Audit of a Real Wi-Fi Deployment to Provide Data, VoIP Communications and an IIoT Item Location Service

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Abstract —As the number of Access Points and stations sharing the unlicensed ISM (Industrial Scientific Medical) bands increases, interference diminishes the theoretical performance of 802.11 standard. This paper presents results of the performance of an IEEE 802.11b/g network in a public facility infrastructure which needed to deploy more than a thousand access points to provide an IIoT (Industrial Internet of the Things) item location service. As a first step to better analyze such network characteristics, this work studies the channel occupancy, the RSSI (Received Signal Strength Indicator) variation and the throughput of a static and mobile station. The study also analyzes the performance of Voice over IP over the wireless network. The results reveal the inefficient use of the wireless medium in a large 802.11 network due to multiple radio propagation conditions.

Index Terms— IEEE 802.11, IIoT, real measurements, VoIP

I. Introduction

Industry 4.0 is currently seen as a future scenario in which wireless communications will play an indisputable role. A new generation of systems are required to provide pervasive connectivity between machines and assets involved in the production, and hence, enable a new leap in industrial automation. In fact, it is indisputable that the mobility of such items, as well as the needs in production flexibility, requires research efforts in the wireless systems arena. Industrial wireless communications create new prospects for reliable automation even in areas of difficult or impossible reach, and play a central role for the availability of information in real-time. The need for wireless communications is steadily increasing in many automation applications. In order to fully exploit the potentials offered by wireless communication for monitoring, control, automation applications and industrial mobile robotics, there is a further need for time-constrained communication protocols that provide bounded latency together with high reliability and energy efficiency.

Wireless Local Area Networks (WLAN) have experimented a constantly increasing deployment in public areas, such as universities, airports, railway stations and other facilities. Thus, it seems reasonable to extend these deployments to support and provide new services for the IIoT. These networks need to offer faster bit rates, for data, video or VoIP services with a total coverage, dealing with multiple radio propagation situations, but they also have to manage massive sensor networks and handle with the also increasing number of users. The access points should be placed in architectural environments that have been designed without considering the characteristics of radio propagation. In addition, overlapping deployments, with other WLAN networks or systems such as Bluetooth or Zigbee produce an uncontrolled increase in radio interference.

Even though multiple channels are defined in IEEE 802.11b/g standard [1] in 2.4 GHz band, these public networks usually utilize only three channels (1, 6 and 11) to minimize channel overlapping. As a result, in high density networks the frequency reuse is very limited producing a saturation of the band.

This work demonstrates the limitations of WLAN systems in the 2.4 GHz band under these situations. Nowadays, most of wireless networks also have available the 5 GHz band, nevertheless, with the rapid increase of wireless devices and needs, it is reasonable to expect that this band will have the same issues presented in this paper in a near future. In [2], the authors discuss about the congestion of IEEE 802.11 in the 2.4 GHz ISM band, but they do not study all the channels simultaneously nor analyze the handover when moving from one access point to another which was critical in our study case.

Other studies like [3], also investigate the performance of Wi-Fi networks in dense environments, but they base their discussion on simulations. On the same topic, [4] proposes a mechanism to adapt the transmission power in high density deployments to reduce interferences, or [5] discusses several procedures to select the Wi-Fi channel under these circumstances.

Our study is focused on investigating the consequences of massive access point deployments by a single network in its performance. The recent study in [6] analyzed the performance of the newest standard, 802.11ac, in a high density indoor deployment. However, they considered just a network with 24 nodes. In our case it was necessary to deploy more than a thousand access points along a site in order to locate with precision the hundreds of moving sensors inside the facility. Specifically, we will monitor the link quality with statistics of received signal strength, throughput characteristics in static and mobile

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environments, number of retransmissions and we will study the channel capacity perceived by a user as the free time available in the medium. Finally, we will analyze the performance of a VoIP system under these unfavorable circumstances.

II. Wi-Fi Briefing

In this section, we will briefly introduce the different concepts about the 802.11 standard necessary to follow and understand the tests and discussions along the paper.

A. Architecture

IEEE 802.11 allows two architecture modes: ad-hoc and infrastructure. In infrastructure mode, one of the Basic Service Set elements takes control of all the communications, this node is known as access point (AP). The AP manages the authentication and association processes and all the traffic must pass through it. In ad-hoc mode, no station prevails over the rest, so spontaneous networks can be created.

Discovering, authentication and association

In order to establish a connection several processes should be carried out: device discovering, authentication and association.

The only way for a station or an AP to discover other devices is sensing the medium. The access points, send periodically a type of control frames (beacons) to inform about their capacities (supported rates, encryption, network name, etc.) and then wait for an authentication request coming from the stations. On their part, the stations instead of waiting passively they can also request the transmission of frame similar to a beacon with a probe request.

In order to begin the data interchange between stations an association between them must be stablished. A station is allowed to send an association request (or reassociation) to any other station with which was already authenticated previously. In ad-hoc mode, each and every one of the stations in the network must be associated with the rest. In infrastructure mode, in a determined time instant a station is only allowed to be associated with a unique AP. In order to perform the handover of a connection between two APs inside the same network, the station shall request a reassociation to the new AP an abandon the previous basic service set. It is important to remark that the association and reassociation processes are always started by the stations.

If privacy is required, the information can be protected using cyphering. Access Points inform about the cyphering policies and requirements inside the beacons and probe response frames.

B. Physical Layer

The IEEE 802.11 standard defines several physical layers. Nevertheless, the APs installed in the facility under study supported only the standards 802.11b and 802.11a/g PHY specifications.

Frequency bands, channels and transmission masks

Wi-Fi networks are designed to operate in ISM bands or common use bands where non-controlled interferences may exist. The physical layers supported by the APs in the site can operate at the 2.4 GHz and 5 GHz ISM bands. The 802.11 standard specifies 14 channels at the 2.4 GHz band. The channel separation is just 5 MHz, so there are only three channels (usually 1, 6 and 11) which can be used without frequency overlapping. At the 5 GHz band, the available bandwidth is increased from 83 MHz to 300 MHz. Thus, the number of channels free of overlapping is incremented up to 14. The transmission spectrum masks, however are slightly different. At 2.4 GHz there should be a -50 dBr at 2 MHz from the carrier, but at the 5 GHz band, 30 MHz away from the carrier the filtering should be over 40 dBr.

Transmission rates and sensitivity

When using the 802.11g specifications, usually backwards compatibility with 802.11b is applied. Then the allowed transmission rates may vary from 1 Mbps up to 54 Mbps. At the 5 GHz band, when employing 802.11a, rates are in the range between 6 Mbps and 54 Mbps. The receiver sensitivity changes also when varying the transmission rate. If a lower rate is chosen, the sensitivity is improved. Typical values range from -93 dBm at 1 Mbps and -73 dBm at 54 Mbps. However, one of the drawbacks of selecting a slow rate is that the global throughput of the basic service set gets also reduced due to the performance anomaly of IEEE 802.11 [7].

C. MAC Layer

Apart from the PHY layer, the IEEE 802.11 standard also specifies mechanisms to manage the medium access.

Carrier detection

In order to check if the medium is busy, 802.11 stations use a carrier detection mechanism. This mechanism is based on the physical energy detection and a virtual carrier detection. The former is done by the PHY layer and depends on the medium and the modulation used. And the later, is based on the duration field included in all the frames. This second mechanism allows to resolve problems like a hidden terminal scenario.

Interframe spacing and backoff

The interframe spacing plays an important role in the coordination of the medium access. The standard defines different types of interframe spacing which allow to prioritize the access to the channel. To guarantee the interoperability between the different transmission rates, the interframe spaces are fixed no matter the rate employed. However, they change depending on the PHY layer used.

Most of traffic in an 802.11 network uses the distributed coordination function, a contention access mechanism similar to that in Ethernet. This process allows that multiple independent stations interact among them without using a centralized control. Basically, the process works as follows: before transmitting a frame, the stations check if the medium is free. If not, they postpone the transmission following an exponential backoff algorithm to avoid collisions

Positive acknowledgement and retransmissions

To guarantee the reliability of communications, Wi-Fi stations must transmit a short acknowledgment frame for each data frame received. If the transmitter does not receive this ACK, the frame should be retransmitted and the contention window incremented. If the frames are lost very frequently, the stations can adapt its transmission rate [8] or reassociate with another AP with better channel conditions. However, these mechanisms depend on the manufacturer implementation.

III. Scenario and Test Description

The network under analysis was designed with several objectives in mind. It was necessary to give Wi-Fi coverage to a public/private site of more than 500000m^2 with several facilities. The radio propagation conditions were diverse: offices, places with clear and unobstructed spaces with just several columns, restricted/crowded area, etc. This causes that the received signal level presents considerable variations [9]. The network should provide the usual wireless data connectivity, and it had also to give also private VoIP services along all the facilities.

However, the biggest challenge was related with IIoT, the Wi-Fi network should be able to provide an additional item location service. The items would be changing frequently their position so, in order to provide this service with enough precision, the deployment of the network consist on more than a thousand Cisco AP. With the design realized and once deployed the network, the item location service performed satisfactorily. Nevertheless, the VoIP users started to issue many complaints about the Quality of service (QoS) of the system.

The incorrect performance of the voice over IP telephony system, could be caused by several reasons: coverage shortage, interferences, erratic moving of the terminal, etc. We designed several tests to check the different implied parameters: signal and interference levels, handover mechanisms, channel occupancy, etc. Nevertheless, these measurements were indirect, i.e. they not come from the terminal or the network, as we did not have available a terminal in engineering mode, nor the network could supply the necessary information. So, we implemented an automatic measurement system with three laptops in promiscuous mode to monitor the three channels used by the network. To synchronize all the captures, first all of them were placed on the same channel and we established a first short test call. After that, and without stopping the capture we changed the monitored channel in two of the laptops. To capture and analyze the data we have employed the software Wireshark. Wireshark, previously known as Ethereal, is a network protocol analyzer extendedly used to solve some communication networks issues and to develop software and protocols. Apart from this equipment, the VoIP tests were initially performed using AASTRA terminals with an Avaya IP telephony system, although at the end we did subjective quality tests also with Cisco VoIP terminals. UDP traffic stress tests were also performed using the iPerf software. Hundreds of quality tests were performed along all the site which helped to select over a dozen reference points were we made an exhaustive analysis.

IV. Results

The network deployed mainly used the 2.4 GHz band using the channels 1, 6 and 11. Additionally, each access point behaved as five virtual AP to provide support to the different services given by the network. This means, that each AP emitted each 100ms, five different beacons, one for each service.

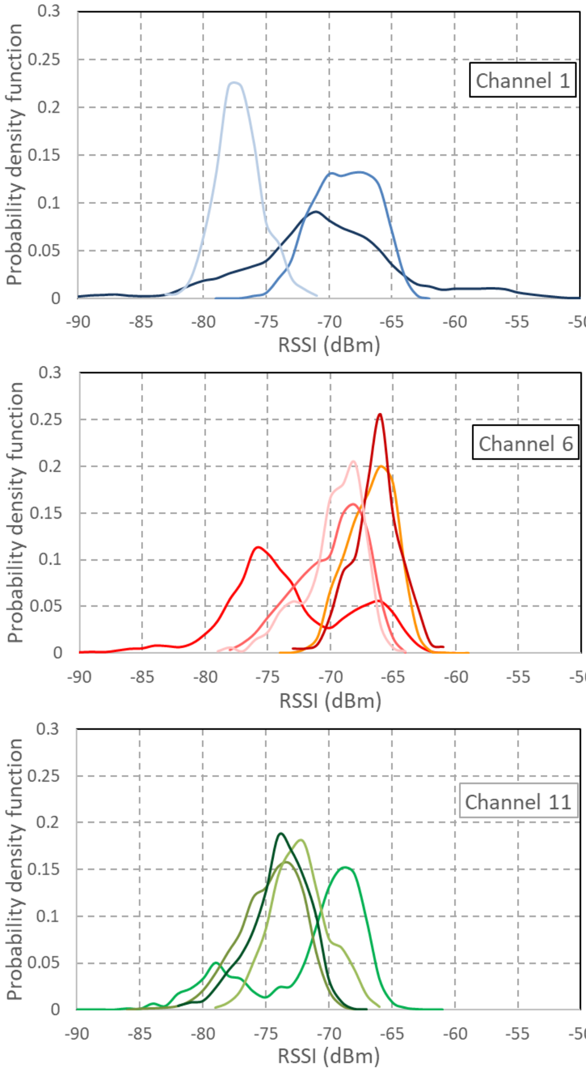
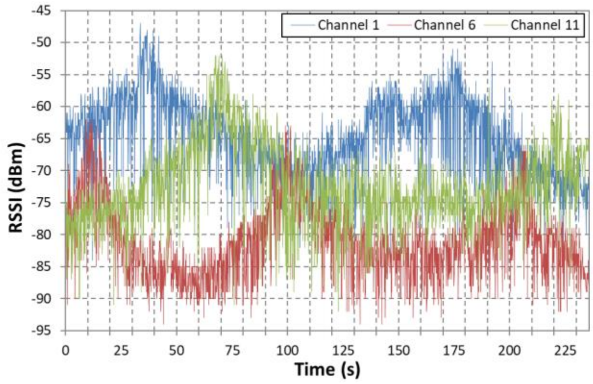


Fig. 1. Probability density function of the RSSI for different access points in channels 1, 6 and 11.

In a network with a high number of deployed AP like this one, even when staying at a fixed point, a station may receive beacons from multiple sources. These beacons may come from access points working on different channels, but, due to the high frequency reuse in the 2.4 GHz ISM band, is very probable to detect some on the same channel as can be seen in Fig. 1. In this figure we represented the probability density function of the beacon RSSI captured during a five-minute window at a fixed location. Each of the lines indicates a single access point of the network under study. We discarded beacons coming from other networks. Thus, as can be observed in this example, at this point, more than ten access points have been detected. A station located here should determine an access point to connect to. However, as can be seen, the problem extends beyond selecting one of the many possibilities because the RSSI variations sometimes exceed 30 dB for a single AP. For example, in channel one, the darkest line shows an access point received beacons with RSSI between -52 and -83 dBm. These variations in the signal level lower the reliability at the physical layer. To improve the reliability, the stations may choose from several modulations. With slower transmission rates, a better sensitivity is achieved. However, this affects to the throughput seen by this station and affects to the rest of the stations in the network due to the performance anomaly of the 802.11 based networks.



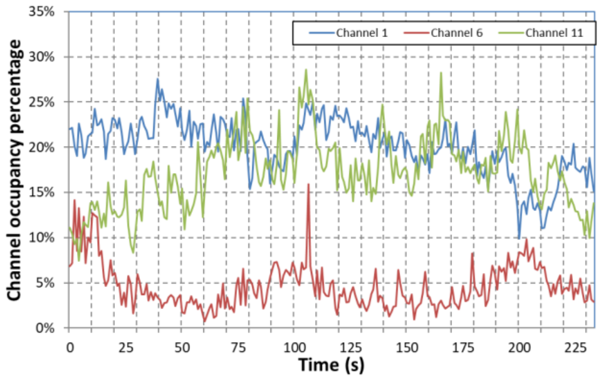
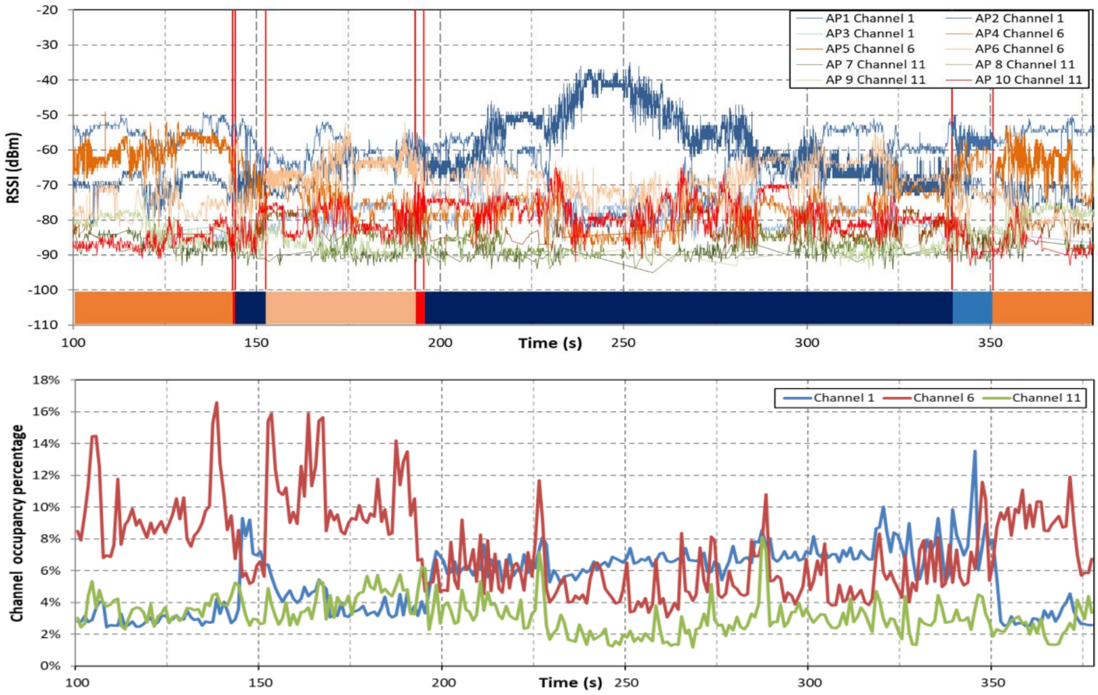


Fig. 2. RSSI and channel occupancy percentage

In Fig. 2 we selected for each of the three different channels the AP with the best channel conditions. At the top figure, the RSSI variations over four minutes are depicted. There, it can be observed the slow variations due to the movement of the station and fast fadings up to 20 dB due to multipath propagation. In these conditions, keeping an optimized PHY layer rate may require complex algorithms and instantaneous handovers between access points.

On the other hand, the other subfigure shows the channel occupancy percentage for each channel. As it can be seen, channels 1 and 11 are found busy between a 10% and a 25% of the time. Due to the CSMA/CA employed in Wi-Fi other stations are not allowed to transmit during these time periods, so they do not have access to the medium and their effective throughput or QoS parameters get affected.

In addition, the hidden terminal problem [10] should be also considered. That is, even though a station could see the channel as free and allowed to use it, its transmission could not be demodulated on the receiver because a hidden terminal simultaneous transmission.



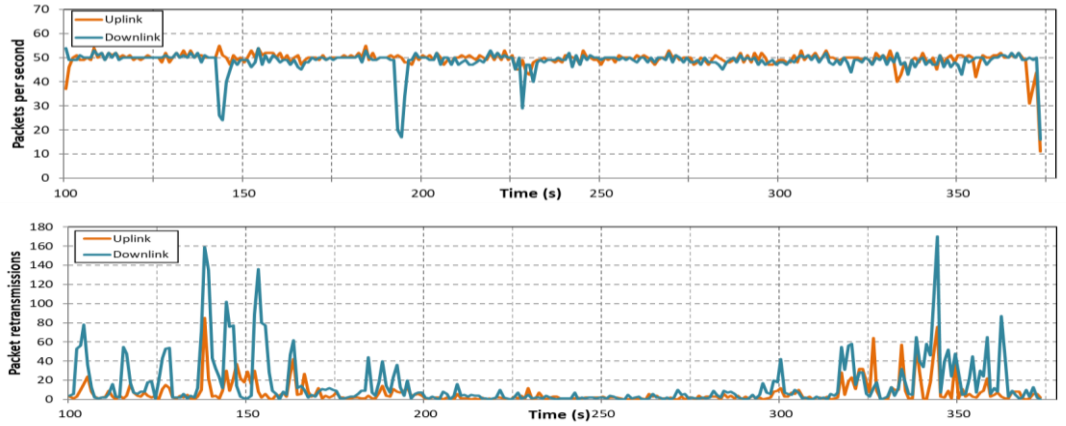


Fig. 1. RSSI, channel occupancy, packets per second and packets retransmissions during a VoIP call at the only reference point with good channel conditions

Fig. 3 and Fig. 4 shows the operation of the network and a terminal during a VoIP call over WLAN under two different scenarios. These scenarios have been selected among more than a dozen points of the site where we realized an exhaustive analysis.

In Fig. 3 the call is done at a restricted access office area which is the only one that presents a satisfactory performance. On the top of the figure is depicted the RSSI of the packets measured on the mobile station location. Its values cover a range between -35 dBm and -93 dBm, near 60 dB of difference. It can also be observed that along all the terminal movement it detects beacons from up to 10 different AP. The received signal level is adequate during all the call with one access point dominating over the rest (dark blue). At the inferior part of the figure there is a color bar that indicates to which AP is the station associated at every moment. The vertical red lines indicate the precise moments of the handover. In this case the terminal makes up to seven handovers along the call. Note that the handover algorithms are decided and implemented by the terminal manufacturer and are not always optimized.

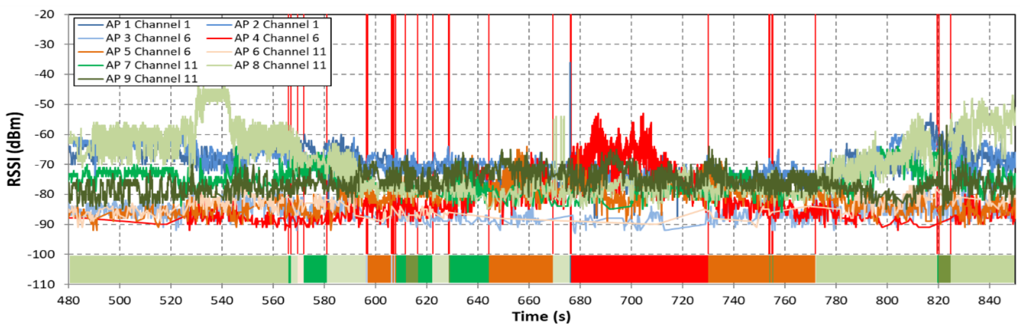
For example, in this case, it can be seen that around the second 140 the terminal decides to switch from one AP to another with a very low signal level. Thus, a few milliseconds later, it is force to do another handover seeking a better connection.

On the other hand, if we analyze the channel occupancy, it can be observed that the channel 6 is the most saturated of all three channels due to IP data traffic. However, this does not affect to the VoIP call even when the station is associated to an access point using this channel.

In the next subfigure, it can be seen that the packet rate of the VoIP over WLAN communication is practically steady, especially on the uplink at the moments prior to a handover.

A similar and related effect is depicted also at the last subfigure where the packet retransmissions are represented. In this case, when the signal level starts to be insufficient, the number of retransmissions increases considerably, primarily, at the downlink. The reason behind this behavior is that the sensitivity of the AP is better than the sensitivity of the mobile terminal.

On the other hand, in Fig. 4, the same metrics are shown for an unfavorable scenario. In this second case, the VoIP call is done at an unrestricted area, with a combination of open spaces, walls, columns and considerably crowded. At the top of the figure, the RSSI signal variations seen at the location of the mobile terminal are depicted. Looking at the general profile of the figure along all the movement of the mobile station, at every moment it sees at least one of the nine AP detected with a minimum RSSI of -75 dBm. So, although the signal levels are worse of that shown in Fig. 3 and hardly ever there is an AP which could be outlined over the rest, the signal level is at least 15 dB over the sensitivity of the receiver. However, along the call, the mobile station completes up to 25 handovers because it has difficulties to select the best AP at a determined time due to the high level of interference and seeing a signal to interference ratio very unfavorable.



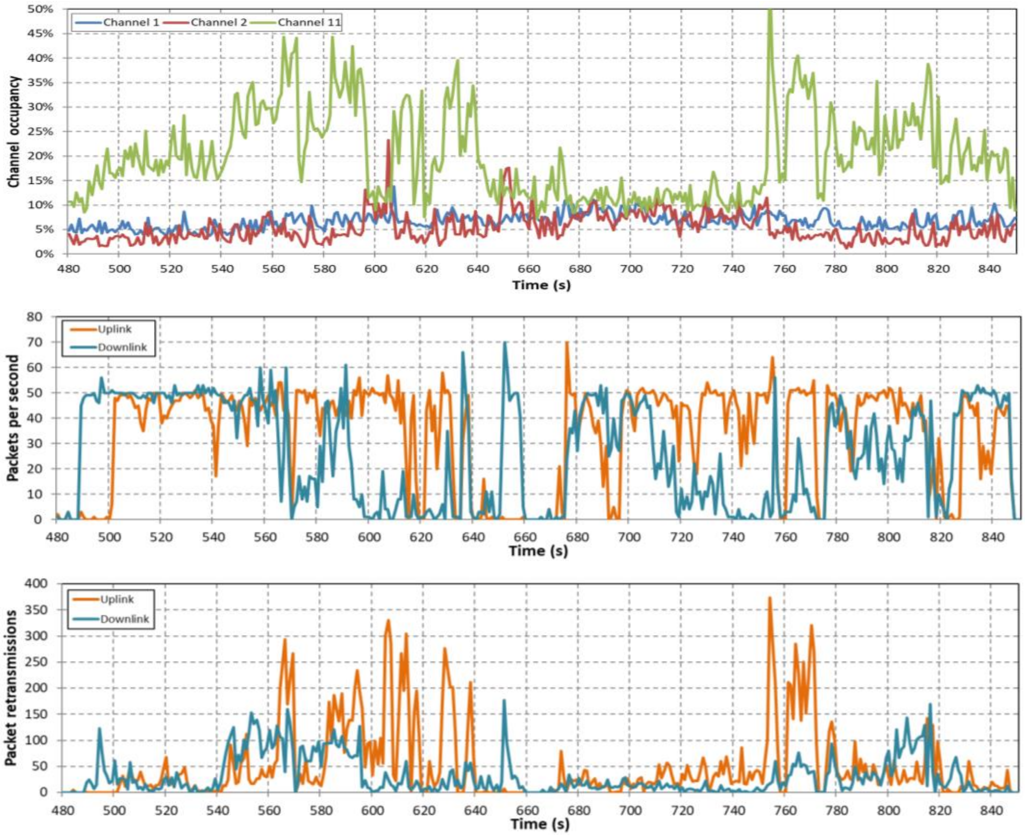


Fig. 4. RSSI, channel occupancy, packets per second and packets retransmissions during a VoIP call at a reference point with bad channel conditions

Analyzing the channel occupancy, it can be seen, that the network at this point is considerably saturated. This causes that the VoIP terminal finds troubles to transmit its frames accomplishing the QoS requirements.

Regarding the frames per second test, it can be noted that exist several moments, both in the uplink and downlink, with unacceptable losses. In these cases, maintaining the link becomes impossible and, as it could be expected, the number of retransmissions increases and repeats in a continuous way. These effects cause cuts on the VoIP communication and the consequent user complaints.

V. Conclusions

In this paper we have presented a real deployment of a Wi-Fi network working on the 2.4 GHz ISM band which should provide standard communications services (wireless data connectivity and a private VoIP telephony system) and, in addition, an IIoT service as is the location of mobile items inside several facilities in a 500.000 m2 site.

The item location service required the placement of more than a thousand access points, much more than the required by a standard Wi-Fi deployment. Combining the poor flexibility of the saturated 2.4 GHz band and the difficulties of planning a deployment in a site with metallic elements, different floors, free spaces, columns, etc. made that the received signal level had great variations. This complicated the handovers of the VoIP telephony system not only when the user was moving, but also when standing still at unfavorable positions because the high density of AP combined with the normal use of the network made the CSMA/CA access very limited. All of this caused that the number of retransmissions and cuts in communications increased, making impossible to guarantee the QoS in the VoIP calls. Nevertheless, the item location service performed satisfactorily.

In order to improve the telephony system QoS without renouncing to the current performance of the item location service, a possible solution could be to move all the elements in the network, or at least, the part of the telephony system to the 5 GHz ISM band or develop and use a centralized handover mechanism.

Acknowledgment

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References

[1] IEEE Std 802.11 -2016, "Part 11: wireless lan medium access control (mac) and physical layer (phy) specifications," 2016.

[2] J. W. Van Bloem, R. Schiphorst, T. Kluwer, and C. H. Slump, "Spectrum utilization and congestion of ieee

802.11 networks in the 2.4 ghz ism band," *J. Green Eng*., vol. 2, pp. 401–430.

[3] F. M. Abinader, *et al*., "Performance evaluation of ieee 802.11n wlan in dense deployment scenarios," in *Proc. IEEE 80th Vehicular Technology Conference (VTC2014-Fall)*, 2014, pp. 1–5.

[4] F. S. Chaves, *et al.*, "Adaptive transmit power for wi-fi dense deployments," in *Proc. IEEE 80th Vehicular Technology Conference (VTC2014-Fall)*, 2014, pp. 1–6.

[5] S. Kajita, T. Amano, H. Yamaguchi, T. Higashino, and M. Takai, "Wi-Fi channel selection based on urban interference measurement," in *Proc. 13th International Conference on Mobile and Ubiquitous Systems: Computing, Networking and Services - MOBIQUITOUS 2016*, 2016, pp. 143–150.

[6] L. Simic, J. Riihijarvi, and P. Mahonen, "Measurement study of ieee 802.11ac wi-fi performance in high density indoor deployments: Are wider channels always better?" in *Proc. IEEE 18th International Symposium on A World of Wireless, Mobile and Multimedia Networks (WoWMoM)*, 2017, pp. 1–9.

[7] M. Heusse, F. Rousseau, G. Berger-Sabbatel, and A. Duda, "Performance anomaly of 802.11b," in *Proc. INFOCOM*, 2003.

[8] S. Khan, S. Ullah, A. Ahmed, and S. A. Mahmud, "A survey of rate-adaptation schemes for ieee 802.11 compliant WLANs," *KSII Trans. Internet Inf. Syst*., vol. 7, no. 3, pp. 425–445, 2013.

[9] R. Akl, "Indoor propagation modeling at 2.4 GHz for IEEE 802.11 networks," in *Proc. Sixth IASTED Int. Multi-Conference Wirel. Opt. Commun.*, 2006.

[10] A. Tsertou and D. I. Laurenson, "Revisiting the hidden terminal problem in a csma/ca wireless network," *IEEE Trans. Mob. Comput.*, vol. 7, no. 7, pp. 817–831, Jul. 2008.

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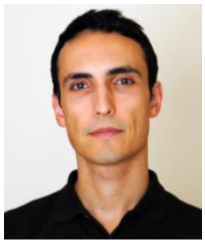

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