Latency Modelling in IEEE 802.11 Systems with non-IEEE 802.11 Interfering Source

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***Abstract*—Centralised wireless network management becomes increasingly common but requires information about wireless links to be able to properly use the existing spectrum. IEEE 802.11 employs the Distributed Coordination Function (DCF), which uses a decentralised Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) approach to control the access to the wireless medium. Both IEEE 802.11 and non-IEEE 802.11 sources can interfere with the transmission and degrade performance, but the impact of non-IEEE 802.11 interfering sources has not been extensively researched yet in literature. Only systems without a non-IEEE 802.11 interfering sources are considered in existing models. In this paper we explore the impact of non-IEEE 802.11 interference through realistic measurements in a large-scale wireless testbed. Based on these observations, we discuss the impact of an interfering source and identify the main components that affect the delay. We also propose an outline of a possible analytical model that we will extend in future work.**

I. INTRODUCTION

Wireless networks, especially IEEE 802.11, are used in a plethora of scenarios, ranging from small home networks to networks for large-scale events such as conferences and festivals. Particularly, in scenarios with a high number of stations, interference and collisions degrade the performance significantly. However, interference is not only caused by other IEEE 802.11 stations, but also by non-IEEE 802.11 sources, such as other radios (e.g., Bluetooth, IEEE 802.15.4, Long-Term Evolution (LTE) in unlicensed bands [1]) and even microwaves, screens or other Radio Frequency (RF) equipment. While interference from IEEE 802.11 stations already manifests a higher latency and lower throughput due to the employed back-off mechanism, the interference caused by non-IEEE 802.11 devices multiplies these negative effects due to the fact that those devices do not apply the rules of the IEEE 802.11 Medium Access Control (MAC) protocol and can cause latencies of up to several seconds depending on the location and surrounding environment of the device [2, 3].

This performance drop is caused by the way IEEE 802.11 handles transmissions. Contrary to licensed spectrum technologies that use a centralised resource allocation mechanism, such as LTE, IEEE 802.11 employs a Listen-Before-Talk (LBT) protocol to manage transmissions, implemented by means of a CSMA/CA protocol: before a station sends a packet, it senses the medium and only if the medium is idle, it will transmit the packet. The medium is sensed in two ways, Carrier Sense (CS) and Energy Detection (ED). The first detects and decodes IEEE 802.11 traffic and estimates how long the channel will be busy by reading the preamble. The latter detects energy from any source that surpasses a specified threshold. Therefore, the ED will detect the presence of non-IEEE 802.11 sources and prevents stations from sending if the detected energy is above a certain threshold. If a collision occurs (e.g. when the interfering source becomes active while a packet is being transmitted), the station backs off with the value of the back-off timer randomly chosen from its current Contention Window (CW) and re-transmit the packet. The size of the CW is doubled at each collision.

A first step in better managing IEEE 802.11 networks in current heterogeneous environments is to accurately assess the impact of non-IEEE 802.11 interference. This can be used to provide better Quality of Service (QoS) management for IEEE 802.11 networks, but also trigger handovers, or facilitate the application of load balancing to avoid links that are predicted to have degraded performance. However, little is known how this non-IEEE 802.11 interference impacts IEEE 802.11 performance exactly. This paper is the first that aims at accurately assessing the impact of non-IEEE 802.11 sources on the performance of IEEE 802.11 networks using measurements in a wireless testbed.This large-scale testbed approach allows the highest realism in assessing the complex interdependencies between wireless protocols. We characterise the interfering source in a general way so that different types (e.g. Bluetooth, LTE, microwaves, etc.) can be described by it. Based on the characterisation of the interfering source and the measurements from the wireless testbed, we outline a possible analytical model that will be further explored in future work.

The contributions of this paper are twofold. First, we have set up an experimental testbed consisting of one access point, up to 25 stations, and an interfering source. Using this testbed, we present measurement results with variable number of stations, variable packet arrival rates, and variable parameters that characterise the interfering source. Second, we identify the different factors that determine the packet latency in an IEEE 802.11 network with interfering source and outline an analytical model based on these factors..

The paper is organised as follows. First, we present related work and currently used models in Section II. Then we characterise a non-IEEE 802.11 interfering source and describe the impact of said source on an IEEE 802.11 network in Section III. Afterwards, we explain the reason why IEEE 802.1 reacts in this way and outline the components of an analytical model in Section IV. We conclude in Section V.

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II. RELATED WORK

Interference in wireless systems has been studied for a variety of interfering sources and it is known that different types of interference can have a detrimental effect. Simple probe requests can already have a significant effect on the performance of the network, although the station does not actively participate in the channel [4]. Ever denser network deployments increase the amount of interference between networks [5]. This can be passively monitored as well [6]. Additionally, interference can come from adjacent channels as well, as the frequency bands overlap [7]. Although, adjacent channels can improve throughput if used correctly [8]. Because of this, more and more managed tools attempt at detecting the presence of non-IEEE 802.11 interference. Airshark proposes a solution to detect non-IEEE 802.11 (Wi-Fi) interference with commodity hardware [9]. It is also shown that User Datagram Protocol (UDP) throughput is severely, over 90 %, reduced by different interfering sources such as a video camera, an analogue phone, or a microwave. Similar, the effect of digital cordless phones, baby monitors, and frequency hopping Bluetooth was explored. While Bluetooth has a minimal effect on throughput, cordless phones and baby monitors can completely drop the connection [10]. The general occupancy of the 2,4 GHz band can reach up to 34 % during busy hours [11] IEEE 802.11 networks also interfere with other network technologies like ZigBee and Bluetooth Low Energy, where the latter is performing slightly better [12]. Yi et al. provide accurate deployment guidelines for ZigBee to coexist with IEEE 802.11 based on interference avoidance and distance [13]. Large-scale and dense network measurements show that IEEE 802.11 performance can be severely degraded [3]. The high latency also indicates an interfering source. Introducing LTE into the unlicensed spectrum has severe impact on the performance of IEEE 802.11 [1, 14]. The throughput of IEEE 802.11 can decrease up to 98 % while LTE is barely affected.

In addition to the previously discussed measurements and real-life experience, analytical models have been developed that aim at modelling the latency and throughput of IEEE 802.11. One of the most prominent contributions for modelling IEEE 802.11 behaviour is the work from Bianchi [15]. It models the throughput in the saturated case, using a Markov chain to describe the process of the IEEE 802.11 transmission mechanism. Other authors extended this work and adjusted shortcomings such as accuracy, dropped packets, latency, jitter, power consumption, and the unsaturated case [16, 17].Combined models for the unsaturated and saturated case are presented as well [18].Error prone channels are taken into account in too [19]. Multi-hop networks are also taken into consideration where the authors focus on end-to-end latency [20]. At last, computation time is considered to show that in some cases a more inaccurate, but faster model is more beneficial [21]. None of these analytical studies consider interfering sources though.

III. IMPACT OF NON-IEEE 802.11 INTERFERENCE ON IEEE 802.11 NETWORKS

In this section, we explore the impact of the presence of an interfering source on the performance of an IEEE 802.11 network by means of a series of experiments on a testbed. We focus on the average packet latency, which consists of two parts, the waiting time in the queue and the access latency. When a packet is ready for transmission, it is placed in the MAC queue. The time needed to reach the head of the queue is called the waiting time in the queue. Once at the head of the queue, the station has to compete with other stations for getting access to the medium. This time is called the access delay. Finally, the packet is transmitted and in case of successful transmission, an acknowledgement is received. The total time between the arrival of the packet in the queue and the time instant the acknowledgement is received, is called the packet latency. In what follows, we first characterise the interfering source. Next, we describe the setup used in the experiments. Then we present results that show the impact of an interfering source on the performance of an IEEE 802.11 network.

A. Characterising an interfering source

We model the interfering source as an on/off process with exponentially distributed on and off periods. Interruptions of the medium access due to the interfering source generating energy above the ED threshold, occurs according to a Poisson process with rate ν. For example, a microwave oven, among others, can be modelled in such a way [22]. We assume that no new interruptions start during an ongoing interruption. We denote the random variable representing the length of the interruptions by u and we assume that u is exponentially distributed with mean $E[u]$. In view of the Poisson assumption, the average time the interfering source is not active (or generates energy below the threshold) is given by $\frac{1}{\nu}$. Then clearly the fraction of time the interference source is active is given by:

$$p_a = \frac{E[u]}{E[u] + \frac{1}{\nu}} \tag{1}$$

B. Experimental Setup

The w-ilab.t [1] lab facility has been used for our experimental study. W-iLab.t is an experimental, generic, heterogeneous wireless testbed, allowing large-scale wireless experimentation. It consists of 100 wireless nodes, supporting several wireless radios (IEEE 802.11, Bluetooth, etc.), Software Defined Radios (SDRs), and controllable robots, for mobility scenarios. For both the initial analysis and later validation, we use configurations of 15, 20, and 25 stations on the 5 GHz band with IEEE 802.11a. All stations are connected to one access point (AP) and are transmitting packets for 60 seconds. The experiment for each configuration was repeated 5 times to get reliable results. Additionally, we installed a Software Defined Radio (SDR) to generate interference according to the model defined in Section III-A. The stations are of type Zotac

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[1] http://doc.ilabt.imec.be/ilabt-documentation/index.html

TABLE I

AIRTIME OCCUPATION OF INTERFERING SOURCE FOR DIFFERENT PROBABILITIES AND TIMESLOTS USED IN THE PRESENTED EXPERIMENTS.

E[v] / $\frac{1}{\nu}$	$9 \cdot 10^{-5}$	$4.5 \cdot 10^{-4}$	$9 \cdot 10^{-4}$
$9 \cdot 10^{-4}$	9.1 %	33.33 %	50 %
$1.8 \cdot 10^{-4}$	33.33 %	71.4 %	83.33 %

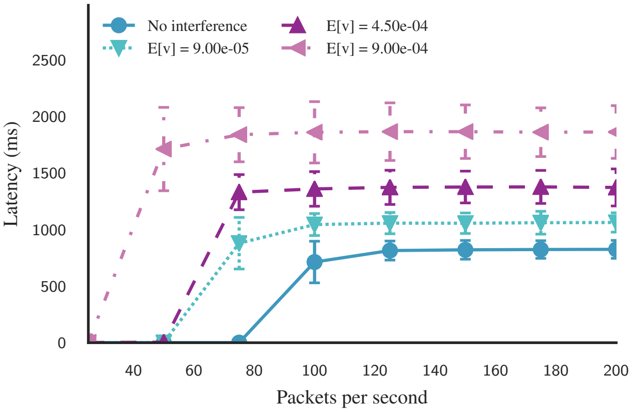

Fig. 1. Latency without and with interference with $\frac{1}{\nu} = 9 \cdot 10^{-4}$ s and 25 stations.

Zbox ID10 with IEEE 802.11n capable wireless cards, the AP consists of a PC Engines APU 1d4 with an IEEE 802.11ac enabled wireless card, and the SDR is a USRP N210.

For this experiment the occurrence of interference is set to two modes: $\frac{1}{\nu}$ equal to $9 \cdot 10^{-4}$ s and $1.8 \cdot 10^{-4}$ s. The interference duration $E[u]$ was set to: $9 \cdot 10^{-5}$ s, $4.5 \cdot 10^{-4}$ s, and $9 \cdot 10^{-4}$ s. The packets have a size of 1500 bytes and are sent at a fixed bit rate of 54 Mbps.

The number of packets per second was varied between 25 and 200 packets per second. We used a continuous packet source that generates packets on the MAC layer according to a Poisson process.

C. Results

As discussed in Section III-A, this combination of ν and $E[u]$ leads to different levels of airtime usage of the interfering source. We chose these values in such a way that the airtime usage varies from very little (9.1 %) to a significant amount (83.33 %). This is illustrated in Table I, which shows the relationship.

In the following graphs, we consider three parameters: the duration of the interference $E[u]$, the arrival rate of interference ν, and the number of stations N. All three different parameters have an impact on the saturation point, the point where the medium is fully used and therefore all participants are heavily competing for airtime, and the maximum delay.

Figure 1 shows the latency for variable $E[u]$. The interfering source becomes active according to $\frac{1}{\nu} = 9 \cdot 10^{-4}$ s, while the number of stations is fixed to $N = 25$. For once, we observe that for a fixed value of ν and an increase in duration of the interference the saturation point is reached earlier as the interfering source is occupying an increasing amount of the airtime. At the same time, we observe an increase of the average packet latency under saturation as well as stations have to wait longer until they can transmit.

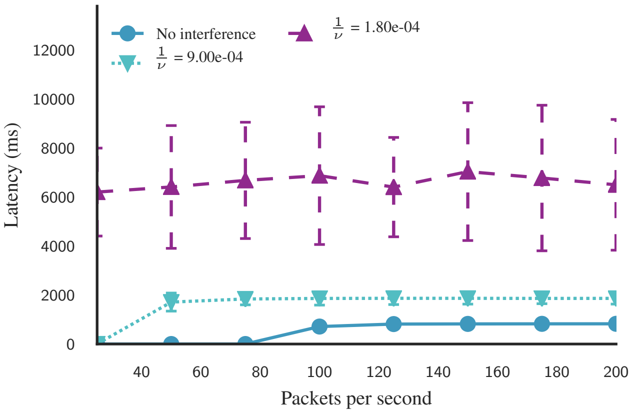

Fig. 2. Latency without and with interference with $E[u] = 9 \cdot 10^{-4}$ s and 25 stations.

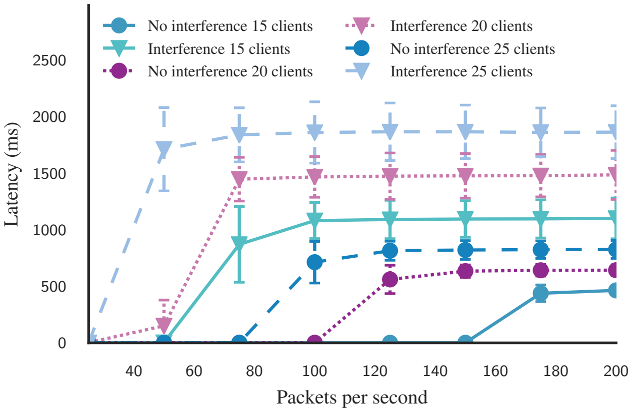

Fig. 3. Latency without and with interference with $\frac{1}{\nu} = 9 \cdot 10^{-4}$ s and $E[u] = 9 \cdot 10^{-4}$ s.

Figure 2 shows the impact of an increased packet rate and different values of ν. In this case, the number of stations was set to 25 and $E[u]$ to $9 \cdot 10^{-4}$ s. Similar to the previous case, an increase in ν shifts the saturation point towards lower load value due to a higher airtime usage of the interfering source. At the same, the average packet latency under saturation increases as well, in this case much more drastically then previously. Remark the large confidence interval for $\nu = 1.8 \cdot 10^{-4}$. This test yielded a very low number of successfully transmitted packets and therefore the variation is much higher.

In the last figure, Figure 3, the number of stations N varies from 15 to 20 to 25 while $E[u]$ and ν are kept constant: $E[u] = 9 \cdot 10^{-4}$ s, while $\frac{1}{\nu} = 9 \cdot 10^{-4}$ s. Even when no interference is present, the saturation point as well as the maximum latency shift with an increasing number of stations. A similar behaviour can be observed when interference is present. The interference is occupying a part of the airtime and the existing stations have to compete for the remaining airtime.

Summarising, we can see that a non-IEEE 802.11 interference source can heavily degrade performance. Saturation is reached much earlier and latency increases significantly due to competition in airtime usage. The latency can reach up to a maximum of 10 s, which means every type of connection suffers greatly. Obviously, the decrease gets worse the more interference is present in general, but there is an indication that different pairs of values of ν and $E[u]$, may lead to different behaviour of the average packet latency (both in absolute value and saturation point), although the fraction of time the interference source is active is the same for these pairs.

IV. DISCUSSION AND OUTLINE

From the previous experiments, it is clear that interference has a strong effect on the packet latency in an IEEE 802.11 network. While the effect of an increasing number of stations in a system with interference has a similar effect as in a system without interference, the effect of the parameters defining the interfering source, namely ν and $E[u]$ is more important. In what follows we discuss the reasons behind this impact.

First, when the interfering source becomes active, it does so regardless of other stations transmitting. Contrary to IEEE 802.11 stations, it does not listen to the channel and hence ignores the LBT IEEE 802.11 MAC protocol. While other wireless protocols may follow a similar principle, a microwave for example does not. This behaviour is also observed when LTE is present near an IEEE 802.11 network [1, 14]. As soon as the source becomes active, it collides with the packet being transmitted and hence interrupts the ongoing transmission. In addition, the affected station has to double its contention window, increasing the access latency. With a higher arrival rate ν, this effect is more prominent as the transmission of an important part of the packets do get interrupted by the interfering source becoming active.

Second, during the time the interfering source is active, no station can transmit packets. Each station that has a packet ready for transmission senses the channel as busy, as it detects the energy of the interfering source, and hence will postpone the transmission. This can also clearly be seen in the results where the latency increases significantly when $E[u]$ increases.

Third, the activity of the interfering source has an additional effect due to the back-off mechanism. As long as the interfering source is active, a station in the back-off state has to stop the countdown process. This implies that the value of $E[u]$ has an important impact on the access latency.

From the above discussion it is clear that the way the IEEE 802.11 MAC protocol is designed leads to additional packet latency in the presence of an interfering source. While ED and CS and the exponential back-off mechanism are a good compromise to grant access to stations that have similar behaviour, they do not work well when sources not obeying the same rules are present.

From this discussion, we can identify three components that are necessary for an analytical model:

First, based on the ED function of an IEEE 802.11 station, which senses for energy on the channel before it tries to send a packet, the station defers from transmitting a packet when the interfering source becomes active as it detects energy on the channel. In other words, the medium is not available for the duration of the activity of the interfering source (i.e. for $E[u]$ seconds on average). This time is referred to as the first component.

Second, the exponential back-off algorithm of the IEEE 802.11 MAC leads to additional latency. Indeed, in case a packet is being transmitted when the interfering source becomes active, it is lost in a collision with the signal of the interfering source. As a result, not only the packet needs to be re-transmitted, but in addition, the station will have to double its contention window for the next back-off phase. This additional latency is referred to as the second component.

Third, all stations having a packet ready for transmission while the interfering source is active, sense the medium active and hence will enter in a back-off phase after the interfering source becomes inactive again. The stations that are in back-off phase during the activity of the interfering source have to stop their back-off process until the medium is free again. This is referred to as the third component.

From these three components an analytical model can be formed that can predict the saturation point and maximum latency at saturation with an interfering source, based on values without an interfering source.

V. CONCLUSION

In this paper the performance of an IEEE 802.11 in the presence of an interfering source is investigated. Using large-scale measurements made in an IEEE 802.11 testbed, we show that the performance is heavily affected by such an interfering source, depending on its characteristics. Three characteristics of IEEE 802.11 were identified as components of an analytical model. First, the ED of a station will sense the medium busy as long as the interference source is active. Second, when the interfering source becomes active, it interrupts the current transmission and forces the station to increase its CW. Third, stations ready to transmit while the interfering source is active will enter an additional back-off when the interfering source becomes inactive. Based on these components, it is possible to formulate an ana

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REFERENCES

[1] A. M. Cavalcante, E. Almeida, R. D. Vieira, F. Chaves, R. C. Paiva, F. Abinader, S. Choudhury, E. Tuomaala, and K. Doppler, “Performance evaluation of LTE and

Wi-Fi coexistence in unlicensed bands," *IEEE Vehicular Technology Conference*, no. April 2015, 2013.

[2] IEEE Computer Society, "IEEE Standard for Information technology–Telecommunications and information exchange between systems Local and metropolitan area networks–Specific requirements - Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications," *IEEE Std 802.11-2016 (Revision of IEEE Std 802.11-2012)*, vol. 2016, pp. 1–3534, 2016.

[3] P. Bosch, J. Wyffels, B. Braem, and S. Latré, "How is your event Wi-Fi doing? Performance measurements of large-scale and dense IEEE 802.11n/ac networks," in *Proceedings of the IM 2017 - 2017 IFIP/IEEE International Symposium on Integrated Network and Service Management*, no. Im, 2017, pp. 701–707.

[4] X. Hu, L. Song, D. Van Bruggen, and A. Striegel, "Is There WiFi Yet? How Aggressive WiFi Probe Requests Deteriorate Energy and Throughput," in *Proceedings of the 2015 ACM Conference on Internet Measurement Conference - IMC '15*, 2015, pp. 317–323.

[5] S. Biswas, J. Bicket, E. Wong, R. Musaloiu-E, A. Bhartia, and D. Aguayo, "Large-scale Measurements of Wireless Network Behavior," in *Proceedings of the 2015 ACM Conference on Special Interest Group on Data Communication - SIGCOMM '15*, 2015, pp. 153–165.

[6] U. Paul, A. Kashyap, R. Maheshwari, and S. R. Das, "Passive Measurement of Interference in WiFi Networks with Application in Misbehavior Detection," *IEEE Transactions on Mobile Computing*, vol. 12, no. 3, pp. 434–446, 2013.

[7] P. Fuxjäger, D. Valerio, and F. Ricciato, "The myth of non-overlapping channels: Interference measurements in IEEE 802.11," in *2007 Fourth Annual Conference on Wireless on Demand Network Systems and Services, WONS'07*, 2007, pp. 1–8.

[8] E. G. Villegas, E. López-Aguilera, R. Vidal, and J. Paradells, "Effect of adjacent-channel interference in IEEE 802.11 WLANs," in *Proceedings of the 2nd International Conference on Cognitive Radio Oriented Wireless Networks and Communications, CrownCom*, 2007, pp. 118–125.

[9] S. Rayanchu, A. Patro, and S. Banerjee, "Airshark: Detecting Non-WiFi RF Devices using Commodity WiFi Hardware," in *Proceedings of the 2011 ACM SIGCOMM conference on Internet measurement conference - IMC '11*, 2011, p. 137.

[10] S. Gollakota, F. Adib, D. Katabi, and S. Seshan, "Clearing the RF smog: Making 802.11 Robust to Cross-Technology Interference," in *Proceedings of the ACM SIGCOMM 2011 conference on SIGCOMM - SIGCOMM '11*, 2011, p. 170.

[11] M. Cardenas-Juarez, M. A. Diaz-Ibarra, U. Pineda-Rico, A. Arce, and E. Stevens-Navarro, "On spectrum occupancy measurements at 2.4 GHz ISM band for cognitive radio applications," in *2016 International Conference on Electronics, Communications and Computers (CONIELECOMP)*, 2016, pp. 25–31.

[12] J. R. Lin, T. Talty, and O. K. Tonguz, "An empirical performance study of Intra-vehicular Wireless Sensor Networks under WiFi and Bluetooth interference," in *GLOBECOM - IEEE Global Telecommunications Conference*, 2013, pp. 581–586.

[13] P. Yi, A. Iwayemi, and C. Zhou, "Developing ZigBee Deployment Guideline Under WiFi Interference for Smart Grid Applications," *IEEE Transactions on Smart Grid*, vol. 2, no. 1, pp. 110–120, 2011.

[14] F. M. Abinader, E. P. Almeida, F. S. Chaves, A. M. Cavalcante, R. D. Vieira, R. C. Paiva, A. M. Sobrinho, S. Choudhury, E. Tuomaala, K. Doppler, and V. A. Sousa, "Enabling the coexistence of LTE and Wi-Fi in unlicensed bands," *IEEE Communications Magazine*, vol. 52, no. 11, pp. 54–61, 2014.

[15] G. Bianchi, "IEEE 802.11-saturation throughput analysis," *IEEE Communications Letters*, vol. 2, no. 12, pp. 318–320, 1998.

[16] P. Raptis, V. Vitsas, and K. Paparrizos, "Packet delay metrics for IEEE 802.11 distributed coordination function," *Mobile Networks and Applications*, vol. 14, no. 6, pp. 772–781, 2009.

[17] P. P. Pham, "Comprehensive analysis of the IEEE 802.11," *Mobile Networks and Applications*, vol. 10, no. 5, pp. 691–703, 2005.

[18] E. Felemban and E. Ekici, "Single hop IEEE 802.11 DCF analysis revisited: Accurate modeling of channel access delay and throughput for saturated and unsaturated traffic cases," *IEEE Transactions on Wireless Communications*, vol. 10, no. 10, pp. 3256–3266, 2011.

[19] F. Daneshgaran, M. Laddomada, F. Mesiti, and M. Mondin, "Unsaturated throughput analysis of IEEE 802.11 in presence of non ideal transmission channel and capture effects," *IEEE Transactions on Wireless Communications*, vol. 7, no. 4, pp. 1276–1286, 2008.

[20] A. M. Abbas and K. A. M. A. Soufy, "A queue state driven analysis of IEEE 802.11 DCF for ad hoc networks under non-saturation conditions," *International Journal of Computational Science and Engineering*, vol. 12, no. 2/3, p. 237, 2016.

[21] Y. W. Kuo, W. F. Lu, and T. L. Tsai, "A framework to approximate the delay distribution for IEEE 802.11 DCF protocol," in *Proceedings - MICC 2009: 2009 IEEE 9th Malaysia International Conference on Communications with a Special Workshop on Digital TV Contents*, no. December, 2009, pp. 874–879.

[22] H. Kanemoto, S. Miyamoto, and N. Morinaga, "Statistical model of microwave oven interference and optimum reception," in *ICC '98. 1998 IEEE International Conference on Communications. Conference Record. Affiliated with SUPERCOMM'98 (Cat. No.98CH36220)*, vol. 3, 1998, pp. 1660–1664.