Before the
Federal Communications Commission
Washington, D.C. 20554

In the Matter of Request by Google LLC For Waiver of Section 15.255(c)(3) Of the Commission's Rules	File No.

To: Chief, Office of Engineering & Technology

REQUEST FOR WAIVER

Google LLC requests authorization to operate certain fixed and mobile field disturbance sensors in the 60 GHz band at a conducted power, mean power spectral density (PSD) Equivalent Isotropically Radiated Power (EIRP), and mean EIRP consistent with European Telecommunications Standards Institute (ETSI) standard EN 305 550.[1] The Commission presently allows operation of "mobile radars in short-range devices for interactive motion sensing" within the 60 GHz band, but at power levels too restrictive

[1] ETSI, *Electromagnetic Compatibility and Radio Spectrum Matters (ERM); Short Range Devices (SRD); Radio Equipment to be Used in the 40 GHz to 246 GHz Frequency Range; Part 2: Harmonized EN Covering the Essential Requirements of Article 3.2 of the R&TTE Directive*, ETSI EN 305 550-2 V1.2.1 (Oct. 2014), *at* http://www.etsi.org/deliver/etsi_en/305500_305599/30555002/01.02.01_60/en_30555002v010201p.pdf (EN 305 550). An updated version of EN 305 550 includes the same power levels and is expected to be cited in the Official Journal of the European Union in November 2018. *See* ETSI, *Short Range Devices (SRD); Radio Equipment to be Used in the 40 GHz to 246 GHz Frequency Range; Harmonised Standard for Access to Radio Spectrum*, EN 305 550, V2.1.0 (Oct. 2017), *at* http://www.etsi.org/deliver/etsi_en/305500_305599/305550/02.01.00_20/en_305550v020100a.pdf; ETSI, *Work Programme*, *at* https://portal.etsi.org/webapp/workProgram/Report_Schedule.asp?WKI_ID=46714.

for optimum use of the sensors.[2] Grant of this waiver request would "encourage the provision of new technologies and services to the public" consistent with Section 7 of the Communications Act of 1934,[3] align with the Commission's intent to allow radars to "detect hand gestures very close to a device to control the device without touching it," allow certification and marketing of devices including the Google sensors without adversely affecting operation of other devices in the 60 GHz band, and advance the Commission's efforts to harmonize its regulations and keep pace with global standards.[4]

I. Project Soli Benefits Consumers By Allowing Touchless Interactions with Devices.

Project Soli emerged from the work of Google's Advanced Technology and Projects (ATAP) group, which focuses on development of mobile technologies.[5] Using a sensor that operates between 57 and 64 GHz, Project Soli devices capture motion in a three-dimensional space using a radar beam. Data collected by the Project Soli sensor can be used to enable touchless control of device functions or features. For instance, sensor data allows devices to be more "aware" of their surroundings to allow them to enter sleep mode due to inactivity in their environment, or to allow users to trigger simple actions without having to touch the device. This could be particularly meaningful for users with mobility, speech, or tactile impairments.

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[2] *See In the Matter of Use of Spectrum Bands Above 24 GHz For Mobile Radio Services, et al.*, Report and Order and Further Notice of Proposed Rulemaking, 31 FCC Rcd. 8014, ¶ 337 (2016) *(Spectrum Frontiers Order)*.
[3] *See* 47 U.S.C. § 157(a).
[4] *Spectrum Frontiers Order* ¶ 337.
[5] *See* Soli *at* https://atap.google.com/soli/.

Grant of this waiver request would promote the public interest and further the goals underlying Rule 15.255. In July 2016, the Commission updated its 60 GHz rules in the *Spectrum Frontiers Order* to promote implementation of "mobile radars in short-range devices for interactive motion sensing."[6] While power levels adopted in the *Order* and set forth in Section 15.255(c)(3) of the Commission's rules may ensure that radars "operate at very short distances" to "minimize their harmful interference potential," they are too restrictive to adequately enable the types of activity expressly intended by the Commission.[7] Field testing of device prototypes within the currently allowed power levels has demonstrated that blind spots can occur as close as 5 cm to the sensor location. User studies of gesture-based operation conducted by Google have found that this is a considerably shorter distance than what users desire or expect for this functionality. Low power levels lead to user dissatisfaction from missed motions, the perception of intermittent operation, and ultimately fewer effective interactions.

II. Grant of the Waiver Would Advance Commission Policies To Harmonize U.S. Rules with Global Standards Without Generating Harmful Interference.

For the past two decades, the 60 GHz band has been utilized under the Commission's Part 15 rules for unlicensed operation.[8] The *Spectrum Frontiers Order*

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[6] *See Spectrum Frontiers Order* ¶ 337.
[7] *Id.*
[8] In 1995, the Commission adopted Rule 15.255 for unlicensed operation in the 59-64 GHz band. *See Amendment of Parts 2, 15, and 97 of the Commission's Rules to Permit Use of Frequencies Above 40 GHz for New Radio Applications*, First Report and Order and Second Notice of Proposed Rulemaking, 11 FCC Rcd at 4496, ¶ 33 (1995). In 2000, the Commission added 57-59 GHz. *See Amendment of Part 2 of the Commission's Rules to Allocate Additional Spectrum to the Inter-Satellite, Fixed, and Mobile Services and to Permit Unlicensed Devices to Use Certain Segments in the 50.2-50.4 GHz and 51.4-71.0 GHz Bands*, Report and Order, 15 FCC Rcd. 25264 (2000). The Commission extended the

ushered in potential use of “mobile radars in short-range devices for interactive motion sensing” at 60 GHz.[9] Although industry’s request for operation of mobile radars at power levels equal to “general technical requirements for communications devices”[10] operating in the 60 GHz band was unopposed,[11] the Commission was cautious when adopting its new rule. Citing lack of “sufficient information” about operation of these devices,[12] the Commission limited power levels for interactive motion sensing radars like Project Soli to the limits for fixed field disturbance sensors: peak transmitter conducted output power of –10 dBm and peak EIRP of 10 dBm.[13]

ETSI standards, however, allow for operation of generic short range devices within the 60 GHz band at power levels higher than permitted under the Commission’s rules. ETSI’s EN 305 550 standard permits operation of Project Soli technology and similar devices between 57 and 64 GHz at a conducted power of +10 dBm, a mean PSD EIRP of +13 dBm/mHz, and a mean EIRP of +20dBm.[14] Permitting use of Project Soli sensors in the U.S. consistent with EN 305 550 power levels would complement previous Commission action to promote harmony and keep pace with international standards.[15]

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coverage of Rule 15.255 to 64-71 GHz in the *Spectrum Frontiers Order. See Spectrum Frontiers Order* ¶ 125.

[9] *Spectrum Frontiers Order* ¶ 337.

[10] Google Comments in GN Docket No. 14-177, *et al.* at 9 (filed Jan. 28, 2016).

[11] *See Spectrum Frontiers Order* ¶¶ 335-336. *See also* 47 C.F.R. § 15.255(c)(1)(i) (limiting the average power of any emission to 40 dBm and the peak power of any emission to 43 dBm for communications devices).

[12] *Spectrum Frontiers Order* ¶ 337.

[13] 47 C.F.R. § 15.255(c)(3).

[14] EN 305 550 at 15 (Table 4).

[15] *See, e.g., In the Matter of Promoting Spectrum Access for Wireless Microphone Operations, et al.*, Order on Reconsideration and Further Notice of Proposed Rulemaking,

The Commission's rules attempt to prevent harmful interference to authorized radio services by limiting transmitter power and spurious emissions. Within the 60 GHz band, unlicensed devices can share spectrum cooperatively.[16] As the Commission has noted, its general policy for such unlicensed devices is that "they are not entitled to interference protection and they must not cause harmful interference to authorized services."[17] Consistent with this principle and the conclusions underlying EN 305 550,[18] testing of Project Soli technology has confirmed that the technology can operate harmoniously with other devices in the 60 GHz band.

Existing permitted users of the 60 GHz band include WiGig systems, a very small number of Federal Mobile, Fixed, InterSatellite and Radiolocation services and

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32 FCC Rcd. 6077, ¶ 13 (2017) (revising a rule to reflect ETSI spurious emission limits to harmonize with the standards that applied to an industry in other countries) (*Wireless Microphone Order*); *In the Matter of Amendment of Part 15 of the Commission's Rules, et al.,* Report and Order and Order, 29 FCC Rcd. 761, ¶ 44 (2014) (noting that harmonizing emission limits with the ETSI limits serves to expand global marketing opportunities for U.S. manufacturers).

16 *See In the Matter of Terrestrial Use of the 2473-2495 MHz Band for Low-Power Mobile Broadband Networks,* Report and Order, 31 FCC Rcd. 13801, ¶ 29 (2016) (noting the Commission has "on many occasions underscored that unlicensed devices operate under the fundamental condition that they are not protected against harmful interference."). *See also* Julius Knapp, Chief, Office of Engineering & Technology, FCC, *Industry Makes Progress on Unlicensed LTE Coexistence* (Sept. 23, 2016), *at* https://www.fcc.gov/news-events/blog/2016/09/23/industry-makes-progress-unlicensed-lte-coexistence (explaining, in the context of LTE, how industry created standards including Wi-Fi, Bluetooth, and Zigbee within the FCC regulatory framework to ensure cooperative sharing of "spectrum by unlicensed devices while recognizing that such devices are not protected from interference.").

17 *See Wireless Microphone Order* ¶ 6.

18 *See, e.g.,* CEPT ECC, *ECC Report 176*: *The Impact of Non-Specific SRDs on Radio Services in the Band 57–66 GHz* at 2, 5-6, Table 1, 17 (Mar. 2012), *available at* http://test.ecodocdb.dk/docdb/download/10688b3c-d70c/ECCREP176.PDF (demonstrating compatibility of services at 60 GHz to propose appropriate power limits) (ECC Study).

non-Federal Fixed, Mobile and Radiolocation services users, and industrial, scientific and medical equipment.[19] A 2012 report by the Electronic Communications Committee (ECC) of the European Conference of Postal and Telecommunications Administrations (CEPT) found that introduction of non-specific short-range devices within the ETSI EN 305 550's power limits was possible without producing harmful interference to existing 60 GHz spectrum users.[20] Simulations conducted for Google and provided with this request show there would be no substantial effect on colocated networks' Wi-Fi throughput from Project Soli sensors.[21] Furthermore, since 2015, application developers have field tested devices containing Project Soli sensors under an FCC experimental license at power levels up to +11dBm EIRP.[22] No reports of harmful interference have

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[19] *See In the Matter of Revision of Part 15 of the Commission's Rules Regarding Operation in the 57-64 GHz Band*, Report and Order, 28 FCC Rcd. 12517, ¶ 3 (2013) (explaining that "there are very few licensed Federal and non-Federal services operating in the 60 GHz band" and that Part 18 industrial, scientific and medical equipment may operate in the "60 GHz band at 61.25 GHz ± 250 MHz.").
[20] *See, e.g.,* ECC Study at 2, 17 (considering the conclusions of ECC Reports 113 and 114, as well as additional compatibility studies developed to consider compatibility between non-specific short-range devices and the Fixed Service to identify power levels acceptable from 57–66 GHz) (citing CEPT ECC, *ECC Report 113: Compatibility Studies Around 63 GHz Between Intelligent Transport Systems (ITS) and Other Systems* (Sept. 2007, rev. May 2009), *available at* http://www.erodocdb.dk/docs/doc98/official/pdf/ECCRep113.pdf; CEPT ECC, *ECC Report 114: Compatibility Studies Between Multiple Gigabit Wireless Systems in Frequency Range 57-66 GHz and Other Services and Systems* (*Except ITS in 63-64 GHz)*(Sept. 2007, rev. May 2009), *available at* http://www.erodocdb.dk/docs/doc98/official/pdf/ECCRep114.pdf).
[21] Dr. Stefan Mangold, Lovefield Wireless GmbH, *Assessing the Interference of Miniature Radar on Millimeter Wave 60 GHz Wi-Fi* (Feb. 21, 2018) at 1, 19, *appended as* Exhibit A.
[22] *See* Experimental Radio Station Construction Permit and License for Call Sign WI2XHG, File No. 0211-EX-PL-2016 (granted Apr. 15, 2016); Experimental Special Temporary Authorization for Call Sign WJ9XBM, File No. 0195-EX-ST-2016 (granted Apr. 2, 2016); Experimental Special Temporary Authorization for Call Sign WJ9XBM, File No. 0973-EX-ST-2015 (granted Oct. 2, 2015).

been reported from the testing, even though the devices operate at a power level higher than allowed under the current rule.

III. Granting a Waiver of Section 15.255(c)(3) to Enable Use of Project Soli Technology at Optimized Power Levels Would Serve the Public Interest.

Section 1.3 of the Commission's Rules allows it to waive any regulatory provision on petition if good cause is shown.[23] Waiver requests are assessed according to the *WAIT Radio v. FCC* standard, which states that waiver is appropriate where requested relief would further the public interest inherent in the underlying rule.[24] This request meets that standard. Implementation of the Project Soli sensor technology would directly advance the policy that the Commission sought to promote when it revised Section 15.255 of its Rules—enabling introduction of interactive motion sensors in smartphones and tablets in the 60 GHz band.

Significant benefits would arise from grant of the waiver request. Consumers are less likely to embrace gesture controls that have significant blind spots or that require complicated choreography to work reliably. With higher signal powers, Project Soli sensors can recognize gestures when a user's hand is farther from a device, which makes the feature much more convenient, intuitive, and useful for consumers. The radar signal could penetrate fabrics, enabling controls that could work in a pocket or a backpack. There would be more flexibility to integrate the Project Soli sensors in devices that partially occlude the antennas due to mechanical constraints. People with

[23] 47 C.F.R. § 1.3.
[24] *WAIT Radio v. FCC*, 418 F.2d 1153 (D.C. Cir. 1969).

mobility, speech, or tactile impairments could better experience the advantages of touchless technologies.

Grant of this waiver request would support American technical leadership in the consumer electronics field. It also would implement the Congressional mandate in Section 7 of the Communications Act of 1934 to "encourage the provision of new technologies and services to the public."[25] Absent permission to operate the Project Soli sensors at the requested power levels, users in European markets would have more robust experiences with devices containing this nascent interactive technology than American customers would. But, with grant of the waiver, Project Soli sensor technology could be implemented in the U.S. on terms equal to—and grow at rates at least as fast as—those overseas.

Conclusion

For the foregoing reasons, Google respectfully requests that the Commission grant this request for waiver of its rules to enable equipment certification, marketing, and effective operation of the Project Soli motion-control technology at a conducted power, mean PSD EIRP, and mean EIRP consistent with those in ETSI standard EN 305

[25] *See* 47 U.S.C. § 157(a). Section 7 calls upon the Commission to act expeditiously. 47 U.S.C. § 157(b). *See In the Matter of Encouraging the Provision of New Technologies and Services to the Public*, Notice of Proposed Rulemaking, GN Docket No. 18-22, FCC 18-8, ¶¶ 3, 6, 31 (rel. Feb. 23, 2018), In this instance, the Commission already determined that Project Soli technology serves the public interest by changing the 60 GHz rules in an effort to advance the technology. *See Spectrum Frontiers Order* ¶ 337. Grant of the instant request would be a mere extension of the previous Commission action to ensure the efficacy of the technology.

550, specifically a conducted power of +10 dBm, a mean PSD EIRP of +13 dBm/mHz, and a mean EIRP of +20dBm.

Respectfully submitted,

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Assessing the Interference of Miniature Radar on Millimeter Wave 60 GHz Wi-Fi

Simulation Study

Feb-21, 2018

Summary

1. Using stochastic simulation, this study assesses the potential interference of miniature radar systems on Millimeter Wave 60 GHz Wi-Fi, for a radar transmission power level of up to 10 dBm.
2. At the antenna locations of eight simulated Wi-Fi stations, three performance indicators are measured: (i) the power and interference levels, (ii) the signal to noise plus interference ratio, and (iii) the resulting degradation of the Wi-Fi system throughput.
3. In general, with a realistic duty cycle of 10%, the resulting interference does not exceed the level of the thermal noise in nearly all simulations and for all radar power levels. As a result, there is no substantial (harmful) effect on the Wi-Fi throughput.
4. The main findings are:
   (i) In 19% of all simulations for a +7 dBm radar (and 27% for a +10 dBm radar), an increase of interference power beyond the noise level can be observed, but only if the radar operates with a duty cycle of 100%. The interference power level does not exceed the thermal noise by more than 10 dB.
   (ii) An SNIR reduction of less than 5 dB can be observed in most of the simulations (80%), and less than 9 dB in nearly all others.
   (iii) In most of the simulations (80%), even with an aggressive duty cycle of 100%, the Wi-Fi throughput is only reduced by max. 10% for a 7 dBm radar, and by max. 16% for 10 dBm radar. Unlicensed radio systems like Wi-Fi can usually cope with such throughput reductions, for example by changing the modulation and coding schemes.

Table of Contents

1. Introduction

This document studies whether consumer-grade short range miniature radar devices create interference on other communicating systems operating in the 60 GHz unlicensed band, focusing particularly on 60 GHz Wi-Fi as specified in IEEE 802.11ad, 2014 or IEEE 802.15.3c, 2009).

Monte Carlo simulation with carefully justified radio system parameters is used to assess the interference impact of the miniature short range radars.

This study is intended to inform the discussion around an increased emission power of the Project Soli short range miniature radar system, as described in Google ATAP (2017), up to a level compliant with the ETSI EN 305 550 standard, although the results potentially could be extrapolated to similar technologies intended to operate within the 60 GHz band. Project Soli is a sensor for touchless gesture interactions in consumer electronics devices (wearables, home networks, phones).

1.1. FCC Rules

The FCC revised its rules for the license-free/unlicensed millimeter wave 60 GHz band in in 2016. This band is referred to as the 57-71 GHz band in section 15.255 of the FCC's rules (FCC, 2016).

Notable spectrum regulatory rules relevant to this study include:

1. In the 57-71 GHz band, operation is not permitted for field disturbance sensors unless employed for fixed operation or used as short-range devices for interactive motion sensing. The miniature short range radar described in Google ATAP (2017) falls under the definition of a field disturbance sensor used for short-range device for interactive motion sensing.
2. For fixed field disturbance sensors or sensors used as short-range devices for interactive motion sensing, the peak transmitter conducted output power[1] must not exceed -10 dBm (0.1 mW) and the peak EIRP level must not exceed 10 dBm (10 mW).
3. For the majority of radio systems operating in the 57-71 GHz band, permitted power levels are higher than for permitted field disturbance sensors employed for fixed operation or used as short-range devices for interactive motion sensing: The average emitted equivalent isotropically radiated power (EIRP) must not exceed +40 dBm (10 W) and the peak power of any emission must not exceed +43 dBm (20 W) EIRP, as measured during a transmission interval.

[1] The averaging interval must not include transmitter off times or periods of reduced power.

1.2. ETSI Standard

The European Telecommunications Standards Institute (ETSI) EN 305 550 standard for the unlicensed 60 GHz band, ETSI EN 305 550 V2.1.0 [ETSI 2014a, 2014b].

The EN 305 550 standard contains three restrictions with which a short range miniature radar system must comply. Two restrictions relate to the mean radiated power, and one relates to the mean power spectral density:

1. The mean radiated EIRP must not exceed 100 mW (20 dBm).
2. The mean transmission output power must not exceed 10 mW (10 dBm).
3. The mean transmission output power spectral density must not exceed 13 dBm/MHz EIRP.

In ETSI terms, the radiated power is the mean Equivalent Isotropic Radiated Power (EIRP) for the equipment during a transmission burst. The mean EIRP refers to the highest power level of the transmitter power control range during the transmission cycle if transmitter power control is implemented.

Further, the mean equivalent isotropic radiated power spectral density is defined as the emitted power spectral density over a defined bandwidth of the transmission, including antenna gain, radiated in the direction of the maximum level under the specified conditions of measurement.

The ETSI standard states that when determining the limits, they should be measured with an "*RMS detector and an averaging time of one millisecond or less*" [ETSI, 2014a].

1.3. 60 GHz Wi-Fi and other Victim Systems operating in the 60 GHz band

This study analyzes the effect of increasing the radio transmission power of a miniature radar system from 0.1 mW to 10 mW on 60 GHz Wi-Fi radio systems in a residential indoor scenario (one room with eight victim devices, see Section 2 for details).

Wi-Fi is the relevant wireless indoor communication system: In this study, Wi-Fi is used as example victim system because of its commercial relevance: 60 GHz Wi-Fi products are the de-facto standard for any in-building wireless networking system "*designed to share, usually within the same room, uncompressed high-definition data signals between consumer entertainment devices, such as high-definition televisions [...]*" [par. 5 in FCC (2013)]. The communication standard is similar to other short-range communication systems, such as future 5G radio systems and IEEE 802.15.3. For example, the standard IEEE 802.15.3 specifies the identical frequency channelization and a similar modulation and coding schemes as 60 GHz Wi-Fi (IEEE 802.15.3c, 2009).

Outdoor wireless communication systems: The unlicensed Millimeter Wave 60 GHz band is also allocated on a co-primary basis to the Federal Mobile, Fixed, Inter-Satellite and Radiolocation services, and to non-Federal Fixed, Mobile and Radiolocation services. These services are mostly relevant for outdoor communication such as Point-to-Point (P2P) communication systems (Example: AIRLINX, 2006). Equipment typically operates outdoors and uses beamforming antennas with high receiver directionality. These systems are "*intended to extend the reach of fiber optic networks by providing service to adjacent structures, provide broadband backhaul links between cellular networks base stations, or interconnect buildings in campus environments*" [par. 5 in FCC (2013)].

The effect on Wi-Fi is expected to be more significant than the effect on outdoor systems: "*Typically, an outdoor P2P 60 GHz transmitter employs a high gain, narrow beamwidth antenna that is aligned with the intended receiver, whereas a low-power indoor 60 GHz networking transmitter uses a lower gain and broader beamwidth antenna to serve several receivers within the network.*" [FCC (2013)]

There is little possibility that such outdoor systems will be harmfully affected by interference from miniature radars in consumer devices, because of their low power nature (mW instead of W), the directionality of the communications systems' receiver antennas, and the different deployment scenarios (generally indoor vs. outdoor/space). Inasmuch as miniature radar effects outdoor systems far less than nearby indoor systems, this study focuses on potential harmful interference to the more vulnerable indoor Wi-Fi systems.

Industrial, Scientific, and Medical (ISM): ISM equipment is permitted to operate at 61.25 GHz ± 250 MHz, under Part 18 of the FCC rules. These are often P2P long range, outdoor, or satellite communication systems that would not be affected by miniature radar consumer equipment for the same reasons stated above.

1.4. Document Outline

This study is outlined as follows. Section 2 describes the residential use case scenario and the analyzed radio systems. It describes the way the systems operate in the radio spectrum, antenna characteristics, and the applied modulation and coding schemes.

All of these characteristics motivate the assumptions for the simulation model, which are summarized in Section 3. Section 4 describes the way the interference is calculated. Section 5 contains the simulation results and key findings, which are summarized in Section 6.

Further details about the Monte Carlo simulation experiment and implementation details are given in the Appendix.

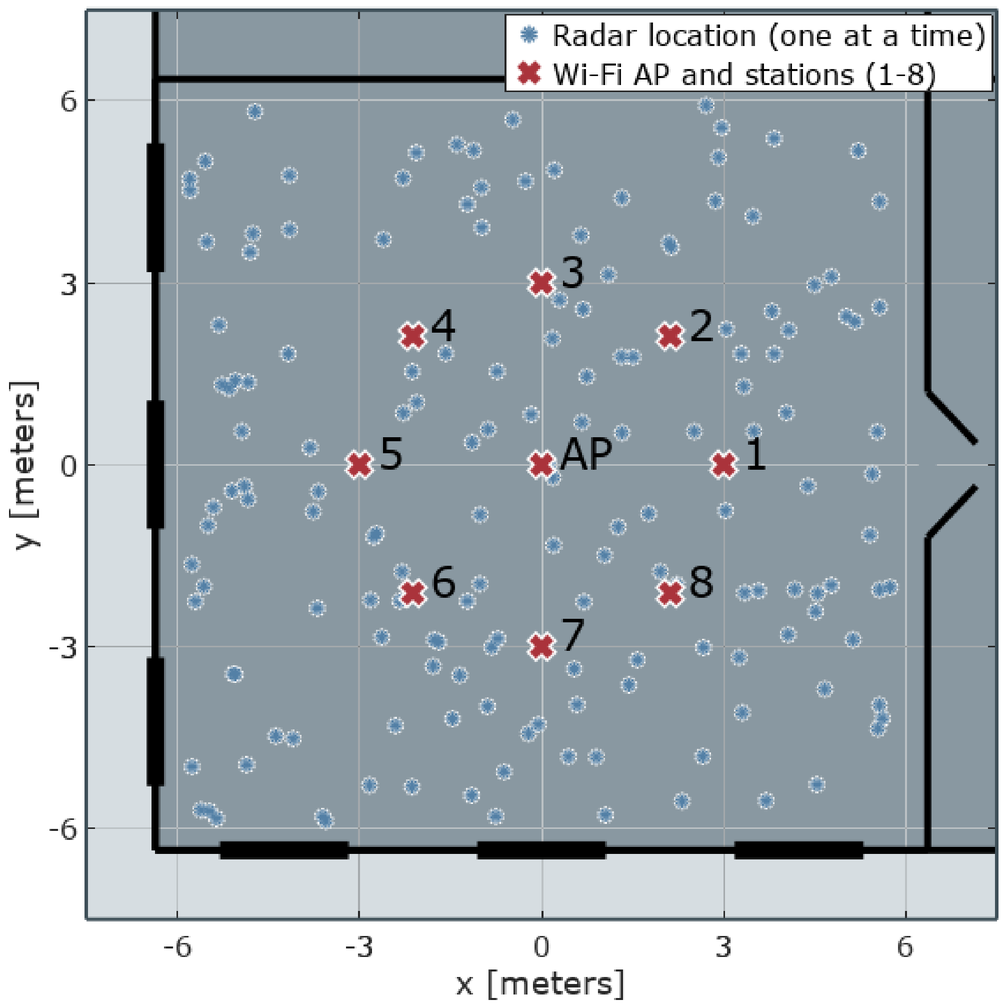


Figure 1: The simulation scenario: One room with eight receiving 60 GHz Wi-Fi stations, served by one 60 GHz Wi-Fi access point. One interfering radar system is located at a randomly chosen xy-location. The location is altered with each Monte Carlo iteration (i.e., with each repetition of the simulation), together with the antenna direction.

2. Scenario

A typical network topology of devices located in a residential room is used to analyze the interference scenario, illustrated in Figure 1. A single room of size 6m × 6m contains eight victim Wi-Fi stations, all located on a circle around the center of the room (three meter radius). There are no obstacles, and effects by the environment (wall reflections, shadowing, multipath) are ignored. A Wi-Fi Access Point (AP) transmits data to each of the eight stations. This AP is located in the center of the room.

The stations are exposed to interference from a single radar interferer. The radar interferer is a radar sensor that can track sub-millimeter motion at high speed and accuracy. It is a small device that fits on one single chip, and is intended to be used across a wide range of mobile, wearable, and stationary devices.

This interferer is positioned at random locations within the room. This location is changed repeatedly, from simulation to simulation, and the impact on the eight Wi-Fi stations is evaluated for all of the random locations. With each new simulation iteration, the antenna direction of the radar interferer also is changed to different, randomly chosen values.

There is no elevation; a 2D scenario is assumed. By assuming that all devices are horizontally aligned and located at the same height in the room, the attenuating effects of antenna characteristics in elevation are ignored in the interference model (for transmitters and receivers). This is a worst case assumption that will lead to more conservative results.

The impact of the radar signal at the location of the eight Wi-Fi stations is calculated with a free-space path loss propagation model, taking into account power budgets, noise levels, duty cycles, antenna directions, and antenna characteristics. The implemented free-space propagation model is a simple free-space attenuation model and documented in the appendix (see Code 2).

3. Radio Systems

3.1. Victim Radio System: 60 GHz Wi-Fi (IEEE 802.11ad, 2014)

In recent years, IEEE's project 802 has successfully created communication standards for short range wireless communication such as Wireless Local and Personal Area Networks (WLAN, WPAN). IEEE 802.11 for Wi-Fi and IEEE 802.15 for ZigBee and Bluetooth are among the standards with commercial success that are widely used today. These standards evolve over time and are regularly amended to enable improvements, including operation at higher frequencies. For example, the unlicensed Millimeter Wave 60 GHz band (14 GHz bandwidth, between 57 and 71 GHz) can be used by radio systems conforming with the Wi-Fi IEEE 802.11ad (2014) standard, and by devices complying with IEEE 802.15.3c (2009) for personal area networks.

Because of the commercial relevance of Wi-Fi for the consumer market, Wi-Fi IEEE 802.11ad (*60 GHz Wi-Fi*) is selected as the victim radio system over IEEE 802.15.3c. However, the two standards specify similar physical layer properties (modulation and coding schemes) and the same frequency channels. Hereafter, we refer to 60 GHz Wi-Fi as the victim radio system. A summary of the technical features of 60 GHz Wi-Fi is given by Cordeiro et al. (2010). Figure 2 illustrates the technical features relevant to this study.

Frequency Channels: There are four frequency channels with a bandwidth of approximately 2.16 GHz per channel that are affected by the miniature radar (with a bandwidth of 7 GHz).

As with legacy Wi-Fi operating at 2.4 GHz ISM or at 5 GHz U-NII, a basic service set (i.e., a cell or a group of stations) is comprised of one AP and its associated Wi-Fi stations.

One group of stations operates at one of the four channels. In the simulation scenario depicted in Figure 1, there is one AP. Hence, one group is modeled transmitting and receiving at one of the four frequency channels.

Listen-Before Talk Medium Access: Wi-Fi stations exchange data packets by using preamble-based listen-before-talk medium access protocol, as indicated in Figure 2. This means that there are times during which an interfering signal at that frequency channel will not create any harmful impact on the victim radio system. Specifically, during idle times and so-called backoff and carrier sensing times, when there are no data packet transmissions, but stations might sense for Wi-Fi

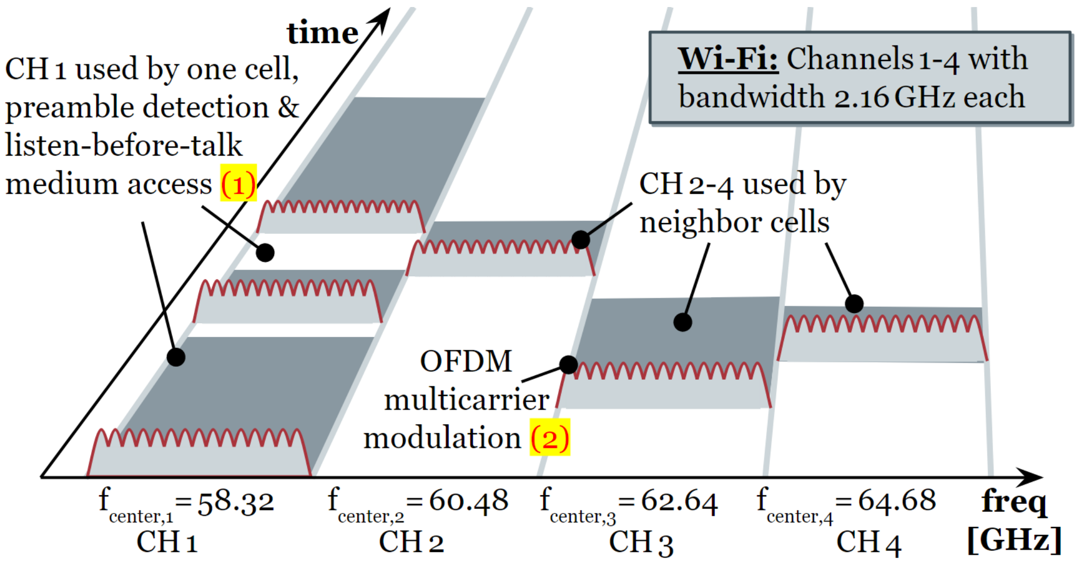


Figure 2: Victim radio system, 60 GHz Wi-Fi: Four frequency channels are shown. A group of Wi-Fi stations associated with each other operates at one channel. Wi-Fi stations exchange data packets using a preamble-based listen-before-talk medium access protocol (1). The majority of packet transmissions use OFDM multicarrier modulation (2).

preambles, any emission by an interferer will not create a significant degrading effect and therefore can be ignored in the simulation.

These periods of Wi-Fi inactivity, which generally total about 20% of the time, are not taken into account in the simulation model's interference calculation, for the sake of simplicity. Taking idle times, backoff, and carrier sensing times into account would reduce the level of predicted interference to Wi-Fi even below the level identified in this analysis.

Orthogonal Frequency Division Multiplexing (OFDM): Packet transmissions with OFDM multicarrier modulation are the modulation and coding schemes with the highest data rates in 60 GHz Wi-Fi, and radar interference would therefore have the worst effect on the Wi-Fi communication performance. OFDM is known for its robust protection against narrowband interference due to the Fourier-transform nature of OFDM: The energy of each bit is transmitted equally at each OFDM multicarrier, similar to spread spectrum modulation. For this reason, an interfering narrowband signal could harmfully interfere with one or a few OFDM subcarriers, but this affects all bits transmitted in an OFDM symbol equally. This effect is taken into account in the simulation as a way of simply treating the radar interference as a broadband interferer.

Table 1 summarizes the key features of the OFDM multicarrier modulation.

Channel bandwidth	2160 MHz
Occupied bandwidth	1830.5 MHz
Modulation	Spread QPSK, QPSK, 16-QAM, 64-QAM
Code rate	1/2 … 13/16
FFT size	512
Number of OFDM subcarriers	355 in total: 336 data, 16 pilot, 3 direct current
OFDM sample rate	2640 MHz
OFDM subcarrier bandwidth	2640 MHz / 512 = 5.15625 MHz
OFDM symbol duration	IDFT/DFT period 0.194us, guard interval 48.4ns
Phy bitrate	693 Mb/s (Mbps) ... 6756.75 Mb/s (Mbps)
Tx and Rx antenna beamform gain	8.5 dBi
Transmission peak power	Used in this study: 150 mW (21.76 dBm) EIRP[2] FCC limit: 20 W (43.00 dBm) EIRP
Receiver noise figure N_f	15 dB (Maltsev et al., 2015)

Table 1: 60 GHz Wi-Fi with OFDM multicarrier modulation (IEEE 802.11ad, 2014, Cordeiro et al., 2010).

3.2. Interferer Radio System: Frequency-Modulated Continuous-Wave (FMCW) Miniature Radar (Google ATAP, 2017)

The interferer radio system is a short range FMCW radar system. It is modelled in this study to operate with a radiated transmitter power of either -10 dBm (FCC rules for field disturbance sensors), or +7 dBm, or +10 dBm (ETSI standard). A 6 dBi transmitter gain antenna as shown in Table 2 is assumed.

In the simulation, a duty cycle of either 100 % or 10 % is used in the simulation model. For 100 %, the radar transmitter is modelled to be always on and operating, hence creating the maximum possible interference on other radio systems. In actual consumer applications, however, a duty cycle of 10% is much more likely to approximate the actual duty cycle for miniature radars.

This short range miniature radar enables touchless gesture interaction in consumer scenarios (for example, wearables, home networks, or cell phones). See Google ATAP (2017) for the intended use cases. The required precision of such a radar system is in the order of millimeters and can only be met by using radars that operate at a bandwidth of multiple GHz.

Table 2 summarizes the relevant features of the low power FMCW radar.

[2] Park et al. (2008) summarizes parameters for 60 GHz Wi-Fi radio transceivers.

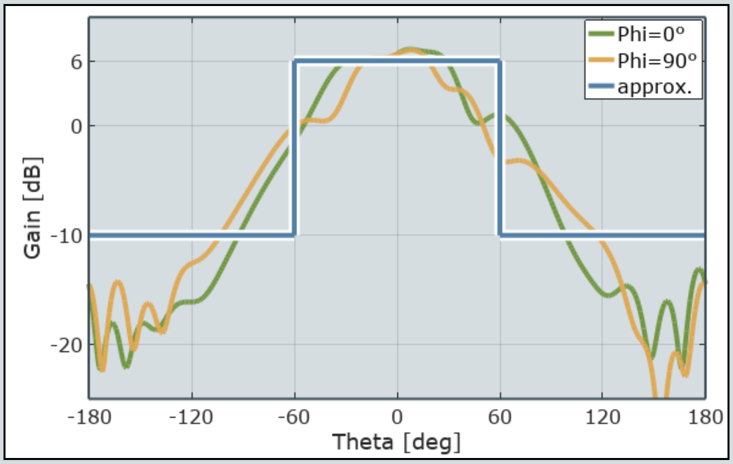
Signal type	continuous wave
Modulation	linear frequency modulation
Signal bandwidth	7000 MHz
Band of operation	57 GHz … 64 GHz
Sweep time	600 us
Transmission power	-10 dBm (0.1 mW) - FCC field disturbance +7 dBm (5.0 mW) +10 dBm (10.0 mW) - ETSI
Duty cycle	100 % (continuous emission) 10 %
Transmitter antenna gain	+6 dBi 

Table 2: Low power frequency-modulated continuous-wave (FMCW) radar (Google ATAP, 2017).

One single radar transmitter periodically and continuously sweeps through the unlicensed 60 GHz band (but only from 57 GHz to 64 GHz) with a sweep time of 600 us, as illustrated in Figure 3.

The continuous wave signal bandwidth of the signal that is sweeping through the band is small when compared to the victim radio system's operational bandwidth of 2.16 GHz, or the OFDM subcarrier bandwidth (~5 MHz).

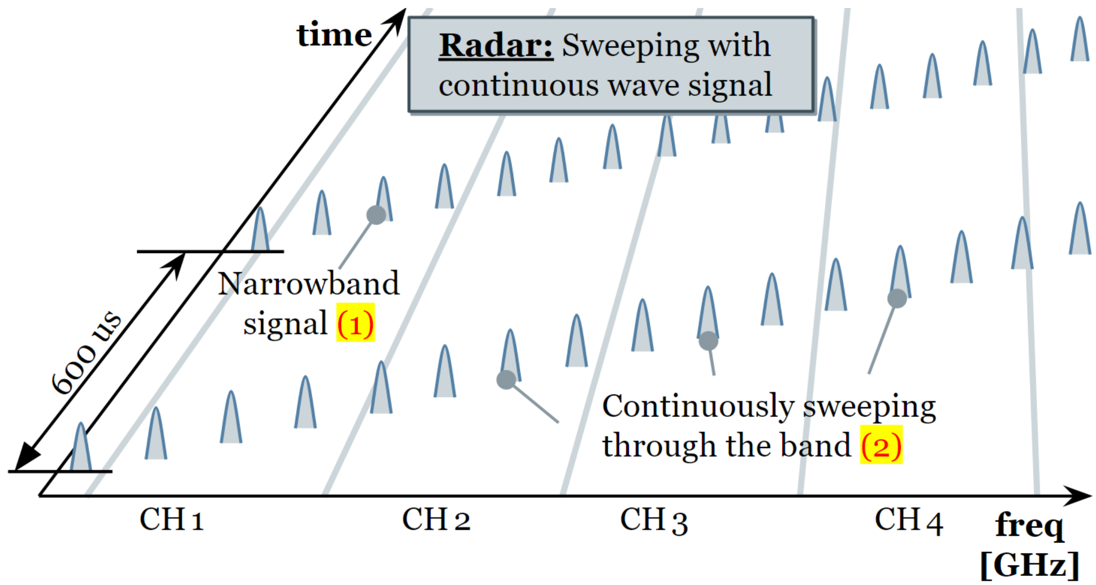


Figure 3: Interferer radio system, FMCW radar: The radar device sweeps continuously through the band of operation from 57 GHz to 64 GHz with a sweep time of 600 us (indicated as (2) in the figure). The signal is a continuous wave narrowband signal (1) with much smaller bandwidth compared to the victim radio system's OFDM subcarrier bandwidth.

4. Interference Model

The following model assumptions are taken for the interference calculations and to assess the impact of radar signals on the victim radio system. For every Monte Carlo iteration i, for each of the eight victim stations, and for each OFDM symbol on an OFDM data subcarrier, the ratio is calculated between the received intended signal S_{rec} to the unwanted radar interference ratio I_{rec}, the CoI, at the location of the receiving antenna. For one radar location, eight such CoI levels are calculated, because there are eight receiving stations. The thermal noise N depends on the OFDM subcarrier bandwidth, the temperature, and the receiver noise figure N_f as defined in Table 1.

In an OFDM symbol with its modulated subcarriers transmitted in parallel, the energy of each transmitted data bit is spread over all subcarriers. This is because OFDM is usually realized with a Fast Fourier Transformation (FFT). This leads to the assumption that any effect of a narrowband interferer, independent of where in the frequency it appears and of which subcarrier will be interfered with, is the same for the transmitted OFDM user data.

The radar interference will affect all data bits across all modulated subcarriers. When it sweeps through the frequency channel used by a 60 GHz Wi-Fi system, whenever the radar signal hits a subcarrier symbol, the interference power is effectively shared with all other subcarriers. This effect is taken into account in the interference calculation. See Figure 4 for an illustration.

The power levels of the receiver antennas are determined by the transmission powers, antenna gains and directions, and a simple path loss model as shown in Code 2.

Further assumptions are summarized as follows:

- Three levels for transmission power of the radar interferer are compared, with the power set to either -10 dBm (FCC field disturbance), or +7 dBm, or +10 dBm (ETSI).
- The victim radio system deploys multi-antenna beamforming, which is common in 60 GHz Wi-Fi, and supports the interference cancellation in the order of the receiver antenna gain.
- The access point at the center of the room broadcasts packets to all stations at an average EIRP transmission power of 150 mW (22 dBm), which is common to consumer grade 60 GHz Wi-Fi.
- To model the effect of preamble-based carrier sensing, a 20 % idle time and carrier sensing time for the victim radio system can be assumed, which is a time during which any interference can be neglected in the simulation model. In this study, this effect is ignored (worst case assumption).

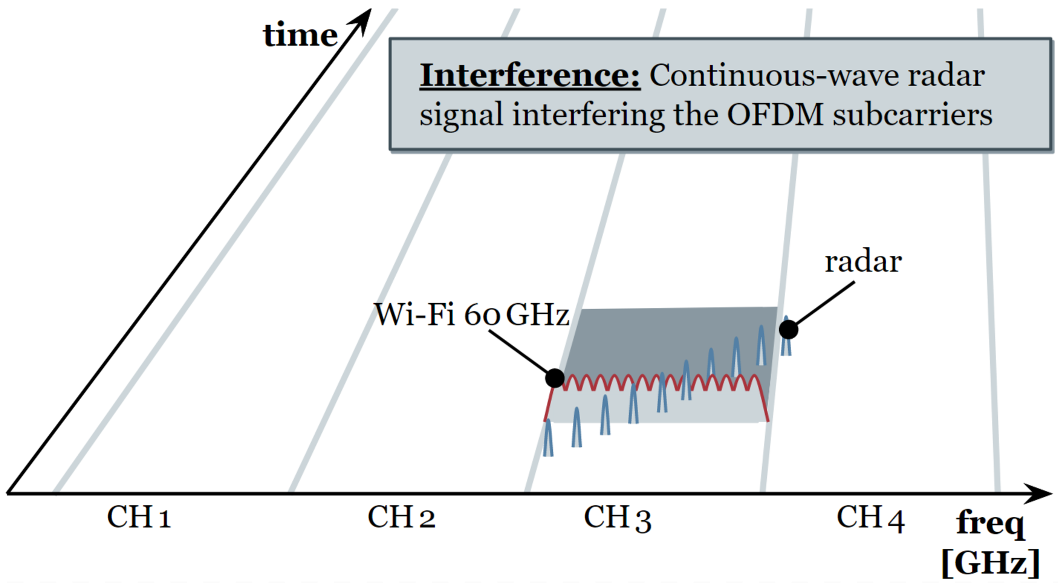


Figure 4: Interference calculation: The continuous wave radar signal is modelled as additional Gaussian noise, which, despite affecting only one OFDM subcarrier at a time, results in noise on all subcarriers.

- All victim radio system transmissions are assumed to be data packets transmitted with the OFDM multicarrier modulation and coding scheme. There are other more robust modulation and coding schemes used by Wi-Fi, for example during beamforming setup phases. These more robust schemes are ignored in this analysis.
- Due to the bit energy spread over all subcarriers in FFT-based OFDM, the interference of the continuous wave narrowband signals on multicarrier signals are mitigated by the number of OFDM subcarriers. This is taken into account by treating the narrowband interference as broadband interferer in the model.
- The FMCW radar signal sweeps through a broader spectrum than one Wi-Fi channel and creates interference only at a fraction of time. However, the sweep time is short. To sweep through one Wi-Fi channel takes less time than the duration of one Wi-Fi OFDM symbol duration (~242 us, see Table 1). Hence, a Wi-Fi data packet transmission is usually affected by multiple repeated sweeps. For this reason, the out-of-channel time is ignored and a continuous interference (worst case assumption) is assumed.

5. Results

Different metrics can be used to evaluate the Wi-Fi performance as the result of changing the radio transmission power of radar devices. This study uses the following three indicators, all measured at the locations of the eight Wi-Fi stations, and taking the antenna beamform into account:

1. The received power and interference levels. Results are shown in Figure 5 and discussed in Section 5.1.
2. The Signal-to-Noise and Interference Ratio (SNIR). The SNIR is evaluated with and without radar interference at three different power levels and for two different duty cycles. Results are shown in Figure 6 and discussed in Section 5.2.
3. The resulting channel throughput in Mbps directly derived from the SNIR. Results are shown in Figure 7 and discussed in Section 5.3.

Four configurations are analyzed: no radar (gray line), the -10 dBm low power radar (blue line), and the higher power radar (+7 dBm, green line; and the ETSI +10 dBm standard, purple line).

For all configurations, the radar is simulated both with an aggressive 100% duty cycle (thicker solid lines in all three figures) and with a more realistic 10% duty cycle (thin lines in all figures).

The results are produced with Monte Carlo simulations with 20'000 iterations.

The three figures show complementary cumulative distribution function (1-CDF, top figure) and the probability density function (PDF, bottom) of the resulting indicators.

5.1. Power Levels

Figure 5 illustrates the power levels at the eight locations of the receiving Wi-Fi stations, taking into account the Wi-Fi receiver antenna characteristics and all system parameters introduced in the previous section.

The two vertical lines indicate the noise level (gray) and the power level of the intended Wi-Fi signal from the access point (black). These two levels are assumed constant.

An increase of the interference power beyond the noise level can be observed only for a duty cycle of 100%, and then only in around 20-30% of the scenarios for the +7 dBm power level. This is also the case for the ETSI-compliant (+10 dBm) power level.

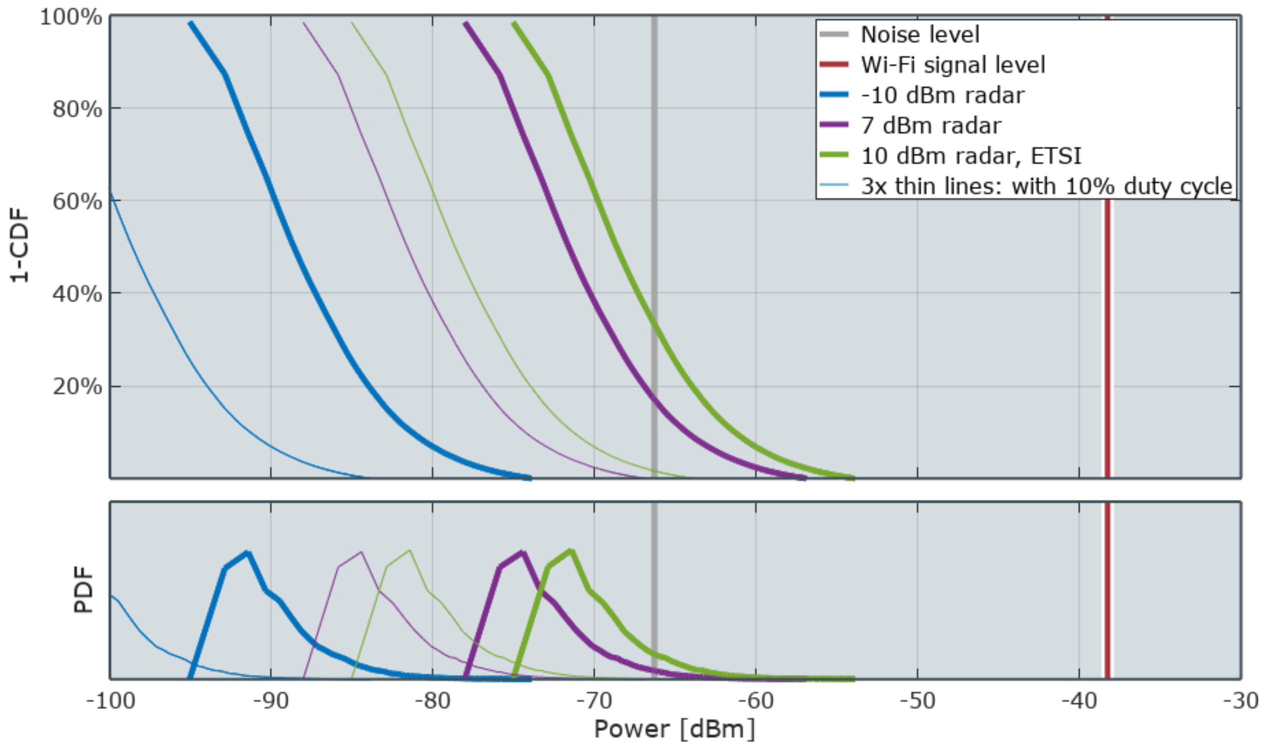


Figure 5: Received power levels at the eight locations of the Wi-Fi stations. Top: Complementary Cumulative Distribution Function (1-CDF). Bottom: Probability Density Function (PDF).

The interference power level increases by less than 10 dB in all cases. When duty cycling is used (thin lines), the resulting interference does not exceed the level of the thermal noise in nearly all cases, including the ETSI level.

5.2. Resulting SNIR Ratio

Figure 6 shows the resulting SNIR, as measured at the eight locations of the Wi-Fi stations, again taking into account the radio parameters and antenna characteristics of the involved systems.

For the +7 dBm radar signal, in 80% of the cases the SNIR is reduced by less than 3 dB, from 28 dB down to a value above 25 dB. With the ETSI-compliant +10 dBm radar, an SNIR reduction of less than 5 dB can be observed in 80% of the cases.

There is no significant reduction of the SNIR when a 10% duty cycle is applied, even for the ETSI level of +10 dBm.

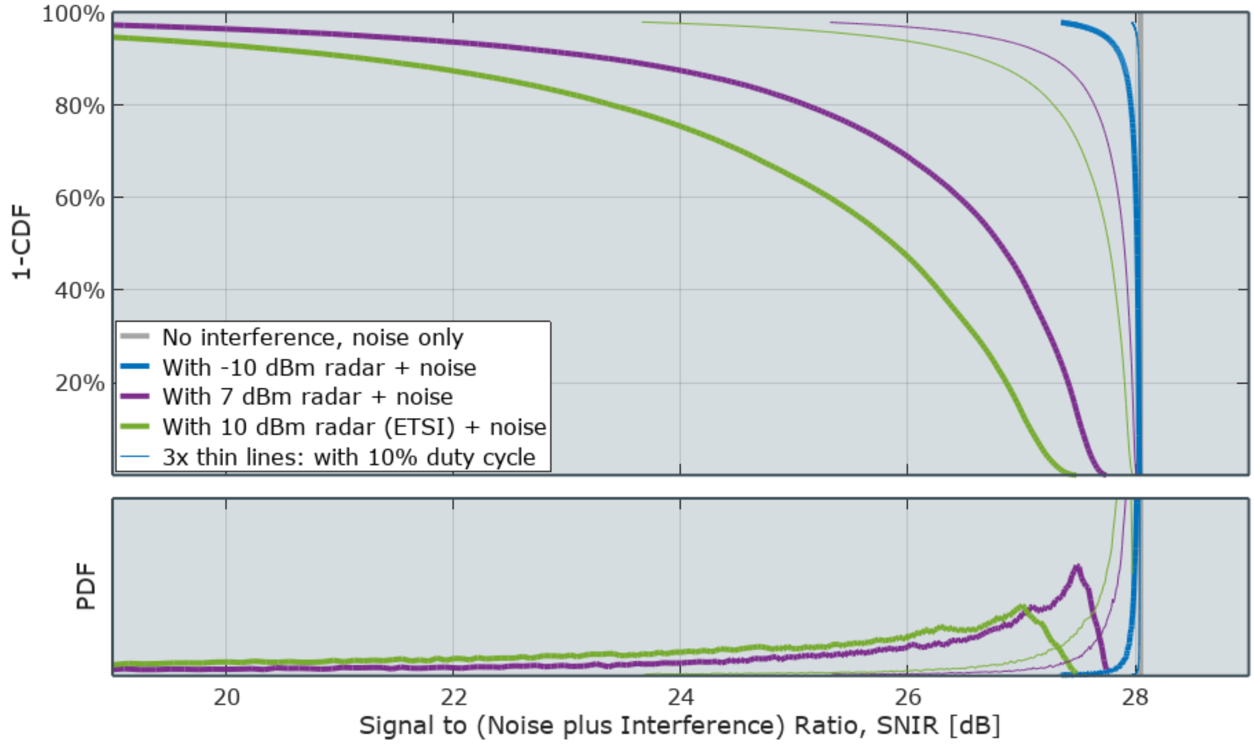


Figure 6: Resulting SNIR at the locations of the eight Wi-Fi stations. Top: 1-CDF. Bottom: PDF.

5.3. Resulting 60 GHz Wi-Fi Throughput

Figure 7 shows the resulting 60 GHz Wi-Fi physical layer throughput. This throughput is given by the channel capacity of an affected Wi-Fi channel, obtained simply through Shannon's channel capacity equation.

In the case of the higher power radars (+7 dBm and +10 dBm emission powers), for 80 % of the scenarios at a 100% duty cycle, the channel capacity is reduced from 8500 Mb/s down to around 7800 Mb/s (+7 dBm) and 7100 Mb/s (+10 dBm, compliant with ETSI's standard).

As before, when more realistic duty cycles of 10% are applied, no significant impact on Wi-Fi can be observed.

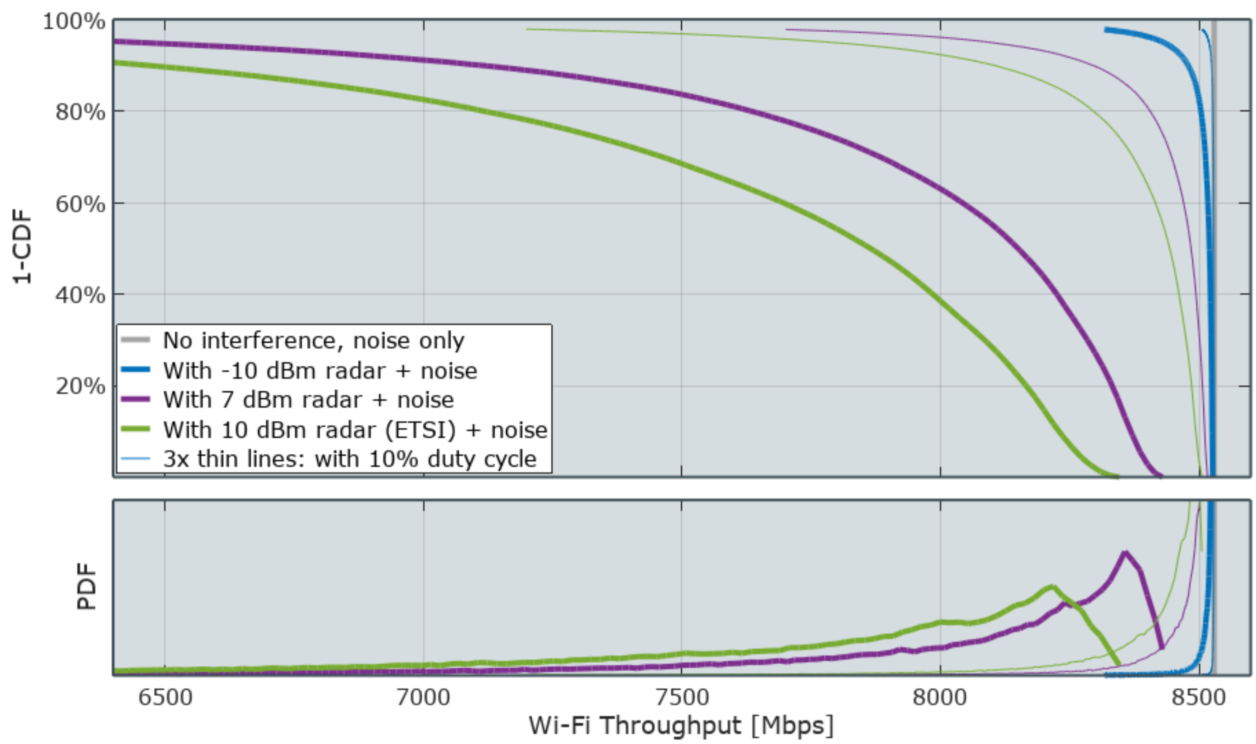


Figure 7: Channel capacity of one Wi-Fi channel, obtained through Shannon's channel capacity equation. Top:1-CDF. Bottom: PDF.

6. Summary

Using stochastic simulation, this study assessed the potential interference of miniature radar systems on Millimeter Wave 60 GHz Wi-Fi, for a radar transmission power level of up to +10 dBm.

At the antenna locations of eight simulated Wi-Fi stations, three performance indicators were assessed:

(i) the power and interference levels,
(ii) the signal to noise plus interference ratio, and
(iii) the resulting degradation of the Wi-Fi system throughput.

Given the residential room scenario and a free space path-loss model, as well as the system assumptions as described in this document, the main findings of this study can be summarized as below.

1. In general, with a realistic duty cycle of 10%, the resulting interference does not exceed the level of the thermal noise in nearly all simulations and for all radar power levels. As a result, there is no substantial (harmful) effect on the Wi-Fi throughput.
2. In 19% of all simulations for a +7 dBm radar (and 27% for a +10 dBm radar), an increase of interference power beyond the noise level can be observed, but only if the radar operates with a duty cycle of 100%. The interference power level does not exceed the thermal noise by more than 10 dB.
3. An SNIR reduction of less than 5 dB can be observed in most of the simulations (80%), and less than 9 dB in nearly all others.
4. In most of the simulations (80%), even with an aggressive duty cycle of 100%, the Wi-Fi throughput is only reduced by max. 10% for a 7 dBm radar, and by max. 16% for 10 dBm radar. Unlicensed radio systems like Wi-Fi can usually cope with such throughput reductions, for example by changing the modulation and coding schemes.

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Appendix

A: Monte Carlo Experiments

A Monte Carlo simulation experiment implemented in GNU Octave is used to stochastically determine the impact on unlicensed 60 GHz Wi-Fi stations. Monte Carlo experiments are computational algorithms that rely on repeated random sampling to obtain numerical simulation results. They are often used in complex physical problems and assessments of spectrum regulation rules. The Monte Carlo technique works by considering many independent events. For each event, a scenario is built up using different random variables, i.e. where the interferer is located with respect to the victim, in what direction the devices face, which channels the victim radio system devices are using, etc. If a sufficient number of simulation trials are considered, then the probability of a certain event occurring can be calculated with a satisfactory level of confidence.

Fixed simulation values are specified for parameters that do not vary throughout the simulation. The technical specifications of the radio systems are extracted from the relevant radio standards or system specifications (e.g., standards produced by IEEE).

B: Simulation Model

```
function [samples_W, samples_dBm radar_positions] = ...
 estimate_interference(NumOfMonteCarloIterations,x_WiFi,y_WiFi,P_Tx_radar_W, Gt, Gr)

 for wificnt = 1:size(x_WiFi,2)
  one_x_WiFi = x_WiFi(wificnt);  one_y_WiFi = y_WiFi(wificnt);
  for mccnt = 1:NumOfMonteCarloIterations % Monte Carlo ...
   x_radar = rand * r * 2 - r;             % randomize radar position
   y_radar = rand * r * 2 - r;
   radar_positions = [radar_positions [x_radar; y_radar]];
   [rx_W rx_dBm] = rxpower(P_Tx_radar_W, x_radar, y_radar, one_x_WiFi, one_y_WiFi,Gt,Gr);
   samples_W = [samples_W rx_W]; samples_dBm = [samples_dBm rx_dBm];
 end
end
```

Code 1: Interference calculation.

```matlab
function [Rx_W Rx_dBm] = rxpower(Tx_W,x_Tx,y_Tx,x_Rx,y_Rx,Gt,Gr)

distance_m = sqrt((x_Tx-x_Rx) .^2 + (y_Tx-y_Rx).^2);
distance_m = max(distance_m,1);  % assume distance>1m
global lambda;
ploss_dB = 20 * log10 (lambda ./ (4 .* pi .* distance_m));
Tx_dBW = 10 * log10 (Tx_W);
Rx_dBW = Tx_dBW + ploss_dB + Gt + Gr;
Rx_dBm = Rx_dBW + 30;
Rx_W = 10 .^ (Rx_dBW ./ 10);
```

Code 2: Propagation model. Because of the high frequency of millimeter wave radios, only line-of-sight paths and antenna directions are taken into account. The environment (wall reflections) is ignored.

```matlab
%% radio parameters for the miniature radar device ---------------------------
 P_TxRadarVers1_dBm = -10;
 P_TxRadarVers2_dBm = +7;
 P_TxRadarVers3_dBm = +10; % ETSI
 Gt_Radar_dBi = 6.5; % tx antenna gain of the miniature radar
 Gt_reverse_Radar_dBi = -10;

 % Given the antenna pattern of the radar device (-60..+60 degree), there is a one
 % in three chance that the radar hits the victim device with its beam, approximately:
 P_TxRadarVers1_dBm = 1/3 * (P_TxRadarVers1_dBm + Gt_Radar_dBi) + 2/3 * ...
   (P_TxRadarVers1_dBm + Gt_reverse_Radar_dBi);
 P_TxRadarVers2_dBm = 1/3 * (P_TxRadarVers2_dBm + Gt_Radar_dBi) + 2/3 * ...
   (P_TxRadarVers2_dBm + Gt_reverse_Radar_dBi);
 P_TxRadarVers3_dBm = 1/3 * (P_TxRadarVers3_dBm + Gt_Radar_dBi) + 2/3 * ...
   (P_TxRadarVers3_dBm + ... Gt_reverse_Radar_dBi);

 cycle = 0.1;   % Duty cycling
 cycle_dB = 10 * log10(cycle);
 P_TxRadarVers1_W = 10^(P_TxRadarVers1_dBm/10) * 1e-3; % W - hence divide by 1000
 P_TxRadarVers2_W = 10^(P_TxRadarVers2_dBm/10) * 1e-3; % also in W
 P_TxRadarVers3_W = 10^(P_TxRadarVers3_dBm/10) * 1e-3; % also in W

%% radio parameters for 60 GHz Wi-Fi ------------------------------------------
 P_TxWiFi_noGain_W  = 0.150;   % 150mW
 P_TxWiFi_noGain_dBm = 10*log10(P_TxWiFi_noGain_W * 1000);
 Gt_WiFi_dBi = 8.5; % WiFi transmitter antenna gain
 Gr_WiFi_dBi = 8.5; % WiFi receiver antenna gain

 % following regulation regarding EIRP, tx power is reduced by antenna gain:
 P_TxWiFi_dBm = P_TxWiFi_noGain_dBm - Gt_WiFi_dBi;
 P_TxWiFi_W = 10^(P_TxWiFi_dBm/10) * 1e-3;
```

```
 % Given the beamforming pattern of the Wi-Fi receiver antenna (8dBi), it might be that the radar
 % system does or does not hit the beam. We therefore introduce a Gr antenna gain
 % that is used for radar interference:
 Gr_WiFi_fromRadar_dBi = 1/4 * Gr_WiFi_dBi + 3/4 * 0;
 Nf_WiFi_dB = 15; % receiver noise figure

%% basic radio physics ------------------------------------------------------
 fc = 60e9; c0=3e8;
 global lambda;
 lambda = c0 ./ fc;
 Bandwidth_Hz = 1830.5e6; % in Hz
 Noise_W   = 10^(Nf_WiFi_dB/10) * 1.3806503e-23 * 293.15 * Bandwidth_Hz; % W, 15dB Nf
```

Code 3: System assumptions and radio parameters.

```
function main(NumOfMonteCarloIterations)

  [P_Rx_WiFi_W P_Rx_WiFi_dBm] = rxpower(P_TxWiFi_W, x_WiFiAP, y_WiFiAP, x_WiFi, ...
     y_WiFi,Gt_WiFi_dBi,Gr_WiFi_dBi);
  P_Rx_W = sum(P_Rx_WiFi_W) ./ size(P_Rx_WiFi_W,1); % averaged over the eight stations
  %% ---------------- MONTE CARLO ----------------
  [Intf1_W Intf1_dBm radar_positions] = estimate_interference(NumOfMonteCarloIterations, ...
     x_WiFi,y_WiFi,P_TxRadarVers1_W,Gt_Radar_dBi,Gr_WiFi_fromRadar_dBi);
  [Intf2_W Intf2_dBm radar_positions] = estimate_interference(NumOfMonteCarloIterations, ...
     x_WiFi,y_WiFi,P_TxRadarVers2_W,Gt_Radar_dBi,Gr_WiFi_fromRadar_dBi);
  [Intf3_W Intf3_dBm radar_positions] = estimate_interference(NumOfMonteCarloIterations, ...
     x_WiFi,y_WiFi,P_TxRadarVers3_W,Gt_Radar_dBi,Gr_WiFi_fromRadar_dBi);

  ColplusN1     = P_Rx_W ./ (Intf1_W + Noise_W);
  ColplusN2     = P_Rx_W ./ (Intf2_W + Noise_W);
  ColplusN3     = P_Rx_W ./ (Intf3_W + Noise_W);
  ColplusN1_duty     = P_Rx_W ./ (Intf1_W * cycle + Noise_W);
  ColplusN2_duty     = P_Rx_W ./ (Intf2_W * cycle + Noise_W);
  ColplusN3_duty     = P_Rx_W ./ (Intf3_W * cycle + Noise_W);
  ColplusN_noI  = P_Rx_W ./ (Noise_W); % no I

  C_WiFi1       = 0.5 * capacity (P_Rx_W, Intf1_W, Noise_W, Bandwidth_Hz); % overhead
  C_WiFi2       = 0.5 * capacity (P_Rx_W, Intf2_W, Noise_W, Bandwidth_Hz);
  C_WiFi3       = 0.5 * capacity (P_Rx_W, Intf3_W, Noise_W, Bandwidth_Hz);
  C_WiFi1_duty  = 0.5 * capacity (P_Rx_W, Intf1_W * cycle, Noise_W, Bandwidth_Hz);
  C_WiFi2_duty  = 0.5 * capacity (P_Rx_W, Intf2_W * cycle, Noise_W, Bandwidth_Hz);
  C_WiFi3_duty  = 0.5 * capacity (P_Rx_W, Intf3_W * cycle, Noise_W, Bandwidth_Hz);
  C_WiFi_noI    = 0.5 * capacity (P_Rx_W, 0, Noise_W, Bandwidth_Hz);
```

Code 4: Monte Carlo simulation. The code is taken from the GNU Octave implementation of the simulation model. It illustrates the simple repetition of the link budget interference calculations for random locations of the interfering devices.