Joint Mobility Management and Multicast Rate Adaptation in Software–Defined Enterprise WLANs

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***Abstract*—The ever–increasing demand for mobile content delivery and multimedia services is bringing renewed interest in multicast communications in Wi–Fi based WLANs. Nevertheless, multicast over Wi–Fi raises several challenges including low data rates and coexistence issues with other unicast streams. Some amendments to the Wi–Fi standard, such as 802.11aa, have introduced new delivery schemes for multicast traffic as well as finer control on the low–level aspects of the 802.11 medium access scheme. However, the logic for using such features is left to the implementer of the standard. In this paper we present *SDN@Play Mobile*, a novel SDN–based solution for joint mobility management and multicast rate–adaptation in Wi–Fi networks. The solution builds upon a new abstraction, named *Transmission Policy*, which allows the SDN controller to reconfigure a multicast transmission policy when its optimal operating conditions are not met. An experimental evaluation carried out over a real–world testbed shows that our approach can deliver significant improvements in terms of both throughput and channel utilization compared to the legacy 802.11 multicast scheme. Finally, we release the entire software implementation under a permissive APACHE 2.0 license for academic use.**

***Keywords*—WLANs, IEEE 802.11, multicast, rate adaptation, software defined networking, mobility, multimedia.**

I. Introduction

Wireless and mobile communications are witnessing an exponential growth in the amount of traffic exchanged. For example, the latest CISCO Visual Network Index [1] reports that Wi–Fi and mobile traffic will account for 49% in 2020. Multimedia communications are becoming dominant, and it is also expected that 78% of the mobile traffic will be video by 2021. Moreover, the emergence of mobile devices and the demand for constant connectivity have led Wi–Fi networks to be deployed everywhere. In an effort to improve the performance, these networks are typically composed of multiple Access Points (APs) to increase the capacity of the network and to provide support for roaming users. Both the industry and the academia are well aware of the importance of multicasting services. This is demonstrated by the undergoing standardization efforts for the emerging 5G networks, which has led to the release of the Multimedia Broadcast Multicast Service (MBMS) by 3GPP [2] and by the increasing body of literature on this topic [3], [4], [5].

Multicast and broadcast services are a particular class of video traffic where contents must be delivered to a group of users. Due to the high bandwidth and low delay requirements of this traffic, multicast transmissions become an effective solution to optimize network resources. Sport events, conferences, game streaming, airports services, and real–time lessons are just some of the scenarios where multicast transmissions can be used. Moreover, wireless multicast can be used also in machine–to–machine communications in scenarios such as transport and emergency systems. Lastly, software upgrades can be also further improved using multicast transmissions.

IPTV services over Wi–Fi are also a good example of multicast video distribution in which most of the users tend to connect to the network through mobile devices. This fact shows how this technology can be widely used for business and entertainment purposes as well as the importance of ensuring reliable transmissions and user mobility. An example of its applicability can be found in the deployment of a campus network IPTV system to enable efficient distribution of multicast traffic over a WLAN [6].

IEEE 802.11–based WLANs dynamically choose among different Modulation and Coding Schemes (MCSes) for frame transmissions. For example, in 802.11a/g WLANs, devices can choose among MCSes resulting in bitrates ranging from 1 to 54 Mb/s, while in 802.11n/ac WLANs higher MCSes are available. However, since according to the IEEE 802.11 standard each frame must be acknowledged by the receiver, the rate selection mechanism is restricted to unicast traffic. This is due to the fact that, in case of multicast transmissions, acknowledgments cannot be used given that they would inevitably collide at the transmitter. As a result, multicast frames are sent at the lowest MCS and do not make use of any feedback mechanism. This implies several drawbacks: (i) the throughput of multicast transmissions is very limited; (ii) the use of basic data rates consumes more radio resources affecting also the capacity available to other (unicast) flows; and (iii) since multicast frames are not retransmitted, the reliability of the multicast streams can be adversely impacted by the channel conditions.

The traditional Wi–Fi network architecture hinders the introduction of new solutions to overcome the problems presented above while maintaining the compatibility with the 802.11 standard. In this regard, Software Defined Networking (SDN) has recently emerged as a new way of refactoring network functions. By clearly separating data–plane from control–plane and by providing high level programming abstractions, SDN allows implementing traditional network control and management tasks on top of a *logically* centralized controller. However, albeit SDN is already an established technology in the wired domain, with OpenFlow playing the role of de–facto standard [7], equivalent solutions for wireless networks have only recently started to appear [8], [9], [10].

In this paper we propose a joint mobility management and multicast rate adaptation algorithm for Software–Defined WLANs. Our work aims at improving the performance of multicast communications while reducing the utilization of radio resources. This goal is achieved in a two–step procedure: (i) selecting the multicast data rate that can deliver the expected quality in terms of performance; and (ii) associating the multicast receivers to the APs in a way that the radio resource utilization across the entire network is minimized. This paper builds upon our previous work [11] by extending the proposed algorithm to account also for mobile multicast receivers and association management. Moreover, we also report on an updated proof–of–concept implementation of the proposed solution and on its field evaluation. The entire implementation, including the controller and the data–path, is released under a permissive APACHE 2.0 license[1] for academic use.

The rest of the paper is structured as follows. In Section II we discuss the related work. The system architecture as well as the joint mobility management and rate control algorithms are presented in Section III. Section IV reports on the implementations details, while Section V describes the experimental evaluation and discusses the results of the measurements campaign. Finally, Section VI draws the conclusions pointing out future research directions.

II. Related Work

In this section we first provide a background on multicast communications in 802.11 WLANs. Then, we review the most relevant related work highlighting our technical contributions.

Multicast communications are an efficient way to send the same information to many clients. In fact, by exploiting the broadcast nature of the wireless medium, it is possible to deliver the same frame to multiple wireless terminals instead of transmitting it individually to each of them. Nevertheless, in IEEE 802.11 WLANs multicast frames are never retransmitted nor acknowledged. As a consequence, the transmission reliability is highly reduced. Moreover, the lack of feedback information prevents the devices from adapting the transmission rate. Consequently, the 802.11 standard recommends the use of the basic data rate for the multicast traffic.

The IEEE 802.11aa amendment [12] has been introduced to improve the performance of the multicast communications while keeping the compatibility with current devices. The amendment improves the multicast reliability level by introducing the Group Addressed Transmission Service. This service specifies several retransmission policies and is composed of two different mechanisms: Direct Multicast Service (DMS) and Groupcast with Retries (GCR). In DMS mode each multicast frame is converted into as many unicast frames as the number of receivers in the multicast group. Each unicast frame may be retransmitted as often as necessary until the AP receives the ACK or the retransmission counter reaches its limit. In spite of ensuring high reliability, DMS does not scale well with the number of receivers in the multicast group.

GCR is a flexible service composed of three retransmission methods: Legacy Multicast, Unsolicited Retries (UR) and Block ACK (BACK). The Legacy Multicast mode is the one defined in the original IEEE 802.11 standard. The UR policy specifies a number of retry attempts, N, in a manner that a frame is transmitted $N + 1$ times. In this way, the probability of a successful transmission is increased. However, UR may unnecessarily retransmit frames, hence increasing the overall network utilization. In BACK mode the AP reaches an agreement with the multicast receivers about the number of consecutive unacknowledged frames. After that, the AP sends a burst of multicast packets up to that number and requests a Block ACK from each receiver. Both this request and the corresponding ACKs are sent in unicast mode. Despite the control traffic overhead is reduced, also this approach does not scale with the number of receivers in the group. A comprehensive description of the various multicast schemes supported by the 802.11 standard can be found in [13].

Multicast rate selection may be achieved by defining feedback gathering mechanisms allowing the transmitter to gain a better knowledge of the status of the wireless medium. Leader–Based Protocols (LBP) are the most common proposals in the literature. LBP [14] aims at improving multicast communications by enabling ACKs. For this purpose, the receiver exhibiting the worst signal quality is selected as a leader of the group and is in charge of sending ACKs. However, a procedure for the leader selection is not provided. The Auto Rate Selection Multicast (ARSM) mechanism [15] divides its operation mode into two phases: in the first one, the group leader is selected, whereas in the second step the Signal–to–Noise Ratio (SNR) derived from the ACKs of the leader is used to adapt the transmission rate. Hierarchical–ARSM (HARSM) [16] is an evolution of ARSM for hierarchical video transmissions over WLANs that ensures a minimum quality of the video sequence for all the receivers. The rate adaptation based on the SNR is also used in SNR–based Auto Rate for Multicast (SARM) [17]. In this scheme, the AP identifies the worst receiver by sending beacon frames to which the stations must reply indicating their own SNR. After that, the APs must inform the remaining stations about the new situation. However, changes at the client side are needed to implement this scheme.

The multicast rate adaptation problem is exacerbated when considering mobile users since their channel conditions constantly change. Based on these conditions, efficient handover solutions are required to migrate these clients from one AP to another in order to ensure that the quality of service requirements of the end–user are met. This is precisely the target pursued in [18], [19]. The mobility problem in multicast is also analysed from the point of view of the wired backbone interconnecting the Wi–Fi APs [20], [21]. These proposals, however, focus on balancing the bandwidth in the backhaul, neglecting the challenges related to the radio access segment.

An efficient handover process must ensure that the communication is not interrupted while performing the association

[1] Available at: http://empower.create-net.org/

with the new AP. Nevertheless, this concept, called seamless handover, is difficult to achieve in traditional network architectures and has motivated the emergence of some SDN–based works. In M–SDN [22] the central controller tracks channel quality information to identify the best APs for a handover. After that, a route from the current AP to the target ones is computed. This approach reduces the service disruption time at the price of generating additional traffic in the network. A multi–channel architecture is introduced in [23], in which several APs share the same MAC address to ensure seamless handover. The validity of this proposal is tested via simulation and over an OpenFlow–based testbed. However, it should be noted that these approaches are targeted at unicast traffic, and to the best of our knowledge, no current work addresses the user mobility problem in multicast environments over SDN–based WLANs.

Quality of Experience (QoE) has often been used as basis for rate adaptation in multimedia applications. In [24] a neural network is designed to build a model that maps QoE measurements into MCSes. PSQA [25] is developed as a hybrid objective–subjective metric that simulates how humans perceive impairments to video transmissions. Similar consideration can be made for [26]. In [27] the authors address the multicast video delivery using a real–life testbed. In this solution the time is split into a transmission and a polling period. During the transmission period, the stations collect the sequence numbers of the received frames. After that, the APs gather that information to calculate the link delivery probabilities. The transmission rate is selected by comparing these values with the ones obtained from the two previous rounds. Changes at the client side are needed to implement this scheme. MultiFlow [28] aims to improve multicast communications using SDN principles. However, results are only presented as a numerical analysis and the channel usage of the proposed scheme may exceed the legacy multicast one when the size of group is greater than a certain threshold.

In spite of the improvements made, most of the aforementioned works have either been tested via simulations or require significant modifications to the wireless client's stack, hence making them incompatible with the IEEE 802.11 standard. Moreover, the mobility problem is further aggravated when considering multicast communications given that both the data rate selection and the handover time affect all the receivers in the network. In this regard, no research work in the literature jointly address association management and multicast rate selection in 802.11–based WLANs. Conversely, in this work we aim at providing a practical and *programmable* multicast rate adaptation and mobility management solution that is fully compatible with the IEEE 802.11 standard and that, by being fully software–defined, can be customized to the requirements of the particular multimedia application.

III. System Design

Current networking technologies have several problems whose solutions often require substantial changes to the network stack. SDN has emerged as a new paradigm capable of addressing such limitations by introducing a fully programmable and modular network, making it possible to implement control and management tasks on top of a (logically) centralized control plane instead of implementing them as distributed applications. Figure 1 depicts the high–level reference system architecture used in this work. As can be seen, it consists of three layers: infrastructure, control and application. The infrastructure layer includes the data–plane network elements (*i.e.* the 802.11 APs) which are in constant communication with the (logically) centralized controller situated at the control layer. Applications run at the application layer leveraging on the global network view exposed by the controller to implement the network intelligence.

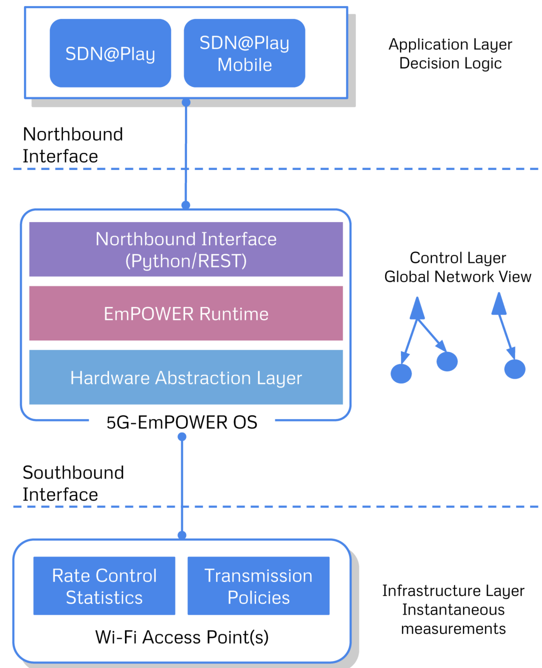


Fig. 1: *SDN@Play Mobile* System Architecture.

As noticed before, OpenFlow is one of the most popular options to implement the link between data–plane and control–plane (the so–called southbound interface). Nevertheless, its features are mostly targeted at wired networks and are poorly suited for controlling 802.11–based WLANs [8]. As a consequence, in the last years several SDN solutions for wireless and mobile networks have emerged. Examples include 5G–EmPOWER [8], Odin [9], and OpenSDWN [10].

The mobility management and multicast rate adaptation scheme presented in this paper has been implemented and tested on top of the 5G–EmPOWER platform [8]. Nevertheless, it should be noted that our work is very general and can be in principle applied to any centrally controlled enterprise WLAN. The system design is described in this section. First, we will summarize the Light Virtual Access Point (LVAP) abstraction which is used to control Wi–Fi stations association [9]. Then, we will introduce the *Transmission Policy* abstraction designed to allow an SDN controller to configure a rate adaptation policy of a Wi–Fi AP. Finally, we will show how these abstractions can be used to implement a joint multicast rate selection and mobility management algorithm.

A. The Light Virtual Access Point Abstraction

Different link layer technologies, or as a matter of fact even different releases of the same technology, can differ significantly in how a client's state is handled. For example, QoS and handover management changed significantly over the lifespan of the IEEE 802.11 family of standards. As a consequence, exposing the implementation details of these technologies would increase the complexity for the programmer and would severely limit the adoption of a certain solution.

The *LVAP* abstraction [9] is a per–client virtual AP that provides a high–level interface for wireless clients state management. The implementation of such an interface handles all the technology–dependent details (*i.e.* the complexities of the IEEE 802.11 protocol) such as association, authentication, handover and resource management, and introduces seamless mobility support. A client attempting to join the network will trigger the creation of a new *LVAP*. For this purpose, a wireless client generates a probe request that will be received at an AP and forwarded to the controller. In case of a new client, the controller will generate a probe response frame through the creation of an *LVAP* at the requesting AP. The *LVAP* will thus become a potential AP for the client to perform an association. Since an *LVAP* is created for each each wireless client, after generating an *LVAP*, probe requests received from the same client by any AP in the network will be ignored.

The controller can also decide whether the network has enough resources to handle the new client and might suppress the generation of the *LVAP*. Similarly, each AP will host as many *LVAP*s as the number of wireless clients that are currently under its control. Such *LVAP* has an identifier that is specific to the newly associated client (in a Wi–Fi network the *LVAP* can be thought as a Virtual AP with its own BSSID). Removing an *LVAP* from an AP and instantiating it on another AP effectively results in a handover.

B. The Transmission Policy Abstraction

The fundamentals of SDN call for a clear separation between control–plane and data–plane. This requires identifying how network resources are exposed (and represented) to software modules written by developers and how those can affect the network state. Due to the stochastic nature of the wireless medium, the physical layer parameters that characterize the radio link between a Wi–Fi AP and a wireless client, such as transmission power, MCS, and Multiple Input Multiple Output (MIMO) configuration must be adapted in real–time to the actual channel conditions. Therefore, any programming abstraction for rate–adaptation in Wi–Fi networks must clearly separate fast–control operations that must happen very close to the air interface, such as rate adaptation, from operations with looser latency constrains, such as mobility management.

In this work we propose the *Transmission Policy* abstraction which allows an SDN controller to reconfigure or replace a certain rate control policy if its optimal operating conditions are not met. The *Transmission Policy* specifies the range of parameters the AP can use for its communication with a wireless client. Such parameters include:

- *MCSes*. The set of MCSes that can be used by the rate selection algorithm.
- *RTS/CTS Threshold*. The frame length above which the RTS/CTS handshake must be used.
- *No ACK*. The AP shall not wait for ACKs if true.
- *Multicast policy*. Specifies the multicast policy, which can be Legacy, DMS or UR.
- *UR Count*. Specifies the number of UR retransmissions.

Transmission Policy configurations can be specified on a L2 destination address basis. As a result, for each destination address and for each AP in the network a specific *Transmission Policy* configuration can be created. Notice that the *Transmission Policy* allows the controller to specify which MCSes can be used by the rate control algorithm implemented at the AP. However, the actual frame–by–frame selection of the MCS is done at the AP and not at the controller.

Table I lists four *Transmission Policy* configuration examples, two for unicast addresses and two for multicast addresses. The first multicast entry (*01:00:5e:b4:21:90*) specifies Legacy as multicast mode. This instructs the AP to send every multicast frame with the specified destination address using 24 Mb/s as transmission rate. We remind the reader that in Legacy mode multicast frames are sent only once and that no acknowledgement is generated by the receivers. The second multicast entry (*01:00:5e:40:a4:b4*) specifies DMS as multicast mode. In this case, for every multicast frame with this destination address, the AP will generate as many unicast frames as the number of receivers in the multicast group. The transmission rate for such unicast frame will be selected by the AP using the list of available MCSes specified by the corresponding unicast *Transmission Policy* configuration. The content of the table is manipulated by the controller using a CRUD (Create, Retrieve, Update, Delete) interface. The details of the signalling protocol can be found in [29].

C. Multicast Rate Adaptation

In this section we illustrate how the *Transmission Policy* abstraction is used to implement *SDN@Play*. This algorithm has the goal of intelligently steering the data rate selection for multicast applications toward a more efficient operating point.

The idea behind *SDN@Play* is to use the link delivery statistics collected by the rate control algorithm implemented at the AP to dynamically adapt the MCS used for multicast transmissions in Legacy mode. However, as stated before, the rate control algorithm is used only for unicast transmissions. As a result, the link delivery statistics will be only computed if unicast traffic is transmitted between an AP and a client. In order to circumvent this issue, we introduce a two phases scheme, sketched in Fig. 2, which is marked by the alternation of two multicast policies defined in IEEE 802.11aa.

In the *first phase* the controller uses the *Transmission Policy* abstraction to set DMS as the multicast policy for a multicast address. We remind the reader that in DMS multicast transmissions are replaced by as many unicast transmissions as the number of receivers in a group[2]. This allows the rate control

[2]Notice that the creation and maintenance of the multicast group is out of the scope of this work.

TABLE I: *SDN@Play* Configuration Examples.

Destination	Type	MCS	RTS/CTS	No ACK	Multicast	UR Count
20:47:47:ac:61:5f	unicast	6, 9, 12, 18, 24, 36, 48, 54	2436	False	n.a.	n.a.
5c:e0:c5:ac:b4:a3	unicast	6, 9, 12, 18, 24, 36, 48, 54	2436	False	n.a.	n.a.
01:00:5e:b4:21:90	multicast	24	n.a.	n.a.	Legacy	n.a.
01:00:5e:40:a4:b4	multicast	n.a.	n.a.	n.a.	DMS	n.a.

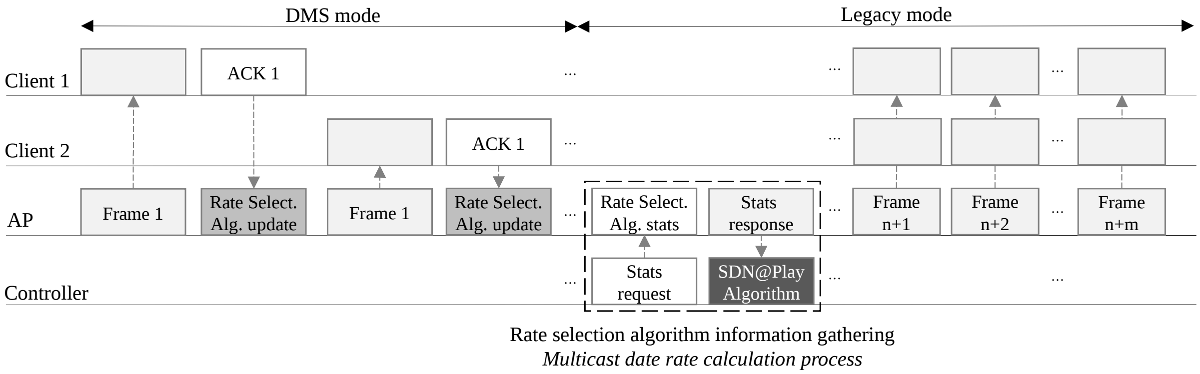


Fig. 2: *SDN@Play*'s two phases scheme. In the *first phase DMS* is used as multicast policy allowing the rate adaptation algorithm to gather link delivery statistics. In the *second phase* the multicast policy is switched to *Legacy* and the collected link delivery statistics are used to compute the optimal multicast MCS.

algorithm at the AP to gather the link delivery statistics for all the receivers (more information about the rate adaptation algorithm is provided in Sec. IV). In the *second phase* the controller uses the link delivery statistics collected during the *first phase* to calculate for each receiver the MCSes with the highest delivery probability. Based on this information, a worst receiver approach is used to compute the MCS currently used for the multicast group, as explained in more detail below.

Let M be the set of receivers in a multicast group, R the set of MCSes supported by the multicast receivers, and U the set of Wi–Fi APs. Moreover, let $P_r^{n,n'}$ be the delivery probability between AP $u \in U$ and receiver $n' \in M$ using MCS $r \in R$. On this basis, we can select the valid MCSes R^n_{valid} for each AP $n \in U$ as the set of MCS indexes with a delivery probability higher than a given threshold r_{th}:

$$R^n_{valid} = \bigcap_{n' \in M} \left\{ r \in R | P_r^{n,n'} > r_{th} \right\} \quad \forall n \in U \tag{1}$$

The multicast transmission rate R^n_{tx} is then given by:

$$R^n_{tx} = \begin{cases} max\left(R^n_{valid}\right) & if\ R^n_{val} \neq \emptyset \\ min\left(\bigcup_{n' \in M} \left\{ \underset{r \in R}{\text{argmax}}(P_r^{n'}) \right\} \right) & otherwise \end{cases} \quad \forall n \in U \tag{2}$$

The threshold r_{th} allows the programmer to set a relation between the reliability level and the channel occupancy ratio. It should be noted that, especially in poor channel conditions, lower rates may have also higher delivery probabilities given that, at a low rate, frames are more likely to be properly transmitted. As an example, let 50% and 95% be two possible values for the threshold r_{th}. The first example would enable the selection of the rates whose delivery probability could be as low as 50%, meaning that each frame will be transmitted on average twice. By contrast, since $1/0.95 \simeq 1$, each frame could be successfully transmitted at the first attempt. In this regard, the use of high values for r_{th} increases the reliability of the multicast transmission with the drawback of increasing also the amount of time the channel remains busy due to the utilization of less efficient MCSes. Hence, a tradeoff for this value must be selected according to the channel conditions. Considering the lack of retransmissions and ACKs in multicast communications, in this work all the measurements have been performed using 95% for the threshold r_{th}.

The two–phases process shown in Fig. 2 is repeated periodically with a configurable ratio between the DMS and Legacy periods. This allows the programmer to trade accuracy for airtime utilization. More specifically, increasing the portion of time of DMS leads to an improvement in terms of reliability at the expense of a higher channel utilization. Conversely, by increasing the fraction of time that Legacy is used, the airtime utilization is improved at the expense of a possible lower delivery ratio (especially if channel conditions are fluctuating). Furthermore, this approach ensures that the selected rate has a high delivery probability even for the receivers experiencing bad channel conditions. Notice that if for a receiver none of the MCS indexes has a delivery probability higher than the input threshold, our algorithm selects for each receiver the MCS index with the highest delivery probability, and from this set, it chooses the lowest MCS index. This is done in order to increase the probability of the transmission being properly decoded by all the receivers in the multicast group.

SDN@Play has been preliminary introduced in [11] for stationary multicast receivers. In the next subsection we describe how the multicast rate selection algorithm has been paired with a mobility management scheme in order to account also for mobile multicast receivers.

D. Mobility Management

SDN@Play Mobile aims at jointly improving client association and multicast rate selection while minimizing the network–wide channel occupancy. To this goal, the stations periodically report to the serving AP the list of neighboring APs together with the experienced channel quality[3]. This information is gathered using the *Beacon Reports* available in IEEE 802.11k [30] and included in the 2012 version of the IEEE 802.11 [31] standard. *Beacon Reports* enable an AP to request its stations to report the list of APs from which they can receive beacon frames on a specified channel or channels. Stations report the measurements obtained from the beacons and probe response frames using a *Beacon Report*. Finally, *Beacon Reports* are aggregated by the AP and reported back to the controller where they are used to build a network–wide downlink channel quality map.

Based on the information obtained from the *Beacon Reports*, *SDN@Play Mobile* periodically checks the channel quality between each multicast receiver and all its neighbouring APs (including the serving AP). If the signal strength between a multicast receiver and its serving AP is below a certain level for five consecutive checks *or* if another AP can provide a considerable channel quality improvement for five consecutive checks, then a handover is triggered. This is intended to reduce the ping–pong effect. It should be noted that these values can be freely set by the implementer based on the sensitivity of the devices or on the quality requirements of the application.

Let $S(n)$ be the set of receivers served by AP $n \in U$, with $S(n) \subset M$. Also, let $\rho^n_{n'}$ be the channel quality between the AP $n \in U$ and the multicast receiver $n' \in M$, *i.e.* the RSSI level of the receiver measured *at* the AP. When a handover process for a given receiver n' is triggered, we compute the average channel quality $\rho(n)$ and the standard deviation $\sigma(n)$ for all the APs in the network:

$$\rho(n) = \frac{\sum_{n' \in S(n)} \rho^n_{n'}}{|S(n)|} \tag{3}$$

$$\sigma(n) = \sqrt{\frac{1}{|S(n)|} \sum_{n' \in S(n)} (\rho^n_{n'} - \rho(n))^2} \tag{4}$$

Notice that, if an AP is not serving any receiver or it does not fall in the coverage area of the receiver n', then the two quantities above are undefined. Furthermore, it is important to highlight that, only in the case that the set of receivers attached to an AP is empty *and* the AP is within range of receiver n', the previous quantities will be set as $|S(n)| = 1$ and $\sigma(n) = 0$.

We then compute the list $\Omega(n')$ of candidate APs for the multicast receiver n'. Remember that the multicast rate of the receiver n' after the handover will be influenced by the channel quality of the receivers already served by the target AP. As a result, in order to ensure that we do not handover the receiver n' to an AP which is serving receivers with much worse channel conditions, we set a lower bound for the construction of the list of candidate APs $\Omega(n')$:

$$\Omega(n') = \{n \in U | \rho(n) - \sigma(n) \leq \rho^n_{n'}\} \tag{5}$$

Notice how this definition could result in an empty set in case that there are no APs within the range of n' that satisfy the channel quality condition. In this case, the channel quality constrain is removed and all the APs are taken into consideration. Using this method the set of candidate APs contains at least the AP that is currently serving the receiver n'.

Once this process is finished, the algorithm chooses the AP in $\Omega(n')$ that would allow the receiver n' to receive the multicast transmission using the most efficient MCS. For more information about how the handover is implemented we refer the reader to [10]. After performing the handover, the multicast transmission rate for all the APs in the network is recomputed. Then the controller can calculate the new network–wide channel occupancy. If as result of the handover the channel utilization has increased, the handover is reverted. If this occurs, and in order to avoid oscillations, the new AP is not considered as candidate AP for the receiver n' for the next 5 iterations of the algorithm.

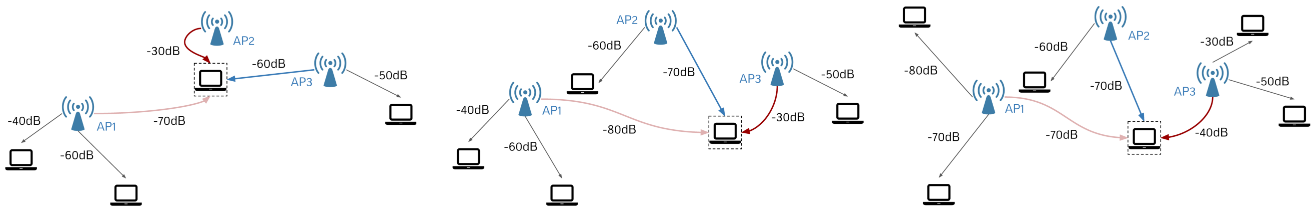
Figure 3 depicts a set of representative network configurations to show how the algorithm would select the best AP for a certain receiver (the dashed one). The link between this receiver and its serving AP is indicated by a blue arrow, while the ones between the remaining stations and their serving APs are represented by grey arrows. The arrows in dark red refer to stronger links with regard to the current one for the evaluated receiver, and which enabled the handover evaluation process. Finally, other equal or weaker links in terms of signal quality are presented by light red arrows. The numerical results derived from the quantities $\rho(n)$, $\sigma(n)$, and $\Omega(n')$ for the scenarios (a), (b) and (c) are reported in Table II.

Figure 3a shows a scenario with an idle AP (AP_2) and where the evaluated receiver is initially attached to AP_3. After computing the quantities mentioned before, the algorithm selects as candidates AP_2 and AP_3. AP_2 is selected as target AP for the handover since it provides the best channel quality. In the second example, shown in Fig. 3b, AP_1 does not meet the quality requirements, as a result, AP_3 is selected for the handover. Finally, a scenario where several stations are attached to the same AP is presented in Fig. 3c. Albeit all the APs qualify as candidates for the handover, AP_3 is selected for the association given that it provides the best channel quality.

IV. Implementation Details

To demonstrate the usefulness of *SDN@Play Mobile* in real–world environments, we have implemented it over the 5G–EmPOWER platform. In particular: (i) we extended the southbound interface allowing it to collect link delivery ratio statistics and *Beacon Reports*; (ii) we extended the data–path implementation to properly handle multicast frames; and (iii) we added support for the new *Transmission Policy* primitive in the 5G–EmPOWER Software Development Kit (SDK).

[3]Notice that, in this work we use the Received Signal Strength Indicator (RSSI) as an estimator of the channel quality. Nevertheless, other channel quality indicators, such as packet loss, could be also used.



(a) Best RSSI from an AP serving no receivers.

(b) Best RSSI from an AP serving a single receiver.

(c) At least two receivers are served by each AP.

Fig. 3: Examples of different network distributions for the selection of the candidates APs.

TABLE II: Numerical results of the different network distribution examples for the selection of the candidates APs.

		$\rho(n)$	$\sigma(n)$	**Interval**	**RSSI**	**Cand.**
Fig. 3a	AP1	-56.67	12.47	[-69.14, -44.20]	-70	No
	AP2	-30	-	[-30, -30]	-30	Yes
	AP3	-55	5	[-60, -50]	-60	Yes
Fig. 3b	AP1	-60	16.33	[76.33, -43.68]	-80	No
	AP2	-65	5	[-70, -60]	-70	Yes
	AP3	-40	10	[-50, -30]	-30	Yes
Fig. 3c	AP1	-73.33	4.70	[78.08, 68.63]	-70	Yes
	AP2	-65	5	[-70, -60]	-70	Yes
	AP3	-40	8.16	[-48.16, -31.84]	-40	Yes

A. Statistics Gathering

The 5G–EmPOWER platform provides a rich set of programming primitives exposed to the programmer trough a Python–based SDK. The list of primitives can be found in [8]. Primitives can operate in either *polling* or *trigger* mode. In the former mode (*polling*) the controller periodically polls the APs for specific information, *e.g.* the number of packets received by a client. In the latter mode (*trigger*) a thread is created at one or more APs and is identified by a firing condition, *e.g.* the RSSI of one client going below a certain threshold. When such condition is verified, a message is generated by the AP.

In this work we added support for a new *polling*–based primitive allowing the controller to access to the rate adaptation algorithm statistics for a given client. For each supported MCS, the Exponentially Weighted Moving Average (EWMA) of the frame delivery probability and the expected throughput in the last observation window are reported. Moreover, the total number of successful and failed transmissions in the last observation period are also reported. This primitive is used by *SDN@Play Mobile* to gather the link delivery statistics for all the wireless clients involved in multicast transmissions. We remind the reader that this information is maintained by the rate adaptation algorithm implemented by the AP. Therefore, no extra computation is added to the APs logic. More information on the particular rate adaptation algorithm used in our prototype is provided in the next subsection.

The IEEE 802.11k amendment introduces a set of mechanisms to collect WLAN radio measurements. The reports are presented as a request/response procedure in the form of action frames that allows to gather statistical reports from the stations. Whenever a station receives a *Beacon Request* from its serving AP, it must report the information contained in the beacon frames received from other APs of the network in its coverage area. In spite of the improvements, not many commercial devices apart from Apple's ones have support for such features [32]. Therefore, other options to obtain this same information must be explored. In this work, Scapy [33] is used to mock the behaviour of 802.11k. Scapy is a powerful packet manipulation tool whose main capabilities include packet generation and sniffing. Since it offers support for decoding a wide range of network protocols, it becomes a real alternative to gather statistical feedback similar to that offered by IEEE 802.11k. In particular, it makes possible to gather the information provided by a *Beacon Request* given that, among other information, the signal strength of the beacons frames of the neighbouring APs in the same network can be obtained.

B. Data–path Implementation

Each AP runs one Click modular router [34] instance implementing the 802.11 data–path. Click is a framework for writing multi–purpose packet processing engines and is used to implement just the wireless client/AP frame exchange, while all the network intelligence is implemented at the centralized controller. Communications between Click and the controller takes place over a persistent TCP connection (*i.e.* the 5G–EmPOWER southbound interface).

Rate adaptation is also implemented in Click using the Minstrel [35] algorithm (ported to C++ from its Linux Kernel implementation). Minstrel operations follow a multi–rate retry chain model in which four rate–count pairs, $r0/c0$, $r1/c1$, $r2/c2$ and $r3/c3$, are defined. Each pair specifies the rate at which a unicast frame shall be transmitted and a fixed number of retry attempts. Once the packet is successfully transmitted, the remainder of the retry chain is ignored. Otherwise, the AP will move to the next pair in the chain. When the last pair has been also tried, the frame is dropped. For each supported MCS, Minstrel tracks the link delivery ratio and the expected packet throughput given the probability of success. Statistics are recomputed every 500 ms. In particular, the rates with the highest throughput, second highest throughput, and highest delivery probability are maintained by Minstrel.

In order to adapt to changes in channel conditions, Minstrel spends part of its time in a so–called *look–around* mode. Specifically, 90% of the time, Minstrel configures the retry chain using the collected link delivery statistics. In the remaining 10% of the time it randomly tries other MCSes to gather statistics. Table III summarizes the criteria used by Minstrel to fill the retry chain in both normal and *look–around* mode.

TABLE III: Minstrel Retry Chain Configuration.

Rate	Look–around		Normal transmission
	Random < Best	Random > Best	
$r0$	Best rate	Random rate	Best rate
$r1$	Random rate	Best rate	Second best rate
$r2$	Best probability	Best probability	Best probability
$r3$	Base rate	Base rate	Base rate

We extended the Click data–path implementation in order to support generalized transmission policies for unicast, multicast, and broadcast addresses as opposed to the original transmission policies that could be specified only for unicast addresses. According to the new transmission policies, the rate adaptation algorithm (*i.e.* Minstrel) will use the first entry in the list of available MCSes if the multicast mode is set to Legacy. Conversely, if the multicast mode is set to DMS, the frame will be duplicated for each receiver in the group and will be fed back to the rate control algorithm which will then apply the unicast transmission policy associated to that receiver.

V. Performance Evaluation

The evaluation presented in this section has been carried out in a real scenario to compare *SDN@Play Mobile* with the multicast scheme defined in the 802.11 standard and with our previous work *SDN@Play*. In [11] *SDN@Play* is compared to the Legacy Multicast and the DMS policies defined in IEEE 802.11. Measurements demonstrate that *SDN@Play* can reduce the network–wide channel utilization by up to 80% while maintaining the required performance level. As opposed to the performance evaluation conducted in [11], in this work we leverage on a larger testbed and we introduce multicast receivers mobility. In this section we shall first describe the testing environment and the evaluation methodology. Then, we will discuss the outcomes of the measurements campaign.

A. Evaluation Methodology

The testbed used for our experimental evaluation is depicted in Fig. 4. The evaluation setup consists of four multicast receivers (MR_i), 3 APs (AP_j), a central controller (C), a video server (S), and an Ethernet switch (SW). The receiver MR_1 is a mobile station, while the remaining three are static.

The measurement campaign is executed over one floor of a typical office environment. During the measurements three receivers ($MR_{2,3,4}$) keep a fixed position, while one receiver (MR_1) moves along a 50 m long corridor. The receiver MR_1 is initially located in close proximity of AP_1 at one end of the corridor (see Fig. 4). Then, the receiver moves from its starting point to the other end of the corridor. The corridor is divided into 10 segments. At the end of each segment the receiver stops for 20 s. This results in an average speed of the mobile client of 0.5 m/s if the stops are not considered.

The scenario presented above is not restricted to office buildings. In fact, a similar video delivery use case applies also to other environments such as conferences, universities, or stadiums. Furthermore, it is important to emphasize that, in contrast to simulations where the mobility model of a station can be precisely controlled, real–world experiments present additional factors that are hard to control. In this regard, the mobility pattern of the receiver has been selected in such a way to improve the reproducibility of the experiments.

The APs are based on the PCEngines ALIX 2D (x86) boards and are equipped with a single Wi–Fi interface (Atheros AR9220 chipset). The AP runs the OpenWRT Operating System (15.05.01) and a Click instance implementing the 802.11 data–path. All experiments are carried out on the 5 GHz band (IEEE 802.11a). The devices running the controller and the multicast receivers are all laptops equipped with an Intel i7 CPU, 8GB of RAM, and running Ubuntu 16.04.1.

During the measurements, a video stream is generated by the video server S and delivered to a group of multicast receivers. The video stream consists of a five minutes sequence encoded using the High Efficiency Video Coding Standard (HEVC) [36] and transmitted using FFmpeg [37]. Two different compression schemes resulting in a final average bitrate of 1.2 Mb/s and 6.2 Mb/s are considered. In this way, it is possible to obtain detailed information regarding how different bitrates determine the performance of the network. Finally, it should be noted that the results presented in this evaluation are also valid for shorter or longer transmissions since the stream duration does not determine the behaviour of the system. Moreover, the resolution and video standard used to encode the sequence is just a way to set the transmission bitrate since other video configurations would only lead to different bitrates. The same applies to other parameters relative to the spatial and temporal aspects of the encoding.

The experiments conducted in this work aim at evaluating how user mobility and bitrate affect the system performance. Conversely, the scalability of SDN@Play was already studied in [11]. Although mobility was not accounted, the conclusions of the previous work are also applicable to the scenario presented in this paper, thus this aspect was left aside in the interest of clarity.

Three different multicast strategies have been considered in this study: *Legacy Multicast*, *SDN@Play*, and *SDN@Play Mobile*. As evaluation metrics we considered delivery ratio and wireless channel utilization. Notice that, since all the experiments are conducted with the wireless interfaces operating in 11a mode, the basic rate used for *Legacy Multicast* is 6 Mb/s. Moreover, in the case of *SDN@Play*, the algorithm has been configured to spend 500 ms in DMS mode and 2500 ms in Legacy mode. Between each measurement the rate adaptation statistics have been cleared. Apart from the multicast video stream, no downlink traffic exists between the APs and the multicast receivers. Consequently, the only opportunity for the Minstrel algorithm to be executed is during the DMS periods. Every measurement has been repeated 5 times to avoid possible fluctuations.

Based on the results obtained in previous experimental analyses we have observed severe performance degradation when the signal quality from an AP is below -75 dB. Similarly, we have noticed that an improvement of 20 dB in terms of signal quality can provide a significant boost in terms of both delivery ratio and channel utilization while at the same time avoiding ping–pong effects.

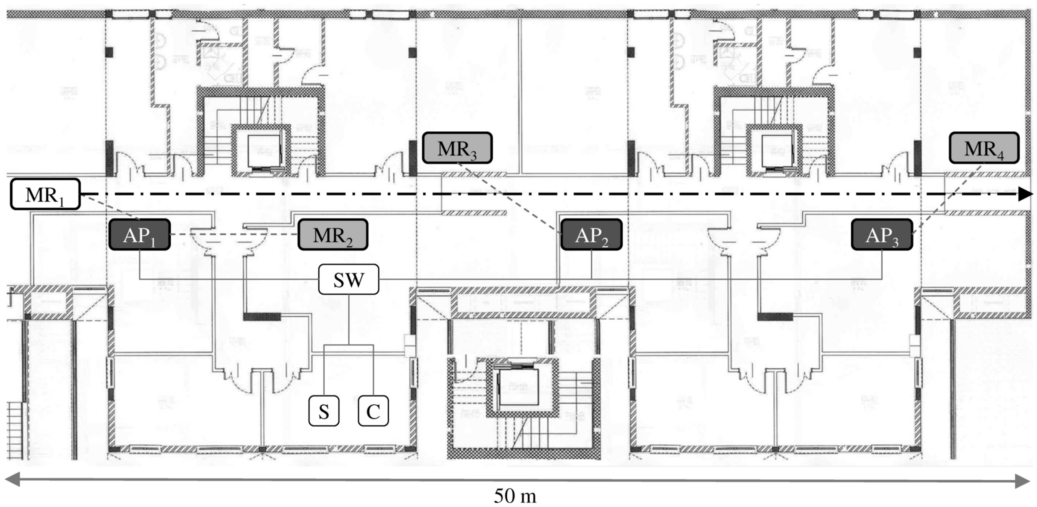


Fig. 4: Testbed deployment layout.

B. Experimental Results

Figure 5 plots the delivery ratio for each receiver using different multicast schemes. At 1.2 Mb/s the performance of the static receivers (MRs 2 to 4) is not affected by the particular multicast scheme. Conversely, *SDN@Play* and *SDN@Play Mobile* provide a significant performance boost to the mobile receiver (MR_1). This is because *Legacy Multicast* cannot adapt to the changing channel conditions experienced by the mobile receiver. Moreover, given the absence of ACKs and retransmissions, the mobile receiver suffers from heavy packet losses as it moves away from AP_1. *SDN@Play* performs better than *Legacy Multicast* since it can configure the multicast rate according to the channel status. Moreover, in DMS mode, *SDN@Play* can retransmit some of the lost frames. Nevertheless, *SDN@Play* does not provide mobility support and, as a result, the mobile station remains attached to the initial AP until the connection is lost and it is reassociated with another AP. By contrast, *SDN@Play Mobile* significantly enhances the performance of the mobile receiver. This is possible due to two main reasons. On the one hand, the algorithm selects the network configuration that minimizes the channel utilization. On the other hand, the receiver is always associated to the AP offering the best channel conditions among the APs that ensure high data rate and good transmission quality. As a consequence, these considerations result in a throughput improvement with regard to the other multicast schemes.

Figure 6 plots the delivery ratio for each multicast receiver using different multicast schemes for a video transmission at 6.2 Mb/s. As can be seen, in the case of *Legacy Multicast* using a video with a higher bitrate results in a sudden performance drop for all the multicast receivers (both static and mobile). The performance drop is particularly significant for the mobile station, which experiences a 70% frame loss ratio. Conversely, *SDN@Play* can improve the performance of the static receivers showing a delivery ratio as good as the one found for the 1.2 Mb/s video. Finally, *SDN@Play Mobile* can improve the delivery ratio of the mobile receiver by 180% bringing it at the same performance level achieved for the 1.2 Mb/s video.

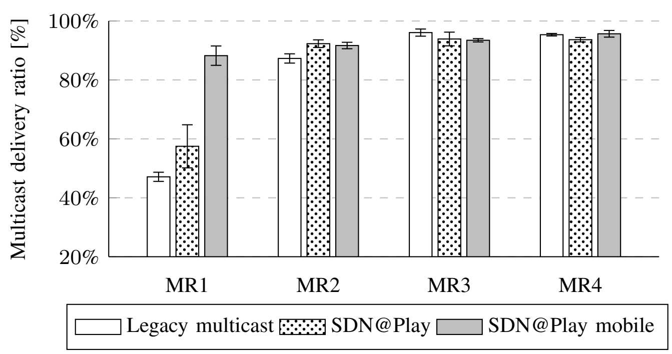


Fig. 5: Delivery ratio for the multicast video transmission at 1.2 Mb/s for each multicast receiver.

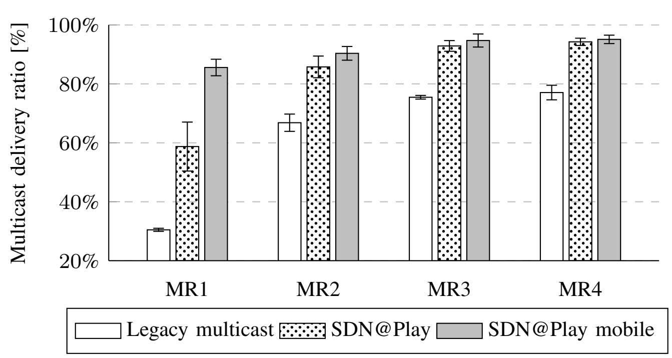


Fig. 6: Delivery ratio for the multicast video transmission at 6.2 Mb/s for each multicast receiver.

Furthermore, given that MR_2 is connected to the same AP than the mobile terminal, it is also worthy to note the performance improvement of *SDN@Play Mobile* with regard to *SDN@Play* for this station. As *SDN@Play* does not provide support for the mobility management and the mobile station keeps attached to the first AP until it losses the connection, it makes a greater number of frames be retransmitted due to the

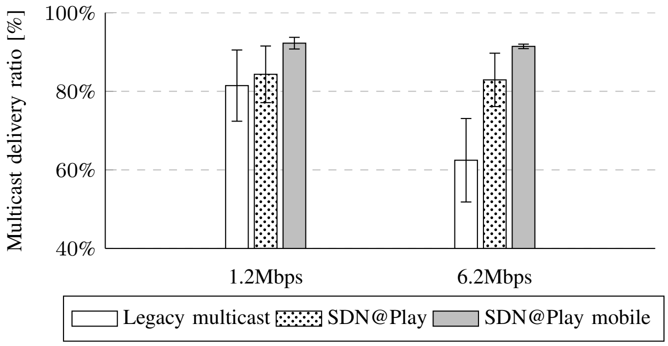


Fig. 7: Network–wide delivery ratio using different multicast schemes at different bitrates.

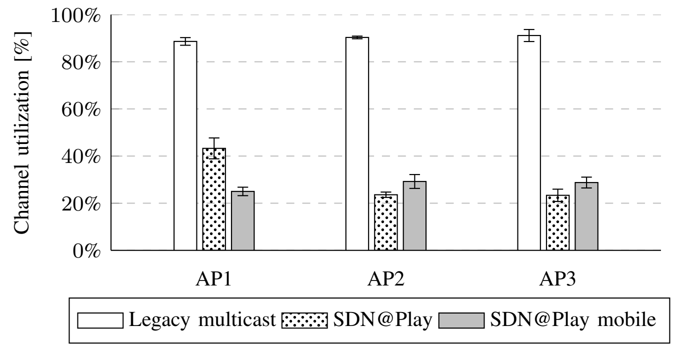


Fig. 9: Channel utilization per AP for the multicast video transmission at 6.2 Mbps.

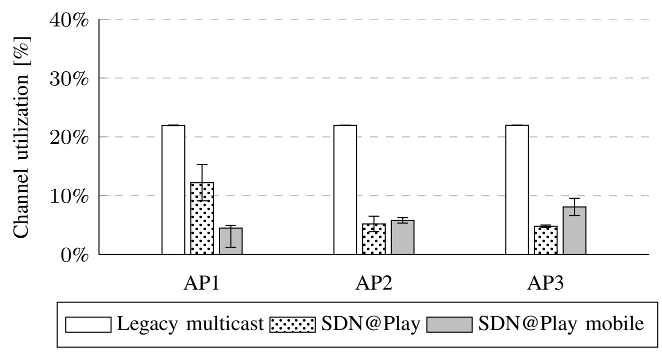


Fig. 8: Channel utilization per AP for the multicast video transmission at 1.2 Mb/s.

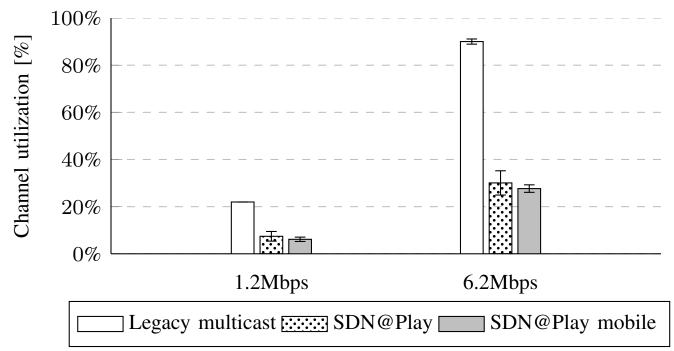


Fig. 10: Network–wide channel utilization using different multicast schemes at different bitrates.

increasing distance and interference. Performing the handover of the mobile receiver when it starts to experience performance drops allows *SDN@Play Mobile* to address this issue and not to impair the quality perceived by the receiver MR_2.

The same behavior can be seen in Fig. 7, which summarizes the average delivery ratio using different multicast schemes and bitrates. Due to the low performance achieved by *Legacy Multicast* and *SDN@Play* for mobile stations, the deviation shown is much higher than the *SDN@Play Mobile* one, which indicates that all the multicast receivers receive practically the same data, regardless of their position.

The fact that *Legacy Multicast* always uses the basic data rates results in a very high channel utilization. As can be seen in Fig. 8, this ratio for the 1.2 Mb/s stream is as high as 20%, while in the case of the 6.2 Mb/s stream (Fig. 9) the utilization reaches 90%, making the channel unavailable for other traffic. By using higher MCS indexes, *SDN@Play* can effectively reduce the channel utilization for both the static and the mobile receivers. This improvement is even more significant in the case of *SDN@Play Mobile*. As a matter of fact, in contrast to the previous case, *SDN@Play Mobile* can specifically address the needs of the mobile receiver by both reducing the channel utilization and balancing the workload across the entire network.

Figure 10 summarizes the network–wide channel utilization using different multicast schemes and bitrates. In this sense, it is shown that both the *SDN@Play* and the *SDN@Play Mobile* multicast schemes achieve a significant reduction in the global channel utilization with regard to *Legacy Multicast*.

Figure 11 plots the instantaneous channel utilization at AP_1 using different multicast schemes. As can be seen, in the case of *Legacy Multicast*, the channel utilization remains constant during the entire transmission. The utilization ratio of this scheme is in most cases higher than the one achieved by the other two multicast schemes. This is due to the fact that *Legacy Multicast* always uses the basic MCS (6 Mb/s in this case). Conversely, when the channel conditions allow it, *SDN@Play* can select higher MCS indexes which in time results in lower channel utilization. However, while the mobile receiver moves away from AP_1, *SDN@Play* is forced to use lower MCS indexes in order to provide the mobile receiver with the expected transmission quality. Eventually, this may lead to choose the basic MCS when the mobile receiver reaches the other end of the corridor. This problem is overcome by *SDN@Play Mobile*, which jointly improves the MCS selection and the receiver association. As can be observed in Fig 11, when *SDN@Play Mobile* is used, the channel utilization of AP_1 remains constant during the entire measurement. The same considerations apply to the scenario with the 6.2 Mb/s video stream (see Fig. 12). However, in this case, *SDN@Play* never reaches the channel utilization of *Legacy Multicast*. This is because the transmission at 6.2 Mb/s makes the channel be fully occupied when the *Legacy Multicast* scheme is used.

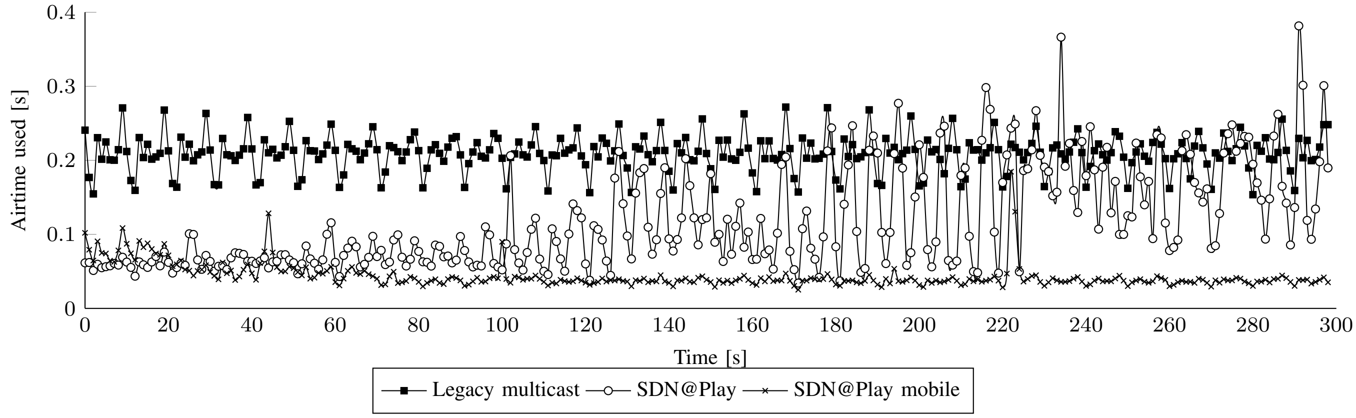


Fig. 11: Channel utilization over time of the AP1 for the multicast video transmission at 1.2 Mbps.

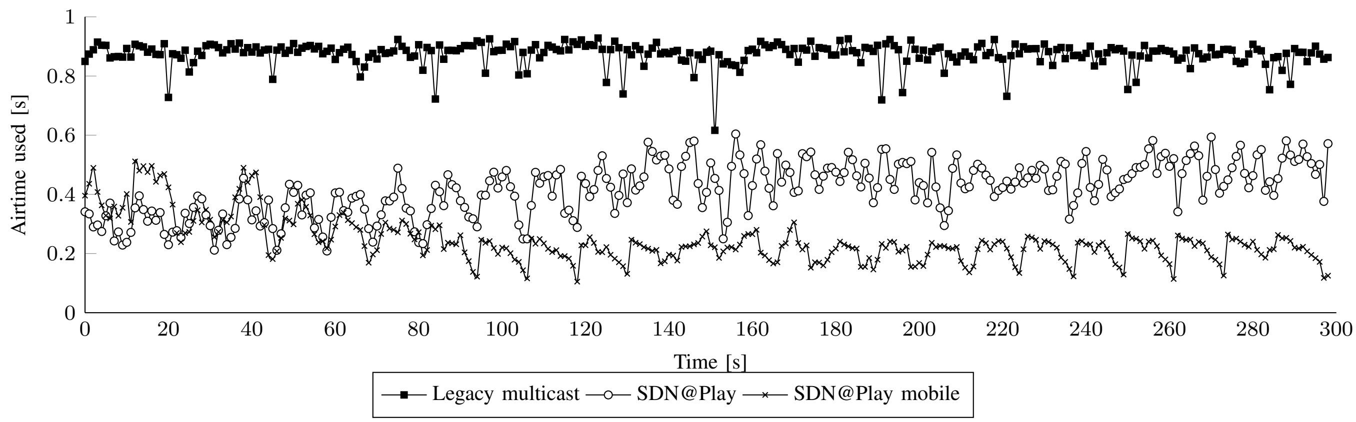


Fig. 12: Channel utilization over time of the AP1 for the multicast video transmission at 6.2 Mbps.

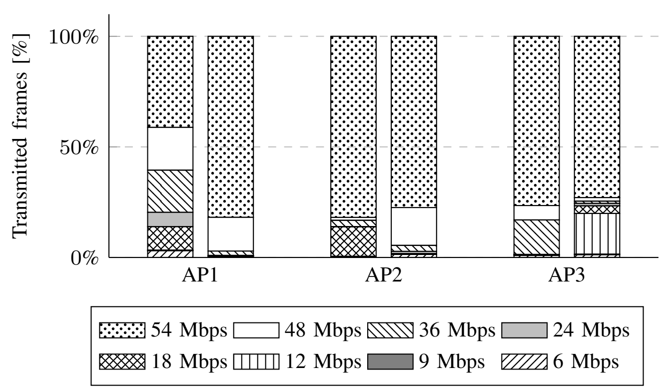


Fig. 13: Distribution of the rates used by *SDN@Play* and *SDN@Play Mobile* per each AP at 1.2 Mbps.

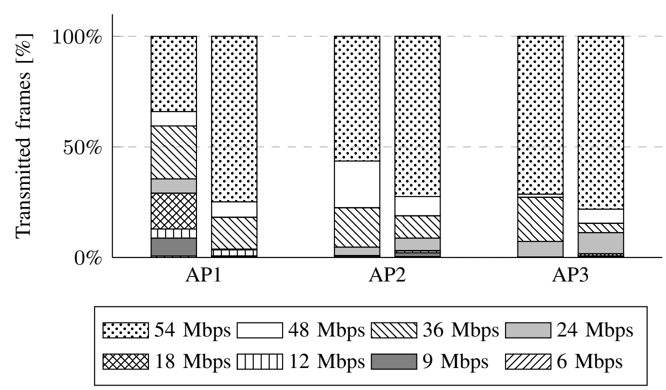


Fig. 14: Distribution of the rates used by *SDN@Play* and *SDN@Play Mobile* per each AP at 6.2 Mbps.

Finally, Figs. 13 and 14 report the distribution of the MCSes used by each AP at 1.2 Mb/s and 6.2 Mb/s, respectively. It should be noted that the *Legacy Multicast* scheme is omitted in this analysis because the lowest MCS index is always used. Although especially at high transmission bitrates *SDN@Play Mobile* selects high MCSes indexes for AP_2 and AP_3 for longer periods than *SDN@Play*, this ratio is considered to be small in comparison with the distribution obtained in AP_1. In this last case, it can be noticed how *SDN@Play Mobile* transmits 70$\%$ of the data at the highest MCS (54 Mb/s). This is due to the fact that *SDN@Play Mobile* is able to properly handover the clients to the AP that provides the highest network performance. On the contrary, this value is approximately the half for *SDN@Play* due to the distance of the mobile station from the AP that it is connected to.

VI. Conclusions

In this paper we have presented a novel multicast rate adaptation and mobility management scheme for 802.11–based WLANs. The proposed scheme uses an SDN approach where the global network view available at a logical centralized controller is exploited in order to coordinate the operations of different APs. The scheme, named *SDN@Play Mobile*, jointly optimizes the multicast rate selection *and* the multicast receivers association with the goal of reducing network–wide radio resource utilization while maintaining the expected transmission quality. *SDN@Play Mobile* has been implemented and evaluated over a real–word testbed using the 5G–EmPOWER platform. Experimental measurements show that *SDN@Play Mobile* can deliver a significant improvement in terms of channel utilization compared to the legacy multicast scheme while maintaining full backward compatibility with the 802.11 standard.

As future work we plan to extend *SDN@Play Mobile* to account for multiple multicast groups. Furthermore, we plan to study the behaviour of the system under different situations. This includes analysing the impact of using different values for the delivery probability threshold r_{th} in the MCS selection as well as studying the impact of the other parameters of the algorithm on the network–wide delivery ratio and channel utilization. Finally, we intend to assess the behaviour of *SDN@Play Mobile* under different user mobility models.

Acknowledgment

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