Chapter 13
The Effect of Non-Wi-Fi Interference on the Throughput of IEEE 802.11 Based Wireless Networks

Ivan Forenbacher, Siniša Husnjak, Ivan Jovović, and Mislav Bobić

13.1 Introduction

In the next few years, IEEE 802.11 or Wi-Fi networks will continue to be one of the main options to meet the ongoing increase of network performance requirements in various industries, such as healthcare, stadiums, and hospitality [1].

IEEE 802.11 networks operate in two frequency bands: 2.4 and 5 GHz with a total of 14 overlapping and 24 nonoverlapping channels available, respectively, depending on the region [2].

However, interference is a perennial issue in IEEE 802.11 wireless networks which can drastically affect network performance, including throughput, if not managed properly. This is primarily because both bands are part of the unlicensed ISM (Industrial, Scientific, and Medical) which is used not only for Wi-Fi but also for non-Wi-Fi communication purposes, as well.

Interference can be categorized into Wi-Fi and non-Wi-Fi interference. The former represents the simultaneous coexistence of various Wi-Fi networks. The latter represents the coexistence of Wi-Fi and non-Wi-Fi devices operating at the same frequency, such as cordless phones, Bluetooth handsets, audio and video transmitters, microwave ovens, or baby monitors.

Both Wi-Fi and non-Wi-Fi interference may result with lower network throughput. This is primarily because the IEEE 802.11 station uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) and Clear Channel Assessment (CCA) mechanism before transmitting to check whether the channel is busy or idle [2, 3].

I. Forenbacher (✉) · S. Husnjak · I. Jovović · M. Bobić
Department of Information and Communication Traffic, Faculty of Transport and Traffic Sciences, University of Zagreb, Zagreb, Croatia
e-mail: iforenbacher@fpz.unizg.hr

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CCA consists of two related functions: carrier sense (CS) and energy detection (ED). The first is used to detect the presence of other Wi-Fi signals and can clearly determine the amount of time the medium will be busy. This is not possible with ED which is used only to detect the presence of non-Wi-Fi signals on the channel.

The Wi-Fi client uses ED primarily to sample the channel periodically to determine the presence of non-Wi-Fi RF energy [3]. The ED requires a predefined threshold that determines if the detected amount of energy is sufficient to report the medium busy or idle. If detected energy is above the threshold, the channel will be marked as busy, and the Wi-Fi station will have less time to transmit. On the other hand, if the Wi-Fi station transmits while there is another active non-Wi-Fi device on the same channel it may experience a loss of packets or a decrease of latency.

In other words, the network throughput depends on how much time the channel will be busy; the more time it's busy, there will be less time to transmit and, consequently, the lower data rates and/or the number of dropped packets will be increased.

IT managers and network practitioners need to completely understand the effects of non-Wi-Fi interference in order to continually improve their networks. Several researchers emphasize that they often ignore network throughput when deploying networks. For example [4, 5], claim they are often focused on ensuring signal coverage rather than achievable effective data rates, thus underestimating non-Wi-Fi devices and their impact on the throughput of IEEE 802.11 wireless network.

To avoid this, it is necessary to perform comprehensive analysis not only from data or transport layer but also from physical as well in order to detect potential non-Wi-Fi RF energy and understand its effect on IEEE 802.11 network throughput [5].

Therefore, we measured the effect of Line6 Relay G30 wireless audio transmitter on IEEE 802.11 network throughput in experimental laboratory environment. Such type of interferer is often used in various multipurpose environments, yet its impact on the network throughput has been often neglected in the literature. Our results can help network professionals, practitioners, and end users in providing additional understandings in troubleshooting non-Wi-Fi interference in local wireless networks.

13.2 Literature Review

The measurement and analysis of the effect of non-Wi-Fi interference on the performance of the IEEE 802.11 network have been the subject of various studies.

For example, researchers from [6] analyzed the influence of Bluetooth devices on the degradation of performance of IEEE 80.11b network and concluded that their coexistence significantly affects the increase of BER. Authors in [7] studied the impact of unintentional interferers like Zigbee. Their results suggest that throughput can drop by 20–40%. Researchers in [8] explored ways to mitigate the impact of microwave ovens on IEEE 802.11 networks.

More recently, a study from [9] analyzed the impact of various common non-Wi-Fi interferers, such as videophone and Bluetooth device, on network throughput. Results suggested that the throughput of the IEEE 802.11 network can be reduced by 26.5% and 7.5% if the Bluetooth handset and videophone, respectively, are in close proximity to Wi-Fi client. Authors in [10] found that radio frequency noise from a mobile computer platform worsens the performance parameters of IEEE 802.11 network, including throughput.

Researchers from [11] measured IEEE 802.11 network throughput and signal strength by simulating various scenarios that can be found in a home environment. Such scenarios included various distances, interferers, such as home appliances or Bluetooth devices, and obstacles between the access point and client device. They concluded that interferer such as microwave oven or Bluetooth device does not affect download and upload network throughput. However, the interference from such devices tends to decrease Wi-Fi signal strength, as well as the wall between Wi-Fi client and access point.

On the other hand, authors in [5] analyzed the effect of various devices such as microwave ovens, analog wireless video cameras, analog cordless phones, digital cordless phones, Bluetooth handsets, and wireless jammers on the throughput of the IEEE 802.11 network. Their results suggest that the immediate vicinity of the microwave oven can reduce throughput by 100% so that the Wi-Fi network becomes unusable. Similarly, an analog wireless video camera and an analog cordless phone can reduce the network throughput by 90–100% because they transmit continuously, thus occupying the channel for a significant amount of time.

However, previous work has only focused on devices mostly used in a home environment. To the best of authors' knowledge, the effect of a wireless audio transmitter on the throughput of IEEE 802.11 wireless network is not widely understood despite that is often used in various hospitality facilities. According to a recent survey, in such facilities, Wi-Fi is more important than, for example, parking or breakfast [12].

To fill these gaps, we measured the magnitude of wireless audio transmitter Line6 Relay G30 on the throughput of IEEE 802.11 network. We used an experimental laboratory environment in which we configured the IEEE 802.11 network and installed the Line6 Relay G30 wireless audio transmitter. The throughput was measured with two-speed test applications—Internet Speed Test and Speedtest By Ookla.

13.3 Equipment and Methods

13.3.1 Equipment Used

Wi-Fi Client

Mobile phone iPhone SE was used as Wi-Fi client. It was released in 2016 and supports IEEE 802.11a/b/g/n/ac standard, as well as Wi-Fi tethering. Additionally,

Table 13.1 D-Link DIR-615 general settings

Feature	Settings
BSSID	d_8
802.11 mode	b/g/n mixed mode
Band	2.4 GHz
Channel no.	6
Channel width	20(22) MHz

it supports HSPA, GSM, CDMA, EVDO, and LTE. The device falls in Category 4 according to LTE-A standard.

Non-Wi-Fi Interferer

Wireless audio transmitter Line6 Relay G30 was used as a non-Wi-Fi interferer. It was set up to operate on mode RF2 with two channels at 2428 and 2453 MHz which are near to central frequencies of Wi-Fi channel 4 in 2.4 GHz spectrum. Its range is up to 30 m, depending on the surroundings.

IEEE 802.11 Access Point

D-Link DIR-615 access point was used which supports IEEE 802.11b, g, and n standards. It has two fixed omnidirectional antennas with a gain of 2 dBi. Table 13.1 shows access point general settings.

After a quick examination of the area, we opted for channel 6 to minimize the potential effect of Wi-Fi interference. This is because on this channel the signal strength of other Wi-Fi networks was significantly lower (<−80 dBm) compared to the network tested (>−40 dBm). In addition, the channel was idle during measurement with 0% channel utilization from neighboring networks.

Spectrum Analyzer

Spectrum analyzer allowed us to examine the channel utilization and recognize various signal patterns on the physical layer in the monitored RF spectrum.

Hardware. Dual-band Ekahau USB was used to collect RF spectrum data. It has external RP-SMA Antenna, with a range between −100 and −6.5 dBm, and a resolution of 0.5 dBm. It supports both 2.4 and 5 GHz bands.

Software. Metageek Chanalyzer was used for real-time visual representation of collected RF spectrum data.

Throughput Test Application

Speedcheck Internet Speed Test[1] was used to measure the throughput of a wireless network. It is ranked the Apple App Store's top application for measuring network throughput. The application consists of iOS-based client and a worldwide network of high-speed servers for reliable results.

The test is Internet-based and performs through three general steps. First, the client establishes multiple connections with the closest throughput server. Second, the client application downloads or uploads a certain amount of data. Finally, the test ends once the configured amount of time expires and the final results are displayed.

13.3.2 *Experimental Wireless Network Settings*

An experimental network architecture was established in the Laboratory for Modeling and Optimizing Information and Communication Networks and Services at the Department of Information and Communication Traffic.[2]

Figure 13.1 shows the experimental network architecture settings we used for measuring wireless network throughput. The architecture consisted of the following nodes: iOS mobile phone with preinstalled throughput test client, IEEE 802.11b/g/n access point, a workstation with spectrum analyzer, Line6 Relay G30 wireless audio transmitter, and throughput test server.

Since the throughput test uses an Internet-based server, download and upload test path was *iOS Throughput Client → D-Link DIR-615 access point → Internet → Throughput Test Server*.

13.3.3 *Methods for Throughput Measurement and Data Analysis*

Throughput Measurement

Throughput was measured for previously described experimental network architecture settings. For measurement purposes, we have defined two scenarios:

- *Scenario 1 (control scenario).* Mobile phone is connected to access point (SSID = d_8) without introduced non-Wi-Fi interference. Figure 13.2 shows the settings of Scenario 1 on the physical layer.

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[1] More information: https://apps.apple.com/us/app/speedcheck-internet-speed-test/id616145031.

[2] More information: https://www.fpz.unizg.hr/ikp/eng.php.

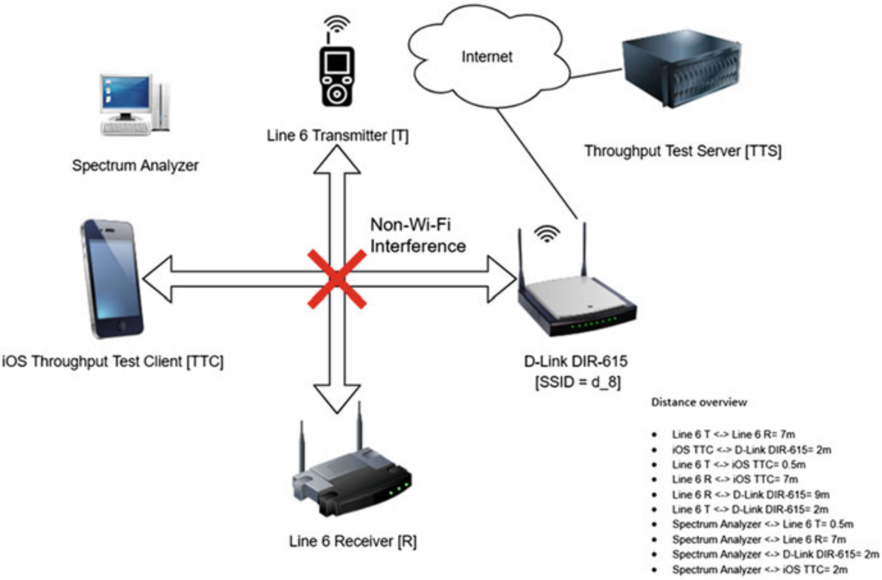

Fig. 13.1 Experimental network architecture settings for measuring the effect of non-Wi-Fi interference on the throughput of wireless network

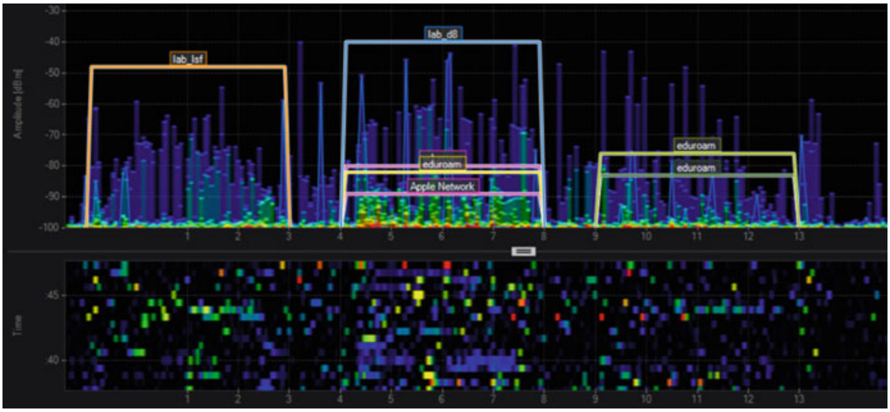

Fig. 13.2 RF spectrum of Scenario 1 in 2.4 GHz band without introduced non-Wi-Fi interference (d_8 is represented by blue line)

– *Scenario 2 (treatment scenario).* Mobile phone is connected to access point with introduced non-Wi-Fi interference from Line6 Relay G30 wireless sound transmitter. Figure 13.3 shows the settings of Scenario 2 on the physical layer.

Throughput was tested through four steps:

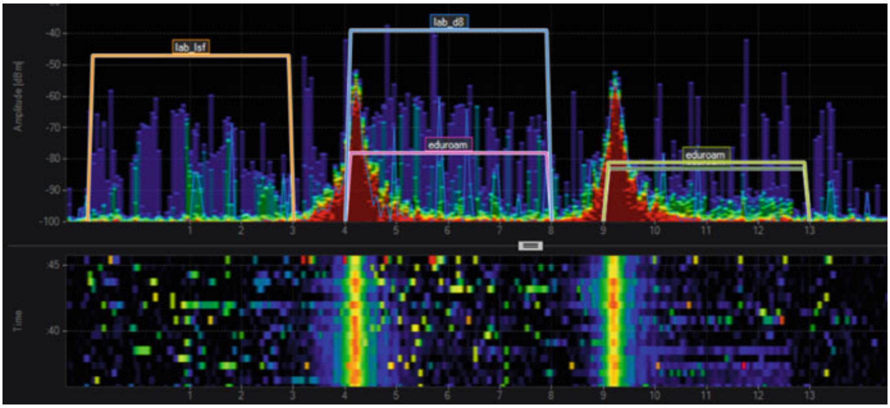

Fig. 13.3 RF spectrum of Scenario 2 in 2.4 GHz band with introduced non-Wi-Fi interference (Line6 Relay G30 is represented by two red peaks)

Step 1: 30 download measurements for Scenario 1
Step 2: 30 download measurements for Scenario 2
Step 3: 30 upload measurements for Scenario 1
Step 4: 30 upload measurements for Scenario 2

This resulted in a total of 60 measurements for download and 60 measurements for upload, or 120 in total. During all steps, all devices in the network were at a constant distance, and measurements were taken exclusively at periods with 0% of channel utilization which was examined by spectrum analyzer.

Data Analysis

Post-measurement data analysis was performed through four steps:

Step 1: Mean values for download and upload data rates for each scenario were obtained.
Step 2: Normality assumption for the data was evaluated.
Step 3: Bartlett's or Levene's test was chosen based on the results from the previous step to test the homogeneity of variances. The test was conducted separately between download and upload data rates obtained from Scenarios 1 and 2.
Step 4: Appropriate two-sample *t*-test was selected on the basis of the results from the previous step. The test was performed separately between download and upload data rates obtained from Scenarios 1 and 2 to test alternative hypothesis whether the mean difference is:

(a) greater than zero ($H_{\text{alternative}}$: diff > 0)
(b) different from zero ($H_{\text{alternative}}$: diff = 0)
(c) less than zero ($H_{\text{alternative}}$: diff < 0).

13.4 Results

13.4.1 Descriptive Statistics

Figure 13.4 shows the mean data rates. For scenario 1, the mean download data rate was 11.0878 Mbps with a standard deviation of 5.8539, while for Scenario 2 mean download data rate dropped to 1.66233 Mbps and a standard deviation of 1.1249.

The mean upload data rate during Scenario 1 was 14.9593 Mbps with a standard deviation of 3.8534 and then dropped to 2.2386 Mbps during Scenario 2 with a standard deviation of 1.8239.

13.4.2 Normality Test

We evaluated the normality of the data in order to select appropriate variance test in the next step. Figure 13.5 shows box plot for measured data rates by scenario. The middle line of the rectangle represents the median, and upper and lower limits represent the interquartile range.

After visually inspecting the box plot, we performed additional normality test based on skewness/Kurtosis to obtain the overall test statistics and test the null hypothesis that Download/Upload variables are normally distributed. Table 13.2 shows the results for normality test.

13.4.3 Variance Homogeneity Test

Since the overall test statistic for download from Scenario 1 (Table 13.2) was statistically significant at 5% level, we opted for Levene's test which is more robust to possible violations of normality assumptions.

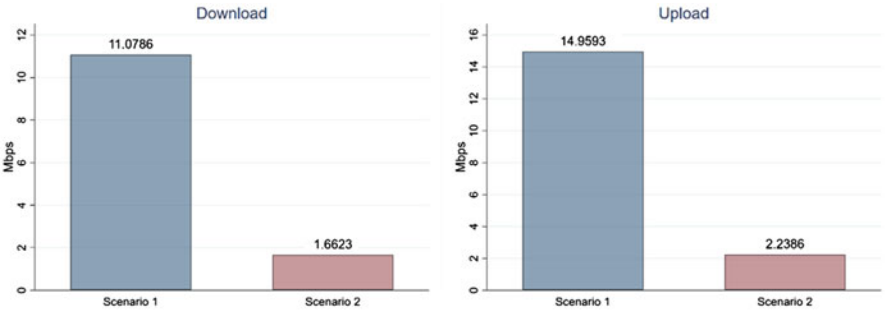

Fig. 13.4 Mean data rates

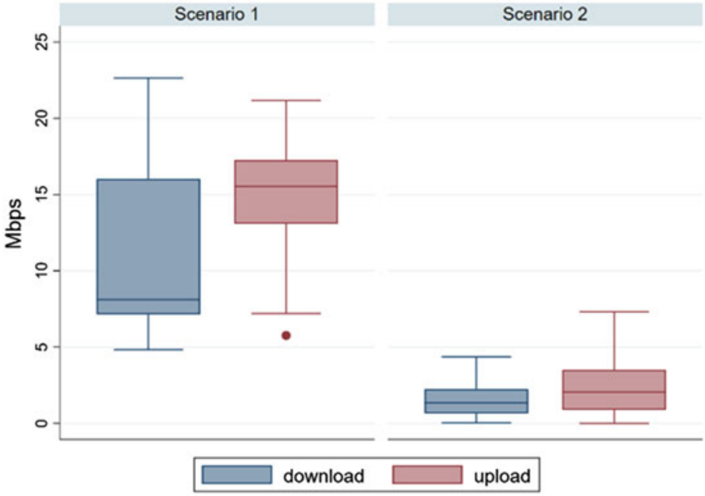

Fig. 13.5 Box plot of data

Table 13.2 Skewness/Kurtosis test

Variable	Scenario	Obs	Pr(skewness)	Pr(Kurtosis)	Overall test statistics	
					Adj chi2(2)	Prob > chi2
Download	Scenario 1	30	0.0265	0.5439	5.16	0.0759
Download	Scenario 2	30	0.0532	0.6844	4.11	0.1283
Upload	Scenario 1	30	0.1362	0.7623	2.56	0.2786
Upload	Scenario 2	30	0.0626	0.3746	4.38	0.1120

Table 13.3 Levene's test of homogeneity of variances for *download*

Group	Mean	Std. dev.	Frequency
Scenario 1	30	5.8539	30
Scenario 2	30	1.1249	30
Total	6.3705	6.3252	60
W_0	45.6455	df(1, 58)	$\Pr > F = 0.0000$
W_{50}	14.7967	df(1, 58)	$\Pr > F = 0.0003$
W_{10}	33.0838	df(1, 58)	$\Pr > F = 0.0000$

Tables 13.3 and 13.4 show statistically significant results from Levene's test with all p values < 0.001. Levene's test statistics W_0, W_{50}, and W_{10} were calculated based on the mean, median, and 10% trimmed mean, respectively.

The final step was to perform the t-test with unequal variances whose results are shown in the following section.

Table 13.4 Levene's test of homogeneity of variances for *upload*

Group	Mean	Std. dev.	Frequency
Scenario 1	30	3.8534	30
Scenario 2	30	1.8239	30
Total	8.599	7.0762	60
W_0	10.2758	df(1, 58)	$\Pr > F = 0.0021$
W_{50}	9.6094	df(1, 58)	$\Pr > F = 0.0029$
W_{10}	9.9085	df(1, 58)	$\Pr > F = 0.0025$

13.4.4 *t-Test with Unequal Variances*

Tables 13.5 and 13.6 show the results of a *t*-test for mean download and upload data rates, measured with Speedcheck Internet Speed Test.

13.5 Discussion

The main goals of this experiment were to analyze to what extent wireless audio transmitter Line6 Relay G30 affects the throughput of IEEE 802.11b/g/n/ network and to test whether the mean download or upload differ before and during non-Wi-Fi interference.

We found that Line6 Relay G30 caused a very serious degradation of network throughput. Mean data rates (Fig. 13.4) were reduced by 85%—from 11.0786 to 1.6623 Mbps for download, and from 14.9593 to 2.2386 Mbps for upload.

We tested the mean difference with *t*-test with unequal variances, obtaining statistically significant results at 1% level with p values < 0.001. Therefore, we can confirm alternative hypotheses that the mean difference between Scenarios 1 and 2 is not equal to zero ($H_{\text{alternative}}$: diff $= 0$, p value < 0.0001) and that is less than zero ($H_{\text{alternative}}$: diff < 0, p value < 0.0001). In other words, this means that measured data rates from Scenario 1 will be greater than those from Scenario 2.

To evaluate the validity of performing the *t*-test with unequal variances, we conducted two pre-estimation tests. First, we tested the normality assumptions of the data, obtaining results (Table 13.2) insignificant at 5% level and all p values > 0.05. Therefore, the null hypothesis that data don't violate normality assumptions cannot be rejected. Second, we tested the homogeneity of variances with Bartlett test since the normality assumption was not violated. The results were insignificant at 1% level and we couldn't accept the null hypothesis that variances are equal.

Therefore, we can confirm that data rates were seriously reduced during simultaneous coexistence of both IEEE 802.11b/g/n network and active interferer on the same channel in 2.4 GHz band. This is because Line6 Relay G30 wireless audio transmitter transmits continuously, thus occupying the channel most of the time.

Table 13.5 *t*-Test results comparing mean *Download* data rates of both scenarios

Group	Obs	Mean	Std. err.	Std. dev.	[95% Conf. interval]	
Scenario 1	30	11.0786	1.0687	5.8539	8.8927	13.2645
Scenario 2	30	1.6623	0.2053	1.1249	1.2422	2.0824
Combined	60	6.3705	0.8165	6.3252	4.7365	8.0044
Difference		9.4163	1.0883		7.197	11.6356
Diff = mean (Scenario 1) − mean (Scenario 2)						$t = 8.6520$
H_{null}: diff = 0			Satterthwaite's degrees of freedom = 31.139			
$H_{\text{alternative}}$: diff < 0 $\Pr(T < t) = \mathbf{1.0000}$		$H_{\text{alternative}}$: diff != 0 $\Pr(\lvert T\rvert > \lvert t\rvert) = \mathbf{0.0000}$			$H_{\text{alternative}}$: diff > 0 $\Pr(T > t) = \mathbf{0.0000}$	

Table 13.6 *t*-Test results comparing mean *Upload* data rates of both scenarios

Group	Obs	Mean	Std. err.	Std. dev.	[95% Conf. interval]	
Scenario 1	30	14.9593	0.7035	3.8534	13.5204	16.3982
Scenario 2	30	2.2386	0.333	1.8239	1.5576	2.9197
Combined	60	8.599	0.9135	7.0762	6.771	10.4269
Difference		12.7206	0.7783		11.1491	14.2922
Diff = mean (Scenario 1) − mean (Scenario 2)						$t = 16.3426$
H_{null}: diff = 0				Satterthwaite's degrees of freedom = 41.3728		
$H_{\text{alternative}}$: diff < 0 Pr($T < t$) = **1.0000**		$H_{\text{alternative}}$: diff != 0 Pr($\|T\| > \|t\|$) = **0.0000**			$H_{\text{alternative}}$: diff > 0 Pr($T > t$) = **0.0000**	

In other words, Wi-Fi station will detect non-Wi-Fi energy from the interferer on the physical layer and will either back-off from accessing the channel or will try to transmit but with an increased probability of dropped packets. In both cases, the network throughput will be significantly reduced.

This is consistent with the results from [5] that suggest that similar devices such as analog wireless camera or analog cordless phone can reduce the throughput of IEEE 802.11 network by a similar amount.

In contrast to other devices, Line6 Relay G30 reduced the network throughput three times more than Bluetooth handset or baby video monitor. For example, according to [9] such devices can reduce the throughput of IEEE 802.11 wireless network by 26.5% on average.

13.6 Conclusion

Interference is an important problem in 802.11 wireless networks. In this paper, we have measured the effect of audio video transmitter Line6 Relay G30 on the throughput of IEEE 802.11b/g/n network in 2.4 GHz band in laboratory environment. Such non-Wi-Fi device is often used in various hospitality facilities and may significantly affect the performance of Wi-Fi network.

To anticipate this, we suggest that it is necessary to diagnose the potential permanent and interim presence of non-Wi-Fi RF energy on the physical layer during network planning and deploying, and its impact on the network. We suggest that solutions for deploying of 802.11 wireless networks should pay special attention to non-Wi-Fi devices, especially in the hospitality industry where low Wi-Fi network performance can result in negative users' reviews (Red Roof Inn., 2020).

Our study may pave the way for similar future studies that should concentrate on interference measurements in different environments and scenarios to get a complete picture about the effects of nonhome and non-Wi-Fi interferers on IEEE 802.11 on wireless network performance.

Taken together, our analyses lead to the conclusion that intensive interference from devices like Line6 Relay G30 wireless audio transmitter may be critical for Wi-Fi communications if located near Wi-Fi stations, and can even interrupt communication or lower data rates to a level where IEEE 802.11 network is unusable.

Our study may help network practitioners and professionals, as well as end users to gain greater understandings of non-Wi-Fi interference landscape which may prove useful during the deployment of IEEE 802.11 wireless networks.

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