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RESEARCH ARTICLE

An Intelligence-Based Framework for Managing WLANs: The Potential of Non-Contiguous Channel Bonding

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ABSTRACT Managing WLANs efficiently while optimizing performance remains a challenge. This article proposes an innovative approach that utilizes the strengths of Software-Defined Networking (SDN) to create an advanced framework for WLAN management. Since the implementation of fully centralized solutions is not always feasible, the proposed framework adopts both decentralized and centralized policies. By leveraging the programmability of SDN, the framework aims to enhance WLAN performance and improve overall network efficiency. We present the design, implementation, and evaluation of the SDN-based framework, showcasing the potential of non-contiguous channel bonding and channel allocation. Algorithms for coexistence of heterogeneous WLANs, channel bonding and management are developed. We investigate the performance of heterogeneous WLANs and show how the framework can facilitate management of mixed WLANs. We conducted extensive simulation experiments that confirmed the need for such framework. The results have shown that channel assignment can significantly improve network throughput as well the fairness among WLAN users. However; under high interference; non-contiguous channel bonding did not outperform contiguous channel bonding.

INDEX TERMS 802.11ac, channel bonding, SDN, WLANs, WLAN management.

I. INTRODUCTION

The increasing demand for high-performance WLANs requires effective management solutions that can dynamically adapt to changing network conditions while ensuring optimal performance.

The WLAN standards 802.11n [1] and 802.11ac [2] are both widely used for wireless communication. The 802.11n also known as "Wireless-N," is a Wi-Fi standard that was introduced in 2009. It provides significant improvements over its predecessor, 802.11g, in terms of speed and range. 802.11n operates on both the 2.4 GHz and 5 GHz frequency bands and supports multiple-input multiple-output (MIMO) technology, which allows for the use of multiple antennas to transmit and receive data. This standard is capable of delivering theoretical maximum speeds of up to 600 Mbps. The 802.11ac, also known as "Wi-Fi 5", is a Wi-Fi standard that was introduced in 2013. It represents a significant advancement over 802.11n in terms of speed, capacity, and overall performance. 802.11ac operates exclusively on the 5 GHz frequency band and supports wider channel bandwidths and advanced MIMO technology, including beam-forming. It can deliver theoretical maximum speeds of up to several gigabits per second (Gbps). Since the introduction of 802.11ac, a newer standard called 802.11ax, also known as "Wi-Fi 6," has been released. Wi-Fi 6 provides further enhancements in terms of speed, capacity, and efficiency compared to 802.11ac. It introduces technologies like Orthogonal Frequency Division Multiple Access (OFDMA) and Target Wake Time (TWT) to better manage and allocate resources in high-density environments with numerous connected devices.

Channel bonding which is a feature of recent standards, allows combining multiple adjacent channels to increase the available bandwidth and improve network performance.

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There are two main approaches to channel bonding: static channel bonding and dynamic channel bonding. With Static Channel Bonding (SCB), the channels are configured and fixed. This means that specific channels are selected and bonded together, forming a wider channel for data transmission. This approach provides a consistent and predictable channel arrangement but may face challenges in crowded or congested Wi-Fi environments. Dynamic channel bonding (DCB) allows the WLAN system to automatically select and configure the bonded channels based on real-time conditions. The system continuously monitors the RF environment and assesses the available channels for bonding. It takes into account factors such as signal strength, interference levels, and channel occupancy to determine the optimal channel bonding configuration. DCB is particularly useful in dynamic Wi-Fi environments where channel conditions may change over time. It helps optimize the channel allocation and adapt to varying network conditions, enhancing overall network performance and reliability. With both SCB and DCB, only contiguous channels are bonded. The 802.11ax introduced the mechanism of non-contiguous channel bonding, whereby a node can bond non-consecutive channels found free in the whole working spectrum.

A deep look at many scientific research publications in recent years clearly shows different conclusions about methods of managing WLANs. While some studies indicate the effectiveness of centralized methods and optimal solution algorithms, many other studies suggest the adoption of distributed solutions, reducing the amount of control data required to be communicated between controlled entities and the controller. Frequent exchange of large volume of control data and measurements constitutes an obstacle to the application of central solutions. There are many studies that have concluded that, it is difficult to find optimal solutions in a reasonable real time, which constitutes another obstacle to their adoption. Nowadays, with the current revolution in artificial intelligence systems (AI) and machine learning algorithms, many attempts have emerged to apply them in the field of WLAN management. However, these methods still need more studies on the possibility of applying AI-based solutions, especially the real time required to find the solution and the cost of its implementation. All of this has prompted some researchers to promote heuristic algorithms, trying to convince the research community that they offer reasonable, logical, and applicable solutions.

All of these challenges face a fundamental problem related to the dynamic changes in WLANs and the difficulty of predicting potential changes in the elements that play a role in determining the performance of WLANs, especially the user traffic, heterogeneous deployments, used channels, channels bandwidth, the number of users and their mobility patterns.

This article introduces an SDN-based framework that leverages the strength of SDN, offering a novel approach to WLAN management. The proposed framework is a start step towards the development of a flexible and efficient solution for WLANs management. We focus on three important issues: Channel bonding, channel allocation, and heterogeneous deployments of WLANs. The key contributions of the work can be summarized as follows:

- The proposed framework combines the flexibility and control of SDN, to address the limitations of traditional WLAN management approaches and unlock new possibilities for network optimization.
- The framework facilitates the management of WLANs, utilizing simple as well as complex algorithms. Unlike proposed SDN frameworks; which only offer centralized control; the proposed framework adopts different candidate methods based on network conditions and possibility of applying solutions at affordable costs in the sense of time and signaling overhead. Such methods can be fully centralized or even involve individual nodes.
- We present case studies and evaluated different approaches for WLAN management, with a focus on non-contiguous channel bonding. Algorithms are presented for coexistence of heterogeneous WLANs, channel bonding and allocation.

The following table defines the acronyms and the terminology used in the article.

TABLE 1. Table of acronyms.

Acronym	Definition
AI	Artificial Intelligence
AP	Access Point
CB	Channel Bonding
DCB	Dynamic Channel Bonding
MAC	Medium Access Control
MIMO	Multi Input Multi Output
RTS/CTS	Request to Send/Clear to Send
SCB	Static Channel Bonding
SDN	Software Defined Networking
SNIR	Signal to Noise and Interference Ratio

The rest of the article is organized as follows: Section II discusses relevant work. Section III details the proposed framework. Case studies are presented in section IV. Results are presented and discussed in section V, before we conclude the article in section VI.

II. RELATED WORK

Huge research work can be found in literature addressing different problems related to WLAN management. The authors of [3] have investigated the performance of mixed WLANs. The authors tried to overcome the coexistence problems by altering some MAC parameters. Further, the authors found that some features of new standards should be should be carefully implemented in order to achieve the expected gain. Other research that has addressed the performance of mixed deployments and performance enhancement through MAC layer configuration methods was published in [4], [5], [6], [7], [8], and [9]. Protocols for multipath routing in MANETs have been addressed in [10] and [11]. On the other hand, a lot of works are devoted to study CB in WLANs. In [12] the authors have analyzed the performance of SCB and DCB for 802.11ac WLANs. The authors found that DCB improves network throughput and reduces delay. The authors of [13] propose a method for the selection of primary channels with DCB for dense WLANs. Their proposed method does not only consider the occupancy time of primary channels but also the activities on potential secondary ones. In their article [14], the authors propose an intelligent channel bonding technique for WLANs. The authors identified the network factors that influence the performance of channel bonding. They found that channel width selection should consider not only a link's signal quality, but also the strength of neighboring links, their physical rates, and interferer load. Other DCB methods have been proposed in [15], [16], [17], [18], [19], and [20]. These methods are based on collision-detection, carrier sensing adaptation, or load. Recently, machine learning based solutions have been applied to address CB as an online decision-making problem involving multiple agents [21], [22], [23], [24].

III. SDN-BASED FRAMEWORK FOR WLAN MANAGEMENT

The proposed framework is based on the SDN architecture. SDN offers an evolving approach to managing and controlling network resources by decoupling the control plane from the data plane. The generic SDN architecture is comprised of three planes: Infrastructure, control, and application. The infrastructure plane includes network elements that operate according to the rules provided by the controller. The control plane has a controller that configures devices. The controller is responsible for making decisions about how to handle network traffic based on network policies and configurations. It communicates with network devices to enforce these decisions. The application layer consists of applications that define the policies and rules that should be followed by network elements.

In SDN-based WLANs, SDN enables centralized control and management of APs. This centralized control allows for dynamic solutions based on real-time network conditions, optimizing the network performance. SDN controllers have a global view of the network, allowing adoption of methods to management of WLANs. By monitoring factors such as channel utilization, signal strength, traffic patterns, neighboring WLANs, characteristics of neighbors, interference levels, controllers can intelligently manage WLANs, ensuring optimal performance. By dynamically managing WLANs based on real-time monitoring, SDN-based WLANs can prevent bottlenecks and congestion, ensuring a smooth and efficient user experience. A communication protocol, such as OpenFlow, enables the controller to communicate with APs to enforce decisions as well as commands. The Openflow protocol sends control signals and commands that configures and manages network elements.The SDN controller establishes a connection to each network element to pass messages using the Transmission Control Protocol (TCP).

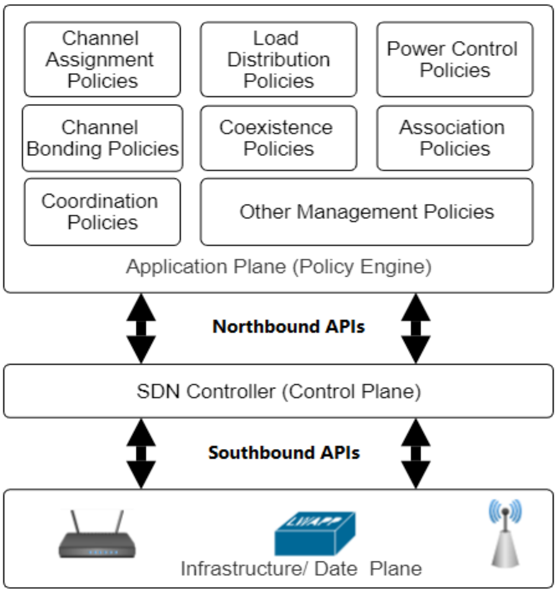


FIGURE 1. The SDN-based framework.

The proposed framework consists of the following components (shown in figure 1):

a) SDN Controller: The SDN controller acts as the brain of the WLAN network, providing a centralized point of control and management. It communicates with the WLAN infrastructure elements (access points, switches, etc.) and applies all decisions based on network management policies. The communication between the policy engine and the SDN goes through the northbound APIs, which are the links between the policy engine and the SDN controller.

b) WLAN Infrastructure Elements: These include access points, switches, and other network devices that form the WLAN infrastructure. These elements are responsible for forwarding data according to the instructions received from the SDN controller. The controller communicates with the network elements through the southbound APIs.

c) Network Policy Engine: A policy engine enables determining the required actions to be applied in order to improve WLAN performance. The policy engine produces configuration instructions for the SDN controller, ensuring consistent enforcement across the WLAN network. Based on the global view that the system has on the network elements, the policy engine will be able to:

- Intelligently decide on configurations to achieve optimal or at least satisfactory performance by executing optimal solution algorithms, heuristic algorithms, or distributed algorithms. The decision is based on the cost of implementing candidate solutions as well as the expected performance gain.
- Enforce and implement coordination among interrelated WLANs, whenever such coordination is expected to improve performance.
- Request individual nodes to independently and adaptively decide on configuration following best effort approach, whenever the execution and implementation

of centralized or heuristic solutions is not feasible or incurs high overhead. Over time, each node learns the settings through which it gains the best possible performance. Nodes re-evaluate their settings which may need to be changed due to configuration changes by other nodes.

Such architecture enables the controller to enforce configurations resulted from complex solutions as well as to instruct individual nodes to implement simple mechanisms such as RTS/CTS. The policy engine should be able to select the proper policy which can be implemented by a node(s), individually, cooperatively, or in a centralized manner.

It should be noted that this article is just the starting point in our research towards building and implementing this framework. The following sections will focus on important cases as a preliminary study on the extent of benefits that can be achieved through the proposed framework. In future research, precise policies will be addressed. Further, functions splitting among entities of the different planes will be considered.

IV. CASE STUDIES

For the evaluation of the proposed framework, we focus on three important issues: Channel Assignment, Channel Bonding, and Heterogeneous WLANs. These methods shall run on the policy engine. Decisions are passed to the controller which forwards them to network elements.

We consider a network of WLANs served by a set of N APs $\in \{AP_1, AP_2, AP_3, \ldots, AP_N\}$ and M users $U \in \{U_1, U_2, U_3, \ldots, U_M\}$. APs operate on pre-configured 802.11 primary channels. Channel of AP_i is C_i. Interference causes contention and packets loss. The effective interference does not only depend on strength of received signal from an interfering node, but also on the activity level of the interferer. The interference is not only among APs of WLANs, but also it highly impacts reception of packets at users.

According to the widely known Shannon capacity formula,

$$Capacity = BLog_2(1 + SINR) \tag{1}$$

The capacity primarily depends on channel bandwidth, as well as the signal to interference and noise ratio (SINR) given by:

$$SINR_{mk} = \frac{P_k}{N_0 + \sum_{\substack{\forall l \in M,N \\ l \neq m,k}} I_{ml}} \tag{2}$$

where $SINR_{mk}$ is the SINR at user m associated with AP_k. P_k is the received signal power from AP_k measured at user's m antenna, N_o represents the noise power, and I_{ml} represents the interference measured by user m from source l. The term $\sum_{\substack{\forall l \in M,N \\ l \neq m,k}} I_{ml}$, represents the interference measured from all APs and users of other cells. A more realistic modeling of the interference shall cope with the fact that the effective interference depends on the activity level α of interfering

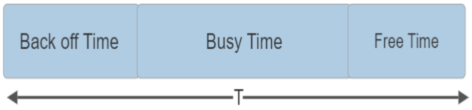


FIGURE 2. Activity measurement.

devices. Hence, we modify the above equation as:

$$SINR_{mk} = \frac{P_k}{N_0 + \sum_{\substack{\forall l \in M,N \\ l \neq m,k}} \alpha_l I_{ml}} \tag{3}$$

To ensure successful reception, $SINR_{mk}$ should be greater than a predefined threshold value $SINR_{min}$. To maximize $SINR_{mk}$ for user m associated with AP_k, we need to minimize:

$$I_m = \sum_{\substack{\forall l \in M,N \\ l \neq m,k}} \alpha_l I_{ml} \tag{4}$$

Note that, the user activity does not only depend on the number of frames it exchanges or the physical rate at which frames are transmitted, but also on the contention. This is due to the fact that, users' transmissions may be queued until they get the chance to occupy the channel. To incorporate this fact in the model, we measure the activity level as:

$$\alpha_l = \frac{B_l + T_l}{T} \tag{5}$$

where B_l represents the time U_l spent in backoff due to contention, and T_l is the time U_l spent in transmission or reception measured during a measurement temporal window T (see figure 2). With coordinated operation, this window is shared among APs. Further, the temporal window shall be larger than the maximum possible back-off. APs can measure their activity levels in the same way. Note that, the activity of any node depends on the time a node has spent in backoff as well the time it has spent in transmission or reception.

A. PRIMARY CHANNEL ALLOCATION

The mutual interference between two WLANs covered by (AP_i,AP_j) is the interference that AP_i and its associated users measure from all nodes that belong to AP_j including AP_j plus the interference that AP_j and its associated users measure from AP_i and its associated users. It can be expressed as:

$$I(AP_i, AP_j) = \sum_{m \in AP_j} I_{im} + \sum_{m \in AP_i} I_{jm} \tag{6}$$

During operation, associated users report measurements about the interference levels as well as sources of interference. Further, users report their activity levels. This can be achieved by employing the 802.11k/v protocol amendments. APs send local status to the SDN controller, including the activity of each connected user, interference from each cell. The controller updates it local records about the status of each AP. The channel allocation scheme, running by the policy engine, starts assigning orthogonal primary channels to WLANs that measures the highest interference and then moves to WLANs that measures high interference from already assigned WLANs until all WLANs are assigned channels.

B. CHANNEL BONDING

Different studies have shown the benefits and challenges of implementing CB. Researchers have shown that, there are scenarios in which channel bonding have significantly improved network performance. Other studies have identified scenarios in which CB may lead to unfair and degraded performance. In this part, we firstly analyze the mutual impact of CB on WLAN performance. Then, we implement a DCB policy that decides on bonding based on channel occupancy time measurements.

DCB was first introduced in IEEE802.11n. It allows two adjacent 20 MHz channels to be bonded together to create a single 40 MHz channel. The DCB functionality was further expanded in IEEE 802.11ac to bind up to eight 20-MHz channels, for a maximum transmission bandwidth of 160 MHz. Although IEEE 802.11ax maintains this cap, IEEE 802.11be, or "extreme throughput," aims to facilitate transmissions over channels of 320 MHz. A primary channel is firstly fixed and secondary consecutive channel(s) can be bonded to the primary if found free at the transmission time.

With non-contiguous DCB, any channel that is sensed free can be bonded to the primary channel. In this case, there is no need for selecting consecutive channels to be bonded to the primary channel. The system can select channels from the set of available free channels. Standards claim that such flexibility may enhance system performance through efficient channel allocation algorithms, where the condition of adjacency is released.

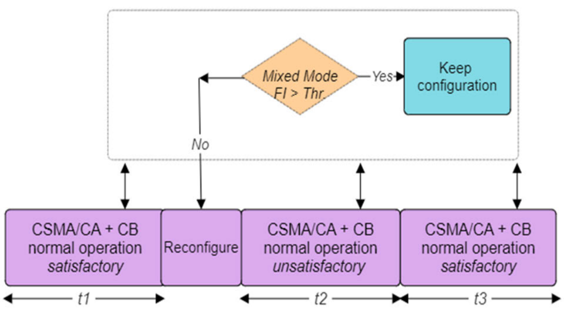


FIGURE 3. **Coexistence Policy.**

In this article, we will study the performance of a simple policy, whereby each node picks the widest set of non-contiguous channels upon having sensed them free during the back-off procedure. The set of channels that can be used in WLAN is assigned by the policy engine based on measurements of activity and channel occupancy periods within neighboring cells. The pseudocode of this policy is shown in Algorithm 1.

C. HETEROGENEOUS WLANS

In this part, we develop a simple policy to coordinate the operation of mixed mode WLANs. When the policy

Algorithm 1 Non-Contiguous CB

Input: Measurements
Process Measurements
Iteration $t \leftarrow 0$
while WLAN active **do**
  if ($LowPerformanceisDetected$) **then**
    Do that
    Determine a primary C_i for each APi
    Find best candidate bonding channels L_i, for APi.
    $APi \leftarrow C_i, L_i$
    AP i announces new channel list to associated users
    Normal operation
  end if
  $t \leftarrow t + 1$
  Update measurements
  Process measurements
end while

engine learns degraded performance of users due to existence of heterogeneous WLANs that operate within the same spectrum, it re-configures the impacted WLAN as well as reallocate channels across heterogeneous networks. The simple pseudo code of the coexistence policy is given in Algorithm 2 and illustrated in figure 3.

V. RESULTS AND DISCUSSION

In this section, we present the results of extensive simulation experiments conducted using the Netsim [25]. We present the results of the case studies considered in this article. WLANs are deployed in an area of 500 X 500 m. All nodes (users and APs) are compliant with 802.11n, ac protocol standards. APs are randomly distributed in the area. Users are static, their locations are randomly determined. Table 1 shows the parameters used in the simulations.

Algorithm 2 Coexistence Policy

Input: Measurements
Process Measurements
Iteration $t \leftarrow 0$
while WLAN active **do**
  while t not finished **do**
    Normal operation with CSMA/CA
  end while
  $t \leftarrow t + 1$
  Measure Fairness Index FI
  if ($MixedModeisDetected$ AND FI$\leq$ Thr) **then**
    Determine common channels.
    Interfering nodes of heterogeneous WLANs avoid using common secondary channels for bonding.
    Update channel list for each WLAN.
    Invoke channel allocation policy.
  end if
end while

CBR traffic is used with 200ms inter-frame time intervals. The simulation time is set to 300 seconds. Performance is measured in terms of throughput and fairness using the widely used Jain's fairness index, given by [26]:

$$J(n_1, n_2, n_3, .., n_N) = \frac{(\sum_{i=1}^{N} n_i)^2}{N \sum_{i=1}^{N} (n_i)^2} \quad (7)$$

TABLE 2. Simulation parameters.

Parameter	Value	Parameter	Value
Packet payload	1460 B	CBR	5.84 Mbps
MAC header	272 bits	Prop. Delay	3 µs
PHY header	192 bits	slot time	9 µs
ACK	240 bits	SIFS	16 µs
ACK Timeout	337 µs	DIFS	50 µs

A. CHANNEL ASSIGNMENT AND BONDING

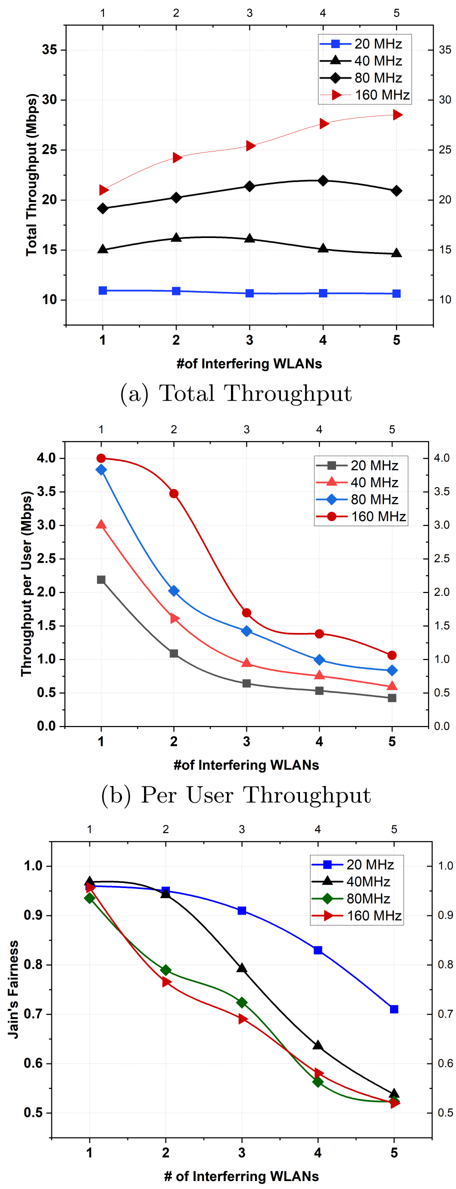
First, we present the results of using same channel width by all WLANs that operate in the 5GHz band. We increase the number of interfering WLANs from 1 to 5. Figure 4a plots the total throughput as a function of the number of interfering WLANs, while figure 4b plots the average throughput per user. As expected, the results show that the total throughput highly improves as the channel width increases. However, the total throughput does provide complete picture. Observing the per user throughput, we notice that it gets degraded as the number of interfering WLANs increases. Further, the distribution of throughput among users becomes very much unfair as can be seen in figure 4c. We noticed that large number of users were starving experiencing almost zero throughput.

Figures 5, 6, 7, 8 illustrates the throughput share for each WLAN with different channel bandwidths. Obviously, WLANs get higher throughputs as the channel width increases, but again the question of how this throughput is distributed among the users in still valid.

In order to study the performance of contiguous and non-contiguous DCB, we conducted experiments for both scenarios. Also, we examined the effect of combining channel assignment with contiguous and non-contiguous DCB. Results are shown in figure 9, and 10. Clearly, employing the channel allocation policy significantly improves the throughput performance as well as the fairness index (figure 11). However, we found that the use of non-contiguous DCB only introduces marginal performance improvement. This is due to the fact that most of the 20MHz channels were noticed to be used by the nodes, making it not easy for the nodes to find free channels. Figure 12 shows the throughput share among WLANs.

B. HETEROGENEOUS WLANS

In this subsection, we present the result of deploying neighboring heterogeneous 802.11n and 802.11ac WLANs. Figure 13 plots the total throughput and the average per



(a) Total Throughput

(b) Per User Throughput

(c) Faineess Index

FIGURE 4. Throughput for different channel widths.

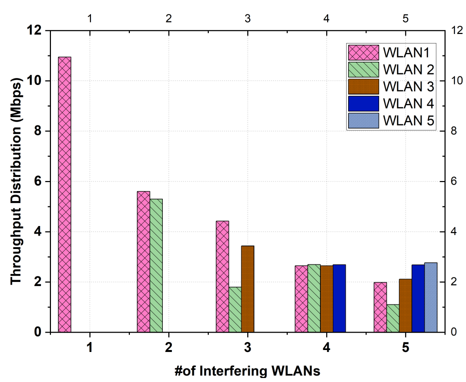


FIGURE 5. 20MHz.

user throughput for different scenarios. Throughput fairness among users is plotted in figure 14. When one standard is

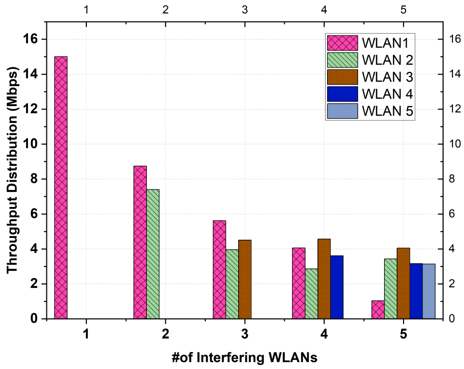


FIGURE 6. 40MHz.

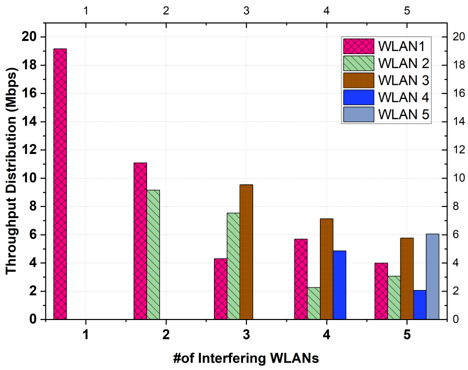


FIGURE 7. 80MHz.

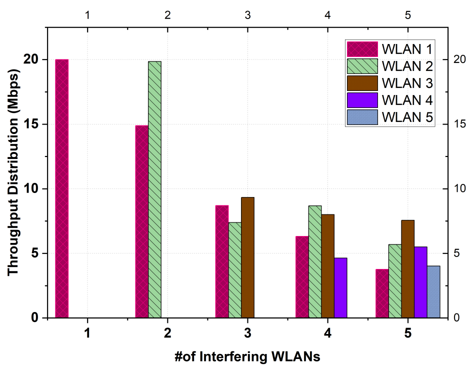


FIGURE 8. 160MHz.

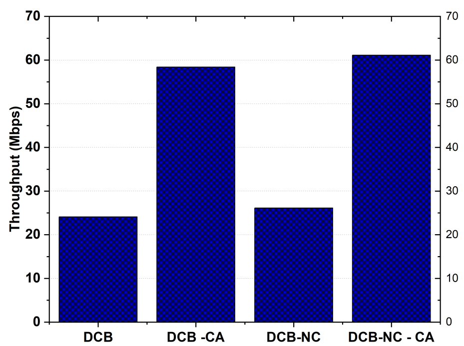


FIGURE 9. Throughput.

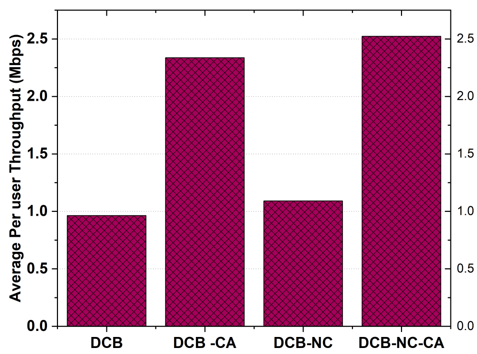


FIGURE 10. Per user throughput.

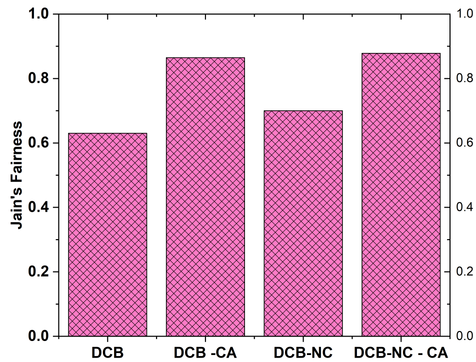


FIGURE 11. Fairness index.

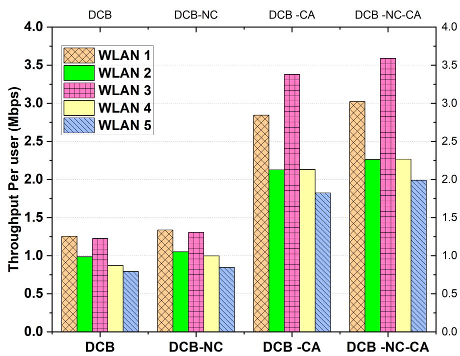


FIGURE 12. Per user Throughput with each WLAN.

only used, both 802.11n and 802.11ac WLANs experience the best throughput performance and the 802.11 CSMA/CA guarantees fair share of resources among users. The fairness index was measured to be about 99%. However, with heterogeneous deployment, we noticed that throughput dropped by about 50% due to spectrum sharing. Further, we noticed that 802.11n WLAN is more negatively affected due to the existence of 802.11ac in its neighborhood. Importantly, we found that the mix deployment leads to unfair distribution of the resources among WLANs. The fairness index dropped from 99% to 58%, meaning that many users were starving. A simple coordination policy that arranges channels used by nodes in the overlapping area was noticed to overcome this problem. Although, it does not improve overall throughput, but it was able to better fairly distribute it among users.

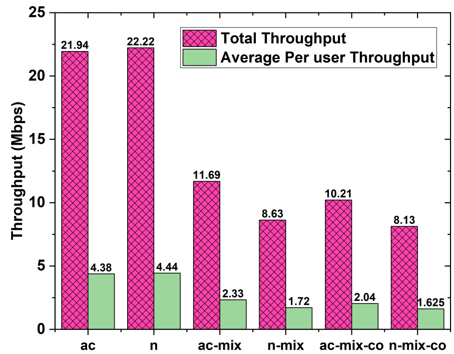


FIGURE 13. Throughput.

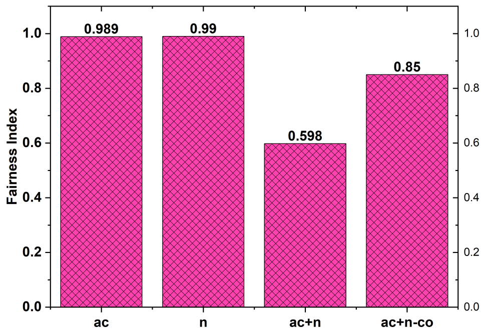


FIGURE 14. Fainess index.

The results of our study stress the fact that a general look on totals or even averages is not enough to judge on solutions. Further, optimization and machine learning based solutions should not only aim at optimizing a global parameter or reward, but rather they should focus on per user experience in order to achieve a compromised solution between optimality and fairness.

VI. CONCLUSION

We developed a framework for managing WLANs based on the SDN technology. The framework is intelligent in the sense that it does not only decide which policy to apply in order to enhance performance, but also it is able to select among approaches that are feasible to be implemented. Results have shown that optimal and machine learning based solutions that aim to maximize totals could lead to degraded performance in terms of per user experience. The results have also shown that non-contiguous channel bonding does not introduce significant performance enhancement.

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