Improvements to Multimedia Content Delivery over IEEE 802.11 Networks

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***Abstract*—Wireless technologies have come to stay, fuelled by the digital world in a global culture that expects instant access to information. The explosive increase in Wi-Fi enabled devices and the incessant demand for high quality multimedia contents require to find innovative ways for accommodating these latency sensitive applications. In this Dissertation we explore multimedia content distribution over IEEE 802.11 networks and tackle the existing difficulties through three main approaches. First, we endeavour to enhance the channel access and the QoS provisioning by relying on machine learning models. Then, we leverage the SDN paradigm to provide efficient radio resource management through adaptive channel assignment and traffic distribution methods. Finally, we propose an integral SDN-based solution to address the shortcomings found in multicast multimedia transmissions in Enterprise WLANs.**

***Index Terms*—WLANs, 802.11, Software-Defined Networking, Machine Learning, QoS, Multimedia.**

I. INTRODUCTION

The breakthrough in wireless technologies and the society's demand to be permanently connected have made wireless communications a fundamental aspect of daily life. The past few years have witnessed an explosion in high quality multimedia contents and a change in the consumption patterns of end users. This fact, combined with the simplicity, low cost and multimedia support of the IEEE 802.11 standard [1], have led Wi-Fi networks to prevail on the market and have created new challenges in network performance and user experience.

The emergence of platforms such as Netflix or Youtube has increased the popularity of multimedia content distribution. These services have a large impact in terms of throughput, latency and jitter on the quality perceived by users if not handled adequately. However, although the IEEE 802.11e amendment [2] introduced traffic differentiation capabilities, the performance of voice and video transmissions is not meeting expected standards, especially as the network load increases, and mobility and scalability aspects are involved. This situation becomes worse in the case of multicast traffic. In scenarios such as sports events and conferences in which the content must be simultaneously delivered to several users, multicast provides an efficient communication mode. Nevertheless, in 802.11 networks this transmission mode faces serious reliability and scalability problems.

In this Dissertation we explore multimedia content distribution over IEEE 802.11 networks. On the one hand, data mining and machine learning techniques are crucial in finding traffic patterns, which makes it possible to identify the most important determinants in the performance and Quality of Service (QoS) level of voice and video services. On the other hand, Software-Define Networking (SDN) enables a global vision of the network status, which is exploited to perform flexible and efficient resource allocation and to improve the performance of multicast communications.

The remaining of the paper is organized as follows. Section II focuses on providing greater QoS level on the medium access in Wi-Fi networks. Section III delves with radio resource management by introducing adaptive channel assignment and traffic distribution methods. Section IV intends to improve multicast transmissions by enabling rate selection and seamless user mobility. Section V shows an overview of the publications that support this work. Finally, in Sec. VI we draw our conclusions and present some future research.

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II. QOS-ORIENTED CHANNEL ACCESS

A. Challenges

In the original IEEE 802.11 standard, the Distributed Coordination Function (DCF) controls medium access, which assigns the same priority to all the applications. The IEEE 802.11e amendment extends DCF and introduces Enhanced Distributed Channel Access (EDCA) as a medium access function capable of classifying and prioritizing traffic streams. EDCA establishes four Access Categories (ACs) named Voice (VO), Video (VI), Best Effort (BE) and Background (BK). They make use of its own traffic queue and have its own set of medium access parameters: Arbitration Interframe Space (AIFS), Transmit Opportunity (TXOP) and Contention Window (CW). In contrast to DCF, EDCA specifies different waiting times for each type of traffic.

Although the standard allows the modification of the EDCA parameters, it recommends a set of values to guarantee compatibility with all Wi-Fi compliant devices (Table I). In fact, due to the complexity involved in calculating these parameters in real-time, this feature is not used in commercial APs. Nevertheless, it has been proved that 802.11e does not accurately handle voice and video traffic [3]–[5]. Moreover,

TABLE I
DEFAULT EDCA PARAMETER SET IN IEEE 802.11E.

AC	CW_{min}	CW_{max}	AIFSN	TXOP
AC_BK	aCW_{min}	aCW_{max}	7	-
AC_BE	aCW_{min}	aCW_{max}	3	-
AC_VI	$(aCW_{min}+1)/2-1$	aCW_{min}	2	3.008 ms
AC_VO	$(aCW_{min}+1)/4-1$	$(aCW_{min}+1)/2-1$	2	1.504 ms

TABLE II
AIFSN VALUES FOR THE CHANNEL ACCESS PREDICTION SCHEME.

AC	S0	S1	S2	S3	S4	S5	S6	S7	S8	S9
BK	7	8	9	8	9	12	10	12	14	14
BE	3	4	5	4	5	6	6	8	10	12
VI	2	2	2	3	3	3	4	5	6	7
VO	2	2	2	2	2	2	2	2	2	2

TABLE III
CW VALUES FOR THE CHANNEL ACCESS PREDICTION SCHEME.

AC	CW 1		CW 2	
	CW_{min}	CW_{max}	CW_{min}	CW_{max}
BK	$2 \cdot aCW_{min} + 1$	aCW_{max}	$2 \cdot aCW_{min} + 1$	aCW_{max}
BE	$2 \cdot aCW_{min} + 1$	aCW_{max}	$2 \cdot aCW_{min} + 1$	aCW_{max}
VI	aCW_{min}	$2 \cdot aCW_{min} + 1$	$2 \cdot aCW_{min} + 1$	$2 \cdot aCW_{min} + 1$
VO	$(aCW_{min}+1)/2-1$	aCW_{min}	aCW_{min}	aCW_{min}

TABLE IV
CW-AIFSN CONFIGURATIONS FOR THE PREDICTION SCHEME.

AC	Config. 1	Config. 2	Config. 3	Config. 4
AIFSN	Predicted	Predicted	Prev. comb.	2nd Prev. comb.
CW	Default	CW 1	CW 1	CW 2

several studies have shown that the appropriate selection of the EDCA parameters leads to efficiency enhancements and contributes to reducing the delay and the collisions in the network. However, only the CW and the AIFS are associated with the highest enhancements [6]–[8]. Notice that the AIFS is derived as $AIFS[AC] = AIFSN[AC] \cdot SlotTime + SIFS$.

B. Contributions

Based on the issues discussed before, we aim to dynamically adapt the EDCA parameters to the network status. To this end, we first analyse the performance of the standard EDCA values, showing that collisions arise from a medium load level for voice and video traffic because these ACs use the same AIFSN and a small value for the CW. This collision ratio can be decreased in two ways: (i) shifting the AIFSN values of all the ACs; and (ii) adjusting the size of CW. Moreover, we study the most relevant factors in determining the network status, named the number of active transmissions of each type of traffic, the bitrate, the transmission rate, the presence of legacy DCF stations and the channel utilization. In this context, we propose a three-phase predictive scheme relying on Artificial Intelligence (AI) techniques, and specifically, on a *J48* classifier [9] and on an *M5* regression model [10].

The first phase adapts the AIFSN combination that performs best for voice and video while ensuring the aggregated network throughput. It first begins with a deep training step involving a wide range of scenarios. To this end, as can be observed in Table II, 10 AIFSN configurations have been selected by considering the performance and collision requirements discussed above. The training and validation steps take into account a variable number of legacy and QoS stations that deliver constant and intermittent traffic at different bitrates.

The second phase tunes the CW to address the issues found by only steering the AIFSN combination. The values evaluated for the CW size are shown in Table III. However, some AIFSN-CW combinations may increase the priority of the stations using DCF with respect to those that use EDCA. To address these pitfalls, Table IV presents four approaches that combine the increase in CW with the use of lower values for AIFSN than those predicted in the first phase.

The third phase combines the two previous phases. As can be seen in Table IV, eight predictive schemes are designed, four of them for each initial model (*M5* and *J48*). In this sense, an exhaustive analysis allows it to identify a group of traffic patterns to distinguish the models that achieve the highest performance based on network conditions. In this way, the algorithm is able to dynamically adapt the EDCA parameters according to the network status and, as a result, to enhance the performance of the delay sensitive services and the QoS level. Details of the algorithm's design can be found in [11].

The results of the performance evaluation of the algorithm are presented in terms of voice+video throughput in Fig. 1. In particular, it can be seen that the enhancement is higher when the network is only composed of stations that use EDCA, as depicted in Subfig. 1b. In fact, as the network load increases, this enhancement becomes higher, being it from 30%. By contrast, in Subfig. 1a it is shown that this improvement is slightly smaller in the presence of legacy stations. It should be noted that this proposal can be applied directly to commercial devices since changes in the 802.11 protocol are not required.

III. CHANNEL SELECTION AND USER ASSOCIATION

A. Challenges

Given that the standard does not specify a procedure for the user association, in WLANs users normally select the AP with the strongest Received Signal Strength Indicator (RSSI) [12]. However, this may lead to an inefficient user distribution and to an increase in the interference and collisions. Furthermore, the limited number of radio channels in Wi-Fi networks may result in overlaps in the coverage area of several APs.

In this context, an effective collision domain isolation and channel assignment strategy acquires particular importance. To address this situation, significant research has been conducted by minimizing the number of clients per AP [13] or by making the APs operate on non-overlapping channels to reduce the interference [14], [15]. However, the required changes to the 802.11 standard of some of these proposals show that

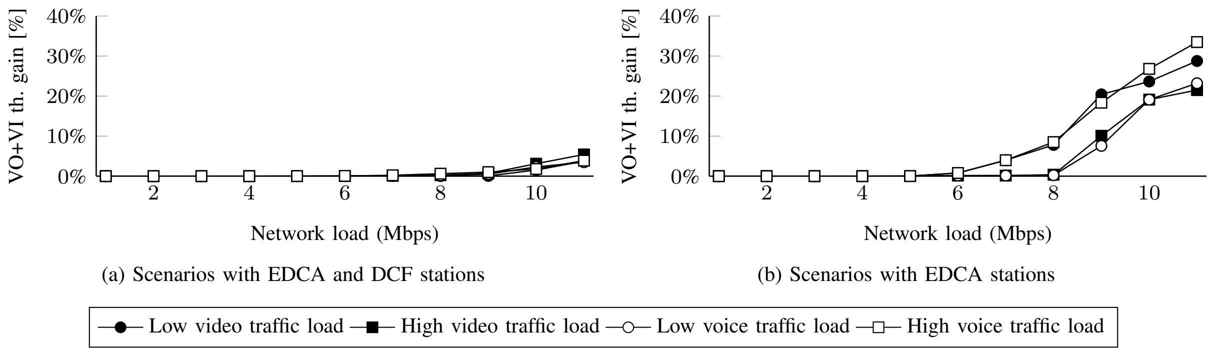

Fig. 1. Voice+Video throughput gain achieved by the dynamic scheme on the basis of two different voice and video traffic loads.

the traditional architecture is often inflexible and ignores the specific requirements of users and applications.

SDN enables network programmability and becomes a good solution for the lack of coordination in the traditional deployments. User distribution inevitably involves reassociation processes that degrade network performance, which shows the need for supporting seamless migration mechanisms especially when delivering multimedia content. Interference and association problems have been studied from the SDN perspective, for example, by reconfiguring the transmission power of the APs [16], or by balancing the traffic over different connection nodes [17], [18]. However, an effective user association scheme must consider the global network status to ensure optimal performance, and be carried out along with a user association algorithm to mitigate interference issues.

B. Contributions

In this Dissertation we take advantage of the flexibility provided by SDN to design a joint user association and channel assignment solution named *Wi-Balance*. As shown in Fig. 2, we implement these algorithms as network applications taking as a reference the 5G-EmPOWER MEC-OS System [19]. Furthermore, the APs are located in the infrastructure layer and just follow the operations from the SDN controller.

The channel assignment solution is based on a recursive constraint programming algorithm that aims to minimize the number of APs in the same collision domain. This algorithm first assigns a channel to the APs with the lowest number of available channels. From this group of APs, it first selects the ones with the highest number of neighbours already assigned. Furthermore, if all the channels have been selected, the one that is less used is chosen. Notice that this assignment is not static and the process is executed upon changes in the network.

After the channel assignment, *Wi-Balance* creates a channel quality map including the signal strength perceived from all the APs for each station in order to perform an effective user association. This information is retrieved by the SDN controller from the APs. Furthermore, it estimates the channel utilization of each AP and the average utilization across the network using the link delivery statistics from the APs and the amount of data transmitted and received by all the users.

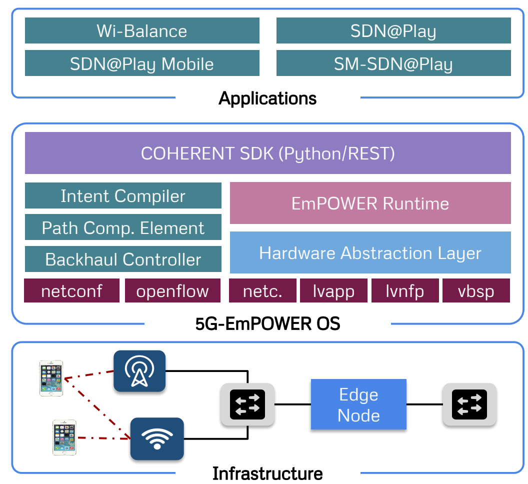

Fig. 2. 5G-EmPOWER MEC-OS System Architecture.

If a significant difference is found, a reassociation process is triggered. In this sense, *Wi-Balance* selects for the handover the user with the lowest result for the product between the channel utilization of the AP and the perceived RSSI.

Handovers in WLANs usually require substantial time for the reassociation. Nevertheless, the use of the *LVAP* abstraction, a per-client virtual AP, allows it to transparently shift the client information between APs without dropping the connection [19]. Moreover, APs involved in a handover may be operating on different channels. In such cases, the Channel Switch Announcement (CSA) procedure must be used to inform the user about the channel change. Following the *LVAP* abstraction, the CSA procedure is adapted to ensure that the connection is never interrupted despite the channel change.

This proposal has been assessed in a real-world scenario and compared with RSSI-based user association schemes. As depicted in Fig. 3, the results showed a reduction in the channel utilization by up to 30% by means of a more efficient user distribution and a decrease in channel contention. Consequently, as can be observed in Fig. 4, the throughput increased by up to 25% without penalizing network fairness. Further details of the evaluation can be found in [20].

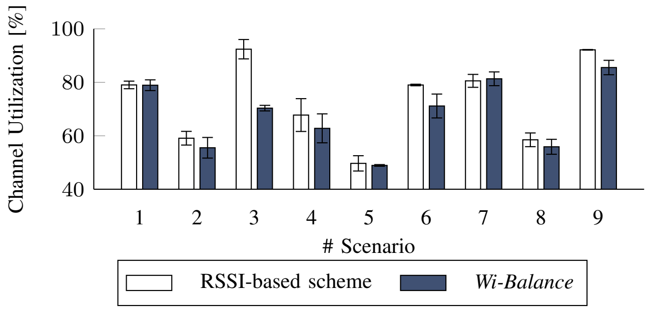

Fig. 3. Network-wide channel utilization in the *Wi-Balance* evaluation.

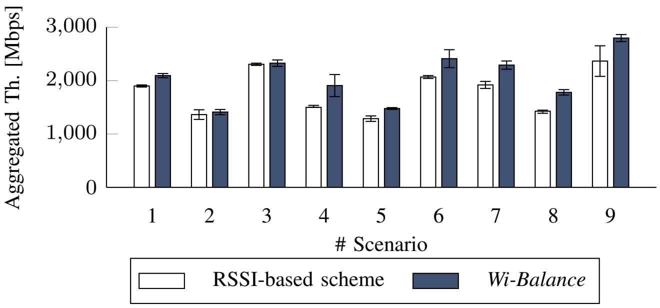

Fig. 4. Network–wide aggregated throughput in the *Wi-Balance* evaluation.

IV. Robust Multicast Distribution

A. Challenges

Scenarios such as live events, conference meetings and Internet Protocol Television (IPTV) are good examples where multicast is an efficient transmission mode to simultaneously deliver the same data to several users [21]. However, multicast in 802.11 lacks frame acknowledgements and retransmissions, which makes impossible to gather feedback information from the users and, hence, to adapt the transmission rate. For this reason, the standard recommends the use of the lowest data rate to increase the probability of all the users receiving the data. As a result, the wireless medium is occupied for longer periods, which increases the radio resource utilization.

The IEEE 802.11aa amendment [22] aims to support robust audio and video streaming and introduces four multicast mechanisms: (i) *legacy*, is the multicast mode defined in the original standard; (ii) *Direct Multicast Service (DMS)*, transforms each frame into as many unicast frames as the number users in a group; (iii) *Unsolicited Retries (UR)*, specifies a number of attempts, N, so that a frame is transmitted $N+1$ times; and (iv) *Block ACK (BACK)*, sends a burst of multicast frames up to a given number, and requests a unicast Block ACK to each user. The main features and limitations of 802.11aa are summarized in [23]–[25]. Despite the improvements achieved, it does not provide any procedure to adapt the data rate. As a consequence, several traditional proposals [26], [27] as well as SDN-based solutions [28], [29] intend to address the reliability and rate selection problems.

When contents are distributed to roaming users, multicast services must include mobility management mechanisms. Efficient operations across multiple APs require global visibility, which is not usually provided by traditional architectures. Although the concept of seamless mobility has motivated the emergence of SDN-based approaches [30], [31], currently they do not address the special necessities of multicast services. This problem intensifies when several streaming applications must be simultaneously delivered. Nevertheless, very little progress has been made in integrating rate adaptation features while ensuring high scalability in multicast [32].

B. Contributions

This Dissertation aims to design a scalable scheme for multicast data rate selection that provides seamless user mobility and makes it possible to manage several multicast sessions. To this end, we introduce the *Transmission Policy* abstraction, which enables the configuration of rate control policies, and specifies the Modulation and Coding Scheme (MCS) and the 802.11aa policy to be used. This abstraction lays the foundation for implementing *SDN@Play*, an algorithm capable of steering the multicast data rate and improving transmission reliability. *SDN@Play* is introduced as an SDN application, as can be seen in Fig. 2.

Rate Selection. Since multicast traffic lacks of feedback information from the users, this operation is performed in two phases. In the first phase (the shortest one), the controller sets DMS as multicast policy with the aim of retrieving the rate control statistics of all the users in a multicast group. This information is used to calculate the MCS with the highest delivery probability, which is calculated as the intersection of these data rates. Then, the controller sets legacy multicast as the policy to be used during the second phase and instructs the APs to use the MCS calculated before. This process is periodically repeated with a configurable ratio between the DMS and the legacy periods [33].

Mobility Management. *SDN@Play Mobile* extends *SDN@Play* to account for mobile users and associate them to the AP that also reduces the network resource utilization. Leveraging IEEE 802.11k [34], users periodically report to their AP on the signal quality (RSSI) perceived from the APs in their coverage area. Based on this information, the SDN controller builds a channel quality map, used to find possible signal drops and check whether another AP can deliver significant improvements for a certain user. Finally, the algorithm selects for a user the AP that would use the highest MCS while offering a considerable signal strength [35].

Multicast Services Orchestration. Since one instance of *SDN@Play* is necessary for each multicast group, the performance would be greatly impaired when transmitting several services due to the overlap of the DMS phases. To reduce this overhead, *SM-SDN@Play* schedules the unicast period (DMS) of each multicast group in different time slots. The duration of the two periods (Legacy and DMS) is divided into n parts: one part for the DMS period, and $n-1$ parts for the legacy one. When a multicast group is created, the algorithm

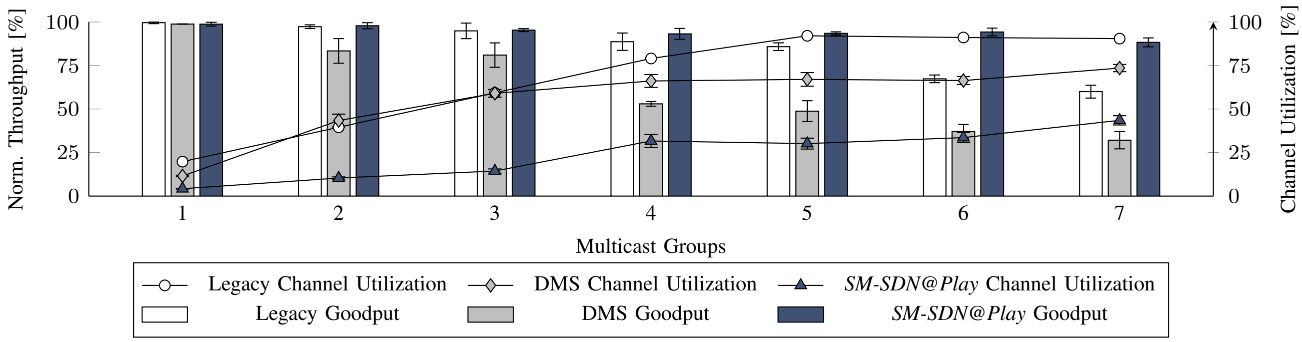

Fig. 5. Multicast performance evaluation for an increasing number of multicast groups.

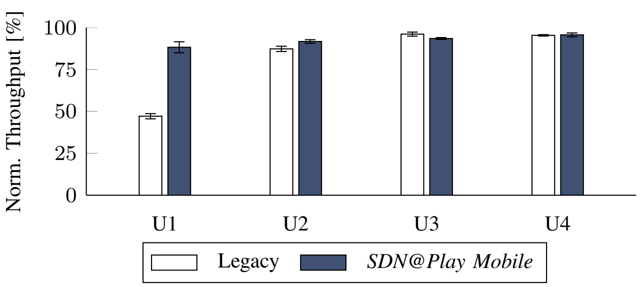

Fig. 6. Multicast performance evaluation for mobile and static receivers.

schedules it in a free slot. In case that all the slots are busy, the DMS periods of two groups would coincide; however, this is considered an unlikely event with negligible impact on the network performance [36].

SDN@Play has been evaluated in a real-world testbed. The first test evaluates the performance when handling several multicast groups. All of them are composed of 3 users attached to a single AP, which transmits a multicast video at 1.2 Mb/s. In Fig. 5 it is shown the reduction in the channel utilization achieved by our algorithm due to the fact that it adapts and increases the data rate, hence occupying the channel for shorter periods. In the second scenario a single multicast application is delivered by 3 APs to 4 users: one mobile ($U1$) and three static ($U2$, $U3$ and $U4$). In Fig. 6 it can be seen that while the throughput of the static users is maintained with respect to the legacy policy, the performance of the mobile user ($U1$) is highly increased by *SDN@Play Mobile*. Further information on the measurements can be found in [35], [36].

V. Publications and Dissemination

The work presented in this paper is based on the Doctoral Thesis entitled “Improvements to Multimedia Content Delivery over IEEE 802.11 Networks” presented at the University of Castilla-La Mancha (Spain) in collaboration with Fondazione Bruno Kessler (Italy) [37].

The proposals introduced throughout the manuscript have been published on international conferences and journals. They can be grouped according to the contribution as follows:

- *QoS-Oriented Channel Access,* [11], [38]–[40].
- *Channel Selection and User Association,* [20], [41], [42].
- *Robust Multicast Distribution,* [33], [35], [36], [43], [44].

VI. Conclusions

Recently, in addition to offering high-density Wi-Fi, there is an incessant demand for multimedia facilities due to the rapid penetration of digital content across multiple devices. In this regard, high definition video streaming services have generated considerable interest. Therefore, accommodating these latency sensitive applications requires new and innovative techniques in network management to deliver revolutionary network services and enhance the end-user experience.

In this work it has been shown that multimedia communications in WLANs are subject to many constraints. In this sense, this problem has been tackled from different perspectives. On the one hand, we have focused on improving the QoS differentiation provided by IEEE 802.11e by exploiting artificial intelligence techniques. On the other hand, we have leveraged the hardware abstractions provided by SDN to address two principal aspects that have been particularly difficult to deal with in the current monolithic Wi-Fi architectures: network resource allocation and multicast services distribution. These proposals can be applied directly to commercial devices since changes in the 802.11 protocol are not required.

The work presented in this Dissertation encourages new research directions. In the short term, in order to further improve the service-oriented vision, network slicing enables an scenario where each slice is characterized by different settings and dynamic control policies. In this respect, other more sophisticated approaches could be introduced to prioritize the user operations in a more effective way. In the long term, we intend to reinforce high scalability and resilience. Since in SDN most of the operations are undertaken on the control layer, it becomes a critical point of failure as well as a potential bottleneck [45]. In this regard, more than one controller may be needed for ensuring high performance. This problem could be addressed by distributing multiple controllers across the network. Hence, a procedure for selecting the appropriated controller in each case must also be investigated.

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