A, all the flows are transmitted at the default power level (i.e., 20dBm); and Scenario B includes the RRM algorithm with power control where the adaptive power level is used according to each flow's demand (i.e. required bitrate). The power level distribution of the flows in each scenario are presented in Fig. 6-(a), with the transmission power level distribution of scenario A flows represented in the blue bar, and the power level distribution of scenario B flows represented in the yellow bars. Fig. 6-(b) shows a comparison of the interference levels measured in the network using the RRM algorithm without and with power control (i.e. channel assignment without and with power control). The results presented in this figure show that the complete RRM algorithm (Scenario B) offers a 15dB reduction in the interference over the channel assignment only algorithm (Scenario A).

We also assess the performance of our RRM algorithm with regards to its adaptability to meet the QoS requirements of three classes of flows. Low transmission rate flows: the transmission rate of these flows will vary between 100Kbps and 1.6Mbps. Medium transmission rate flows: the transmission rate of these flows will vary between 200Kbps and 3Mbps. High transmission rate flows: the transmission rate of these flows will vary between 500 Kbps and 6Mbps.

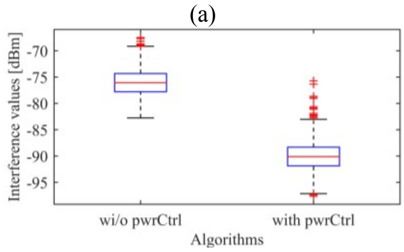
A user's demand dependency of the proposed power control mechanism is expected to result in a higher power level when the average demand of the users is high. This has been shown in Fig. 7-(a) where the distribution of adopted power levels are compared for the flows with low and high transmission rates. The higher the average demand, the higher the median of the adopted power levels. However, higher values of transmission power jeopardise network-wide control of the interference level achieved through the optimal channel assignment. Fig. 7-(b) depicts the average interference levels measured in the network after the RRM algorithm is applied for the above three classes of flows. The results presented in this figure show that higher transmission rate flows result in higher interference. This shows that the proposed radio configuration algorithms cannot meet the demands of flows with high rates requirements, without resulting in higher interference levels throughout the network. Subsequently, although the transmit power adjustment will help to increase the transmission rate of a flow, it could result in higher interference levels that degrades the network-wide served quality.

To address this limitation, we propose to apply an upper-bound threshold for the maximum acceptable deviation of interference quantity from its optimal value (denoted as δ in Section IV). The effect of this improvement is shown in figure 8 where the optimal value is achieved by applying the channel assignment optimisation algorithm, and deviation from this value is a result of the new flows' corresponding downlink transmission powers. The higher acceptable deviation (50% in Fig. 8-(a)) results in a higher network-wide interference compared to the lower acceptable deviation of 5%. Note that in both cases, eventually, the channel assignment process will be triggered to re-adjust the channels. This could be too frequent and disruptive with a very low deviation threshold.

By introducing a threshold on the power level for the sake of interference control, we expect a reduction of the positive correlation between adjusted power levels and the demand of the flows, as shown in Fig. 8-b. This figure shows the correlation between the transmit power and the required data rate increases with the transmission rate demands for low and medium rate flows. However, this correlation drops when high rate flows are used. This is due to the fact that the RRM tries to control the

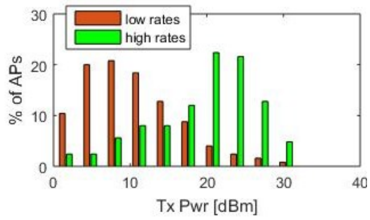


(a)



(b)

Fig. 6: power adjustment performance and its interference control impact



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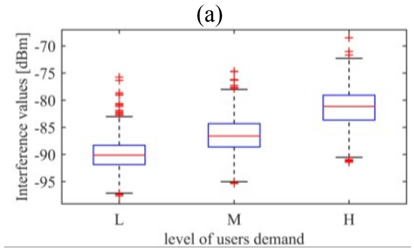
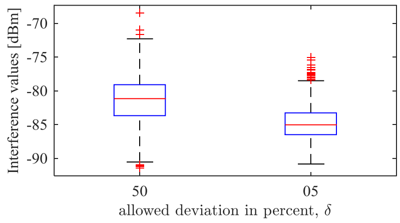


(b)

Fig. 7: interference intensification as a result of the users' demand dependency of power levels



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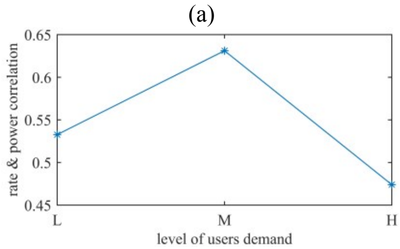

(b)

Fig. 8: correlation between user's demand and power level through a network-wide interference control

interference in the network by denying very high transmission power levels.

VI. Conclusion

In this paper we have presented a fine grained radio configuration algorithm that uses transmission power control and channel assignment to address radio interference in dense Wi-Fi environments. The proposed algorithm is designed for a SDWN Wi-Fi framework where the controller acts as the central management entity upon which the algorithm is executed. The algorithm relies on network-wide status information as well as flow-based quality demands. The performance of the algorithm has been assessed through simulation and the obtained results show that it provides a lower interference while maintaining the status for a wide range of users' quality demands. This is achieved by taking into account the correlations and mutual relationships between transmission power levels, the required quality of the users and the network-wide interference quantity in the proposed algorithm.

The future extension of the proposed flow-based mechanism in this work will take into account some important characteristics of the use cases such as dynamism in the pattern of the user demand as well as their distribution throughout the network.

Acknowledgment

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References

[1] B. Abeysekera, K. Ishihara, Y. Inoue, M. Mizoguchi, "Network-Controlled Channel Allocation Scheme for IEEE 802.11 Wireless LANs: Experimental and Simulation Study", Vehicular Technology Conference (VTC Spring), Seoul, Korea, 18-21 May 2014.

[2] K. Zhou, X. Jia, L. Xie, Y. Chang, and X. Tang, "Channel Assignment for WLAN by Considering Overlapping Channels in SINR Interference Model", International Conference on Computing, Networking and Communications (ICNC), Maui, Hawaii, USA 30 Jan.- 2 Feb. 2012.

[3] A. Mishra, S. Banerjee, and W. Arbaugh, "Weighted coloring based channel assignment for WLANs." SIGMOBILE Mob. Comput. Commun. Rev. 9(3): 19-31, 2005.

[4] M. Yu, X. Ma, W. Su, and L. Tung, "A new joint strategy of radio channel allocation and power control for wireless mesh networks." Computer Communications 35(2): 196-206, 2012.

[5] Lingzhi Wang, Cunqing Hua, Rong Zheng and Rui Ni, "Online channel selection and user association in high-density WiFi networks," Int. Conf. on Communications (ICC), 8-12 Jun., London, UK, 2015.

[6] K. Ramachandran, R. Kokku, Z. Honghai, and M. Gruteser, "Symphony: Synchronous Two-Phase Rate and Power Control in 802.11 WLANs," Networking, IEEE/ACM Transactions on, vol. 18, pp. 1289-1302, 2010.

[7] Zou, M., et al. "Throughput Improvement of 802.11 Networks Via Randomization of Transmission Power Levels." IEEE Transactions on Vehicular Technology 65(4): 2703-2714, 2016.

[8] V. Navda, R. Kokku, S. Ganguly, S. Das, "Slotted Symmetric Power Control in managed WLANs," Tech. Rep., NEC Lab. America, 2007.

[9] "Software-defined networking: The new norm for networks," Palo Alto, CA, USA, White Paper, Apr. 2012. [Online]. Available: https://www.opennetworking.org/images/stories/downloads/sdn-resources/white-papers/wp-sdn-newnorm.pdf.

[10] R. Riggio, T. Rasheed, and F. Granelli, "EmPOWER: A Testbed for Network Function Virtualization Research and Experimentation", IEEE SDN for Future Net. and Services, 11-13 Nov., Trento, Italy, 2013.

[11] J. Schulz-Zander, L. Suresh, N. Sarrar, and A. Feldmann, "Programmatic Orchestration of WiFi Networks," USENIX Symposium on Networked Systems Design and Implementation (NSDI), Philadelphia, PA, USA, 19-20 Jun. 2014.

[12] F. Bouhafs (Editor), "Wi-5 initial architecture", Deliverable D2.4 of Wi-5 project, Dec. 2015, available at http://www.wi5.eu/wp-content/uploads/2015/02/D2_4-Wi-5-Initial-Architecture-final-1.pdf.

[13] J. Saldana (Editor), "Specification of Smart AP solutions version 1", Deliverable D3.2 of Wi-5 project, Dec. 2015, available at http://www.wi5.eu/wp-content/uploads/2015/02/D3_2-Specification-of-Smart-AP-solutions-final.pdf.

[14] A. Raschellà, F. Bouhafs, M. Seyedebrahimi, M. Mackay, Q. Shi, "A Centralized Framework for Smart Access Point Selection based on the Fittingness Factor", International Conference on Telecommunications (ICT), Thessaloniki, Greece, 16-18 May, 2016.

[15] M. Seyedebrahimi, F. Bouhafs, A. Raschellà, M. Mackay, Q. Shi, "SDN-Based Channel Assignment Algorithm for Interference Management in Dense Wi-Fi Networks", European Conf. on Networks and Communications (EuCNC), Athens, Greece, 27-30 June, 2016.

[16] M. Achanta, "Method and Apparatus for Least Congested Channel Scan for Wireless Access Points," US Patent No. 20060072602, Apr. 2006.