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Next generation IEEE 802.11 Wireless Local Area Networks: Current status, future directions and open challenges

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ABSTRACT

A new generation of Wireless Local Area Networks (WLANs) will make its appearance in the market in the forthcoming years based on the amendments to the IEEE 802.11 standards that have recently been approved or are under development. Examples of the most expected ones are IEEE 802.11aa (Robust Audio Video Transport Streaming), IEEE 802.11ac (Very-high throughput at < 6 GHz), IEEE 802.11af (TV White Spaces) and IEEE 802.11ah (Machine-to-Machine communications) specifications. The aim of this survey is to provide a comprehensive overview of these novel technical features and the related open technical challenges that will drive the future WLAN evolution. In contrast to other IEEE 802.11 surveys, this is a use case oriented study. Specifically, we first describe the three key scenarios in which next-generation WLANs will have to operate. We then review the most relevant amendments for each of these use cases focusing on the additional functionalities and the new technologies they include, such as multi-user MIMO techniques, groupcast communications, dynamic channel bonding, spectrum databases and channel sensing, enhanced power saving mechanisms and efficient small data transmissions. We also discuss the related work to highlight the key issues that must still be addressed. Finally, we review emerging trends that can influence the design of future WLANs, with special focus on software-defined MACs and the internet-working with cellular systems.

1. Introduction

The IEEE 802.11 standard for Wireless Local Area Networks (WLANs), commonly known as WiFi, is a mature technology with more than 15 years of development and standardisation. The earliest version of the IEEE 802.11 standard was realised in 1997 as a wireless alternative or extension to existing wired LANs using Ethernet technology. However, since its appearance, the IEEE 802.11 specification has continuously evolved to include new technologies and functionalities, and several amendments to the basic IEEE 802.11 standard have been developed. WLANs are currently not only the most common Internet access technology; but they have also expanded across a wide variety of markets, including consumer, mobile and automotive [1]. WLANs are thus widely available everywhere (homes, public hotspots, enterprise environments) and IEEE 802.11-based radio interfaces are found in many types of devices.[1]

Several factors have contributed to the success of the IEEE 802.11 family of standards, *interoperability*, *ease of use*, and *flexibility* being among the most important. First, the IEEE 802.11 standards were initially designed to be used within unlicensed spectrum bands, referred to as Industrial Scientific and Medical (ISM) bands. More precisely, most IEEE 802.11 standards work in 2.4 GHz and 5 GHz frequency bands, which are globally available, although local restrictions may apply for some aspects of their use. Thus, anyone can deploy a WLAN in those bands given that a few basic constraints, such as a maximum transmission power, are satisfied. On the downside, this also means that most WLANs are deployed in an uncontrolled fashion with limited or no consideration of interference issues. This has made it especially challenging to guarantee performance bounds and reasonable Quality of Service (QoS) levels. This problem is further exacerbated by *network densification*, i.e., the emerging trend of deploying a large number of base stations in hotspot areas to cope with the

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[1] According to ABI Research, in 2013 more than two billion IEEE 802.11-enabled devices were shipped.

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increase in traffic demands [2]. A second fundamental characteristic of the IEEE 802.11 standards is the adoption of a media access control (MAC) protocol called Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). The main reason is that IEEE 802.11-based systems are half-duplex, i.e., a station cannot carrier-sense/receive while it is sending, and it is hence impossible to detect a collision as in the case of transmissions over twisted copper wires (e.g., using Ethernet). A major advantage of the CSMA/CA method is that channel access procedures are simple and cheap to implement, as they do not impose stringent timing requirements on the radio interface. Furthermore, CSMA/CA protocols are scalable and they provide easy support for mobility and decentralised network architectures, from classical ad hoc networks to emerging people-centric networks [3,4]. On the negative side, CSMA/CA protocols can only provide a best effort transmission service and major efforts have been dedicated to the design of mechanisms for supporting better QoS, such as in the IEEE 802.11e amendment [5].

The perceived shortcomings of the first WLAN products have driven the evolution of the IEEE 802.11 standards [6]. In particular, throughput enhancements have been a key priority in the IEEE 802.11 technology development. The key enabler for high-throughput WLANs was the adoption of new physical-layer techniques. The first of these techniques was the orthogonal frequency-division multiplexing (OFDM), which allowed achieving maximum data rates up to 54 Mb/s. However, it is only with the adoption of the IEEE 802.11n amendment in 2009 that the throughput performance of WLANs came close to that of a wired Ethernet network, as a result of the introduction of multiple-input multiple-output (MIMO) technologies [7]. At the same time, new amendments to the original standard were proposed to foster a more diversified use of WLAN products in various application domains. For instance, the IEEE 802.11p amendment was approved in 2010. This defines enhancements to the IEEE 802.11 standards to support vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication (together referred to as V2X) in the 5.9 GHz band, which is licensed for Intelligent Transportation Systems (ITS) [8]. Following the same diversification strategy, the IEEE 802.11s amendment was approved in 2011; this described how wireless mesh networks should operate on top of the existing IEEE 802.11 MAC protocol [9]. This includes the specification of new infrastructure-based elements needed for mesh networking and the routing protocol to establish mesh paths between these elements. In an attempt to consolidate and systematise all the adopted IEEE 802.11 enhancements, the last IEEE 802.11 standard (identified as IEEE 802.11-2012) was finally released to incorporate in an unique specification all the amendments published from 2008 to 2011 [10].

As pointed out above, the technological development of the WLAN specifications is a continuously evolving process. Thus, while the IEEE 802.11–2012 major revision of the IEEE 802.11 standard was finalised, the IEEE 802.11 working group was also rapidly moving its focus towards next-generation WLANs [11]. Three key drivers were forecasted: (i) Machine-to-Machine communications (ii) High-Definition Multimedia Communications and (iii) “Spectrum Sharing” in licensed bands by using cognitive radio technology. Specifically, with the emergence of the *Internet of Things* (IoT) vision, i.e., a world were all sorts of smart objects (ranging from home appliances to small battery powered devices) are connected to the Internet [12], a low-power WLAN technology is required [13,14]. At the same time, the widespread diffusion of mobile devices with diverse networking and multimedia capabilities, as well as the wide adoption of advanced multimedia applications, is fuelling the growth of *mobile video traffic*, which was already more than half of the global mobile data traffic by the end of 2013 [15]. Thus, WLANs need specific functions to cope with various multimedia applications, including real-time interactive audio and video, or streaming live/stored audio and video [16]. Finally, new regulations for the *unlicensed usage of TV white spaces* are offering new opportunities for additional spectrum utilisation, which can be particularly useful to improve rural coverage of WLANs [17]. However, cognitive radio mechanisms are required for enabling WLAN communications in TV white spaces. A new generation of amendments is consequently under development or has been completed since 2012 to address these new application requirements. The most relevant are the IEEE 802.11aa (approved in 2012), IEEE 802.11ac (approved in 2013), IEEE 802.11ad (approved in 2012), IEEE 802.11af (approved in 2013), IEEE 802.11ah (in progress, expected for 2016), and IEEE 802.11ax (in progress, expected in 2019), among other.s[2]

In this survey we discuss the most compelling challenges of the new usage models and applications for WLANs that we have identified above. Then, based on those scenarios, we classify and review a selected group of IEEE 802.11 amendments, i.e., IEEE 802.11ac, IEEE 802.11ax, IEEE 802.11aa, IEEE, 802.11ah and IEEE 802.11af, by describing the new technologies and functionalities they introduce to cope with these challenges, such as multi-user MIMO techniques, groupcast communications, dynamic channel bonding, spectrum databases and channel sensing, enhanced power saving mechanisms and efficient small data transmissions. A summary of the main features of these amendments in provided in Table 1. It is important to point out that the IEEE 802.11 specifications do not define all mechanisms, but they typically provide the building blocks and interfaces to allow different manufacturers to implement compatible procedures. Thus, we also provide a detailed review of the main research activities in the various areas and we identify open technical challenges. Finally, we look at emerging new trends for WLANs, with a special interest in Programmable WLANs and LTE-WiFi interworking. Overall, this survey provides a comprehensive overview of the most relevant features in next-generation WLANs, which may be of interest to both researchers and engineers working in the field. For the sake of completeness, in Table 2 we also list the other on-going IEEE 802.11 amendments that have not been analysed in this survey.

Given the importance of WLANs, other surveys have been published on the IEEE 802.11 standards. Earlier surveys primarily focused on presenting the different classes of proposed MAC protocols [18]. A complete overview of the wealth of amendments that have been accepted or were in the process of being standardised before 2010 is provided in [1]. More recently, other surveys have given detailed consideration to specific amendments (e.g., IEEE 802.11s [19]), or classes of similar amendments [11,16,20]. However, none of the existing surveys follows our use-case oriented approach and covers in such detail all the amendments that we believe will be relevant in coming years. We also include some of the latest advances and related research.

The structure of this survey is illustrated in Fig. 1 and explained in the following. In Section 2 we introduce the four key scenarios for WLAN technologies that are considered here. In Section 3 we focus on high-throughput WLANs, presenting the IEEE 802.11ac, IEEE 802.11ax and IEEE 802.11aa amendments. Section 4 discusses the IEEE 802.11ah amendment to support M2M communications and we review the IEEE 802.11af for WLANs operating in TV white spaces. Finally, Section 6 presents some emerging trends for future WLANs.

2. Future scenarios and new challenges

WLANs can be found everywhere. They are common in homes, offices, public parks in cities, shops, airports and hotels, among many different places. Today’s WLANs are able to provide a fast and reliable wireless access to Internet for browsing the web, exchanging files, chatting, receiving and answering e-mails, and for low-quality real-time audio/video streams, as just a few representative examples of their current usage. This situation is changing rapidly however. The

[2] The association between the IEEE 802.11 amendments and the different use cases is specified in Section 2.