

# Coexistence Issues in Future Wi-Fi Networks

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**Abstract.** Current advancements within the Wi-Fi domain, such as network densification, traffic offloading, and IoT support, pave the way for increased user and operator satisfaction with future (5G and beyond) network deployments. However, without seamless coexistence of novel and legacy Wi-Fi devices as well as between heterogeneous Wi-Fi networks, the goal of ubiquitous and effortless wireless access may be delayed. In this paper, we identify several future Wi-Fi use cases based on current trends in the research community as well as developments within IEEE 802.11 and analyze the functionalities required in these use cases taking into consideration two important aspects: coexistence between new and legacy Wi-Fi devices as well as inter-network interference. Through our research we show that, despite several identified shortcomings and open issues, Wi-Fi will definitely be a crucial component of future network deployments.

**Keywords.** Coexistence, interference, scalability, very high throughput, Wi-Fi

## 1 Introduction

Wi-Fi is one of the main wireless access network technologies having achieved widespread adoption through operation in unlicensed bands and low device cost. It is a rapidly evolving technology with 1-2 amendments to the 802.11 standard published annually. This evolution is driven by increased traffic demands: according to Cisco's Visual Networking Index it is expected that there will be over 11.6 billion mobile devices producing and consuming a total of 30.6 exabytes of monthly traffic by 2020.

A key feature of Wi-Fi, permeating all its functionalities, is its reliance on operating in unlicensed network bands. Therefore, with the congestion of the 2.4 GHz and 5 GHz bands, 802.11 is currently expanding to other bands: sub 1 GHz for Internet of Things (IoT) applications and 60 GHz for line-of-sight device-to-device (D2D) connectivity. Additionally, with existing technologies already close to the theoretical limits of spectrum utilization [1] the concept of network densification is emerging as a possible solution. Furthermore, such problems as insufficient backhaul throughput (Section 2.3), strong requirement of cellular traffic offloading (Section 2.4), and lack of support for IoT applications (Section 2.5) are being considered by the 802.11 working group. All these developments lead to new Wi-Fi use cases (Section 2) supported by novel Wi-Fi functionalities (Section 3). However, they all raise the fundamental issue of coexistence.

We define coexistence as either the ability of new and legacy devices to cooperate (*device coexistence*) or the ability of different networks to share the same spectrum (*network coexistence*). The former is related to the increasing number of 802.11 amendments, which define different physical (PHY) and medium access control (MAC) layer enhancements. The coexistence of heterogeneous devices implementing these amendments may lead towards suboptimal network operation due to necessary

backward compatibility (Section 4.2). The latter is related to the observed densification of wireless networks and the increased number of wireless technologies operating in the unlicensed spectrum (e.g., ZigBee), which increases the probability of inter-network interference and collisions among frames transmitted by contending devices leading to inefficient spectrum utilization (Section 4.3). Our studies show that in the case of both d2d and network coexistence there exist open research areas (Section 5).

## 2 Future Wi-Fi Use Cases

Based on current research trends [1] and developments within IEEE 802.11 [2], several future Wi-Fi use cases can be identified (Fig. 1). These include a high throughput wireless local area network (WLAN) in the form of a *gigabit Ethernet replacement*, *improved capacity WLAN* based on multi-user multiple-input and multiple-output (MU-MIMO) transmissions, using *Wi-Fi as a backhaul*, providing *traffic offloading*, and *supporting IoT applications*.

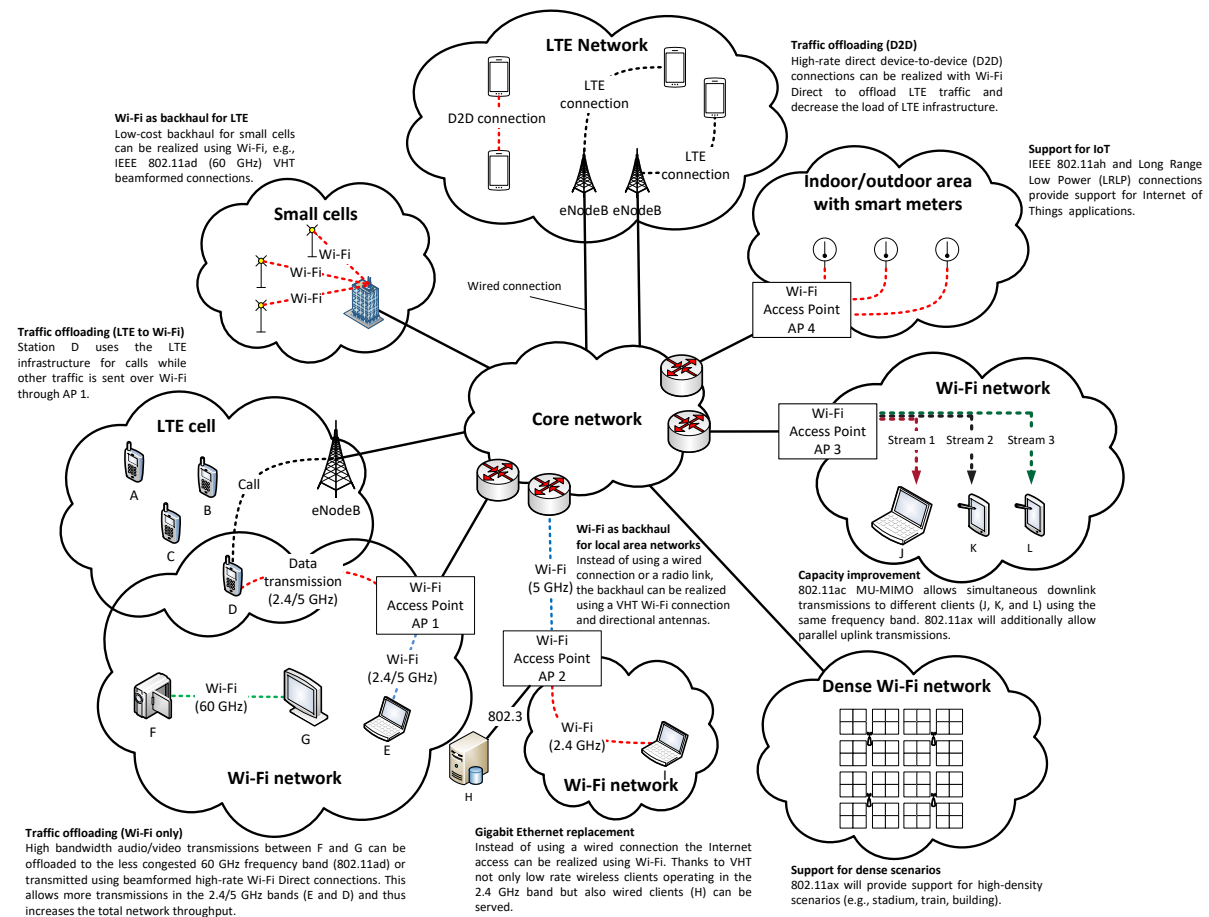


Fig. 1. Possible Wi-Fi use cases in future network deployments

### 2.1 Gigabit Ethernet Replacement

The most straightforward advantage of the latest gigabit Wi-Fi amendments (802.11ac/ad/ax, Section 3.1) is the possibility to replace traditional gigabit Ethernet connections (e.g., server H in Fig. 1) with wireless links. With these amendments it is possible to serve either more stations with the same throughput as before or the same number of stations with improved throughput. The former advantage is especially important from the perspective of dense access networks and the latter – from

the perspective of backhaul links supporting these networks (Section 2.3).

## 2.2 Capacity Improvement with MU-MIMO Transmissions

IEEE 802.11 access points (APs) typically have more antennas than mobile stations. Therefore, 802.11ac introduced downlink MU-MIMO, which allows a single AP to transmit parallel beamformed streams to different stations<sup>1</sup> (J, K, and L in Fig. 1) on the same frequency. Beamforming, previously used in single-user (SU) systems to achieve higher data rates, can now be used to increase the overall Wi-Fi network capacity. As a result, stations equipped with a smaller number of antennas do not degrade network performance by occupying the wireless channel with their lower data rates. Additionally, since MU transmissions are realized in parallel and possibly with different data rates, the distance from the AP is less important than in traditional SU systems in which faraway stations (using low rates) could severely impact the performance of others by delaying their transmissions.

## 2.3 Wi-Fi as Backhaul

With the latest amendments supporting very high throughput (VHT), using Wi-Fi links to provide backhaul connectivity is becoming an alternative for wired connections, especially when deploying wired infrastructure is problematic or economically unjustified [3]. Providing a backhaul (or transit<sup>2</sup>) connection for a Wi-Fi AP (AP 2 in Fig. 1) is certainly the most straightforward application of this concept. However, an emerging idea is to use low cost unlicensed point-to-point 60 GHz backhaul links (IEEE 802.11ad) for small cells to reduce the backhaul cost<sup>3</sup> (cf. the small cells in Fig. 1).

Operating in an unlicensed spectrum is subject to interference from other networks or non-Wi-Fi devices. However, since backhaul links are fixed point-to-point connections interference can be avoided by using highly directional antennas. With the development of MIMO arrays of directional antennas [4] point-to-point links could profit from 802.11ac MIMO transmissions but strict regulatory restrictions limit the transmit power of multiple transmitters so that range extensions will be limited. These restrictions are less severe for single radio transmitters in point-to-point links but using only one spatial stream detracts from the maximum transmission speed.

## 2.4 Traffic Offloading

Offloading traffic from 3G/4G to other radio networks can bring a significant reduction in operating costs for mobile network operators (MNOs). Since traffic growth will most likely exceed the development capabilities of mobile networks, MNOs are looking to move a fraction of their traffic to other technologies. Additionally, since 60-80% of mobile data traffic comes from indoor or stationary locations, the requirements of MNOs are met by Wi-Fi. The interoperation of mobile networks with local Wi-Fi hotspots may considerably decrease the operator's cost of transmitting a single bit per second while providing better energy efficiency (e.g., separate data flows can be transmitted over different access technologies: station D in Fig. 1). Another possibility is to use D2D communication (realized, e.g., using Wi-Fi Direct high-speed connections) to decrease the load of eNodeBs in Long-Term Evolution (LTE) networks to avoid unnecessary capital and operational expenditure [5].

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<sup>1</sup> Up to four downlink connections at a time, four spatial streams per user, and a total of eight spatial streams are allowed by the standard. In the uplink direction, stations currently transmit to the AP sequentially. However, *uplink* MU-MIMO transmissions are under development in 802.11ax.

<sup>2</sup> IEEE 802.11ak will enhance of the ability of 802.11 to provide internal transit links within 802.11q bridged networks.

<sup>3</sup> <http://www.bluwirelesstechnology.com/>

A different perspective for traffic offloading is within a Wi-Fi-only environment. With 802.11ad (operating in the 60 GHz band) it becomes possible to offload traffic from the crowded 2.4/5 GHz bands (stations F and G in Fig. 1). Additionally, due to the limited range of 60 GHz transmissions (typically within a single room), mutual interference can easily be avoided and the overall capacity offered within a single building can become comparable to the capacity currently offered by wired-only connections. Analyzing this scenario from another perspective, the 2.4/5 GHz connections can be treated as inter-room backhaul and the 60 GHz links as ultra-fast connections.

## 2.5 Support for IoT

IoT and machine to machine (M2M) communication provides new market opportunities. Over the years different protocols have been proposed for IoT (e.g., ZigBee, Bluetooth, 6LoWPAN, and proprietary solutions) because Wi-Fi was not designed to meet IoT requirements. However, in 2010 TGah started working on adapting 802.11 to IoT (by targeting the sub 1 GHz band) and in 2015 IEEE started a discussion on the need of new long range low power (LRLP) band-agnostic enhancements for IoT. Therefore, future Wi-Fi will become an alternative (cf. the network connected to AP 4 in Fig. 1) to the currently available technologies operating in unlicensed frequency bands with a range advantage (about one kilometer).

## 3 New Wi-Fi Functionalities

To meet the requirements of future use cases (Section 2), Wi-Fi is evolving to support a number of new functionalities: high throughput with QoS support, efficient spectrum usage and network management, energy efficiency, and flexibility of implementation. This evolution is mainly based on new 802.11 amendments and new Wi-Fi Alliance technologies (Table 1). In the following, we briefly describe new Wi-Fi functionalities and assess their impact on device and network coexistence.

**Table 1. Relationship between the new Wi-Fi use cases, related problems, amendments to IEEE 802.11 or Wi-Fi Alliance technologies, the provided functionalities, and relevant coexistence types. Upcoming amendments are in italics; amendments incorporated into IEEE 802.11-2012 are underlined. For completeness, we also include amendments not explicitly mentioned in this paper.**

Identified use cases	Generalized network problem	Amendment	Amendment-provided functionalities	Coexistence type
Gigabit Ethernet replacement	Limited throughput	<u>802.11n</u> , 802.11ac, 802.11ad, <i>802.11ax</i>	Improved network efficiency. Tradeoff between per user data rate and system capacity (i.e., the number of served users). Support for emerging high-bandwidth applications.	Network
System capacity improvement	Single-user transmissions and handheld stations with limited number of omnidirectional antennas	802.11ac, <i>802.11ax</i>	Beamforming which enables parallel multi-user transmissions with optional QoS support.	Device and network
Wi-Fi as backhaul	Difficulty deploying wired	802.11ac, 802.11ad,	Support for VHT, directional antennas, and beamformed	<b>Small cells:</b> Network

	backhaul connections to APs. Requirement for low cost backhaul with VHT in case of LTE small cells.	802.11ah, 802.11ax	transmissions. Low cost, high throughput backhaul for LTE small cells.	<b>Cable replacement:</b> Network
Traffic offloading (mobile to Wi-Fi)	Mobile traffic growth	802.11u, 802.11ad, 802.11ai, 802.11aq, Wi-Fi Direct, Wi-Fi Aware	Network discovery and selection based on offered services and access conditions; faster link setup, reduced airtime required for a transmission.	<b>LTE to D2D:</b> Network  <b>LTE to Wi-Fi:</b> Network
Traffic offloading (Wi-Fi to Wi-Fi)	Congested Wi-Fi spectrum and close proximity of Wi-Fi deployments	802.11ac, 802.11ad, 802.11af, 802.11ah, 802.11aj, 802.11ax, Wi-Fi Direct, Wi-Fi Aware	Decreased interference between networks by moving to new (less occupied) frequency bands (sub 1 GHz, 45 GHz, 60 GHz, TV white space) and better use of existing frequency bands (2.4/5 GHz).	Network (if out of 60 GHz range)
Support for IoT applications	Current Wi-Fi does not support IoT applications	802.11ah, Low Power Long Range, Wi-Fi Direct, Wi-Fi Aware	Long-range low-power connectivity assures support for IoT and M2M applications. Real-time and energy-efficient discovery mechanisms are required to improve user experience.	Network (with Zigbee, in USA, and Z-Wave)
Support for dense scenarios	Problems with increased probability of collisions and higher interferences	802.11ax	Solutions to increase area throughput and energy efficiency (under development).	Device and network

### 3.1 High Throughput and Efficiency

Recent standardization efforts, collectively referred to as VHT, have been focused on increasing the throughput of Wi-Fi devices [2]. They have led to the recently published 802.11ac and 802.11ad amendments. The former is intended for the 5 GHz band and it builds on the most attractive features of 802.11n. The latter is intended for the 60 GHz band, which allows only line-of-sight communication but has not yet been used in Wi-Fi. In both amendments, VHT of up to 7 Gb/s has been achieved<sup>4</sup> and is supported by the following PHY enhancements: high-density modulation (256 QAM for 802.11ac and 64 QAM for 802.11ad), increased channel bandwidth (up to 160 MHz for 802.11ac and 2.16 GHz for 802.11ad), and advanced transmission techniques (including downlink MU-MIMO for 802.11ac and beamforming for 802.11ac/ad). The PHY enhancements are supported by changes at the MAC layer.

<sup>4</sup> In contrast to Ethernet connections, the effective throughput of Wi-Fi connections is much lower than the peak throughput due to a large transmission overhead. Additionally, the Wi-Fi transmission overhead increases with the network density.

Some, such as clear channel assessment on secondary channels and use of request-to-send/clear-to-send (RTS/CTS) for bandwidth selection, are necessary to support new PHY functionalities. Others, such as enabling large data frame sizes, decrease the medium access overhead and thus increase user throughput.

Furthermore, TGax was formed in 2014 in response to the emergence of dense Wi-Fi deployments. Its main goal is to extend existing 802.11 functionalities and provide new solutions to improve efficiency as measured by area throughput and average per-station throughput. TGax focuses on ultra-dense network environments (such as corporate offices and stadium deployments) and hopes to leverage such promising technologies as uplink MU-MIMO, orthogonal frequency-division multiple access, and adaptive channel sensing.

Moving towards highly efficient VHT Wi-Fi is challenging since, in order to provide efficient medium access in future network deployments, the coexistence of new and legacy devices (both stations and APs, cf. Section 4.2) as well as improved inter-network interference avoidance (Section 4.3) are required. Full backward compatibility may decrease both network performance (e.g., the mandatory low data rate transmission of the 802.11 frame preamble and header) as well as fairness in channel occupancy (low rate frames take longer to transmit). Additionally, interference may occur not only between networks operating on overlapping channels but also on disjoint ones (Section 4.3) since in future dense deployments there will be, e.g., one user per square meter and an AP every 10 meters. This can be even more problematic if channels wider than 20 MHz are used.

## 3.2 Network Management

The densification of Wi-Fi networks necessitates more advanced network management, e.g., to coordinate the operation of neighboring networks, both in the spatial and frequency domains. This is especially true for the new amendments which increase channel bandwidth. 802.11n allows 20/40 MHz channels while 802.11ac allows 20/40/80/160 MHz channels. Optimal frequency usage requires context-aware channel selection, since interference occurs both on overlapping and disjoint channels (Section 4).

Short-term network coexistence (in the timescale of individual data frames) is achieved by using RTS/CTS frames to reserve the widest channel possible. Long-term coexistence requires network-wide management optimization. Among the standardization efforts in this domain is 802.11aa with its overlapping basic service set (OBSS) management functionality, designed to coordinate the operation of Wi-Fi networks and mitigate the neighbor capture effect<sup>5</sup>. Briefly, it allows quantifying the load and interference status of each network, signal this information among neighboring networks, and perform channel selection and cooperative resource sharing [6]. While OBSS management was designed for networks operating on the same channel, our studies show that an extension of this functionality is required due to the possibility of significant interference between networks operating on disjoint frequency channels (Section 4.3).

Future Wi-Fi networks should also exhibit a degree of autonomy in terms of both long-term (frequency band, bandwidth, channel selection) and short-term (data rate) configuration. The development of such algorithms is usually beyond the scope of the 802.11 standard. However, ETSI is in the process of standardizing a generic autonomic network architecture (GANA) which supports self-\* functionalities (i.e., self-healing, self-configuration, self-optimization, and self-configuration) in any network type [7]. GANA unifies the concepts of autonomic networking, cognitive networking, and self-

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<sup>5</sup> The neighbor capture effect occurs when a network is located between two other networks which do not sense each other. If the outer networks are under heavy traffic load, the middle network senses the medium permanently busy and is thus prevented from accessing the channel.

management within a single holistic architectural reference model and can be applied to any network architecture including Wi-Fi. These emerging autonomic solutions will be able to relieve network administrators from various management tasks including assuring network coexistence.

Complementarily to the above, there is a need for a well-standardized management interface of 802.11. Emerging efforts, labelled "802.11 as a Component", are targeted towards the definition of such an interface for flexible management and control of Wi-Fi networks, e.g., to minimize inter- and intra-network interference. With a standardized control interface, Wi-Fi could become a component (with Wi-Fi implementation as a "plug-in") of 5G converged networks, accessible to network operators.

Additionally, due to the scarcity of the available radio spectrum, the Third Generation Partnership Project (3GPP) considers scenarios for the deployment of LTE small cells in the unlicensed ISM band. However, LTE may severely impact Wi-Fi transmissions since the former's channel access mechanisms have not been designed to provide fair competition for resources with other technologies in a shared band [8]. As a result, LTE tends to take over the resources from Wi-Fi. Therefore, joint deployment of LTE and Wi-Fi in the same unlicensed band requires defining new rules (e.g., flexible spectrum access, channel selection, blank subframes, and transmit power control) for collaborative radio resource management [8].

### **3.3 Energy Efficiency**

Increased energy consumption is one of the key challenges for future network deployments. Analysis of raw numbers can lead to the conclusion that 802.11ac doubles the efficiency of 802.11n as measured in bits per microjoule [9]. In reality this gain is not so evident, because energy consumption depends on many factors. Thus, the utilization of a wider channel width with a lower modulation and coding scheme (MCS) can be less energy efficient than using a higher MCS and a smaller channel width, achieving the same overall throughput performance. A thorough analysis of the dependency between channel width, adaptation of transmission rate, and spatial stream usage is shown in [10]. The overall conclusion is that decreasing power consumption should be achieved by three setup rules: a smaller than the maximum channel width allocation, data rate adaptation, and increasing the number of parallel spatial streams. These rules have a common goal which is achieving a comparable throughput rate to setups with wider channel allocations but with lower energy efficiency. A further decrease in energy usage may be expected from employing more intelligent power-saving methods in the future.

Minimizing energy consumption is also one of the goals of 802.11ah and LRLP (Section 2.5), both targeted towards M2M networks, as well as that of TGax, where it is one of the key metrics for dense deployment scenarios. The capability to handle multiple simultaneous transmissions in spatial and frequency domains as well as in the uplink and the downlink directions requires decreasing the level of interference through limitation of transmission power at the APs and stations. The realization of reliable transmission is achieved with the use of additional mechanisms, e.g., beamforming or adaptive clear channel assessment.

### **3.4 Network Flexibility**

#### **3.4.1 Software-Defined Networking**

Another desirable feature of future Wi-Fi networks is that of flexibility and adaptability. This can be achieved through the recent paradigm shift towards software-defined networking (SDN). The SDN approach is applicable to network-wide optimization as exemplified by the CROWD project [1], which uses it to address emerging issues in both high density access networks (with heterogeneous radio

technologies) and their integrated backhaul networks. Additionally, SDN can be used to optimize each individual Wi-Fi network in a dense environment, e.g., to allow the AP to fully control the individual medium access method used by each station in its network and dynamically adapt the behavior according to context [11]. Furthermore, novel centralized, OpenFlow-based SDN architectures for Wi-Fi appear in the literature [12]. All these SDN solutions are complementary and have the potential for supporting Wi-Fi in future network deployments. They can facilitate the deployment of new protocols and mechanisms, e.g., to provide the flexibility required to support autonomic solutions, support energy saving, as well as facilitate management (e.g., to avoid inter-network interference).

### 3.4.2 Virtualization

Network virtualization enables decoupling service provisioning from the underlying infrastructure. This ties to the concept of dense wireless access networks, where the existing infrastructure usually belongs to separate operators. A service provider may wish to provide a seamless experience for mobile users roaming within the range of these distinct networks. Using virtualization mechanisms, the service provider can receive dedicated resources while being unaware of the underlying infrastructure. Additionally, by having a single infrastructure for different service providers provides a new way of mitigating inter-network interference. In the Wi-Fi domain, virtualization has thus far been implemented mainly at the interface level, allowing one AP to control multiple networks [13]. However, solutions are emerging which consider the virtualization of resources in Wi-Fi backhaul networks [14]. This paves the way for new business scenarios which take advantage of the intrinsic characteristics of dense networks.

## 4 Experimental Results on Device and Network Coexistence

While a basic performance study of 802.11ac networks can be found in [15], we attempt to analyze the performance of Wi-Fi networks from two different perspectives: (1) coexistence between heterogeneous (new and legacy) Wi-Fi devices (both stations and APs) and (2) inter-network interference (including old and new amendments). Both perspectives, as highlighted in Section 3, are crucial in the transition phase towards VHT deployments as well as for newly envisioned Wi-Fi applications described in Section 2.

### 4.1 Testbed Settings

We used commercially available 802.11a/n/ac devices (APs and stations). The 802.11ac devices were equipped with a Broadcom BCM4360 dual-band AC chipset which supports up to three spatial streams and 20/40/80 MHz channels. To test the interoperability between 802.11ac and legacy devices we additionally used 802.11a/n APs and stations equipped with Atheros AR9580 chipsets which support up to three spatial streams and 20/40 MHz channels. With a single station attached to an AP, the maximum throughput achieved for TCP downlink connections at the network layer was about 700 Mb/s for 802.11ac (80 MHz channel), 300 Mb/s for 802.11n (40 MHz channel) and 25 Mb/s for 802.11a (20 MHz channel).

Measurements were performed using the *iperf* network testing tool. The presented results are the average maximum throughput values of downlink TCP connections<sup>6</sup>. Error bars are included in the figures; they represent 95% confidence intervals. The tests were performed in two locations: room A

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<sup>6</sup> Tests were also performed for UDP flows but no qualitative differences were found.



(2.5 x 5 m; all devices in proximity of 1 m) and room B (7 x 15 m; APs placed in the corners of the room with stations placed 0.5 m from their APs; 802.11ac APs were placed diagonally across the room). No other devices operating in the 5 GHz band were observed within the building.

In most configurations each AP served only a single station. This was intended to analyze the best case scenario, i.e., the case when multiple Wi-Fi networks are deployed in the same area. An example of such a scenario is a building floor in which each end user connects to its own AP but the maximum Wi-Fi throughput is limited due to interference coming from neighboring devices. If more stations were served by each AP or more networks were present in the same area, the results would be worse due to higher overhead and increased interference, however, the general conclusions would remain valid.

## 4.2 Device Coexistence

Coexistence issues between new and legacy Wi-Fi devices always emerge when novel 802.11 amendments are brought to the market. Additionally, within dense deployments, configuration of numerous networks to operate on non-overlapping channels becomes challenging, especially when wide spectrum is exploited to achieve high throughput provided by the recent amendments. Therefore, we focus on scenarios when only overlapping channels are available. We demonstrate that the answer to the question of whether new 802.11ac APs should be added to existing infrastructure or legacy APs (802.11a/n) should be replaced altogether is rather complex.

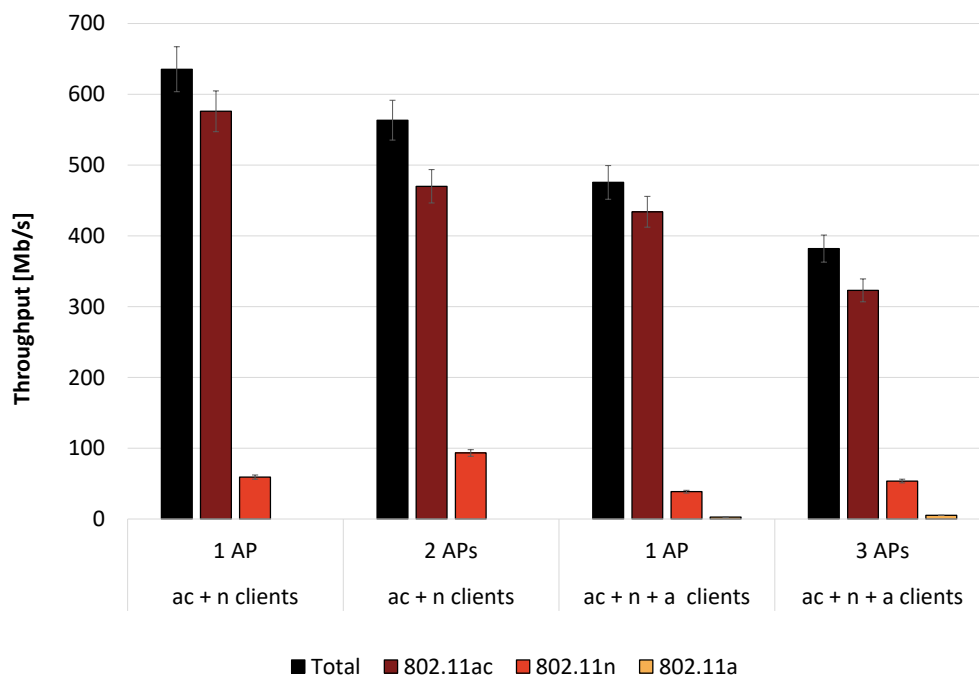


Fig. 2. Per-station downlink throughput in configurations with one, two, and three APs. Each configuration includes an 802.11ac AP and, in configurations with two or three APs, additional 802.11a and/or 802.11n APs. Each AP was set to use the maximum channel width (20, 40, and 80 MHz, respectively) and the same primary channel. Tests were performed in room A.

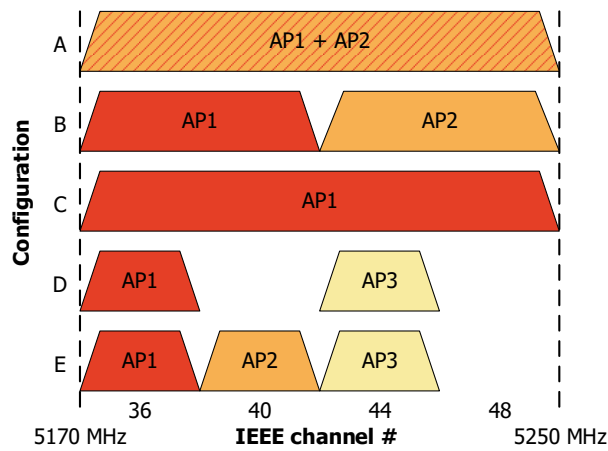
In our tests (Fig. 2) we evaluated the performance of a scenario with heterogeneous Wi-Fi devices. Standard off-the-shelf devices with default settings were used. We compared the performance of a single 802.11ac AP serving two or three different stations (802.11n/ac or 802.11a/n/ac) with the performance of two APs (802.11n and 802.11ac) and three APs (802.11a, 802.11n, and 802.11ac), each

serving one station of the same type. In the former case, connecting non-802.11ac stations to the AP substantially decreased the overall network throughput (the older the standard, the higher the observed degradation). This is due to the well-known performance anomaly phenomenon. In the latter case, the overall performance, measured as the sum of throughput achieved by each standard was worse, however, legacy networks (802.11a, 802.11n) achieved slightly higher throughput. Despite the interference between devices, the throughput offered by the 802.11ac AP was, in the case of 802.11n and 802.11ac stations, greater than 300 Mb/s, which is suitable for serving high bandwidth consuming applications. These results (for one associated station per AP) present an upper bound on the achievable throughput and extend to cases with more networks (as verified by our simulations, not presented here). Finally, we conclude that even though full backward compatibility decreases overall network performance, it does not eliminate legacy equipment and allows slower equipment replacement.

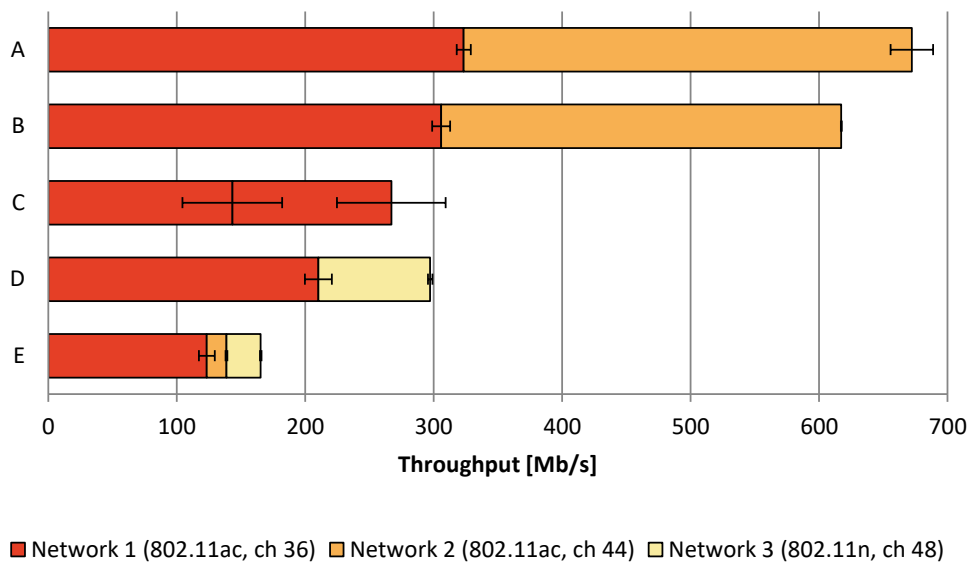
### 4.3 Network Coexistence

Wi-Fi deployments suffer from inter-network interference because they operate in a limited frequency domain. We demonstrate how heterogeneous networks (operating with different channel settings, implementing different 802.11 amendments) can negatively impact each other. These tests were performed in room B. The following five configurations were studied (Fig. 3a):

- Configuration A: two 802.11ac networks share an overlapping 80 MHz channel,
- Configuration B: two 802.11ac networks configured on non-overlapping 40 MHz channels,
- Configuration C: one AP and two stations (one located 0.5 m from the AP and one located 16 m from the AP), 802.11ac devices only using a single 80 MHz channel,
- Configuration D: one 802.11ac network and one 802.11n network configured on non-overlapping 20 MHz channels.
- Configuration E: two 802.11ac networks and one 802.11n network configured on non-overlapping 20 MHz channels.



(a)



(b)

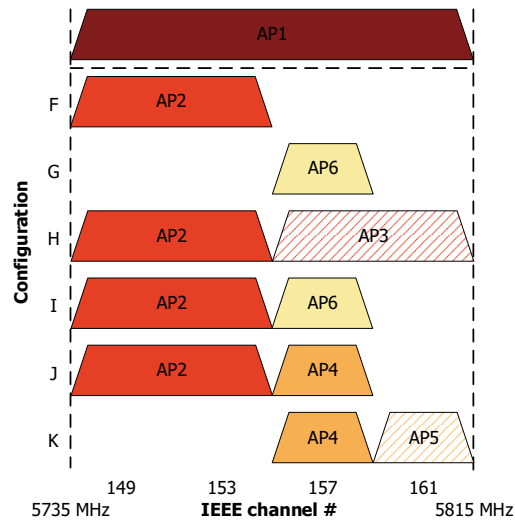
Fig. 3. Network coexistence: (a) the network configurations in the frequency domain, (b) per-station downlink throughput in configurations A–E. Configuration: **A** – Network 1 and Network 2 share an overlapping 80 MHz channel, one station per AP; **B** – Network 1 and Network 2 use two disjoint 40 MHz channels, one station per AP; **C** – Network 1 uses an 80 MHz channel, single AP with two stations; **D** – Network 1 and Network 3 use two disjoint 20 MHz channels, one station per AP; **E** – three networks use disjoint 20 MHz channels, one station per AP. Primary channels set at each network are given in brackets. Tests performed in room B.

Fig. 3b presents the downlink throughput results for both overlapping and non-overlapping channels (the primary channel of each AP is given in brackets). Similar results were obtained for configurations A and B. The available throughput was fairly divided both for overlapping 80 MHz and disjoint 40 MHz channels. However, in configuration C the per-station throughput decreased and the throughput of each link became unstable. This was caused by a larger distance from the AP of one of the stations.

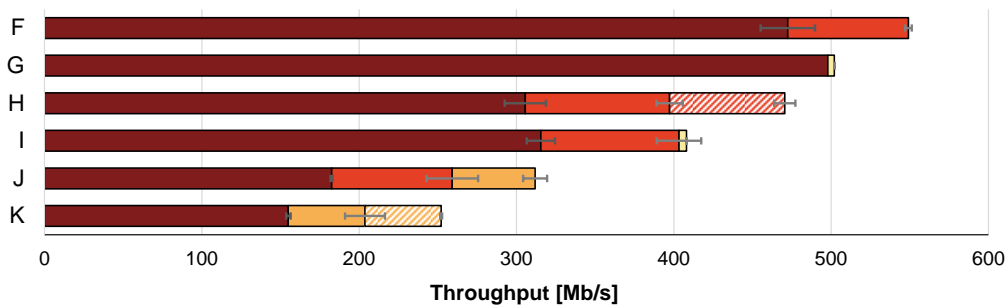
When both stations were close to their APs (configurations A and B), their throughput was about twice as high. This confirms the thesis that in the future per-room AP deployments will be required to obtain VHT. Additionally, when two APs are separated in frequency (configuration D), i.e., both use disjoint 20 MHz channels, the interference is negligible. However, when a third network is added on a neighboring channel (configuration E), per-station throughput drops. In particular, the performance of the second network is severely reduced because of inter-channel interference (even though disjoint channels are used).

Having observed, in the previous experiment in configuration A, that two 802.11ac networks located in one room can satisfactorily share an 80 MHz channel, we now ask what would be the optimum configuration of pre-802.11ac APs operating in the vicinity of an 802.11ac AP using an 80 MHz channel. Fig. 4 presents the performance results from a series of tests conducted in room A for an 802.11ac network coexisting with legacy 802.11a and 802.11n networks. Each network consisted of one station and one AP of the same type. Different configurations of overlapping channels were analyzed and the most interesting results have been selected for presentation. All 802.11n and 802.11a channels were disjoint but overlapping with the selected 802.11ac 80 MHz channel (Fig. 4a). To emphasize the performance degradation, the measured throughput values (Fig. 4b) were additionally related to the performance of each network operating in undisturbed conditions (Fig. 4c). The following six configurations were analyzed where one 802.11ac network (AP1) overlapped with:

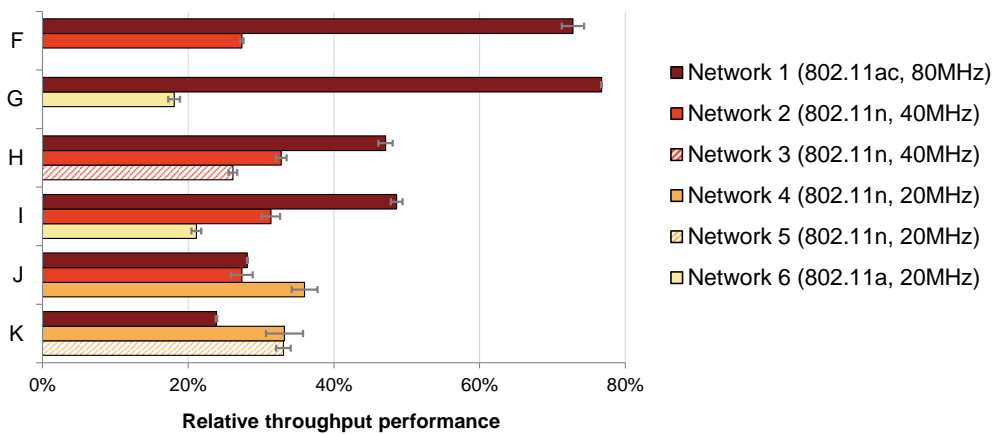
- Configuration F: one 802.11n network, 40 MHz channel,
- Configuration G: one 802.11a network, 20 MHz channel,
- Configuration H: two 802.11n networks operating on disjoint 40 MHz channels,
- Configuration I: one 802.11n network, 40 MHz channel and one 802.11a network, 20 MHz channel,
- Configuration J: two 802.11n networks operating on disjoint 40 MHz and 20 MHz channels,
- Configuration K: two 802.11n networks operating on disjoint 20 MHz channels.



(a)



(b)



(c)

Fig. 4. Network coexistence: (a) the network configurations in the frequency domain, (b) per-station downlink throughput and (c) downlink throughput of overlapping networks normalized to the maximum throughput obtained in each non-overlapping network in configurations F–K. Configurations include one 802.11ac AP together with: **F** – one 802.11n AP; **G** – one 802.11a AP; **H** – two 802.11n APs operating on disjoint channels; **I** – one 802.11n AP and one 802.11a AP; **J** – two 802.11n APs (one using a 20 MHz channel); **K** – one 802.11n network and one 802.11a network (both with disjoint 20 MHz channels). Primary channels set at each AP are given in brackets. Tests performed in room A.

The obtained results show that the performance of 802.11a is strongly limited, by the overlapping 802.11ac network, to about 4-5 Mb/s (20% of the initial throughput) thus making it almost unserviceable (Configurations G and I). Simultaneously, 802.11n performance is less degraded (down to about 25-35%) by the 802.11ac network (Configurations F, H-K). Still, the throughput offered by 802.11n is much higher than for 802.11a operating in undisturbed conditions. Additionally, an overlapping 802.11n network with a 20 MHz channel (Scenario J) has a greater impact on 802.11ac than the 802.11a network (Scenario I) since 802.11n supports frame aggregation and, therefore, 802.11n transmissions take longer than 802.11a transmissions when the same channel width is used by both amendments. Furthermore, the coexistence of 802.11n and 802.11ac networks improves when wider (40 MHz) channels are used by 802.11n APs (Configurations H, J) because with 20 MHz channels a portion of the available bandwidth is wasted.

Due to space limitations and to preserve the clarity of figures we do not present results obtained for the same scenarios when all channels overlap (i.e., all APs have the same primary channel). For such settings, we conclude that the overall network throughput drops by several percent, the 802.11a and 802.11n networks obtain a 30-40% lower throughput (because of increased overlapping among channels), and the 802.11ac network gains about 10% higher throughput (because of decreased interference).

We conclude that self-configuration in terms of channel frequency and channel bandwidth selection, transmission power management as well as adaptive channel sensing (currently being considered by TGax) constitute a strong requirement for future Wi-Fi deployments. Otherwise, poor network performance is inevitable, especially if networks are operating in close proximity. Therefore, the Ethernet cable replacement possibility by VHT Wi-Fi is currently less evident than in theoretical approximations which do not consider interference from legacy Wi-Fi devices. The observed behavior also highlights the shortcomings of the current 802.11a OBSS management mechanism, which does not consider interference from adjacent non-overlapping channels.

## 5 Guidelines and Challenges

Based on the experiments performed and an analysis of the literature, we have extracted the following guidelines for overcoming coexistence issues in Wi-Fi networks:

- **Use beamforming.** Beamforming the antenna radiation pattern increases throughput while decreasing the level of interference. Beamforming coupled with MU transmissions may considerably improve spatial efficiency and reduce airtime load (and thus latency).
- **Use frame aggregation.** The continuous transmission of multiple data frames after successful channel contention partially resolves performance anomaly issues and increases overall network performance. This is especially important for the latest PHY layers such as IEEE 802.11ac where the transmission time of a single data frame without frame aggregation is usually very short and, considering the PHY and MAC overhead involved, can be inefficient.
- **Use wide channels and multiple antennas.** Configure APs with multiple antennas and as wide channels as possible to decrease frame transmission times and increase network capacity.
- **Use spatial and frequency separation.** Perform a detailed site survey to detect existing networks and bandwidth occupancy when deploying a new Wi-Fi-based high throughput service. Achieve spatial separation by using directional antennas and deploying APs on a per-room basis to obtain maximum throughput (802.11ac's 256-QAM cannot be achieved without line-of-sight connectivity). Achieve frequency separation by selecting less occupied radio channels of desired width. Also, place neighboring APs on disjoint channels and, ideally, avoid

adjacent channels to reduce inter-channel interference.

- **Use 802.11ad as backhaul.** Backhaul connections for Wi-Fi APs can be setup using low-cost license-free point-to-point 802.11ad links operating in the 60 GHz band. Highly directive antennas should be used to decrease interference and improve range.
- **Upgrade wired backhaul.** Access links should support Gb/s speeds to take advantage of 802.11ac and its successors.
- **Upgrade APs.** Considering device coexistence, the introduction of an 802.11ac AP should be done rather as a replacement than as an addition to existing legacy APs.
- **Eliminate legacy devices.** Maintaining backward compatibility with legacy devices (802.11a/b/g) impacts network performance and limits the advantages of the latest 802.11 amendments.
- **Limit the performance anomaly phenomenon.** Try to centrally locate the AP in order to avoid having faraway stations transmitting with the lowest available rates.
- **Introduce autonomy.** Wi-Fi networks should exhibit self-management, i.e., be equipped with mechanisms allowing them to actively adapt to current radio conditions. This includes dynamic transmission power management, neighboring station discovery, channel occupancy detection, frequency band selection, and other reconfiguration mechanisms.

The analysis performed in this paper has also lead us to conclude that there are unresolved problems, where future research could help improve coexistence of future Wi-Fi networks (Table 2).

**Table 2. Open research areas related to coexistence of Wi-Fi networks**

Requirement	Open research area	Comments
Efficient medium access	Coexistence of new and legacy devices; improved collision avoidance	Full backward compatibility decreases performance (e.g., mandatory low data rate transmission of frame preamble and header) as well as fairness in channel occupancy (low rate frames take longer to transmit).
Optimal frequency use	Context-aware channel selection	Interference occurs both on overlapping as well as disjoint channels; performance is worsened by dense deployments.
Integration of new radio technology	Efficient use of beamforming, MU-MIMO, high modulation	Recent radio technologies have novel hardware and software requirements.
Integration with other systems	Coexistence with LTE in the same frequency band	Development of collaborative radio resource management mechanisms is required.
Optimal transmission power and carrier sensing threshold selection	Coexistence of many Wi-Fi devices in dense environments	Operation of Wi-Fi devices in close proximity increases the level of interference; optimal transmission power and carrier sensing threshold settings can improve performance and minimize interference.
Quality of service support	Coexistence of QoS - aware and legacy devices	QoS parameters should be carefully selected and tuned for dense networks due to prioritized approach of QoS guarantees in Wi-Fi networks as well as performance anomaly problem caused by legacy devices without QoS support (low rates cause longer transmission of best-effort data frames).
Mobility support	Smooth handovers	Station movement can result in collisions, link breakage,

		variation in the number of contending stations, backward compatibility issues, new admission control decisions, and the need for handover mechanisms.
Multi-hop operation	Efficient transmission in multi-hop environments	Limited range of Wi-Fi networks necessitates multi-hop transmissions. This requires solving problems of hidden and exposed stations as well as contention between locally generated and forwarded traffic.
Self-management	Short and long-term adaptability	Varying radio and traffic conditions as well as the large number of configurable parameters require a high degree of network autonomicity. Efficient network-wide management for Wi-Fi networks is also an open issue.

## 6 Conclusions

The evolution of Wi-Fi networks and their widespread adoption will result in coexistence issues for future network deployments. In this paper, we have identified future Wi-Fi use cases, analyzed the functionalities required by these use cases (based on the latest and upcoming 802.11 amendments as well as available Wi-Fi solutions related to novel network paradigms), and evaluated the performance of the latest available devices from two different perspectives: coexistence between Wi-Fi devices and coexistence between networks. We have identified guidelines for ensuring interoperability as well as outlined future research directions. Fortunately, the evolving 802.11 standard is targeted towards overcoming some of these issues. For example 802.11ax promises to improve spatial reuse. Further solutions will be the results of adopting the latest networking trends (such as autonomicity and software-defined networking) for Wi-Fi networks.

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## Bibliography

- [1] H. Ali-Ahmad, C. Cicconetti, A. de la Oliva, M. Draxler, R. Gupta, V. Mancuso, L. Roullet, and V. Sciancalepore, "CROWD: An SDN Approach for DenseNets," in Proc. of Second European Workshop on Software Defined Networks, 2013.
- [2] W. Sun, O. Lee, Y. Shin, S. Kim, C. Yang, H. Kim, S. Choi, "Wi-Fi could be much more," IEEE Communications Magazine, vol. 52, no. 11, pp.22-29, 2014.
- [3] R. Liao, B. Bellalta, J. Barcelo, V. Valls, M. Oliver, "Performance analysis of IEEE 802.11ac wireless backhaul networks in saturated conditions," EURASIP Journal on Wireless Communications and Networking, 2013:226.
- [4] O. Darvishi, B. Abolhassani, H.S. Rad, "On the efficiency of directional antennas in MIMO communication systems." Proc. of Sarnoff Symposium, 2009.



- [5] J. Liu, Y. Kawamoto ; H. Nishiyama ; N. Kato ; N. Kadowaki "Device-to-Device Communications Achieve Efficient Load Balancing in LTE-Advanced Networks," IEEE Wireless Communications Magazine, vol. 21, no. 2, pp. 57-65, Apr. 2014.
- [6] K. Kosek-Szott, M. Natkaniec, S. Szott, A. Krasilov, A. Lyakhov, A. Safonov, and I. Tinnirello, "What's new for QoS in IEEE 802.11?" IEEE Network, vol. 27, pp. 95–104, 2013.
- [7] M. Wodczak, T. B. Meriem, B. Radier, R. Chaparadza, K. Quinn, J. Kielthy, B. Lee, L. Ciavaglia, K. Tsagkaris, S. Szott, A. Zafeiropoulos, A. Liakopoulos, A. Kousaridas, and M. Duault, "Standardizing a reference model and autonomic network architectures for the self-managing future internet," IEEE Network, vol. 25, pp. 50–56, 2011.
- [8] Fuad M. Abinader et al., "Enabling the Coexistence of LTE and Wi-Fi in Unlicensed Bands", IEEE Communications Magazine, 2014.
- [9] LitePoint, "IEEE 802.11ac: What Does it Mean for Test?", white paper, 2013.
- [10] A First Look at 802.11ac in Action: Energy Efficiency and Interference Characterization, Yunze Zeng, Parth H. Pathak and Prasant Mohapatra, IFIP Networking 2014, available online: <http://www.phpathak.com/publication.html>
- [11] P. Gallo, K. Kosek-Szott, S. Szott and I. Tinnirello, "SDN@home: A method for controlling future wireless home networks," in IEEE Communications Magazine, vol. 54, no. 5, pp. 123-131, May 2016.
- [12] C. Donatos et al., An OpenFlow Architecture for Energy-Aware Traffic Engineering in Mobile Networks, IEEE Network, vol. 29, np. 4, pp. 54 - 60, July/August 2015
- [13] A. Banchs, P. Serrano, P. Patras, and M. Natkaniec, "Providing Throughput and Fairness Guarantees in Virtualized WLANs Through Control Theory." Mobile Networks and Applications, vol. 17, no. 4, pp. 435-46, 2012.
- [14] K. Kosek-Szott, J. Gozdecki, K. Loziak, M. Natkaniec, S. Szott, M. Wagrowski, "VIMENO: A Virtual Wireless Mesh Network Architecture for Operators." Proc. of WinSys, 2013.
- [15] M.-D. Dianu, J. Riihijarvi, M. Petrova, "Measurement-based study of the performance of IEEE 802.11ac in an indoor environment," Proc. of ICC, 2014.