Pasi Suhonen

Radio Frequency Interference Measurements in WLAN Networks

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PREFACE

Modern society depends on wireless communication transferring information between machines and humans. Wireless networks, such as WLAN networks, usually function without problems, but there can also be challenging difficulties. Most young network engineers have the capability for solving problems in the data link layer and above. This study has been done to evoke awareness of the first and most essential thing for successful wireless data transfer, i.e. the proper functioning of the physical layer. During the course of study, I learned that even normal everyday household machines, such as microwave ovens and Bluetooth device, can in the worst case cause serious interferences for the WLAN network physical layer signal operating in the 2.4 GHz ISM frequency band.

I have spent many hours and long nights to bring this study into a successful end. I would like to thank my instructors B.Sc.(Eng.) Markku Hintsala for teaching me modern spectrum analyzer technology and Principal Lecturer Matti Fischer for guiding me through the thesis writing process. Special acknowledgements go to my wife Kirsikka Suhonen and M.A.D.Sc.(Econ.) Marjukka Lehtinen for supporting and encouraging me during all those challenging times while studying. This study has been a long journey for me, but thanks to these remarkable people now it is successfully finished.

Hyvinkää, 15 March 2019
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External radio frequency interference signals are causing malfunctions and disruptions to indoor and outdoor WLAN devices degrading their Quality of Service (QoS). This study aims to help hospitals to ensure that their WLAN networks function without interference. To address this issue, this study adds to the knowledge of how to detect and measure interference signals from external sources and what kind of measurement equipment can be used for interference measurements. In practice, there were some challenges in data gathering in a hospital environment due to confidentiality and technical measurement test setup reasons. Instead of performing measurements in hospital premises, an experimental WLAN network was constructed in a sales office environment for interference and data bandwidth measurement purposes.

The study is divided in a theoretical framework and a practical part. The theoretical part focuses on explaining typical RF-interference signal characteristics and WLAN standards physical layer properties. The typical structure of hospital WLAN networks and properties of modern spectrum analyzer and measurement antennas were also described in theory. In the practical part of the study, a microwave oven and a Bluetooth loudspeaker were used as external interferer sources inside the experimental WLAN network. The frequency, power level, RF-bandwidth of interference signals and WLAN network data bandwidth were measured with a spectrum analyzer and a network performance software tool. The results of this study shows that an external interference source, such as a microwave oven or a Bluetooth device can cause problems to the WLAN network physical layer signal, and in the worst case dramatically decrease networks quality of service and performance. A modern real time spectrum analyzer in combination with a highly directive measurement antenna are the most effective choice of measurement equipment for detecting and measuring wideband, narrowband and periodical spurious interference signals in the WLAN networks.

Keywords	Interference, WLAN network, Spectrum analyzer

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Appendix 1. Spectrum analyzer measurement results for microwave oven RF-interference signals in swept tuned and real time modes.

Appendix 2. Spectrum analyzer measurement results for Bluetooth loudspeaker RF-interference signals in swept tuned and real time modes.

List of Abbreviations

ADC	Analog to Digital Converter
ADSL	Asymmetric Digital Subscriber Line
CSMA/CA	Carrier Sense Multiple Access with Collision Avoidance
CW	Continuous Wave
DANL	Displayed Average Noise Level
dB	Decibel
dBm	Decibel milliwatt
DC	Direct Current
DFS	Dynamic Frequency Selection
DHCP	Dynamic Host Configuration Protocol
DSSS	Direct Sequence Spread Spectrum
DUT	Device Under Test
EAP	Extensible Authentication Protocol
EMF	Electromagnetic Field
EMI	Electro Magnetic Interference
E-Plane	Plane which contains electric field vector for linearly polarized antenna
FFT	Fast Fourier Transform
FHSS	Frequency Hopping Spread Spectrum
FPGA	Field Programmable Gate Array
HPBW	Half Power Beamwidth
H-Plane	Plane which contains magnetic field vector for linearly polarized antenna
IEEE	Institute of Electrical and Electronics Engineers
IF	Intermediate Frequency
IP	Internet Protocol
IP2	Second Order Intercept Point
IP3	Third Order Intercept Point
ISM	Industrial, Scientific and Medical
IT	Information Technology
LAN	Local Area Network
LCD	Liquid Crystal Display
LHC	Left Hand Circular Polarization of Incoming Signal E Vector
LNA	Low Noise Amplifier
LO	Local Oscillator
MAC	Medium Access Control

MIMO	Multiple Input Multiple Output
MU-MIMO	Multi User Multiple Input Multiple Output
NIC	Network Interface Card
OCXO	Oven Controlled Crystal Oscillators
OSI	Open Source Interconnection
PBX	Private Branch Exchange
PDA	Personal Digital Assistant
PLL	Phase Locked Loop
PSK	Pre Shared Key
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
R&D	Research and Development
RAM	Random Access Memory
RBW	Resolution Bandwidth
RF	Radio Frequency
RFI	Radio Frequency Interference
RHC	Right Hand Circular Polarization of Incoming Signal E Vector
SHI	Second Harmonic Intercept
SSB	Single Side Band
SSID	Service Set Identifier
TCP	Transmission Control Protocol
TCXO	Temperature Compensated Crystal Oscillator
TKIP	Temporal Key Integrity Protocol
TPC	Transmit Power Control
UDP	User Datagram Protocol
UNII	Unlicensed National Information Infrastructure
UWB	Ultra Wide Band
VBW	Video Bandwidth
VLAN	Virtual Local Area Network
VSWR	Voltage Standing Wave Ratio
WAN	Wide Area Network
WIPS	Wireless Intrusion Prevention System
WLAN	Wireless Local Area Network
WPA2	Wi-Fi Protected Access II
WPA2-AES	Wi-Fi Protected Access II with Advanced Encryption Standard

1 Introduction

Over the past decade, the number of wireless transmitter devices has dramatically increased in the world. Wireless technology has become a critical part of our daily lives but, at the same time, radio frequency interference has become a real problem. Every significant electronic device leaks radiation. Today's radio frequency spectrum is very crowded. Almost every frequency is being shared by some other wireless device. These signals are creating noise, such as interference with other nearby signals, and causing disruptions for device and service functionality. Individual noise sources can consist of, for example, normal household appliances, cell phones, poorly shielded power lines or light systems. Locating an interference source, known as interference hunting, will be a major issue for engineers and spectrum managers in the future.

Today, Wireless Local Area Networks (WLAN) are deployed in almost all public and private facilities and buildings, and they allow users to access the Internet without being physically tied to a specific location. Electrically operated devices can cause interference in WLAN networks, and larger institutions, such as hospitals, can face truly complex issues in relation to interference signals. Devices with built-in transmitters include wide range of medical and commercial wireless devises.

Network administrators often deploy WLAN networks without knowing that non-wireless devices are also operating in the 2.4 GHz ISM band. For example, trace capture programs designed for Local Area Network (LAN) site surveys detect network traffic activity from data link layer and up (see figure 7). This means that they cannot detect any RF interferences coming from non-wireless devices. [4] For a more complete picture of the RF interference activity on the 2.4 GHz ISM band, network administrators also need to consider the physical layer, which is the focus of this study. The functionality of the first layer (physical layer) is an absolute necessity for the functionality of the rest of the layers.

1.1 Background of case company Rohde&Schwarz

The case company in this project is Rohde&Schwarz. It is a leading international company specialized in delivering products and services for commercial and government customers in the field of wireless communication technology. The company was founded in 1933 by two doctors Dr. Lothar Rohde and Dr. Hermann Schwarz, and the headquarters are located in Munich, Germany. Company revenue was over 2 billion euros in fiscal year 2017/2018 and the worldwide number of employees is around 10,500. The company is family-owned and self-financing. Headquarter is located in Munich. Production factory plants are located in Memmingen (Germany), Teisnach (Germany) and Vimperk (the Czech Republic).

1.2 Technology and business problem for RF interferences in WLAN networks

This study has been ordered by Rohde&Schwarz Finland Oy, one of the around 70 subsidiaries of the parent company Rohde&Schwarz GmbH&Co KG. The offices of the Finnish subsidiary are located in Vantaa and Oulu. The number of local employees is 27, consisting of administration, technical support, service and sales professionals. The product portfolio of Rohde&Schwarz Finland is exactly the same as that of the parent company. Rohde&Schwarz Finland has identified the health services sector as a lucrative business segment.

Radio frequency interference signals are causing malfunctions and disruptions to indoor and outdoor WLAN devices and degrading their quality of service (QoS). It can be difficult to find the interferer signals. Every interferer leaves a footprint that gives a hint as to what type of interferer it is. When the network or data transfer is not operating as it should, administrators typically purchase cheap measurement devices, which only reveal a part of the real problem but do not provide a comprehensive picture of the 2.4 GHz ISM or 5 GHz frequency band interference activity. In a sense, such measurement devices are basically only indicators. This means that the actual interference problem remains unsolved.

The solution would be to acquire a more sophisticated device, but this is not sufficient as such. The user must also know how to operate the device, how to interpret the measurement results and to understand how the WLAN networks and measurement devices work. This requires a willingness to invest in the device and to acquire expertise on the device.

1.3 Research question, scope and structure of the study for RF interference measurements in WLAN networks

This study aims to help hospitals to ensure that their WLAN networks function without interference. To address this issue, this study adds to the knowledge of how to detect and measure interference signals from external sources. The precise objective of this study is to identify and determine the characteristics of typical radio frequency interference signals that are causing problems in the WLAN network physical layer and suggest what kind of measurement equipment can be used for interference hunting. The outcome of this study is a concrete proposal for

- how to measure, detect and identify interference signals from the WLAN network physical layer
- what kind of measurement equipment can be used for interference hunting.

This thesis is divided into seven chapters. Chapter 1 outlines the introduction, objectives, scope and structure of the study. Chapter 2 describes the methods and material used in this study. Chapter 3 presents existing knowledge of technical environment. The purpose of this chapter is to explain the characteristics of radio frequency interference signals, WLAN network physical layer properties and characteristics, the typical structure of hospital WLAN networks and description of most common measurements devices used in interference hunting. Chapter 4 introduces practical interference measurements in office environment. The focus in this chapter is on measurement test setup, WLAN network physical layer interference measurement, WLAN network bandwidth measurement and analysis of measured data. Chapter 5 provides practical implications for the hospital WLAN network environment. Chapter 6 provides a proposal for RF interference measurement in the WLAN network physical layer and suggests what kinds of measurement equipment to use in RF interference hunting. Chapter 7 summarizes, evaluates and concludes the study.

2 Method and material of study

This chapter discusses in detail how the data for this research was collected, processed and analyzed. The study is divided into two parts, theoretical and practical. The theoretical part concentrates on collecting a systematic set of data around the subject. The practical part consists of actual interference measurements in office environment. State of the art measurement devices were used in order to create a high-quality and traceable set of measurement data.

2.1 Research design and approach

As shown in figure 1, the study started with a theoretical framework, which was focusing on collecting a systematic set of data around the subject. The data was collected from technical white papers, articles, literature, application notes and field test reports available in the internet, the university library and databases. The study continued to measurement data collection and the analysis part, where practical interference and WLAN network bandwidth measurements were conducted in business office environment and the measured data was analyzed. Based on the analyzed data, a literature outcome was created. It contains a proposal on how to measure, detect and identify interference signals from the WLAN physical layer and suggests what kind of measurement equipment can be used for interference hunting.

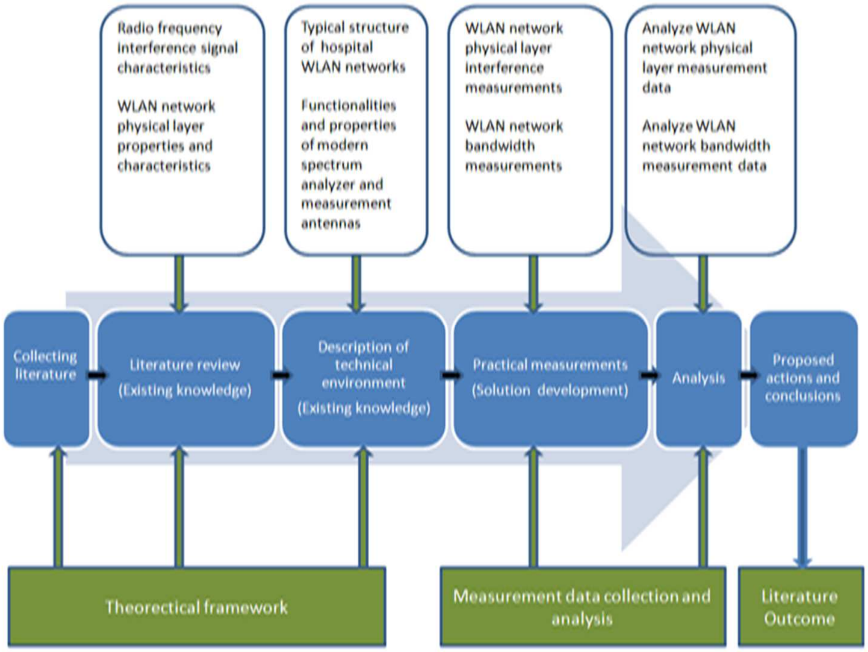


Figure 1. Research design of this study

The first step of the study focused on collecting relevant literature for the theoretical framework. The second step started with a literature review that describes characteristics of typical interfering signals and properties and characteristics of the WLAN physical layer. The third step explored the structure of hospital WLAN networks, functionalities and properties of modern spectrum analyzers and measurement antennas in order to be able to fully exploit the technical properties of the measurement device. The fourth step focused on practical WLAN physical layer interference signal measurements coming from typically used devices that operate at the same 2.4 GHz ISM band as WLAN access points.

Interference signal characteristics of a microwave oven and a Bluetooth loudspeaker were verified and their impact on the WLAN link data traffic bandwidth was studied. These two test devices were selected because they are easily available and widely used. In the fifth step, the properties and characteristics of measured interference signals and their impact on the WLAN link data traffic bandwidth was analyzed. The sixth step created a literature outcome that was based on the analyzed data. An outcome proposed how to measure, detect and identify interference signals from the WLAN physical layer and suggest what kind of measurement equipment can be effectively used for interference hunting.

Every physical environment is unique with respect to RF-interference signals. Such interference can be studied by using many different methodologies and measurement devices. It could be possible to create separate application instructions for various devices, but the list would not be suitable for all environments as such. Possible sources of interference can include electronic devices, mobile networks, broadcasting networks, or electrical appliances such as electrical motors, elevators, lightning appliances and light switches.

The person conducting the measurements must know the environment so that he can recognize signals coming from different sources of interference. This is a long-term and technologically demanding work that can only be learned through practice. This study focuses on interference signals coming from microwave ovens and Bluetooth loudspeakers so that the thesis will not be too extensive. These devices are commonly found in all hospitals.

In practice, the measurements were conducted by first measuring the WLAN access point physical layer signal with a spectrum analyzer without activating external interference sources. The measurement result of the spectrum analyzer and WLAN link data traffic bandwidth was measured and recorded. The purpose of recording the data traffic bandwidth of the WLAN access point was to show how external RF interferences can affect the quality of the service (QoS), such as data traffic bandwidth. After this, external interference sources were switched on one at a time and the measurements explained above were repeated.

The RF interference measurement results of the spectrum analyzer were stored as screenshots in the memory of the measurement device. The purpose of the screenshots was to ensure repeatability and traceability of the measurements and to present the measurement results in a clear graphic format. The person making the measurements analyzed the following properties from the measurement results of the spectrum analyzer: The frequency, bandwidth and power level used in the WLAN access point and the characteristics of the external interference signal, such as frequency, power level and RF- bandwidth.

The IP-data traffic bandwidth used in the WLAN network was measured with Internet Protocol (IP) network bandwidth analyzing tool jPerf [11]. Test measurement results were entered into excel sheet graphical chart presented in this thesis.

The person conducting the measurements of interference signals must have thorough understanding of the following:

- What kind of physical environment measurements are performed
- What is the typical structure of the WLAN networks
- What are the basic properties of expected interference signals
- Which measurement devices are suitable for interference hunting
- How to operate the measurement devices
- How to analyze, store and interpret the measurement results

For the time being, it is not financially reasonable to use artificial intelligence in interference measurements due to high costs. A portable spectrum analyzer costs approximately 5,000 euros while it will take hundreds of thousands of euros to develop artificial intelligence for this purpose.

The measurement results and theoretical considerations can be universally applied in numerous environments. While the focus of this study is on hospitals, there were some practical challenges that posed a problem to data gathering in a hospital environment: First, due to confidential requirements, the data gathered from the hospitals should be kept confidential. However this thesis will be made publicly available. Secondly, in the practical measurement phase, a microwave oven and a Bluetooth loudspeaker were set as interferer sources. In the worst case, interferences coming out of them could have disrupted the functionality and data traffic in the entire WLAN access point.

For these reasons, the practical measurement data for this study was collected from a corresponding environment, i.e. normal office environment after business hours. It was in theory possible that the power level of interference signals from the measured devices is so low that no interference signals could be detected. However, in practice, interference signals were detected from both measured devices.

3 Existing knowledge of WLAN network technical environment

The following chapters provide a brief introduction into common types of Radio Frequency Interference (RFI) and Electro Magnetic Interference (EMI) signals, how they appear in the WLAN network physical layer, and how they are commonly characterized. Basic information from the typical structure of hospital WLAN networks, an overview of the 802.11 physical layer signal and basic operating principles of measurement devices are also included.

3.1 Characteristics of typical radio frequency Interference Signals

Fundamentally, radio frequency interference is associated with degrading device performance and quality of service (QoS). It usually means that the interference signal is impacting a system or device causing it to work outside its normal technical parameters. There are a few basic types of radio frequency interferences that could cause problems for wireless devices. Interference signals are of certain type and are present in various forms. This chapter presents typical types of interference signals that are relevant for this study.

The first interference type is co-channel interference, which is basically crosstalk from other radio transmitters using the same frequency. It can be generated, for example, by cellular mobile networks, poor weather conditions, bad frequency planning or an overly crowded radio spectrum. [6]. Figure 2 shows the generic picture of co-channel interference situation, where different wireless devices are operating in the same radio channel.

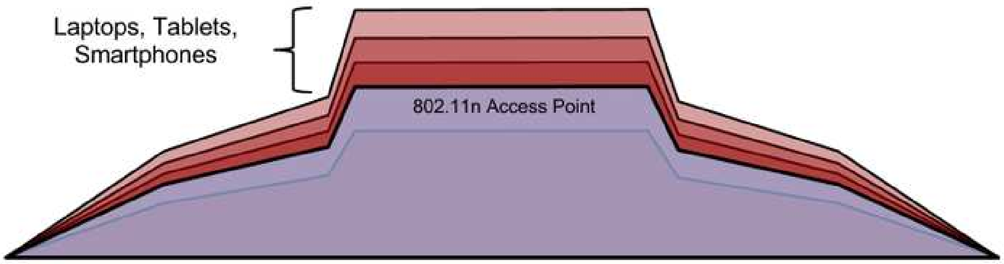


Figure 2. Co-channel interference in 802.11n Access Point. [9]

Wireless devices such as laptops, tablets and smart phones are operating in the same channels as WLAN access points. As shown in figure 2, the RF-power levels of different devices may vary depending on the device in use. All devices working on the same channel have to manage their timing and take turns in operation. This usually results in degraded QoS.

The second interference type is adjacent channel interference, which is caused by irrelevant power coming from a transmitter in an adjacent radio channel. Typically, it is generated by inadequate filtering of interfering modulation products in wireless systems, bad tuning or poor frequency control. [6]. Figure 3 shows a generic picture of adjacent channel interference where different WLAN access points are operating in adjacent overlapping radio channels.

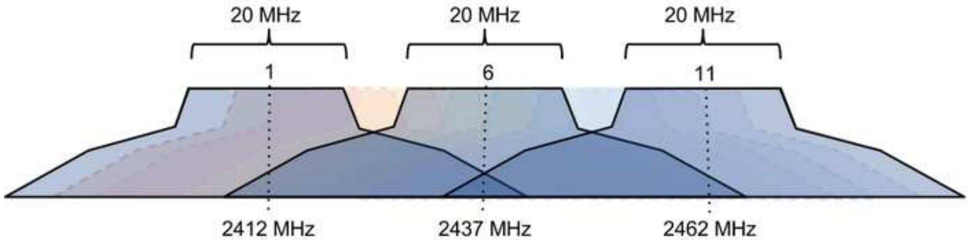


Figure 3. Adjacent channel overlapping of separate WLAN access point channels. [9]

As shown in figure 3, wireless devices using overlapped channels could be transmitting simultaneously. This may cause wireless signal collisions and lead to degraded QoS.

The third interference type is impulse noise, which could be created whenever a flow of electricity is abruptly started or stopped. Many items can create impulse noise, such as electrical motors, bakery ovens, welding equipment, light dimmers and power lines that may arc and spark [6]. Figure 4 shows an example from the Electromagnetic Field (EMF) measurement taken in the presence of normal household appliance interference signals.

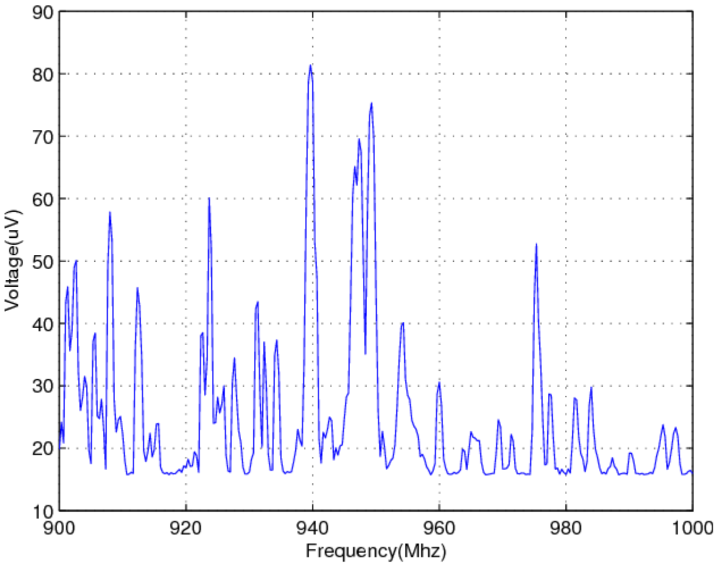


Figure 4. The frequency spectrum of impulse noise measurement. [12]

Interference signals coming from household appliances may cause impulse noise signals effecting a wideband of frequencies as shown in figure 4. The voltage and power levels of interference signals vary in amplitude in respect of different frequencies. An interfering noise signal can also be coming from a defective electronic device or it could be caused by natural sources of interference, such as lightning and the sun.

The fourth interference type is Intermodulation (IM), which is one of the most common and challenging types of interference problems in electronics. Intermodulation distortion (IMD) is caused when two signals are combined in such a way, that they create intermodulation product signals at various combinations of two original frequencies. They are usually created when two or more signals are interacting in a non-linear device using active components, such as amplifiers and mixers.

Intermodulation distortion will produce additional unwanted signals and usually lead to interference problems, which is hard to locate and measure without proper test equipment. [6]. Figure 5 shows the order of different intermodulation products and their frequency components generated by IMD distortion.

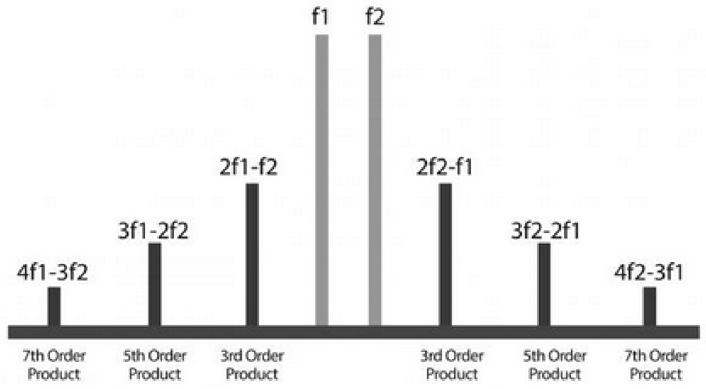


Figure 5. The order of different intermodulation products and their frequencies. [13]

As shown in figure 5, different frequency spectral components are caused by the mixing of two or more fundamental frequency tones (f1 and f2) and their harmonics. Passive intermodulation (PIM) usually occurs in passive devices, such as cables, antennas and connectors that are subject to two or more high power level signals. Passive intermodulation is usually created when two or more high power signals are mixed with device non-linearities, such as loose and corroded connectors. Passive intermodulation can be a severe problem when both high power transmit and receiver signal paths are shared by the same system. If PIM interference find its way to the receiver path, it is very difficult to filter away. [7]

The fifth interference type is emissions such as out-of-band emissions and spurious emission. They are caused by transmitters generating RF-signals that are outside their intended transmission bandwidth. Out-of-band emissions could be caused by distortion in the modulator or consists of broadband noise generated by the transmitter oscillators circuits that is added to the intended signal. Figure 6 shows a generic picture of fundamental, spurious, harmonic and noise level frequency components.

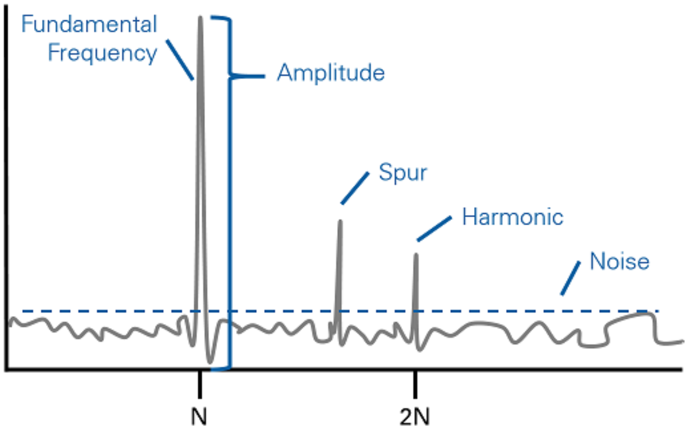


Figure 6. Frequency domain presentation for out-of-band emissions. [14]

Harmonics are the most common spurious emissions caused by the transmitters. They are integer multiples of an operating frequency (fundamental frequency). Amplitude refers to the power level of signals in a specific given frequency. Spurious emissions could be caused, for example, by overriding an amplifier [8; p. 27.11], interleaving anomalies in analog-to-digital converters (ADC) or leakage of oscillator clock signals. Transmitters may also generate broadband noise, which is usually caused by the temperature and ground loops in electronic circuits.

3.2 Typical interference sources on the WLAN network

It is less commonly known that normal household devices, such as microwave ovens and light dimmers, can be a source of RF-interference emissions inside the WLAN network. [1] The first signs of interference from these devices are found in the physical layer of the Open Source Interconnection (OSI) model, which is theoretical model used for describing how information moves from on one networked computer to another networked computer in Local Area Network (LAN). The seven layers of the OSI model are illustrated in figure 7.

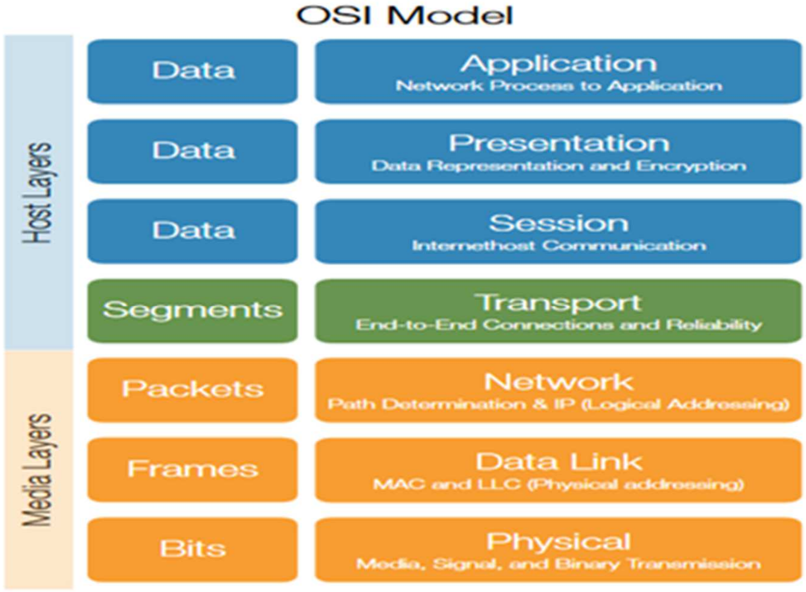


Figure 7. The seven layers of the OSI model. [5]

There are two typical RF-interference mechanisms, the Radio Frequency Interference (RFI) and Electro Magnetic Interference (EMI), which are causing interference problems in WLAN networks. RFI signals are narrowband interferers by their nature appearing in the 2.4 GHz unlicensed ISM band. Normal household appliances are also operating in this same frequency band and they can be potential sources of RFI interference for WLAN access points. Wireless devices such as WLAN access points operating in the 5 GHz frequency band can interfere with, for example, the Doppler and approach radars systems, which are using the same frequency band for their operation. To mitigate these 5 GHz interferences, WLAN access points are using build-in functionalities such as Dynamic Frequency Selection (DFS) and Transmit Power Control (TPS) algorithms.

EMI interferences are wideband by their nature and can appear in the 2.4 GHz or 5 GHz frequency bands. They can be a much larger problem for WLAN network users than RFI interferences. EMI interference sources can disable an entire WLAN network more effectively than a wireless network jammer tuned in the specific frequency. EMI interferences can come from multiple different sources and they often can be contained and isolated with good RF-design work, but some of the EMI interferences cannot be completely eliminated. The general definitions of narrow and broadband interference signals are illustrated in figure 8.

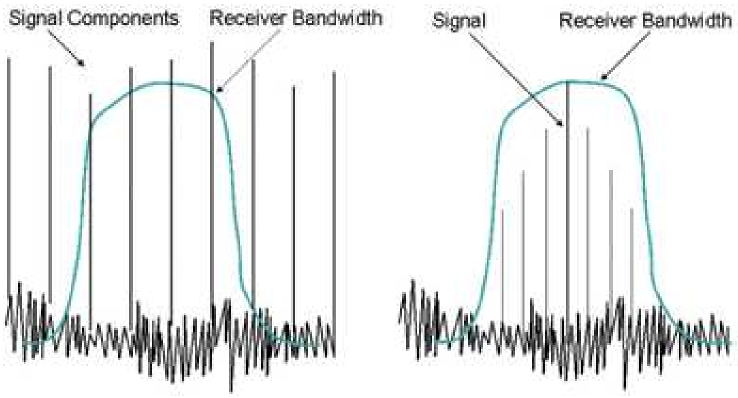


Figure 8. Generic presentation of narrow and broadband interference signals. [10]

The classification between narrow and broadband signals is defined by the occupied frequency spectrum in relation to the measurement receiver Intermediate Frequency (IF) stage resolution bandwidth (RBW). As shown in figure 8, the left picture presents the definition of broadband interference signals and the right picture narrowband interference signals. The colored trace indicates the measurement device RBW filter bandwidth. If the interference signal fits completely inside the RBW filter bandwidth, it is defined as narrowband interference signal. If interference signals are detected outside the RBW filter, the bandwidth is defined as broadband interference signal. Continuous wave (CW) signals are classified as a special form of narrowband interference signals, since they consist of only one narrow spectral line.

Typical WLAN network RFI and EMI interference sources and their basic interference characteristics are listed below.

- Analog cordless phones are typically operating in the 2.4 GHz ISM frequency band. They are using narrow band transmission, which only disturbs the narrow bandwidth of spectrum in use. When they are placed in close proximity of the WLAN access points, they can cause really severe interference problems. [4; p.6]
- Wireless Baby Monitors, both analog and digital, are operating in the 2.4 GHz ISM band. When they are turned on, they will compete for bandwidth with the WLAN access points and can cause performance degradation and wideband RF interference problems, especially when they are placed in close proximity of access points. [4; p.8]
- Bluetooth technology devices are operating in the 2.4 GHz frequency band. Bluetooth devices are based on the Frequency Hopping Spread Spectrum (FHSS) modulation technique, and thus they hop across all channels in the entire 2.4 GHz frequency band in a random manner.

Bluetooth devices can cause wide band interference signals and performance degradation for the WLAN network when they are used in close proximity of WLAN access points. [4; p.10]

- Industrial machines, which are using electrical motors are generating a lot of electrical noise. Especially Direct Current (DC) motors are very noisy sources of EMI radiation. Slip rings and brushes used in them are causing sparks and arcs inside the motors, and thus they tend to generate a lot of wideband electrical noise. Variable frequency drives can disrupt both wired and wireless communication devices if they are not properly located in the buildings and installed and with isolated wiring through proper cable container and routing.
- Power, audio cables, lamp cord and signal transmission line wiring can act as an antenna. The longer the wire is the better antenna it becomes. The tendency of wire to pick up noise signals can be reduced by paying attention to the length of the wire. Shielded cables are recommended to be used in RF applications, in order to reduce the interference signals.
- Digital cordless phones operate either in 2.4 GHz or 5 GHz radio bands, which are also being used by 802.11 WLAN access points. This could lead to a situation in which radio signals from different sources will collide and cause RF interference. Digital cordless phones use FHSS technique and they are operating in the 2.4 GHz ISM frequency band. Their radio signals are hopping across the entire 2.4 GHz band. These frequency hops could cause RF interferences to WLAN access points when placed in close proximity. [4; p.12]
- Digital wireless cameras and video monitors are operating in the 2.4 GHz ISM frequency band. Signals coming from wireless camera or digital monitor can travel quite long distances. They can cause RF interference problems when placed away from close proximity to WLAN access points. [4; p.15]
- Wireless game controllers are typically operating in the 2.4 GHz ISM frequency band. When placed in close proximity of WLAN access points, they can be a source of RF interferences. [4; p.18]
- Microwave ovens operate in the 2.4 GHz ISM frequency band. Radio signals leaking of an operating microwave oven can cause severe wideband RF interference problems, especially when they are placed in close proximity to WLAN access points. [4; p.20]
- Motion detectors based on the microwave detection principle operate in the 2.4 GHz ISM frequency band. They can cause intermittent interferences only when they are operating within same channel bandwidth as the WLAN access point and placed in close proximity. [4; p.22]
- RF jammers are devices designed to disrupt a single frequency or range of frequencies and they are typically characterized by narrow or wide band RF interfering devices. RF jammers designed to block WLAN access points are typically operating in the 2.4 GHz ISM frequency band and they can disrupt an entire WLAN network. Jamming signal range is depending on the RF power of the jammer. [4; p.27]

- ZiBee devices are low power, low cost and short range wireless devices. They are designed to operate in the 860 MHz, 915 MHz or 2.4 GHz frequency band using Direct Sequence Spread Spectrum (DSSS) modulation. The bandwidth of 2.4 GHz ZigBee network devices is fixed to 3 MHz. If ZibBee network happens to operate in same channel with the WLAN access point, chances for interferences are high, otherwise the interference effect from these low power ZigBee devices are low. [4; p.31]
- Remote controlled toys are typically using FHSS or DSSS modulation and they are operating in both 2.4 GHz ISM or 5 GHz frequency bands. They can cause severe RF interferences for WLAN access points operating in same frequencies. The actual severity level of interferences is depending on the range, relative signal levels and amount of data being transmitted by each devise wireless device. [4; p.33]

3.3 Typical structure of hospital WLAN networks

Hospital WLAN networks are using the Institute of Electrical and Electronics Engineers (IEEE) 802.11 protocol and they operate in unlicensed 2.4 GHz Industrial, Scientific and Medical (ISM) and 5 GHz Radio Frequency (RF) bands not only for regular internet access but also for sensitive patient data transfer. [2] To access the internet, computing devices and medical devices need to connect to hospital WLAN networks. Applications running in medical devices cannot handle disruptions in network connectivity. A disruption of even milliseconds can cause a failure in critical patient data transmission. [3]

Devices such as general purpose WLAN clients, embedded WLAN monitoring systems and asset tracking equipment are typically used in the hospital WLAN network. Figure 9 shows most commonly deployed devices and services used in a modern multi-purpose medical WLAN network. [15; p.18]

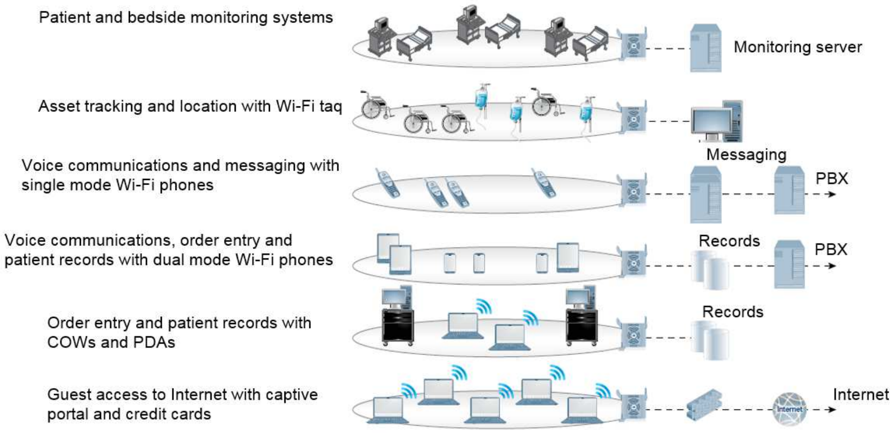


Figure 9. Commonly deployed devices and services, used in modern medical networks. [15; p.18]

Many hospital organizations today are using the 802.11n based WLAN platform for simultaneous support of all applications. The trend nowadays is that instead of having many parallel WLAN networks for guest access and internal communication, all network traffic is combined into a single pipe using a cost-effective and bandwidth-efficient connection towards the Internet. [15; p.18]

Personal computers such as computers on wheels, desktop PCs, laptops and tablets are using WLAN network access while mobile. Desktop PCs and computers on wheels are normally used for accessing patient records, medical orders and hospital internal servers. They should be configured to use Wi-Fi Protected Access II (WPA2) enterprise security protocol with individual user log on credentials and support for voice and video traffic. Personal Digital Assistant (PDA) computers and smart phones usually operate in cellular network, but they are also capable of connecting to organizations’ WLAN network and Private Branch Exchange (PBX) over the WLAN connection. WLAN network parameters should be configured in such a way that they support maximum battery life for smartphone and PDA devices. [15; p.19]

Single mode Wi-Fi phones and voice communicator badges are normally used by clinicians who are working outside their usual office desk. Single mode phones are used as cordless phones operating over the WLAN network. Voice communicator badges provide hands free voice recording and speech recognition for voice command and dialing.

Single mode Wi-Fi phones are typically using WPA2 with Pre Shared Key (PSK) authentication protocol. Therefore proper firewall policies limiting access and protocol use should be added to the network for enhancing network security. It is important to ensure seamless WLAN coverage in all areas where voice over WLAN services are deployed. [15; p.19]

Wi-Fi locating tags are special RF devices optimized for low-cost, small size and long battery life. Tags are attached to mobile devices, such as infusion pumps and wheel chairs, in order to track their position and raise an alarm if equipment leaves a building without proper authorization. With an asset tracking system, clinicians can track devices in real time from a separate screen. When this system is used in the hospital, it is important to ensure that there is a sufficient number of WLAN access points deployed in the areas where asset tracking is performed. The system uses triangulation technique for locating Wi-Fi tags, which requires that at least three access points detect the transmission from the tags. [15; p.20]

Medical devices, such as patient monitoring systems, provide continuous tracking of critical physiological parameters for patient care. WLAN networks provide connectivity between central nursing stations and moving patients. Patient monitors share the same wireless multipurpose 802.11n network with other hospital applications and they send alarms set to trigger after a small number of missed messages. Therefore, it is important to deliver traffic from patient monitors via network without data loss. [15; p.20]

In hospitals, the highest concentration of people is in public areas, such as cafeterias, waiting rooms and atriums. These areas have a high number of users generating most of the WLAN network traffic. While these areas are crowded by many users, they are not difficult to cover with an interference-free WLAN network solution. The most challenging areas from the interference point of view are for example x-ray rooms, which are encased with lead walls as a regulated safety precaution. The purpose of the lead lining is to protect people from hazardous ionizing X-ray radiation. On the other hand, lead walls are creating interference to clinical and medical wireless devices such as patient monitors and WLAN access points. [16; p.4]

Figure 10 shows typical core distribution access segments of the modern hospital campus network, highlighting WLAN access point installation places and data traffic inside the network.

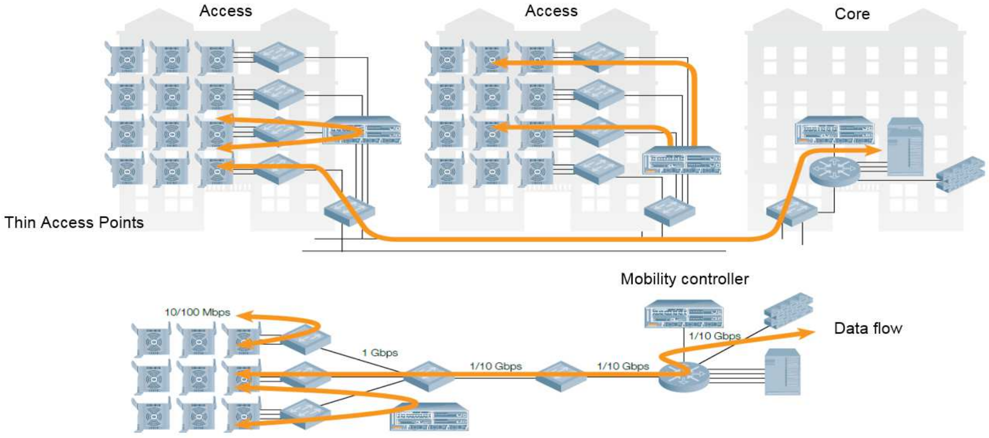


Figure 10. Typical healthcare campus network topology. [15; p.20]

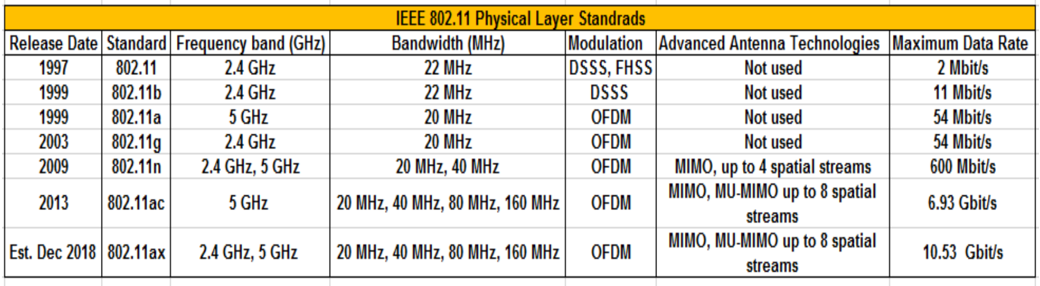
Mobility controllers are positioned as required by data traffic patterns. A network management plane used for network monitoring, alarm generation and device configuration purposes is typically using management software suite, which is connected over Local Area Network (LAN) or Wide Area Network (WAN) to all mobility controllers in the network. A control plane for handling RF coordination, handover between mobility controllers and access points and Wireless Intrusion Prevention System (WIPS) is set up as a secure network of connections between mobility controllers. This allows fast handover between access points homed to different mobility controllers. [15; p.21]

The traffic between mobility controllers and access points is using secure tunnels. Hospital campus mobility controllers are usually positioned in separate data centers with high bandwidth data links and high capacity LAN switches. In case of low data bandwidth and network capacity are needed, mobility controllers can be placed closer to distribution layer switches in order to minimize network traffic between the data center and the hospital building. [15; p.21]

3.4 An overview of 802.11 physical layer standards

This chapter provides basic information of the existing 802.11 physical layer standards in 2.4 GHz ISM and 5 GHz frequency bands. The most important information from the interference measurement point of view is included. Detailed information, such as the physical layer frame structure, packet formats, modulation scheme parameters or error correction techniques are not part of the overall scope of this study. An overview of IEEE 802.11 physical layer standards is shown in table 1 below.

Table 1. IEEE 802.11 physical layer standards. [19]



IEEE 802.11 Physical Layer Standrads

Release Date	Standard	Frequency band (GHz)	Bandwidth (MHz)	Modulation	Advanced Antenna Technologies	Maximum Data Rate
1997	802.11	2.4 GHz	22 MHz	DSSS, FHSS	Not used	2 Mbit/s
1999	802.11b	2.4 GHz	22 MHz	DSSS	Not used	11 Mbit/s
1999	802.11a	5 GHz	20 MHz	OFDM	Not used	54 Mbit/s
2003	802.11g	2.4 GHz	20 MHz	OFDM	Not used	54 Mbit/s
2009	802.11n	2.4 GHz, 5 GHz	20 MHz, 40 MHz	OFDM	MIMO, up to 4 spatial streams	600 Mbit/s
2013	802.11ac	5 GHz	20 MHz, 40 MHz, 80 MHz, 160 MHz	OFDM	MIMO, MU-MIMO up to 8 spatial streams	6.93 Gbit/s
Est. Dec 2018	802.11ax	2.4 GHz, 5 GHz	20 MHz, 40 MHz, 80 MHz, 160 MHz	OFDM	MIMO, MU-MIMO up to 8 spatial streams	10.53 Gbit/s

Radio frequencies used by different versions of 802.11 standards vary between different countries. Basic standard 802.11 specifies maximum data rates up to 2 Mbit/s. It is using the 2.4 GHz frequency band, 20 MHz bandwidth and DSSS or FHSS modulation techniques. Version 802.11b was designed to increase the maximum data rate to 11 Mbit/s. It is using the 2.4 GHz frequency band, 20 MHz bandwidth and DSSS modulation technique. [2; p.4]

Standard version 802.11a is operating in the 5 GHz band. It is using the Orthogonal Frequency Division Multiplexing (OFDM) modulation technique, consisting of 52 separate subcarriers occupying the 20 MHz bandwidth. The maximum data rate of 54 Mbit/s can be achieved in theory, but in practice a throughput of approximately 20 Mbit/s is achieved in real live networks due to physical environment restrictions. Version 802.11g operates in the 2.4 GHz frequency band, using the 20 MHz bandwidth and OFDM modulation technique. A maximum data rate of 54 Mbit/s can be achieved. [2; p.6]

Version 802.11n includes many improvements for WLAN range, throughput and reliability. Advanced OFDM modulation technique and signal processing have been added in order to use multiple antennas and wider channel bandwidths. 802.11n compatible devices can be operated both in 2.4 GHz or 5 GHz frequency bands. The Multiple Input Multiple Output (MIMO) antenna technique and 40 MHz bandwidth are defined in the standard. 802.11n devices are able to transmit and receive simultaneously through multiple antennas ranging from 1 x 1 to 4 x 4 configurations providing maximum data rates 54 Mbit/s–600 Mbit/s. [2; p.6]

Version 802.11ac is providing high data throughput in the 5 GHz frequency band. Wider bandwidth up to 160 MHz, Multi User Multiple Input Multiple Output (MU-MIMO), using up to 8 spatial streams and high density 256 Quadrature Amplitude Modulation (256-QAM) OFDM modulation techniques are used to achieve maximum data rate of 6.93 Gbit/s. [20; p.7]

Version 802.11ax is design to operate in 2.4 GHz or 5 GHz frequency bands. The main goal is to improve user experience and network performance by providing at least four times improvement into average data throughput per WLAN station reaching up to maximum 10.53 Gbit/s. 802.11ax is supporting MU-MIMO in the uplink as well as in downlink directions, using up to 8 spatial streams. A high density OFDM modulation scheme up to 1024-QAM can be used. [21; p.7]

All WLAN devices are supporting 2.4 GHz ISM frequency band, thus it is used almost in all WLAN networks. The 2.4 GHz frequency band is more crowded and sensitive to interferences compared to the 5 GHz frequency band. The total occupied bandwidth for 2.4 GHz frequency band is 85 MHz, covering frequencies 2.400 - 2.485 GHz. The bandwidth for a single channel is 5 MHz wide. In practice, several channels are coupled together in order to increase maximum data rate in the transmission channels. The 802.11 and 802.11b standards are using the 22 MHz wide bandwidth, in 802.11g and 802.11n standards the channel bandwidth is increased to 20 MHz, because a more effective OFDM modulation technique is in use. Channel numbers and their center frequencies for the 2.4 GHz frequency band are shown in figure 11 below.

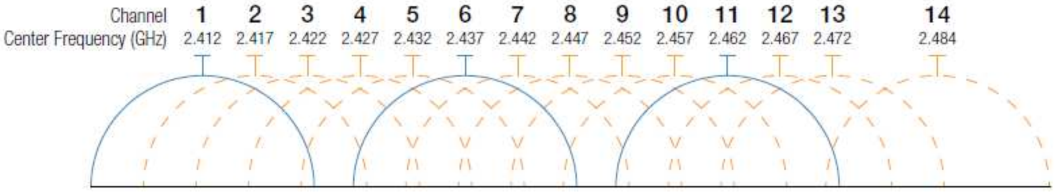


Figure 11. Channel numbers in 2.4 GHz frequency band and their center frequencies. [2; p.10]

Europe and most other parts in the world use 13 channels, Japan is using 14 channels and the United States 11. Most of the WLAN radios are built to listen the 22 MHz wide bandwidth and if they detect traffic in same channel, they do not transmit data before the channel is free. If two WLAN hotspots are configured to run in adjacent channels, for example in channels 1 and 2, they take turns in transmitting and as a consequence they may end up delivering only half of the maximum available data rate capacity per WLAN hotspot. Channels 1, 6 and 11 are not overlapping with each other. As a general rule of the WLAN network design, hotspots should be configured to use non-overlapping channels such as 1, 6 and 11, in order to reach maximum data rates in the network.

The maximum allowed transmitting power for a WLAN device operating in the 2.4 GHz frequency band is 100 mW (20 dBm). The wavelength in the 2.4 GHz frequency band is two times longer than the 5 GHz frequency band. In practice, this means that the 2.4 GHz signal gets less attenuated in free space or building structures such as walls, allowing stronger signal strength and wider network coverage areas using a small number of WLAN hotspots in the network. On the other hand, the 2.4 GHz frequency band is more prone to external interference signals coming from commercial and industrial devices operating in the same frequency band and it is more crowded than the 5 GHz band.

The 5 GHz frequency band has more available channels and they are less error-prone for external interference signals. Maximum data rates can be achieved by increasing the channel bandwidth by coupling several channels together. The 5 GHz band was first defined in standard 802.11a, but during the time it was released it was too expensive and not commonly used. The 802.11n standard made it possible to choose between 2.4 GHz and 5 GHz bands, increasing the number of 5 GHz devices. The channel numbers and available bandwidths for 5 GHz frequency band are shown in figure 12.

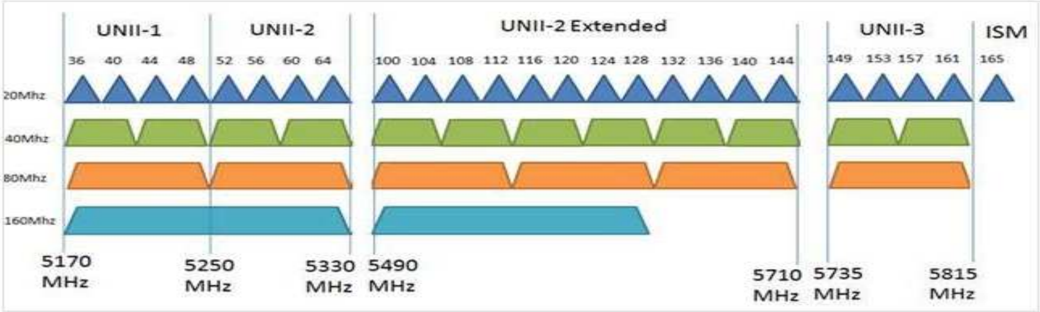


Figure 12. Channel numbers in 5 GHz frequency band and available bandwidths. [22]

5 GHz frequency band devices are using the same 5 MHz single channel bandwidth as is used in 2.4 GHz frequency band. Since every fourth channel is used, channel overlapping is not such a big issue for 5 GHz frequency band devices. The United States divide the 5 GHz frequency band into Unlicensed National Information Infrastructure radio bands (UNII). In Europe, channels 36 - 64 can only be used in indoor environment. The maximum allowed transmitting power for a WLAN device operating in channels 36 - 64 is 200 mW (23 dBm). WLAN devices operating in channels 100 - 140 can be used in both indoor and outdoor environments with a maximum transmission power of 1 W (30 dBm), enabling radio links with ranges of tens of kilometers in the outdoor environment.

WLAN devices used in the 5 GHz frequency band are not allowed to interfere with weather radars that are operating in channels 120 - 128. Therefore, while booting up, they are typically listening channels 120 - 128 for approximately 10 minutes before transmitting anything. If a device detects a weather radar signal operating in the same channel, it will automatically select another transmitting channel. The DFS technique is used in channels 52 - 140. In Europe, the maximum allowed transmitting power for channels 149 - 165 is 25 mW (14 dBm).

The wavelength is a half shorter in the 5 GHz frequency band than in the 2.4 GHz frequency band. In practice, this means that the 5 GHz signal gets more attenuated in free space or building structures such as walls, resulting in a weaker signal strength and smaller network coverage areas using a large number of WLAN hotspots in the network.

3.5 Basic operating principles of measurement devices

3.5.1 Measurement antennas

This chapter provides an overview for general antenna characteristics that need to be considered when choosing an antenna for RF-interference signal measurements. A comprehensive antenna theory describing complex mathematical expressions and formulas is not part of the overall scope of this study.

An antenna basically converts conducted waves into electromagnetic waves, which are then propagating freely in space. An antenna is a reciprocal device, meaning that characteristics and parameters used to describe its functionality are equally valid for transmitting and receiving antennas. [23; p.9]

The most important antenna characteristics typically used for selecting an appropriate antenna for measurement applications are listed below. [23; p.2]

- Polarization
- Radiation density
- Radiation pattern
- Directivity
- Gain
- Effective area
- Input and nominal Impedance
- Impedance matching and VSWR
- Antenna factor
- Bandwidth of an antenna

The plane electromagnetic wave can be characterized by electric and magnetic fields traveling in one direction. Electric and magnetic fields are perpendicular to each other and to the direction the plane wave is propagating. Antenna polarization is determined by the direction of radiated electric field (E), evaluated in a far field. Polarization can further be classified as linear polarization, circular polarization and elliptical polarization. Figure 13 illustrates the plane electromagnetic wave traveling in one direction and the magnitude and direction of its E field vector in case of linear vertical polarization and right hand circular polarization. [23; p.8]

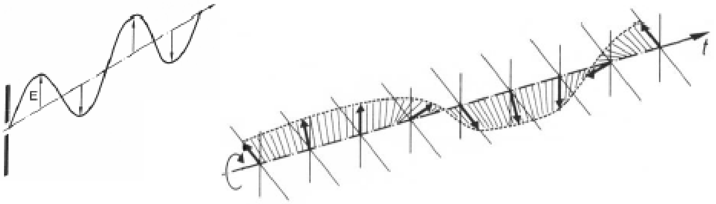
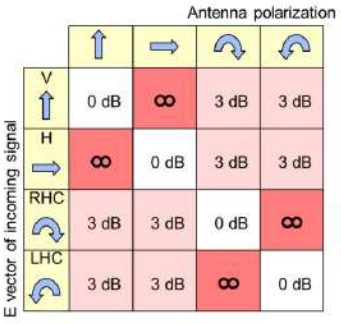


Figure 13. The left picture showing the magnitude and direction of E-field vector in case of linear vertical polarized antenna and the right picture showing the magnitude and direction of E-field vector in case of right hand circular polarized antenna. [23; p.8]

In linearly polarized electromagnetic wave, the E field vector changes its amplitude, and it can be horizontally or vertically polarized. In case of circularly polarized electromagnetic wave, the amplitude of E field vector is constant, but it rotates around the direction of propagation. In elliptically polarized electromagnetic wave, the amplitude and direction of E field vector is changing. The maximum peak position of an elliptically polarized E filed vector can be described by elliptical equation. [23; p.8]

In antenna communication, the transmit and receive antennas must have the same polarization in order to transfer a maximum amount of electromagnetic energy between them. If the receiving and transmitting antennas are not equally polarized polarization mismatch will occur. Figure 14 shows an overview of expected loss of received signal due to polarization mismatch between two antennas.



Antenna polarization

E vector of incoming signal	⇧	⇨	↷	↶
V ⇧	0 dB	∞	3 dB	3 dB
H ⇨	∞	0 dB	3 dB	3 dB
RHC ↷	3 dB	3 dB	0 dB	∞
LHC ↶	3 dB	3 dB	∞	0 dB

Figure 14. Expected loss of received signal due to polarization mismatch. [23; p.8]

In the left-hand column entitled “E-vector of incoming signal”, (V) means vertical, (H) horizontal, (RHC) right hand circular and (LHC) left hand circular polarization. Figure 14 shows that if both transmit and receive antennas have the same polarization, there is no power loss due to polarization mismatch. A horizontally polarized antenna will not communicate with a vertically polarized antenna, loss between them is infinite. The same applies to the communication between the right hand circular and left hand circular antennas. 3 dB loss can be expected if a linearly polarized signal is received with circularly polarized antenna. [23; p.8]

Power density can be described by using an operating principle of an isotropic antenna, which is a lossless omnidirectional antenna radiating uniformly in all directions. An isotropic antenna is only a theoretical model, it does not exist in practice. The formula for calculating power density (S) at any distance from isotropic radiation source is shown in equation 1.

$$S = \frac{P_s}{4\pi r^2} \tag{1}$$

Where:

S = Power density $[\frac{W}{m^2}]$

P_s = Ideally matched transmitter power [W]

r = Range from antenna (radius of sphere) [m]

Figure 15 is showing a picture from the theoretical model of isotropic antenna radiating uniformly in all directions with power density S in homogenous space.

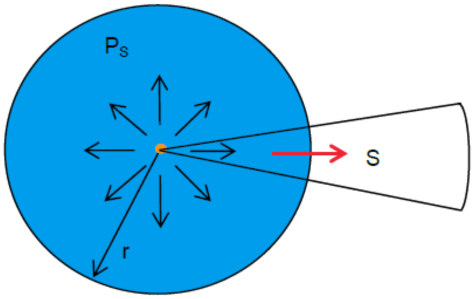


Figure 15. Theoretical model for isotropic radiator in homogenous space. [23; p.9]

As shown in equation 1, the power density (S) decreases by the square of the radius (r), while electromagnetic waves are traveling away from the isotropic antenna. In practice, antenna models, such as log periodic directional antennas, are concentrating power into particular direction. The power density of a directional antenna is depending on the practical gain of an antenna in addition to transmitted power, surface area of a sphere and the distance from an antenna. [23; p.9]

Radiation pattern describes the three-dimensional radiation behavior of an antenna observed in the antenna's far field. It is a visualized presentation showing the variation of the transmitted power radiated by an antenna as a function of direction pointing away from an antenna. Antennas, such as dipoles and monopoles, possess directivity, as shown in figure 16. [23; p.10]

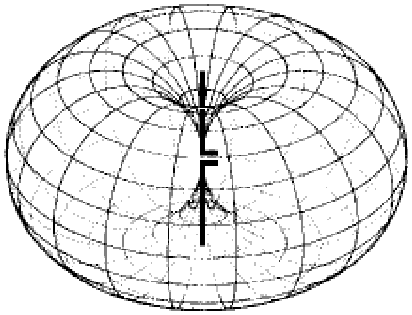


Figure 16. Three dimension radiation pattern of dipole antenna. [23; p.10]

Dipole has a donut shape or toroidal radiation pattern. Figure 16 shows that very little power is transmitted in the direction of antenna's z-axis, showing nulls in the radiation pattern. The maximum of radiation pattern for the dipole antenna is concentrated in the directions of the x- and y-axis.

In reality, all antenna radiation patterns are three-dimensional. Radiation behavior of an antenna can be described with horizontal and vertical patterns, which are visualized in polar coordinates. The radiation behavior of an antenna can be characterized by using these two patterns with well-known antenna types and patterns. A dipole antenna can be mounted both horizontally and vertically. The horizontal radiation pattern for a vertically mounted dipole antenna is shown in figure 17. [23; p.11]

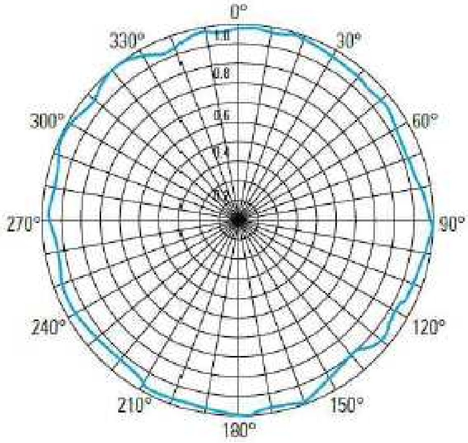


Figure 17. Horizontal radiation pattern of vertically mounted dipole antenna. [23; p.11]

A vertically mounted dipole antenna is radiating equally in all directions in the horizontal plane as shown in figure 17. The vertical radiation pattern of a vertically mounted dipole antenna is shown in figure 18.

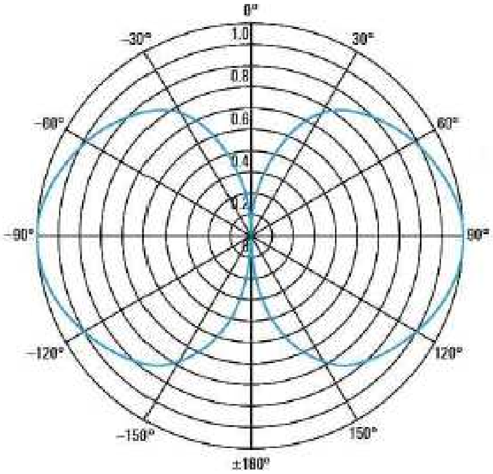


Figure 18. Vertical radiation pattern of vertically mounted dipole antenna. [23; p.11]

Figure 18 shows that a vertically mounted dipole is not radiating equally in all directions in the vertical plane. Nulls of the radiation pattern can be seen in the directions of 0 and 180 degrees. Vertical radiation patterns for the dipole antenna are no longer circular, they are flattened.

For highly directive antennas, such as a log periodic antenna, the radiation pattern can be plotted in the Cartesian coordinates, which can be used for revealing more detailed information of the main beam and adjacent side lobes. Figure 19 shows the radiation pattern in Cartesian coordinates for a highly directive antenna.

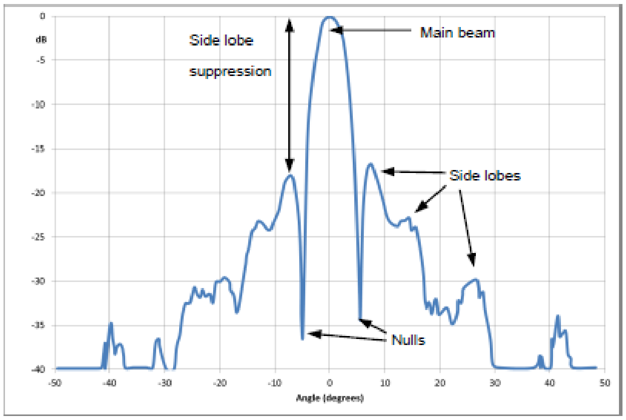


Figure 19. Radiation pattern in Cartesian coordinates for highly directive antenna. [23; p.12]

Parameters such as side lobe suppression, Half Power beam width (HPBW) and front-to-back ratio can be derived using Cartesian coordinates. Figure 20 shows additional parameters of a highly directive antenna radiation pattern.

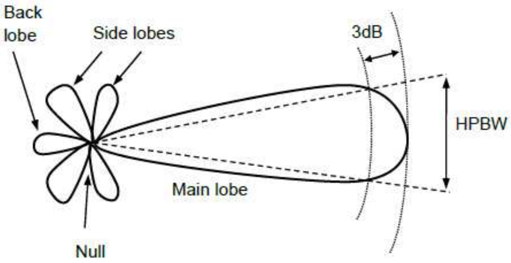


Figure 20. Additional parameters of highly directive antenna radiation pattern. [23; p.12]

Side lobe suppression means relation of antenna radiation pattern main lobe to highest level of side lobe an it is often expressed in decibels. Half power beam width describes the angle between two points in the main lobe when maximum radiated power level is down by 3 dB. The front-to back ratio specifies the ratio of peak gain in forward direction to the gain of back direction and is usually expressed in decibels. [23; p.12]

Directivity is an important parameter of an antenna. It is used for describing how directional antenna radiation pattern is. An isotropic antenna radiates equally in all directions. It has zero directionality, thus its directivity factor expressed in linear form is 1 or 0 dB in logarithmic form. An increased directivity means more focused antenna radiation pattern. The basic formula for calculating antenna directivity (D) is shown in equation 2. [23; p.13]

$$D = \frac{F_{max}}{F_i} \tag{2}$$

Where:

D = Directivity

F_{max} = Radiation intensity achieved in the main direction of radiation

$F_i = \frac{P_t}{4\pi}$ = Radiation intensity for loss-free isotropic radiator with the same radiated power P_t

Directivity (D) can be expressed as a ratio of transmitted radiation intensity F_{max} acquired in the main radiation direction to radiation intensity F_i, transmitted by isotropic antenna with the same amount of radiated power P_t. [23; p.13]

Antennas used in devices such as car radio, cell phones or WiFi hotspots are transmitting and receiving power from all directions, therefore they have low directivity factor. In application areas, such as satellite communication, dish antennas are often used, because transmitted or received power has to be precisely focused into the certain direction. This means in practice that dish antennas have a high directivity factor.

An antenna gain is describing how much an antenna is transmitting power in the main direction of radiation compared to an omnidirectional isotropic antenna source with the same input power. An antenna gain is corresponding to directivity. The formula for calculating antenna gain (G) is show in equation 3. [23; p.13]

$$G = \eta * D \tag{3}$$

Where:
G = Antenna gain
η = Antenna efficiency factor
D = Directivity

Antenna efficiency factor 100% means that antenna gain and directivity would be equal. However, in most of the practical antennas this is possible. Therefore gain can be more easily determined with practical measurements, thus it is more often used for characterizing an antenna. [23; p.13]. Antenna gain is often expressed in logarithmic form as shown in equation 4.

$$g = 10 \log G \tag{4}$$

Where:
g = Antenna gain [dB]
G = Antenna gain

When presenting antenna gain in logarithmic form, the reference is indicated with an additional letter after dB. Antenna gain, which is referred to isotropic radiator is indicated in units of dBi and antenna gain, which is referred to half wave dipole is indicated in units of dBd, where 0 dBd is approximately 2.15 dBi. [23; p.13].

For example, antenna gain of 3 dBi means that the power received or transmitted from the antenna input terminal will be two times higher compared to lossless isotropic antenna with the same input power.

Effective area of an antenna is a parameter, which is normally used for characterizing receiving antennas. Effective area describes how much power a receiving antenna is capturing from the plane wave that is transmitted towards the receiving antenna. The basic formula for calculating the antenna effective area (A_w) is shown in equation 5.

$$P_{r\,max} = S * A_w \tag{5}$$

Where:
A_w = Effective area $[m^2]$
$P_{r\,max}$ = Maximum received power [w]
S = Power density $[\frac{W}{m^2}]$

Effective area is representing how much the receiving antenna is capturing power from the plane wave that is delivered to antenna input terminals. In real antennas, the effective area of an antenna can be calculated by means of measured antenna gain and known wavelength as shown in equation 6.

$$A_w = \frac{\lambda^2}{4\pi} G \qquad (6)$$

Where:
A_w = Effective area $[m^2]$
G = Antenna gain
λ = Wavelength [m]

An input impedance is an important antenna parameter and it is relating to voltages and currents at the input terminal of an antenna. The basic formula for calculating input impedance (Z_{in}) of an antenna is shown in equation 7. [23; p.14]

$$Z_{in} = (R_R + R_L) + jX_{in} \qquad (7)$$

Where:
Z_{in} = Input impedance at input terminal of an antenna [Ω]
R_R = Radiation resistance [Ω]
R_L = Loss resistance [Ω]
jX_{in} = Imaginary part of input impedance at input terminal of an antenna [Ω]

Real part of input impedance present at the antenna feed point is split into the radiation resistance and R_R and loss resistance R_L. [23; p. 14]. Imaginary part of an antenna input impedance consists of capacitive and inductive impedance values. For electrically short linear antennas, the imaginary part of input impedance is capacitive, and in case of electrically long linear antennas it is inductive. The imaginary part of an antenna impedance is zero, when the antenna is operating at resonance. Nominal antenna impedance is usually specified as characteristic impedance of an antenna cable under conditions where antenna and cable characteristic impedances are matching each other. The typical value for nominal antenna impedance in case of RF-measurement equipment is 50 Ω. [23; p.15]

Antenna factor is an important antenna parameter, it underlines the use of an antenna as a sensor of electrical or magnetic field strength measurements device. In typical receiver settings, such as spectrum analyzer, the antenna factor is typically called transducer factor or conversion factor. The basic formula for calculating antenna factor in case of electrical field is shown in equation 8. [23; p.18]

$$K = \frac{E}{U_{RX}} \tag{8}$$

Where:

K = Antenna factor $[\frac{1}{m}]$

E = Electrical field strength $[\frac{dB\mu V}{m}]$

U_{RX} = Output voltage at antenna terminals in 50 Ω $[dB\mu V]$

As shown in equation 8, antenna factor is defined as the ratio of electric field strength and the measured output voltage at its feed point. Antenna factor is typically specified in antennas documentation in a numerical table or graphical form. When an antenna is used in receivers for measuring the precise value of electrical filed strength, the antenna factor is usually expressed in decibels. When the antenna factor and measurement cable losses are well known, the electrical field strength (E), which surrounds an antenna can be calculated in logarithmic form as shown in equation 9. [23; p.18]

$$E = U_{RX} + 20\log\ K + L_{cable} \tag{9}$$

Where:

E = Electrical field strength $[\frac{dB\mu V}{m}]$

U_{RX} = Output voltage at 50 Ω $[dB\mu V]$

K = Antenna factor $[\frac{dB}{m}]$

L_{cable} = Cable loss [dB]

Important terms in antenna design and engineering are gain and directivity. In case antenna factor data is not specified in the datasheet, it is possible to calculate the antenna factor when antenna gain and measurement frequency are known. The conversion between antenna gain and antenna factor in decibels is shown in equation 10. [23; p.18]

$$k = -29.8\ dB + 20 \log \left(\frac{f}{MHz}\right) - g \tag{10}$$

Where:
k = Antenna factor [dB]
f = Measured frequency [MHz]
g = Antenna gain [dB]

The bandwidth of an antenna describes the range of usable frequencies over which an antenna can properly radiate or receive energy. It is common practice to use an impedance match VSWR < 1.5 value for determining the antenna bandwidth. The basic formula for calculating the bandwidth for broadband antennas is shown in equation 11.

$$BW = \frac{F_H}{F_L} \tag{11}$$

Where:
BW = Bandwidth of an antenna [Hz]
F_H = Highest usable frequency [Hz]
F_L = Lowest usable frequency [Hz]

An antenna can be characterized to be broadband when the calculated result in equation 11 is greater than 2. A formula for calculating the antenna bandwidth for narrowband antenna is shown in equation 12. [23; p.19]

$$BW = \left(\frac{f_H - f_L}{f_C}\right) * 100 \tag{12}$$

Where:
BW = Bandwidth of an antenna [%]
f_H = Highest usable frequency [Hz]
f_L = Lowest usable frequency [Hz]
f_C = Center frequency [Hz]

Values in equation 12 can range between 0% and 200% but are in practice only used up to 100%.

3.5.2 Spectrum analyzer

This chapter provides a basic overview of the operating principle for swept tuned and modern FFT (Fast Fourier Transform) based spectrum analyzer technologies and their main performance features. A complete description and detailed operating principle of a spectrum analyzer is not part for the scope of this this study. The main setting parameters and performance features needed for interference hunting in the WLAN network are included in this chapter.

Spectrum analyzer is measuring the amplitude of an input signals frequency component within the limits of full frequency range of the instrument. The primary use for the spectrum analyzer is to measure the power level of spectrum for both known and unknown RF signals. The measured signal is displayed on the screen, where the x-axis presents the frequency of measured spectrum and the y-axis the amplitude of the spectrum. Measurement results are usually presented in logarithmic scale for both axis.

Spectrum analyzer technology has evolved a lot since 1960s when the first models came into the markets. Traditional spectrum analyzers are swept-tuned instruments using the operating principal of super heterodyne receiver. There are three basic types of spectrum analyzers in the market: swept-tuned spectrum analyzer, FFT-based spectrum analyzer and real-time FFT-based spectrum analyzer. Most of the modern day spectrum analyzers are based on FFT technology, but a high number of swept-tuned spectrum analyzers are still in use. A simplified block diagram of a conventional swept-tuned spectrum analyzer operating on the heterodyne principle is shown in figure 21.

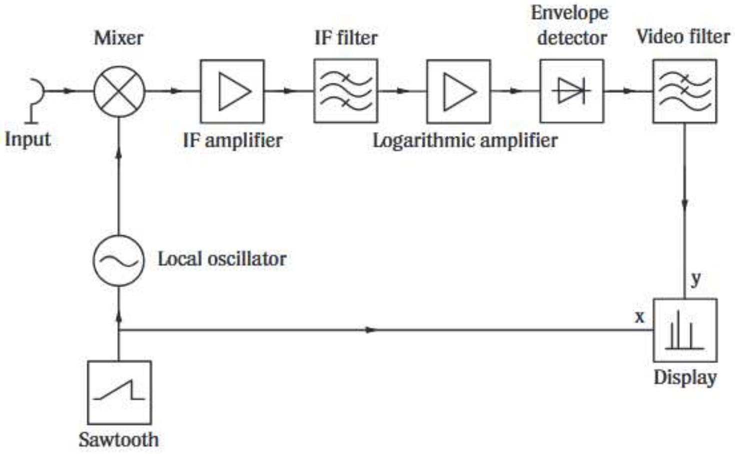


Figure 21. Simplified block diagram of swept tuned spectrum analyzer based on heterodyne receiver design. [24; p.28]

The heterodyne receiver inside the spectrum analyzer is converting the input signal into intermediate frequency (IF) with the aid of a local oscillator (LO) and a mixer. Complete input frequency range of analyzer can be converted into a constant intermediate frequency with the aid of tunable local oscillator. A converted IF signal is fed through the IF amplifier stage before it is fed to the IF filter stage. The resolution bandwidth (RBW) of the spectrum analyzer is determined by fix-tuned IF filters at the intermediate frequency stage. [24; p.28]

Logarithmic amplifier is used for allowing signals in a wide level of range to be displayed on the screen by compressing the IF signal. The envelope of the IF signal is detected by an envelope detector resulting into a video signal. This signal is averaged with the aid of an adjustable low pass video filter stage. The averaged noise free and smoothed signal is fed into the vertical deflection of display unit. Sawtooth signal is used for driving horizontal deflection of display unit and local oscillator stage, because the received signal is displayed as a function of frequency. [24; p.29]

In a modern swept tuned spectrum analyzer, all processes are controlled by several microprocessors. The input signal is sampled in signal chain by the aid of an ADC converter using fast digital signal processors. In the older instruments, the video signal was sampled after an analog envelope detector and video filter stage. In the modern spectrum analyzer, the video signal is digitized to low intermediate frequency and the envelope of the IF signal is determined from digitized samples. In modern analyzers, the local oscillator is no longer tuned with the aid of a sawtooth signal; instead, it is locked to reference frequency via a phase locked loop (PLL). Frequency tuning is done by varying division factors inside the PLL, resulting to a higher frequency accuracy. In the modern spectrum analyzer, cathode ray tubes are replaced by a liquid crystal display (LCD), allowing the use of a more compact design. [24; p.30]

Most of the modern day spectrum analyzers are based on FFT technology. The frequency spectrum of the measured signal is defined by the signal time characteristics. The time and frequency domain can be linked to each other by means of Fourier transform. The frequency resolution of the FFT based spectrum analyzer can be determined by calculating the inverse of time over which the waveform is measured and Fourier transformed. In practical FFT based analyzers, the Fourier transform is made with the aid of powerful signal processing. Simplified block diagram from the FFT based spectrum analyzer is shown in figure 22. [24; p.18]

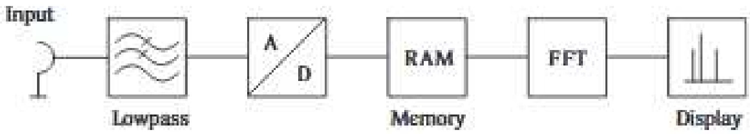


Figure 22. Simplified block diagram of FFT based spectrum analyzer design. [24; p.25]

The bandwidth of an input signal is limited by the analog low pass filter in order to adhere to the sampling theorem. As a general rule the sampling frequency of an ADC converter has to be at least twice the bandwidth of the input signal. The Fourier transform will then produce a spectrum containing all frequencies, without aliasing effects. After the signal has been sampled, the quantized values are stored in random access memory (RAM). The stored values are calculated in frequency domain by the aid of the FFT processor and finally displayed in LCD screen. [24; p.25]

The ADC converter is producing quantization noise due to the quantization of samples. This will cause a limitation to the dynamic range of the analyzer. The higher the number of bits used in the ADC converter is, the lower the quantization noise. In practice, high resolution ADC converters have a limited available bandwidth, therefore a compromise between the analyzer dynamic range and the input frequency range has to be found. [24; p.26]

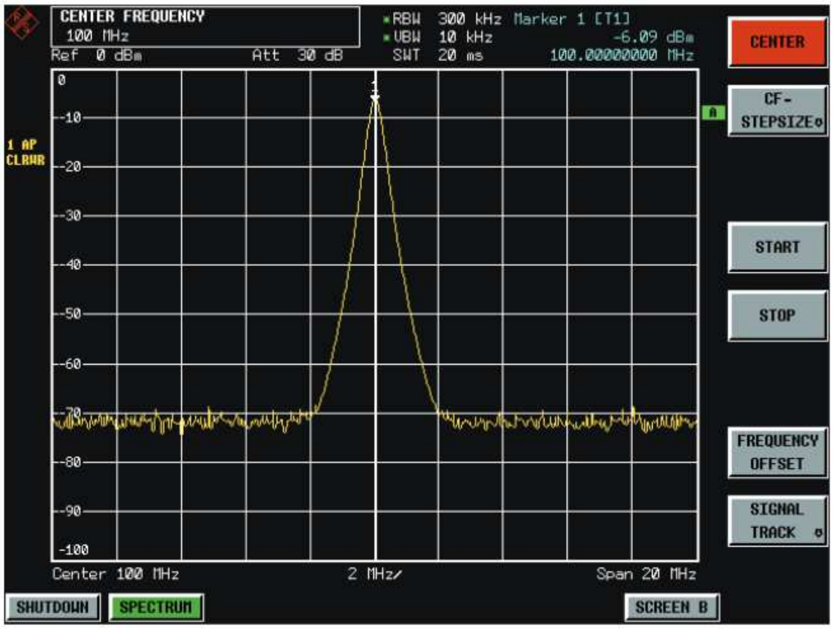
Pure FFT based spectrum analyzers are capable of measuring narrow band signals while maintaining a good dynamic range. One technique to expand the input frequency range and to maintain a good dynamic range is to combine the superheterodyne and FFT analyzer together into a so-called hybrid superheterodyne FFT analyzer. In this method, the input signal is first down-converted into intermediated frequency and then digitized. Superheterodyne or FFT techniques are then used to acquire the spectrum. A hybrid superheterodyne FFT analyzer allows faster sweep times to be used during the measurements. Another benefit is usage of digital RBW filters, with a near perfect shape factor and improved settling time, which cannot be achieved with conventional analog filters. [24; p.26]

Both swept-tuned and hybrid superheterodyne analyzers have a so-called blind time due to frequency sweep, a sampling time of the ADC converter and an FFT processing and calculation time. During the blind time period, information from measured spectrum could be missed. A real time FFT spectrum analyzer is able to sample the input RF signal in the time domain and convert the information back to the frequency domain using the FFT processing without a blind time period. Typically parallel, gapless and overlapped FFT processing is applied in order to acquire an RF spectrum that is not missing any information. The typical real time bandwidth in the modern spectrum analyzers is 800 MHz or even more.

Basic settings that have to be set by the user for spectrum analyzer in order to measure RF signals, such as continuous wave (CW), are listed below:

- Range of displayed frequencies
- Range of displayed signal levels
- Resolution bandwidth
- Sweep time.

The frequency display range can be set by the start and stop frequency range or by the exact center frequency and span around the center frequency. The level display range is used for setting the reference level for maximum signal level to be displayed. Frequency resolution of the spectrum analyzer is set via resolution bandwidth at the IF filter stage. The time which is required to sweep and record the entire selected frequency span is called sweep time. An example of the measured CW signal spectrum is shown in figure 23. [24; p.31]



CENTER FREQUENCY
100 MHz
Ref 0 dBm
Att 30 dB
RBW 300 kHz
VBW 10 kHz
SWT 20 ms
Marker 1 [T1]
-6.09 dBm
100.00000000 MHz
Center 100 MHz
2 MHz/
Span 20 MHz

Figure 23. Graphic display of measured CW signal spectrum. [24; p.31]

Measurement marker 1 is set to center frequency of 100 MHz indicating the signal power level of -6.09 dBm. The reference level is set to 0 dBm and the span to 20 MHz. The resolution bandwidth (RBW) filter is set to 300 kHz and the video bandwidth filter (VBW) to 10 kHz, corresponding to a sweep time of 20 ms. Some of the parameter settings, such as RBW, VBW, span and sweep time are depending on each other. For example, a small resolution bandwidth with a wide span will result to a longer sweep time. [24; p.31]

The most important spectrum analyzer specifications that need to be considered when choosing a spectrum analyzer for measurement applications, such as RF interference signal measurements, are listed below. [24; p.4]

- Frequency range
- Sensitivity
- Distortion
- Resolution
- Frequency and amplitude accuracy
- Dynamic range

The typical RF input frequency range for a modern spectrum analyzer is 2 Hz - 85 GHz. Measurement applications, such as 5G cellular development, military and automotive radar measurements, require even higher frequencies to be measured; therefore, the frequency range of an analyzer can be further expanded up to 500 GHz with external harmonic mixers. Real time spectrum analyzers are typically specified up to 2 GHz internal analysis bandwidth and 800 MHz real time bandwidth.

Inherent noise level is determining the sensitivity of a spectrum analyzer. It can be used to make conclusions of the smallest signal level to be measured with the analyzer. The spectrum analyzer is generating and amplifying inherent thermal noise just like any other active electronic circuit, resulting in a signal-to-noise reduction of an input signal. The sensitivity of a spectrum analyzer is usually specified as a displayed average noise level (DANL) parameter. Displayed noise level is a function of RF-input attenuation and IF stage resolution bandwidth filter settings. Figure 24 shows the displayed average noise level at three different resolution bandwidths. [24; p. 96]

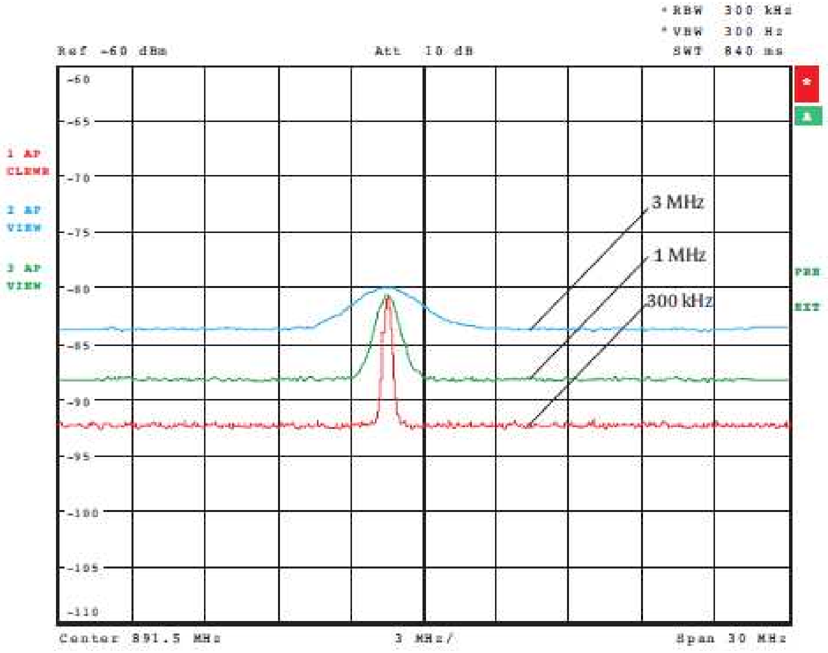


Figure 24. Displayed average noise level at three different resolution bandwidths. [24; p.99]

The maximum sensitivity of a spectrum analyzer is achieved when the RF input attenuation of 0 dB and narrowest available resolution bandwidth is used. Figure 24 shows the average noise level measured with three different resolution bandwidth settings using 10 dB RF input attenuation. The average noise level of an analyzer is decreased when the resolution bandwidth is decreased, as can be seen from the blue, green and red traces. As a general rule, the signal-to-noise ratio of a spectrum analyzer is decreased when the RF input attenuation is increased, therefore affecting the sensitivity of an analyzer. The sensitivity of an analyzer can be enhanced with the aid of a preamplifier. A low displayed average noise level leads to a better sensitivity and performance of the spectrum analyzer, allowing measurements for low power signal levels. [24; p.101]

Spectrum analyzers are typically used in measurement applications for amplifiers and mixers, which are producing distortion in form of harmonics and intermodulation products. First mixer inside the spectrum analyzer is generating harmonic and intermodulation distortion especially with high level of input signals, which is then added to those produced in the measured device. For single tone input signals, such as the sinusoidal signal, the specifications in the spectrum analyzer datasheets are usually referring to the level of second harmonic signal. This parameter is usually specified as second harmonic intercept (SHI) point in the datasheets. [24; p.103]

In addition to harmonics, signals consisting of two tones are producing intermodulation signal distortion, which are even and odd numbered. Even numbered distortion products always occur far away from two original input signal frequencies. Low order odd numbered intermodulation products are created in close vicinity of the original input signals, therefore they are difficult to filter away. Usually second and third order intercept points are specified in analyzer datasheets for nonlinearities, such as intermodulation distortion products created by the spectrum analyzer inside the first mixer. An example of the second and third order intercept point specification is presented in figure 25. [24; p.104]

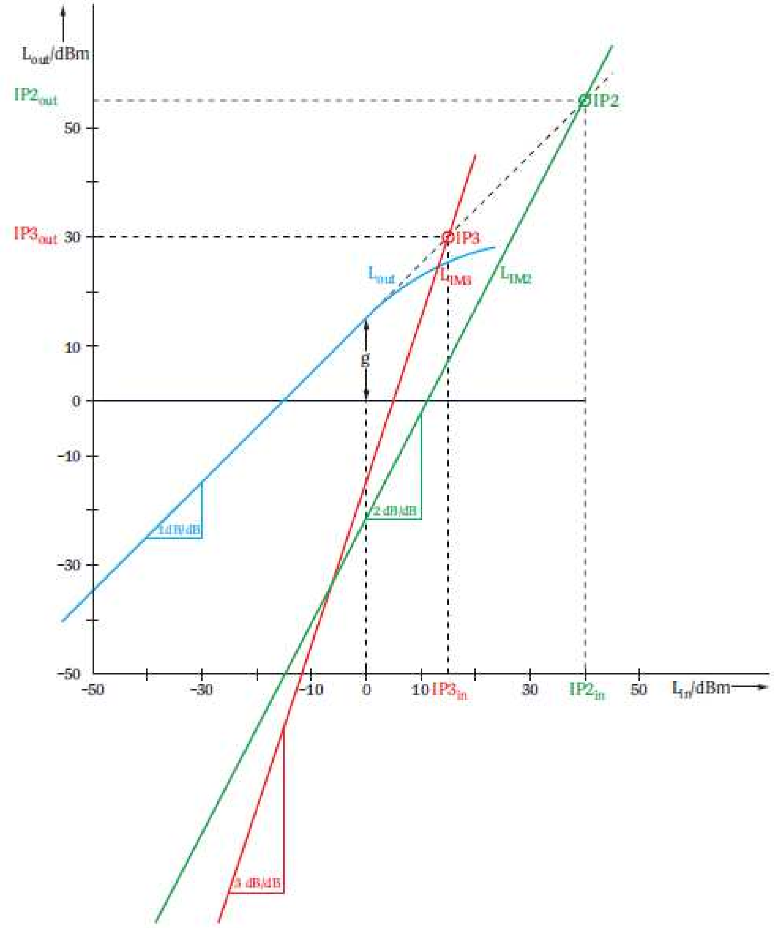


Figure 25. Intercept point of second and third order. [24; p.107]

The logarithmic presentation of the signal level at the input of first mixer is presented in the x-axis and the level of intermodulation distortion signals is presented in the y-axis. The blue curve presents the fundamental signal, the green curve presents the second order distortion product and the red curve presents the third order distortion product. Interfering spectral components operating in the mixer linear range take the form of a straight line as shown in figure 25. The second and third order intermodulation products characteristic curves are theoretically extrapolated beyond the possible operating range. The point where these lines intersect with the extrapolated line of the fundamental signal are defined as intercept points IP2 and IP3. [24; 108]

The slope of fundamental signal and second order and third order distortion signal curves are different. The slope for the fundamental signal curve is 1:1, the second order distortion signal curve 1:2 and the third order distortion signal curve 1:3. For example, the red curve presenting the third order distortion shows that a 1 dB increase of the fundamental signal level at the input of first mixer is causing a 3 dB increase of the distortion signal level. The blue and green curves can be interpreted respectively according to the steepness of their slope. [24; p.108]

The linearity of the spectrum analyzer is determined by the first mixer and IF amplifier. Harmonic and intermodulation distortion products generated by the spectrum analyzer inside these stages can lead to incorrect measurement results. Therefore, it is very important to maintain a proper signal level at the input of the first mixer while doing measurements. The input level of the first mixer is adjusted automatically in most of the modern spectrum analyzers. If the user is overriding the automatic settings and the mixer is overdriven, a warning indication is shown at the screen of the instrument in order to avoid incorrect measurement results. [24; p.112]

The resolution of the spectrum analyzer is determined by the type and shape factor of the resolution bandwidth filter, selected resolution bandwidth and phase noise generated inside the analyzer's internal oscillator circuitry. Modern analyzers are using analog, digital and FFT based resolution bandwidth filters. Analog filters can be used for realizing large resolution bandwidths, typically 100 kHz - 10 MHz. The typical shape factor for analog filters is about 10 - 14. Analog filters cannot be used for implementing ideal Gaussian type filters with a good shape factor. [24; p.54]

Digital filters can be used for implementing narrow resolution bandwidths and realizing ideal Gaussian filters with the typical shape factor of 4.6. Digital filters allow shorter sweep times to be used than analog filters of the same bandwidth. Very narrow resolution bandwidth setting leads to a long sweep time. FFT filters are implemented to shorten a sweep time when narrow resolution bandwidths are used. Maximum frequency span that can be analyzed by the FFT resolution bandwidth filters is limited by the sampling rate of the analyzer ADC converter and size of its sample memory. The typical shape factor for the FFT filter is 2.6. The downsize for FFT filters is that they are not suitable for measuring pulsed signals, and therefore, modern spectrum analyzers contain all filter types analog, digital and FFT. [24; p. 57]

The resolution bandwidth determines resolvability of equal amplitude signals and the filter shape factor determines resolvability of unequal amplitude signals. Figure 26 shows the spectrum of two sinusoidal input signals with different power levels measured with two different resolution bandwidths.

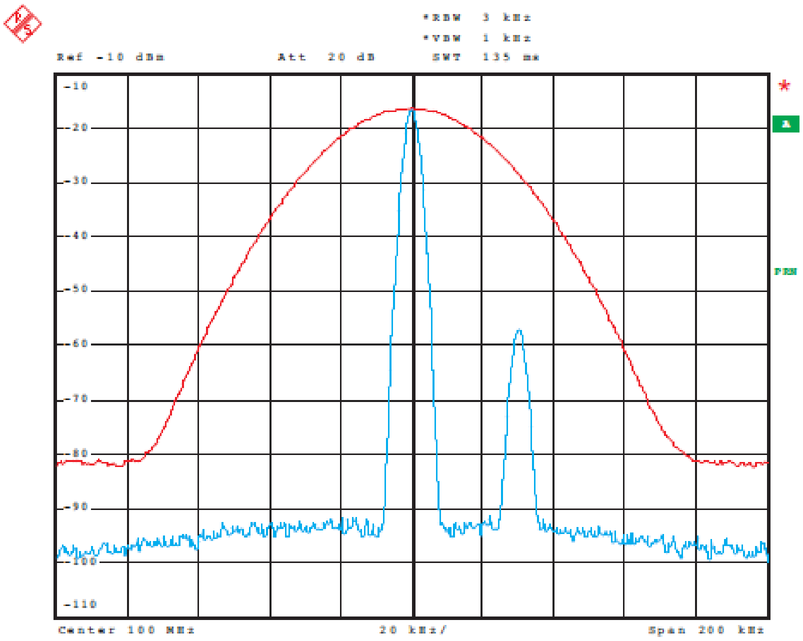


Figure 26. Spectrum of two sinusoidal input signals with two different power levels and resolution bandwidths. [24; p.50]

The red trace is displaying the measurement result using the resolution bandwidth setting of 30 kHz and the blue trace 3 kHz, respectively. If two signals have different power levels, the weaker signal will not be shown in the displayed spectrum when using a high-resolution bandwidth, as shown in figure 26 by the red trace. Weaker signal levels can be displayed by reducing the resolution bandwidth. When reducing the resolution bandwidth, the shape factor of resolution bandwidth filter is important. A low shape factor number refers to more steep skirts in filter design increasing the selectivity of filter. [24; p.49]

The variations of the phase or frequency and amplitude inside analyzer internal oscillator signals is causing phase noise. Spectrum analyzer datasheets are usually specifying the phase noise as single side band (SSB) phase noise referenced to carrier power as function of the carrier offset. Figure 27 shows the definition of single side band phase noise. [24; p.114]

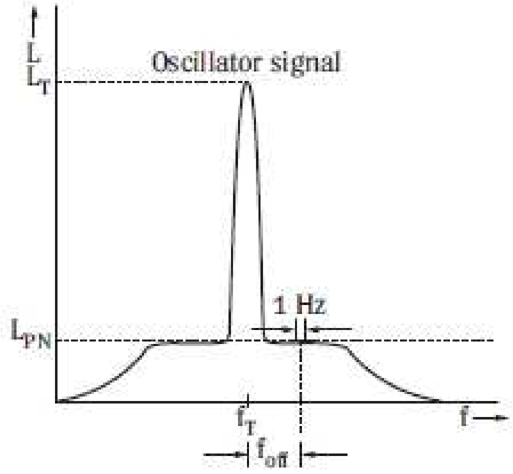
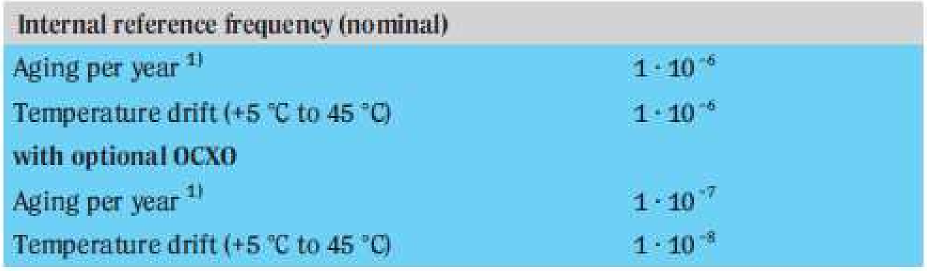


Figure 27. Definition of single sideband phase noise. [24; p.162]

Oscillator phase noise is usually specified at certain carrier offset relative to the carrier level within the 1 Hz bandwidth, the unit dBc is used in specification. Figure 27 shows measured carrier level L_T and phase noise L_{PN} level in the y-axis. Relative frequency offset f_{off} for the phase noise measurement is shown in the x-axis. Phase noise is creating noise sidebands that can prevent resolution of unequal power level signals in close vicinity of measured signal, therefore it is a very important parameter for spectrum analyzer. Low analyzer internal phase noise level means in practice that the analyzer is capable of measuring low level signals in close vicinity of the fundamental signal. [24; p.163]

The accuracy of internal reference oscillator is determining the frequency accuracy of spectrum analyzer. Other oscillators inside spectrum analyzer are synchronized to internal reference oscillator via phase locked loops. Usually, a reference frequency of 10 MHz is used for reference oscillator and its implementation contains temperature compensated crystal oscillators (TCXO) or oven controlled crystal oscillators (OCXO). Figure 28 shows an example from the datasheet extract containing frequency accuracy of TCXO and OCXO reference oscillators of modern spectrum analyzer. [24; p.140]



Internal reference frequency (nominal)	
Aging per year [1)]	$1 \cdot 10^{-6}$
Temperature drift (+5 °C to 45 °C)	$1 \cdot 10^{-6}$
with optional OCXO	
Aging per year [1)]	$1 \cdot 10^{-7}$
Temperature drift (+5 °C to 45 °C)	$1 \cdot 10^{-8}$

Figure 28. Frequency accuracy of TCXO and OCXO reference oscillators of modern spectrum analyzer. [24; p.140]

By using oven controlled crystal oscillator a very high frequency accuracy and small temperature drift are achieved as shown in figure 28. Total frequency error depends on temperature drift and long term frequency stability of reference oscillator. Long term frequency stability is achieved when an analyzer remains permanently switched on. Specifications of oscillator aging per year are typically valid after 30 days of constant operation. [24; p.141]

The level measurement accuracy of a spectrum analyzer has always some uncertainty. Components that contribute to uncertainty are:

- Mechanical switching uncertainty caused by RF input attenuator
- Input mismatch caused by VSWR
- Frequency response of first mixer and input filters
- Reference level accuracy of IF stage gain and attenuation
- RBW filter switching uncertainty
- Display scale fidelity caused by Log amplifier
- Amplitude accuracy of internal calibrator signal

Modern spectrum analyzers are factory calibrated before delivery. Individual measurement errors for different internal stages are recorded in the factory and stored inside the analyzer as correction values. This means in practice that the user can achieve best level measurement accuracy by optimizing his measurement setup and techniques. [24; p.141]

Dynamic range of spectrum analyzer means analyzer ability to simultaneously process signals with different power levels. The limits of dynamic range is depending on the application to be measured. Figure 29 shows an example of analyzer theoretical dynamic range versus real measurement range. Actual dynamic range is depending on second and third order distortion products, 1 dB compression point, displayed average noise level (DANL) and phase noise specification of analyzer.

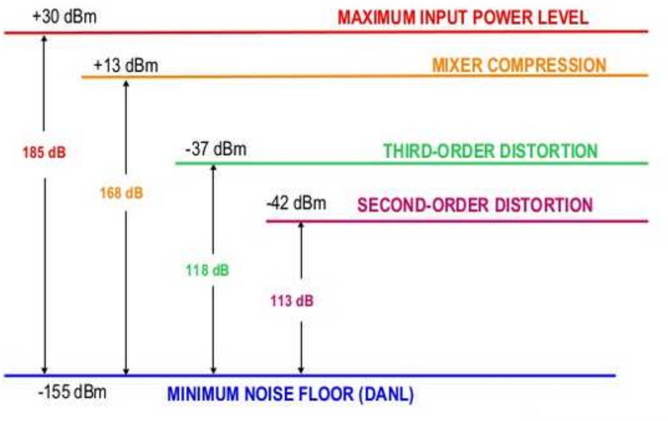


Figure 29. Spectrum analyzer theoretical dynamic range versus real measurement range. [25]

As shown in figure 29, lower level of dynamic range is determined by the internal inherent noise level and phase noise level, generated by the analyzer in different stages. The upper limit of dynamic range is determined by the 1 dB compression point of analyzer electronic stages or intermodulation distortion products generated inside the analyzer in case its first mixer is overdriven. [24; p.125]

The phase noise generated by analyzer local oscillator is mixed into the input signal in the analyzer frequency converting stages such as mixers. If the measured signal level is high, the effects of the analyzer thermal noise level can be neglected. This means in practice that the achievable dynamic range of an analyzer at a small carrier offset is determined solely by the local oscillator phase noise level. [24; p.167]

As shown in figure 27, the phase noise of a spectrum analyzer decreases when carrier offset is increased. At a large carrier offset, the dynamic range of the spectrum analyzer is determined by the analyzer thermal noise level. This means is practice that a high signal-to-noise ratio and 1 dB compression point is required for achieving a better dynamic range for the analyzer, when making measurements far off the carrier. [24; p.167]

A high signal level at the input of the first mixer also create harmonics of the input signal. If these harmonics falls outside of the frequency range, which phase noise of the device under test (DUT) is to be measured they do not cause any disturbance. In case input signal level is greater than the analyzer dynamic range it has to be reduced by using internal or external RF attenuator, in order to achieve reliable measurement results. [24; p.167]

4 RF-interference and data bandwidth measurements in office WLAN network

The following chapters provide a description of an experimental WLAN network test setup, spectrum analyzer and network performance measurement procedures and test results for RF-interference signal and data bandwidth measurements. Finally all measured RF-interference signals and recorded WLAN network data bandwidth values are analyzed and described in more detail.

4.1 Description of test setup

The test setup used for studying physical layer characteristics of two external interferer sources operating at 2.4 GHz ISM frequency band is described in this chapter. Physical measurements were made in Rohde & Schwarz Finland’s sales office. Since the office was equipped with operational public campus WLAN network, RF-interference measurements were performed after normal business hours in order to avoid interfering the campus WLAN network traffic with a microwave oven and a Bluetooth loudspeaker. The measurement setup for experimental WLAN network was constructed inside a storage room where operational overlapping adjacent channels from the campus WLAN network were not interfering the measurement results and where it was possible to achieve a suitable physical measurement arrangement.

Measurement setup consisted of the following equipment

- Buffalo Asymmetric Digital Subscriber Line (ADSL) Wireless Modem Router, providing Local Area Network (LAN) and Wireless Local Area Network (WLAN) connectivity between server and client computers.
- Two Dell latitude laptops used as server and wireless client computers for measuring WLAN network data bandwidth.
- Whirlpool Microwave oven and portable Sony Bluetooth loudspeaker, used as external interference sources.
- Rohde & Schwarz Signal and Spectrum analyzer FSW 26, used for measuring physical layer characteristics of RF-interference signals.
- Aerial directional WLAN antenna, used as measurement antenna.

The test setup used in this study is shown in figure 30.

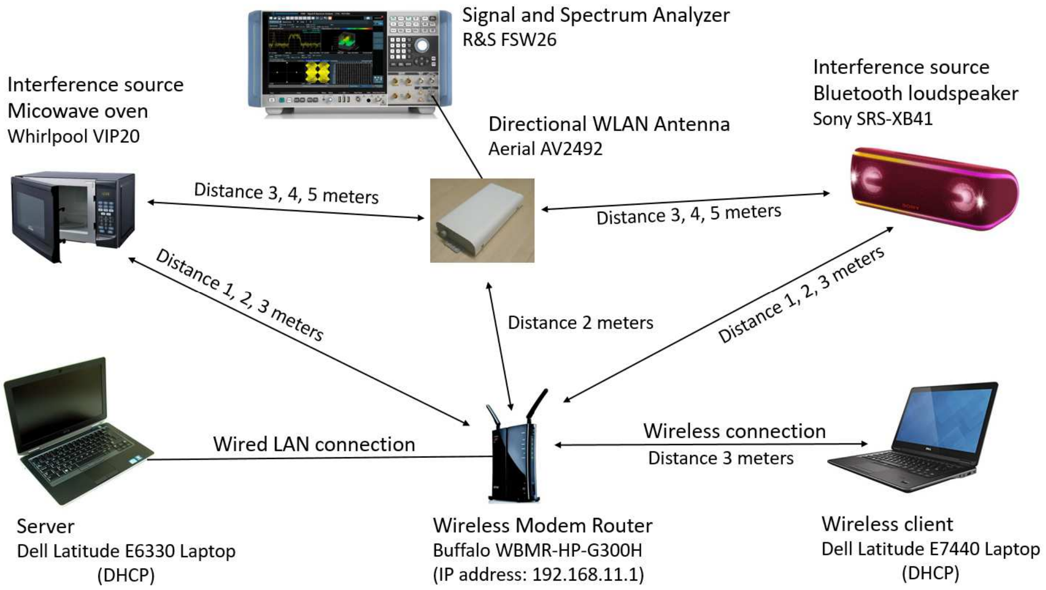


Figure 30. Test setup for RF-interference and data bandwidth measurements.

As shown in figure 30, the wireless modem router was used for providing connection between server and client computers. The modem was not connected to the Internet during measurements procedures. Two computers were used for measuring WLAN network data bandwidth by utilizing a external network data bandwidth software analyzing tool called jPerf [11].

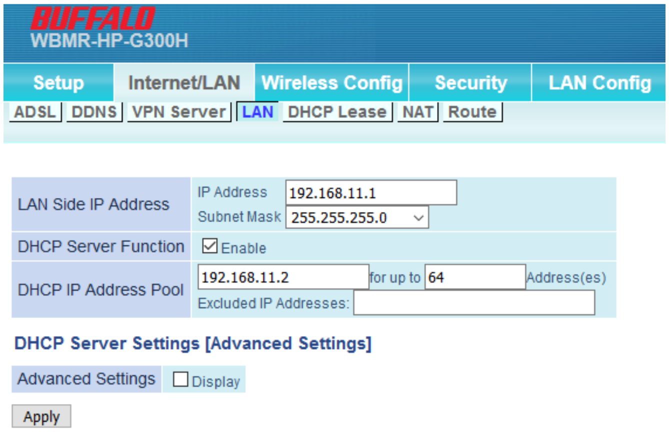
A normal microwave oven and a portable Bluetooth loudspeaker were used as external interference sources inside the experimental WLAN network. During the RF-interference measurements a bowl of cold water was placed inside the microwave oven, which was operated 180 seconds in its maximum output power of 900 W. The Bluetooth loudspeaker was paired with a mobile phone, streaming music from the phone.

The distance between the wireless modem router and external interference sources were changed between 1–3 meters during different phases of measurement. Same measurement routines were repeated three times for each external interferer sources in order to study how physical distance affects the peak power level of interference signal and data bandwidth of experimental WLAN network.

A directional WLAN measurement antenna was placed 2 meters away from the wireless modem router. The antenna was placed at a height of 1.2 meters above the floor level by using a separate tripod. The position or the height of the antenna were not changed during the RF-interference measurements. A modern high quality real time spectrum analyzer was used for measuring the physical layer characteristics of RF-interference signals coming from the microwave oven and Bluetooth loudspeaker.

The server computer was connected to the wireless modem router via category 6 twisted pair Ethernet cable in order to provide good protection against crosstalk and external noise. A wireless connection between client computer and modem router was established. The server and client computers were using their own built-in Network Interface Cards (NIC) for generating network traffic for data bandwidth measurements.

In order to measure reliable data bandwidth values between server and client computers, the IP-addresses of both computers had to be configured into the same subnetwork. Both computers were using the Dynamic Host Configuration Protocol (DHCP) in order to automatically fetch the IP-address from the wireless modem router DHCP address pool. The wireless modem router local area network IP-address and DHCP address pool settings are shown in figure 31.



LAN Side IP Address	IP Address 192.168.11.1 Subnet Mask 255.255.255.0
DHCP Server Function	☑ Enable
DHCP IP Address Pool	192.168.11.2 for up to 64 Address(es) Excluded IP Addresses:

DHCP Server Settings [Advanced Settings]

Advanced Settings	☐ Display

Figure 31. Wireless modem router LAN side IP-address and DHCP IP-address pool settings.

An initial WLAN network scan was performed using a mobile phone application called Wifi Analyzer [26]. The scan indicated that storage room was the only physical place within the entire Rohde & Schwarz sales office where direct adjacent overlapping WLAN channels from campus WLAN network were not present. Therefore, a wireless modem router was set to use WLAN channel 6 in order to avoid interferences coming from campus WLAN network access points during the data bandwidth measurements. The modems configuration for wireless channel setting and RF-bandwidth is shown in figure 32.

Wireless Radio	☑ Enable
Wireless Channel	Channel 6 (Current Channel: Manual Selection)
300 Mbps Mode	Bandwidth : 20 MHz Extension Channel : 1
Broadcast SSID	☑ Allow

Figure 32. Wireless channel and RF-bandwidth settings for wireless modem router.

The Buffalo modem is using two isotropic type antennas for wireless connection, enabling diversity and 40 MHz RF-bandwidth for WLAN communication. Antennas can be physically set to horizontal or vertical position. In theory up to a 300 Mbit/s wireless channel data rate can be achieved by using both two antennas and a 40 MHz bandwidth setting simultaneously.

During the interference and data bandwidth measurements, the wireless channel bandwidth was limited to 20 MHz by using only one wireless RF-channel as shown in figure 32. The modem router supports all three 801.11n, 801.11g and 801.11b physical layer standards. The experimental WLAN network was secured with a proper WPA/WPA2 wireless authentication, TKIP/AES wireless encryption and WPA-PSK pre-shared key protocols for network security reasons.

Rohde & Schwarz FSW 26 spectrum analyzer was chosen as the measurement device for studying physical layer characteristics of external interference sources. FSW spectrum analyzer has an outstanding RF-performance, scalable analysis bandwidth and real time measurement capabilities. The front view of FSW 26 spectrum analyzer is shown in figure 33.

Figure 33. Front view of FSW 26 spectrum analyzer. [27; p.2]

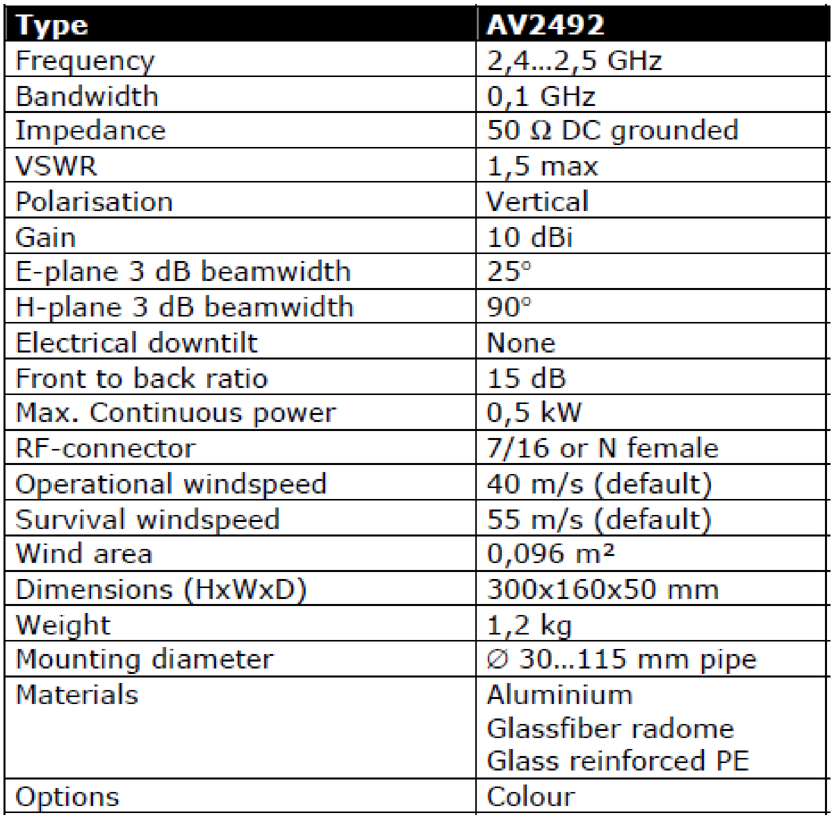
The frequency range of the FSW 26 spectrum analyzer is specified from 2 Hz to 26.5 GHz, thus fully covering the entire 2.4 GHz ISM frequency band. The FSW spectrum analyzer has excellent phase noise and dynamic range characteristics, therefore it is fully suitable for measuring low level wireless signals such as WLAN and Bluetooth signals. The maximum specified real time bandwidth for FSW 26 spectrum analyzer is 800 MHz, thus it is fully capable of measuring the entire 2.4 GHz ISM frequency band in real time. [27].

Aerial directional WLAN measurement antenna was chosen for interference measurements. Figure 34 shows a picture of the measurement antenna setup.

Figure 34. Measurement antenna setup.

The antenna setup consisted of Aerial AV2492 antenna module, antenna cable and tripod as shown in figure 34. The frequency range of antenna module is from 2.4 GHz - 2.5 GHz, thus fully covering the entire 2.4 GHz ISM frequency band. The polarization of an antenna is vertical, therefore it is capable of receiving a maximum amount of energy from vertically polarized wireless modem router antennas. The nominal impedance of AV2492 antenna is 50 ohms, it can be connected directly via a 50 ohm cable into the input of the spectrum analyzer without using separate impedance converters. Antenna E-plane, H-plane and gain values are specified at the factory during the manufacturing process. The characteristics of Aerial AV2492 WLAN antenna module are shown in table 2. [28; p.13]

Table 2. Charcteristics of AV2492 directional WLAN antenna. [28; p.13]



Type	AV2492
Frequency	2,4...2,5 GHz
Bandwidth	0,1 GHz
Impedance	50 Ω DC grounded
VSWR	1,5 max
Polarisation	Vertical
Gain	10 dBi
E-plane 3 dB beamwidth	25°
H-plane 3 dB beamwidth	90°
Electrical downtilt	None
Front to back ratio	15 dB
Max. Continuous power	0,5 kW
RF-connector	7/16 or N female
Operational windspeed	40 m/s (default)
Survival windspeed	55 m/s (default)
Wind area	0,096 m²
Dimensions (HxWxD)	300x160x50 mm
Weight	1,2 kg
Mounting diameter	∅ 30...115 mm pipe
Materials	Aluminium Glassfiber radome Glass reinforced PE
Options	Colour

The AV2492 antenna module is highly directive. As can be seen from table 2, the specified E-plane and H-plane 3 dB beam width values are quite narrow. This means in practice that a high antenna gain can be achieved between 2.4 GHz–2.5 GHz frequencies. The front to back ratio of 15 dB is an indication of quite small back lobes, thus the antenna is not receiving much energy from behind. During the RF-interference measurements, the front panel of the antenna was pointed directly towards an external interference source in order to receive a maximum level of energy. The specified gain of an antenna is 10 dBi, making the AV2492 antenna module suitable for measuring low level signals in 2.4 GHz ISM frequency band.

4.2 Measurements for external RF-interference sources

4.2.1 Reference measurement for campus WLAN network

This chapter provides a description and information of the measurement setup and measurement results for experimental WLAN network reference measurements. The measurement setup was built inside an 18 square meter storage room in Rohde & Schwarz Finland sales office. The setup used for reference measurements is shown in figure 35.

Figure 35. Test setup for reference measurements.

The wireless modem router and server computer were positioned two meters away from the measurement antenna located in the back wall of the storage room. Both the wireless modem router and the server computer were placed in a portable trolley, with the modem on top. The spectrum analyzer was positioned three meters away from the wireless modem router and it was placed in the portable test equipment rack as shown in figure 35.

The reference measurement was started by scanning operational campus WLAN network with mobile phone Wifi application in order to find out which WLAN channels were used by the campus network. The test result taken from the mobile phone screen is shown in figure 36.

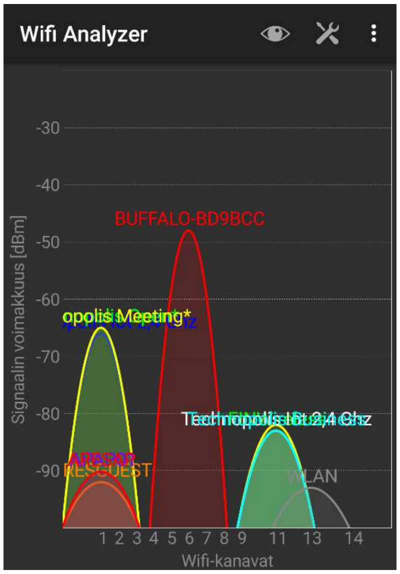
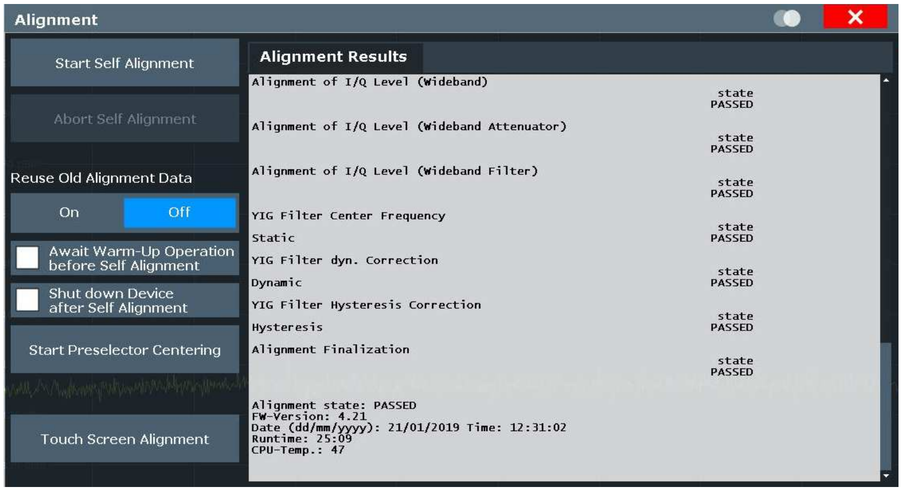


Figure 36. Test result for campus WLAN network scan.

As shown in figure 36, WLAN channels 1, 11 and 13 were occupied by several campus WLAN network access points. The experimental WLAN network access point was activated in channel 6. The physical layer reference measurements were performed with the spectrum analyzer in two modes, the traditional swept tuned and real time mode. Before the spectrum analyzer was ready to be used for measurements, an internal alignment routine was activated in order to verify the correct functionality of the spectrum analyzer internal electronic stages. Figure 37 shows the test results for the spectrum analyzer internal alignment routine.



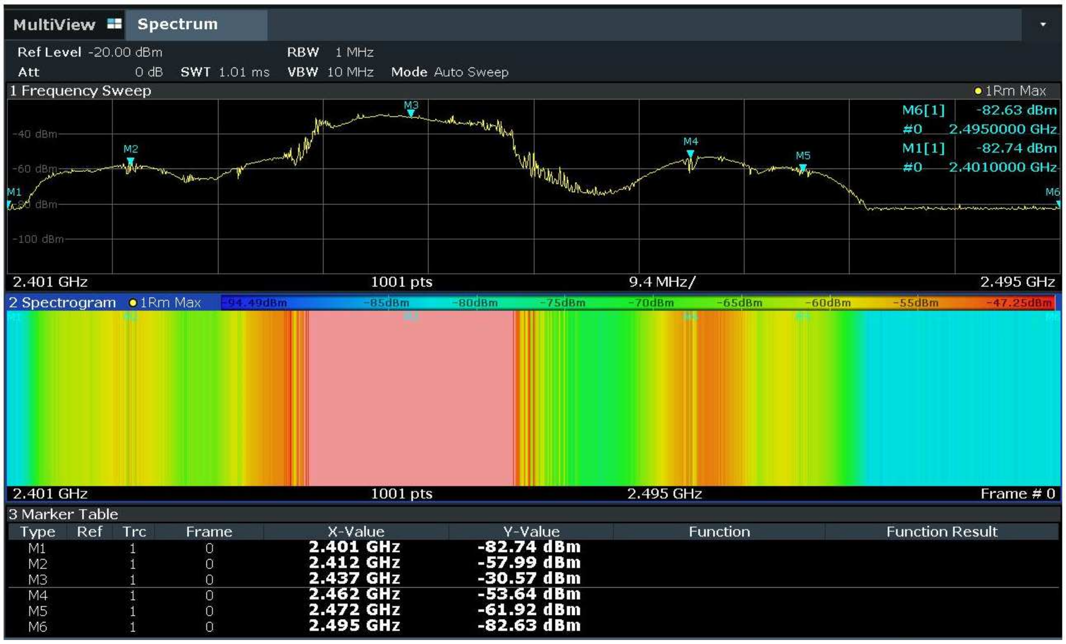
```
Alignment of I/Q Level (Wideband)
                                                            state
                                                           PASSED
Alignment of I/Q Level (Wideband Attenuator)
                                                            state
                                                           PASSED
Alignment of I/Q Level (Wideband Filter)
                                                            state
                                                           PASSED
YIG Filter Center Frequency
                                                            state
Static                                                     PASSED
YIG Filter dyn. Correction
                                                            state
Dynamic                                                    PASSED
YIG Filter Hysteresis Correction
                                                            state
Hysteresis                                                 PASSED
Alignment Finalization
                                                            state
                                                           PASSED

Alignment state: PASSED
FW-Version: 4.21
Date (dd/mm/yyyy): 21/01/2019 Time: 12:31:02
Runtime: 25:09
CPU-Temp.: 47
```

Figure 37. Test results for spectrum analyzer internal alignment routine.

As shown in figure 37, the alignment routine was completed successfully without any internal errors or warnings, the spectrum analyzer was ready to be used for measurements.

The first series of spectrum analyzer measurements were started in the swept tuned mode. The RMS detector and max hold trace function were selected in the spectrum analyzer trace settings in order to measure the maximum power level and achieve clean trace readings for active WLAN access point signals. Frequency range for the measurement was set from 2401 MHz to 2495 MHz, thus covering a total occupied bandwidth of 94 MHz for WLAN channels 1–14 operating in 2.4 GHz ISM frequency band.

The Resolution Bandwidth (RBW) filter was set to 1 MHz and Video Bandwidth (VBW) filter to 10 MHz, resulting in a short sweep time of 1.01 ms. The reference power level was set to -20 dBm and internal attenuator to 0 dB position. In addition to the conventional level versus frequency spectral trace display, a spectrogram display was activated. Figure 38 is showing the measurement results for swept tuned spectrum analyzer reference measurement.



Ref Level -20.00 dBm RBW 1 MHz
Att 0 dB SWT 1.01 ms VBW 10 MHz Mode Auto Sweep

M6[1] -82.63 dBm
#0 2.4950000 GHz
M1[1] -82.74 dBm
#0 2.4010000 GHz

3 Marker Table

Type	Ref	Trc	Frame	X-Value	Y-Value	Function	Function Result
M1		1	0	2.401 GHz	-82.74 dBm		
M2		1	0	2.412 GHz	-57.99 dBm		
M3		1	0	2.437 GHz	-30.57 dBm		
M4		1	0	2.462 GHz	-53.64 dBm		
M5		1	0	2.472 GHz	-61.92 dBm		
M6		1	0	2.495 GHz	-82.63 dBm		

Figure 38. Swept tuned spectrum analyzer reference measurement results for experimental WLAN network. Two meters distance between measurement antenna and WLAN access point.

As shown in the spectrum trace in the upper part of figure 38, the x-axis shows the measured frequency in Gigaherz and y-axis the signal power level in dBm values. Measurement markers M1–M6 were set to the spectrum trace for showing the maximum power level in specific frequency and marker point. Marker M1 was placed in start frequency 2401 MHz for WLAN channel 1 and marker M6 in stop frequency 2495 MHz for WLAN channel 14 in order to show interference signal power levels in band edges of 2.4 GHz ISM frequency band.

Since several operational campus WLAN network access points were active in channels 1, 11 and 13, the measurement markers M2, M4 and M5 were set at the center frequencies of those channels. As shown in the spectrum trace in the upper part of figure 38 and in the marker table in the lower part of the figure, the measured maximum power level for experimental WLAN network access point operating in center frequency 2437 MHz was -30.57 dBm, indicated by marker M3. The measured power level difference for marker positions M1, M2, M4, M5 and M6 referred to marker M3 reading were approximately between 23 dB–53 dB, depending on the measured frequency point and marker position.

The spectrogram, which is visible in the middle part of figure 38, shows how the spectral density varies over time. The x-axis of the spectrogram is showing the frequency in Gigaherz and the y-axis the time in milliseconds. The power density levels are indicated in different colors, red corresponding to the strongest and blue to the weakest power level value. [29; p.50]. As can be seen from the spectrogram trace, the power density around center frequencies of 2412 MHz, 2437 MHz, 2462 MHz and 2472 MHz correlates well with the measured swept spectrum trace. Most of the power was concentrated in WLAN channels 1, 6, 11 and 13, as shown in red, yellow and green colors in the spectrogram trace in the middle part of figure 38. Faint stripes were visible across the entire measured frequency span in the spectrogram trace, indicating changes in power density levels for measured spectral components inside 94 MHz of signal bandwidth.

The same measurement routine was repeated in the real time spectrum analyzer mode. Identical frequency and reference power level settings and marker M1–M6 positions were used during real time measurements. The RBW filter was set to 235 kHz, resulting in a data acquisition time (SWT) of 30 ms for single spectrogram line in frequency domain and measurement time (Dwell Time) of 30 ms for continuous real time measurement mode. The analyzer internal attenuator was set to the 10 dB position. The positive peak detector and max hold trace function were set in the real time spectrum analyzer trace settings, making sure that the maximum peak power level and periodical signal spikes can be detected, measured and displayed correctly. In addition, a persistence spectrum mode was activated, enabling to view very short spectral events that the human eye is not otherwise able to capture. The results for the real time spectrum analyzer reference measurement is shown in figure 39.

Ref Level -20.00 dBm RBW 235 kHz
Att 10 dB SWT 30 ms Dwell Time 30 ms
PA YIG Bypass

3 Marker Table

Wnd	Type	Ref	Trc	Prob	X-Value	Y-Value
1	M1		Current	0.000 %	2.401 GHz	-87.33 dBm
1	M2		Current	0.000 %	2.412 GHz	-52.00 dBm
1	M3		Current	0.000 %	2.437 GHz	-31.00 dBm
1	M4		Current	0.000 %	2.462 GHz	-58.00 dBm
1	M5		Current	0.000 %	2.472 GHz	-58.17 dBm
1	M6		Current	0.000 %	2.495 GHz	-87.17 dBm
1	M7		Current	1.664 %	2.447282 GHz	-93.17 dBm

Figure 39. Real time spectrum analyzer reference measurement results for experimental WLAN network. Two meters distance between measurement antenna and WLAN access point.

As shown in the persistence spectrum in the upper part of figure 39, the color mapping indicates probability of signal occurrence in the measured spectrum, red corresponding to higher and blue lower probability. Higher signal amplitude levels appear brighter in the persistence spectrum display, and lower signal amplitude levels dimmer. [29; p.56]. The white envelope in persistence spectrum is showing the peak power level of measured signals.

As shown by marker M3 in the marker table in the lower part of figure 39, the measured peak envelope power level for the experimental WLAN network access point operating in center frequency of 2437 MHz was -31.00 dBm. The difference for peak power levels in marker positions M1, M2, M4, M5 and M6 referred to marker M3 reading were approximately between 21 dB–56 dB, depending on the marker position and measured frequency point. The total bandwidth for measured WLAN network access point signals was approximately 80 MHz wide.

Instead of just showing the peak envelope power level, the persistence spectrum is able to show detailed spectral components and hidden signals inside the measured frequency span. As shown in the upper part of the persistence spectrum in figure 39, the spectral components of the WLAN access points operating in center frequency 2414 MHz, 2437 MHz, and 2462 MHz were clearly visible. The green color in the persistence spectrum indicated high probability of occurrence for active WLAN access point signals.

Campus WLAN access point operating in center frequency of 2472 MHz in channel 13 was periodically active, thus transmitting only a short duration of time. The probability of occurrence for this signal was low, therefore it was measured and displayed as a white peak power envelope, as shown by marker M5 in the persistence spectrum in the upper part of figure 39. The spectrum analyzers internal noise level was displayed in red color as shown in the persistence spectrum in the upper part of figure 39, because noise has a high probability of occurrence.

In addition, a very low level interferer signal was measured in frequency 2447.282 MHz as shown by marker M7 in the persistence spectrum display in the upper part of figure 39. The source of this interferer was an unknown narrow band wireless device operating in 2.4 GHz frequency band. The curve shaped green color spectrum visible in the persistence display around center frequency 2437 MHz indicated that the experimental WLAN network access point was using Direct Sequence Spread Spectrum (DSSS) modulation technique for broadcasting its Service Set Identifier (SSID) signal.

The functionality and measurement result interpretation for real time spectrogram shown in the middle part of figure 39 were the same as the previously described in swept tuned mode measurement. The real time mode spectrogram was showing that power density for measured signals was concentrating in WLAN channels 1, 6, 11 and 13 as shown by red and green colors in the spectrogram trace in the middle part of figure 39.

4.2.2 Interference measurement for microwave oven

This chapter describes the test setup and measurement results for first external interference source. The test setup used for microwave oven interference measurements is shown in figure 40.

Figure 40. Test setup for microwave oven interference measurements.

The wireless modem router and server computer were positioned two meters away from the measurement antenna in a portable trolley, modem being on top. The spectrum analyzer and client computer were positioned three meters away from the wireless modem and they were placed in a portable test equipment rack. The microwave oven was placed on top of the separate portable trolley as shown in figure 40. The distance between the wireless modem router and microwave oven was changed between 1–3 meters in steps of one meter during the measurements.

In the first series of microwave oven interference measurements, the oven was placed one meter away from the wireless modem router. The distance between the microwave oven and the measurement antenna was three meters. The data bandwidth measurement in server and client computer was started and microwave oven was switched on. The first spectrum analyzer measurements were performed in swept tuned mode. Figure 41 is showing the first swept tuned spectrum analyzer measurement result for microwave oven interference signals.

Ref Level -20.00 dBm
Att 10 dB SWT 1.01 ms
RBW 1 MHz
VBW 10 MHz Mode Auto Sweep

M6[1] -60.77 dBm
#0 2.4950000 GHz
M1[1] -69.81 dBm
#0 2.4010000 GHz

3 Marker Table

Type	Ref	Trc	Frame	X-Value	Y-Value	Function	Function Result
M1		1	0	2.401 GHz	-69.81 dBm		
M2		1	0	2.412 GHz	-43.45 dBm		
M3		1	0	2.437 GHz	-30.05 dBm		
M4		1	0	2.462 GHz	-37.38 dBm		
M5		1	0	2.472 GHz	-34.24 dBm		
M6		1	0	2.495 GHz	-60.77 dBm		

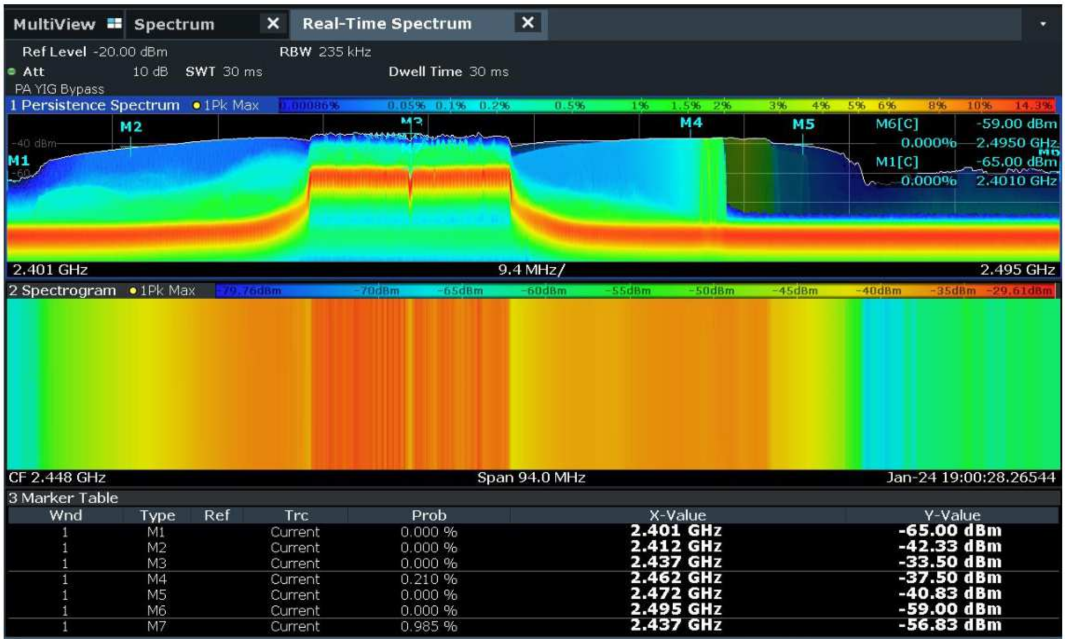
Figure 41. First swept tuned spectrum analyzer measurement results for microwave oven interference signals. Three meters distance between measurement antenna and microwave oven.

Frequency, span, RBW, VBW, sweep time and reference level settings used in spectrum analyzer were exactly the same as described in the previous chapter during reference measurement procedure. The analyzer internal attenuator setting was set to 10 dB due to high interference signal power level in order to avoid overloading the first mixer inside the spectrum analyzer during the interference signal measurements. The RMS detector and max hold trace function were selected under spectrum analyzer trace settings in order to measure maximum power level of interference signals and display clean spectral trace.

As shown in the spectrum trace in the upper part of figure 41 and by marker M3 in the marker table in the lower part of the figure, the maximum power level for experimental WLAN access point operating in center frequency 2437 MHz was -30.05 dBm. Measurement markers M1, M2, M4, M5 and M6 were placed to measure the maximum interference signal power levels in WLAN channels 1, 11, 13 center frequencies and band edges of 2.4 GHz ISM frequency band. Due to interference signals coming from the microwave oven, maximum power levels in marker positions M1–M6 were increased between 0.5 dB–22 dB compared to reference measurement results, depending on the marker position and measured frequency point. The measured bandwidth of interference signal was approximately 80 MHz wide.

As can be seen in the spectrogram trace red, orange, yellow and green color areas in the middle part of figure 41, most of the measured power was concentrated in WLAN channels 1, 6, 11 and 13. The red color was indicating strongest and blue weakest signal power levels in center frequencies of WLAN channels 1, 6 11 and 13 and band edges. The power density levels in 2.4 GHz ISM frequency band edges were quite low, displayed in blue color in the spectrogram trace in the middle part of figure 41.

Next, the same measurement procedure was repeated in the real time spectrum analyzer mode. Figure 42 is showing first real time spectrum analyzer measurement results for microwave oven interference signals.



Ref Level -20.00 dBm RBW 235 kHz
Att 10 dB SWT 30 ms Dwell Time 30 ms
PA YIG Bypass

3 Marker Table

Wnd	Type	Ref	Trc	Prob	X-Value	Y-Value
1	M1		Current	0.000 %	**2.401 GHz**	**-65.00 dBm**
1	M2		Current	0.000 %	**2.412 GHz**	**-42.33 dBm**
1	M3		Current	0.000 %	**2.437 GHz**	**-33.50 dBm**
1	M4		Current	0.210 %	**2.462 GHz**	**-37.50 dBm**
1	M5		Current	0.000 %	**2.472 GHz**	**-40.83 dBm**
1	M6		Current	0.000 %	**2.495 GHz**	**-59.00 dBm**
1	M7		Current	0.985 %	**2.437 GHz**	**-56.83 dBm**

Figure 42. First real time spectrum analyzer measurement results for microwave oven interference signals. Three meters distance between measurement antenna and microwave oven.

As shown in the persistence spectrum in the upper part of figure 42 and in the marker table in the lower part of the figure, measurement markers M1–M6 were set in the center frequencies of WLAN channels 1, 6, 11, 13 and band edges of 2.4 GHz ISM frequency band for measuring the peak power level of interference signals. In addition, measurement marker M7 was set to measure the average signal power level for experimental WLAN access point operating in center frequency 2437 MHz. As shown in the marker table in the lower part of figure 42, marker M3 indicates peak power level -33.50 dBm and marker M7 average power level -56.83 dBm in frequency point 2437 MHz for WLAN access point operating in channel 6. Maximum power levels in marker positions M1–M6 were increased between 2.5 dB–28 dB compared to reference measurement results, depending on the marker position and measured frequency point. Persistence spectrum functionality revealed that the bandwidth for interference signals coming from the microwave oven was actually 94 MHz wide as shown in the persistence spectrum trace in the upper part of figure 42. The red rectangular spectrum visible in the persistence display around center frequency 2437 MHz was indicating that experimental WLAN network access point was using OFDM modulation technique for data transmission.

The probability of occurrence for wideband interfering signal coming from the microwave oven was high. This can be observed in the green color areas in the persistence spectrum in the upper part of figure 42. In addition, a narrow band interference signal was detected in the persistence spectrum as a green color spike between markers M4 and M5, and it was slightly shifting in the frequency axis during the operation of the microwave oven. The source of this interference signal was the microwave oven's magnetron.

As displayed in the spectrogram trace in red, orange and yellow color areas in the middle part of figure 42, most of the power was concentrated in WLAN channels 1, 6, 11 and 13. Faint stripes visible across the entire spectrogram trace indicated changes in power density levels for spectral components inside the measured frequency span. The difference between real time spectrogram and swept tuned spectrogram was that real time spectrogram was detecting quite high power level readings in band edges as shown in the spectrogram trace in green and light blue colors in the middle part of figure 42. The reason for this is because bandwidth of microwave interference signals was 94 MHz wide in reality.

The same measurement procedures for microwave oven interference signals were repeated also in four and five meter distances between the measurement antenna and the microwave oven. These measurements show similar test results for both measurement distances. The peak power levels for interference signals were decreasing as distance between measurement antenna and microwave oven was increasing, while the bandwidth for interference signals remained the same. No other notable spurious interferers were detected during the second and third swept tuned and real time spectrum analyzer measurements. The measurement results for the second and third microwave oven interference signal spectrum analyzer measurements are shown in Appendix 1.

4.2.3 Interference measurement for Bluetooth loudspeaker

This chapter describes the test setup and measurement results for the second external interference source. The test setup used for Bluetooth loudspeaker interference measurements is shown in figure 43.

Figure 43. Test setup for Bluetooth loudspeaker interference measurements.

As shown in figure 43, the wireless modem router and server computer were positioned two meters away from the measurement antenna in a portable trolley, the modem being on top. The spectrum analyzer and client computer were positioned three meters away from the wireless modem and they were placed in a portable test equipment rack. Bluetooth loudspeaker was placed on top of the separate portable trolley. During the Bluetooth loudspeaker interference measurements, the speaker was moved 1–3 meters away from WLAN access point in steps of one meter. Exactly the same spectrum analyzer settings and measurement procedures were used for performing Bluetooth loudspeaker interference measurements as in case of the microwave oven.

In the first series of Bluetooth loudspeaker interference measurements, the speaker was placed one meter away from the wireless modem router. The distance between the loudspeaker and the measurement antenna was three meters. The data bandwidth measurement in server and client computer was started and the speaker was activated. Figure 44 shows the first swept tuned interference signal measurement results for Bluetooth loudspeaker.

Ref Level -10.00 dBm
Att 30 dB SWT 1.01 ms
PA
RBW 1 MHz
VBW 10 MHz Mode Auto Sweep

3 Marker Table

Type	Ref	Trc	Frame	X-Value	Y-Value	Function	Function Result
M1		1	0	**2.401 GHz**	**-42.51 dBm**		
M2		1	0	**2.412 GHz**	**-42.11 dBm**		
M3		1	0	**2.437 GHz**	**-30.94 dBm**		
M4		1	0	**2.462 GHz**	**-38.20 dBm**		
M5		1	0	**2.472 GHz**	**-39.74 dBm**		
M6		1	0	**2.495 GHz**	**-69.36 dBm**		
D7	M1	1	0	**80.5 MHz**	**-19.42 dB**		

Figure 44. First swept tuned spectrum analyzer measurement results for Bluetooth loudspeaker interference signals. Three meters distance between measurement antenna and Bluetooth loudspeaker.

As shown by marker M3 in the spectral trace and the marker table in figure 44, the measured maximum power level for experimental WLAN access point operating in center frequency 2437 MHz was -30.94 dBm. Measurement markers M1, M2, M4, M5 and M6 were set to measure maximum power levels in WLAN channels 1, 11, 13 center frequencies and band edges of 2.4 GHz ISM frequency band. Due to signals coming from the Bluetooth loudspeaker, the maximum power levels in marker positions M1–M6 were increased between 15 dB–40 dB compared to reference measurement results, depending on the marker position and measured frequency point. The measured bandwidth for Bluetooth interference signals was 80.5 MHz as displayed by marker D7 in the marker table in figure 44.

The red, orange, yellow and green color areas in the spectrogram trace in the middle part of figure 44 shows that most of the power was concentrated in WLAN channels 1, 6, 11 and 13. Faint stripes were visible across the spectrogram trace, indicating the frequency hopping nature of the Bluetooth payload signal inside the measured frequency span.

Next, the same measurement procedure was repeated in the real time spectrum analyzer mode. Figure 45 shows first real time spectrum analyzer interference signal measurement results for Bluetooth loudspeaker.

Ref Level -20.00 dBm RBW 235 kHz
Att 10 dB SWT 30 ms Dwell Time 30 ms
PA YIG Bypass

3 Marker Table

Wnd	Type	Ref	Trc	Prob	X-Value	Y-Value
1	M1		Current	0.000 %	**2.401 GHz**	**-73.50 dBm**
1	M2		Current	0.000 %	**2.412 GHz**	**-43.33 dBm**
1	M3		Current	0.000 %	**2.437 GHz**	**-32.33 dBm**
1	M4		Current	0.000 %	**2.462 GHz**	**-40.83 dBm**
1	M5		Current	0.000 %	**2.472 GHz**	**-40.83 dBm**
1	M6		Current	0.000 %	**2.495 GHz**	**-87.50 dBm**
1	D7	M1	Current	10.611 %	**80.5 MHz**	**-33.67 dB**

Figure 45. First real time spectrum analyzer measurement results for Bluetooth loudspeaker interference signals. Three meters distance between measurement antenna and Bluetooth loudspeaker.

As shown in the marker table in the lower part of figure 45, measurement markers M1–M6 were set in the center frequencies of WLAN channels 1, 6, 11,13 and band edges of 2.4 GHz ISM frequency band for measuring peak power level of interference signals. Marker D7 was set to measure the total bandwidth of the Bluetooth payload signal. Marker M3 was showing a peak power level of -32.33 dBm in the center frequency

2437 MHz for WLAN access point operating in channel 6. Marker D7 indicated that the measured bandwidth for Bluetooth payload signal was 80.5 MHz, as shown in the marker table in the lower part of figure 45. Maximum peak power levels in marker positions M1–M6 were increased between 9 dB–18 dB compared to reference measurement results, depending on the marker position and measured frequency point.

The probability of occurrence for Bluetooth signal peak power levels were quite low. This can be observed in the dark blue color areas in the persistence spectrum, as shown the upper part of figure 45. The frequency hopping nature of the Bluetooth signal payload could clearly be identified from the narrowband blue colored sub-channels, visible in the persistence spectrum as shown in the upper part of figure 45.

In addition, narrow green signal spikes were visible around marker positions M2, M4 and M5 as shown in the persistence spectrum display in the upper part of figure 45. The source of these spikes were campus WLAN network access points transmitting in WLAN channels 1, 11 and 13. The red, orange, yellow and green color areas in the spectrogram display in the middle part of figure 45 indicated that most of the power was concentrated in WLAN channels 1, 6, 11 and 13. Faint visible stripes in the spectrogram were indicating that the measured interference signal came from a frequency hopping device.

The same measurement procedures for Bluetooth loudspeaker interferences were also repeated in four and five meter distances between the measurement antenna and the Bluetooth device. These measurements show similar test results for both measurement distances. The peak power level of interference signals were decreasing as the distance between measurement antenna and Bluetooth loudspeaker was increasing, while the bandwidth of interference signals remained the same. No other spurious interference signals were detected during the second and third swept tuned and real time spectrum analyzer measurements. The measurement results for the second and third Bluetooth loudspeaker interference signal spectrum analyzer measurements are shown in Appendix 2.

4.3 Recording of WLAN network data bandwidth

4.3.1 Reference data bandwidth measurement

In this chapter, the test setup for the reference data bandwidth measurement inside the experimental WLAN network and measured test results are described. During the reference measurement, both of the external interference sources, i.e. the microwave oven and the Bluetooth loudspeaker, were switched off. Test setup used for the reference measurement is shown in figure 46.

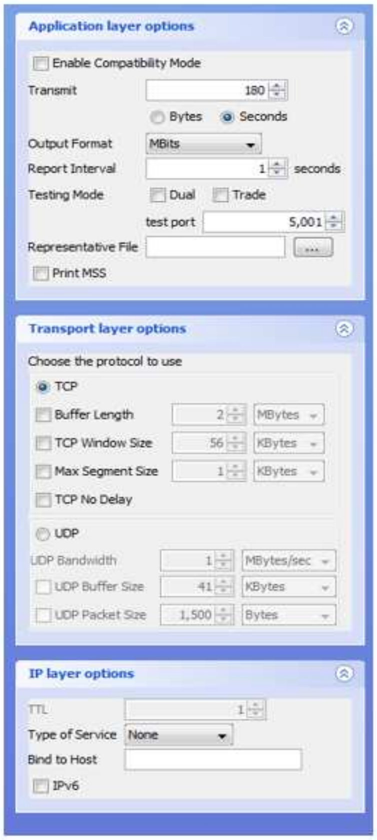
Figure 46. Test setup for reference data bandwidth measurement.

The wireless modem router and server computer were positioned 2 meters away from the back wall of the storage room. They were placed in the portable trolley, the modem being on the top level. The wireless modem router was set to operate in the center frequency of 2437 MHz in WLAN channel 6. The wireless client computer was positioned 3 meters away from the wireless modem and it was placed on top of another portable trolley as shown in figure 46.

The reference data bandwidth was measured and recorded with the network performance software tool jPerf, which is able to create network traffic for data bandwidth measurements. The software can be set to run in two main modes, the server and the client. It can be configured to create network traffic by using the Transmission Control Protocol (TCP) or the User Datagram Protocol (UDP). In order to run a successful data bandwidth measurement, the IP-addresses of both the server and the client computers need to be set to operate inside the same local area subnetwork.

Separate copies of jPerf software were installed for both the server and the client computers. The server computers jPerf software was started in server mode and it was using the server computers' network interface card IP-address for network communication. No further configurations for server computer were needed, it was ready for measurements waiting for client computer connection.

The client computers jPerf software was started in client mode. TCP test parameters for data bandwidth measurement was set for creating network traffic. The server computer IP-address was set to client computers jPerf software. Figure 47 shows the application and transport layer settings used in the client computers jPerf software during the reference data bandwidth measurement.



Application layer options

☐ Enable Compatibility Mode
Transmit 180
○ Bytes ● Seconds
Output Format MBits
Report Interval 1 seconds
Testing Mode ☐ Dual ☐ Trade
test port 5,001
Representative File
☐ Print MSS

Transport layer options

Choose the protocol to use
● TCP
☐ Buffer Length 2 MBytes
☐ TCP Window Size 56 KBytes
☐ Max Segment Size 1 KBytes
☐ TCP No Delay
○ UDP
UDP Bandwidth 1 MBytes/sec
☐ UDP Buffer Size 41 KBytes
☐ UDP Packet Size 1,500 Bytes

IP layer options

TTL 1
Type of Service None
Bind to Host
☐ IPv6

Figure 47. Application and transport layer settings for client computers jPerf software.

As shown in figure 47, the transmit time for generated data streams was set to 180 seconds. The reporting interval for test results was set to 1 second, the used TCP test port to 5001 and output format Mbit/s. During the data bandwidth measurements, the client computer jPerf software was generating TCP data packages in order to create network traffic. The buffer length, TCP window size, max segment size and TCP no delay settings were left at their default values. After all test parameters were set for the server and client computers, the actual reference data bandwidth measurement was performed. Figure 48 shows the test result for reference data bandwidth measurement.

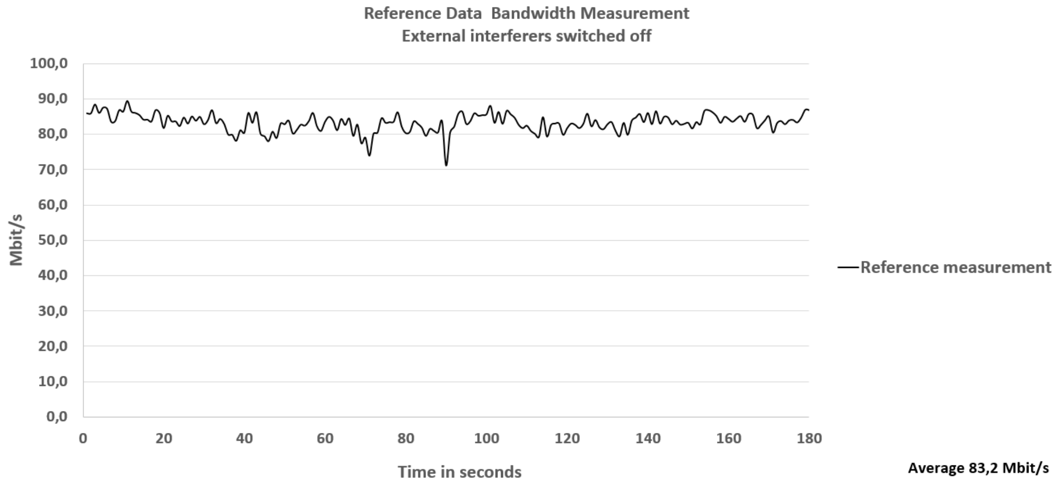


Figure 48. Measurement result for reference data bandwidth, external interferers switched off.

In figure 48, the x-axis presents the total measurement time in seconds with step size of twenty seconds and the y-axis the measured data bandwidth in Mbit/s for experimental WLAN network access point operating in channel 6. The server computer jPerf software was recording 83,2 Mbit/s as average data bandwidth value within 180 seconds of measurement time. The theoretical top speed for wireless network interface card supporting 802.11n protocol is up to 600 Mbit/s, but in practice a data bandwidth of approximately 80 Mbit/s–150 Mbit/s can be achieved in public WLAN networks most of the time.

4.3.2 Data bandwidth measurement under external interference sources

This chapter presents test results for experimental WLAN network data bandwidth measurement, performed between client and server computers under external interference source signals. In the first series of measurement, the microwave oven was placed between 1–3 meters away from the WLAN access point in steps of one meter. The measured test results for the first series of average data bandwidth measurement are shown in figure 49.

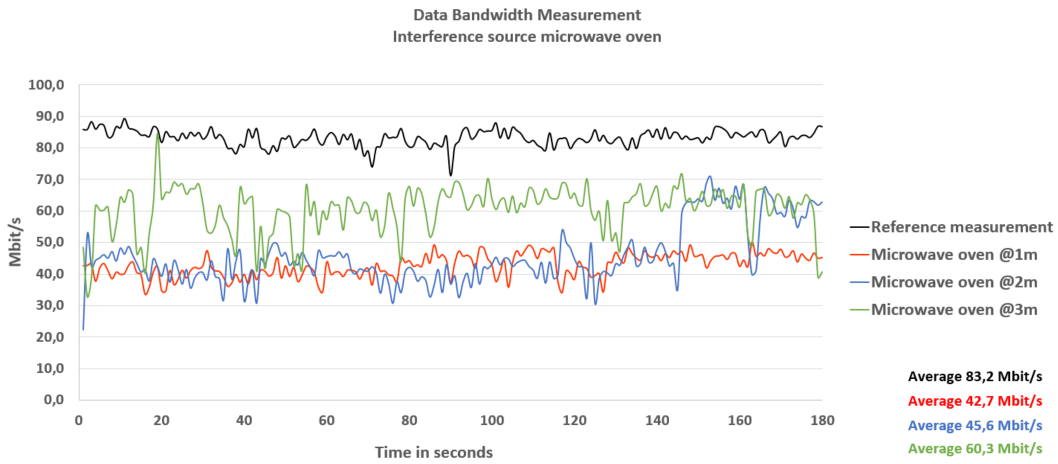


Figure 49. Test results for average data bandwidth measurement under microwave oven interference signal.

In figure 49, the x-axis presents the measurement time in seconds with a step size of twenty seconds and the y-axis the measured data bandwidth in Mbit/s. Separate measurement results are plotted with different traces and colors. The reference measurement result without external interferer signal is shown in black trace. Measurement results under the microwave oven interference at different distances are shown in red, green and blue traces. The total time for one single measurement was 180 seconds, which was repeated three times.

The average data bandwidth between the server and the client computer was reduced from the reference value of 83.2 Mbit/s to 60.3 Mbit/s–42,7 Mbit/s after the microwave oven was switched on. The closer the microwave oven was placed towards the WLAN access point, the lower were the data bandwidth values recorded. When the microwave oven was placed at a distance of three meters away from the WLAN access point, the data bandwidth values were slowly rising towards the reference value.

As shown by the green and blue traces in figure 49, a few high spikes in recorded values were observed when the microwave oven was placed two and three meters away from the WLAN access point. The red trace indicates that the measured data bandwidth was quite flat over the entire measurement time while the microwave oven was placed one meter away from the WLAN access point.

In the second series of data bandwidth measurements, the Bluetooth loudspeaker was placed between 1–3 meters away from the WLAN access point in steps of one meter. Figure 50 shows the measured test results for the second series of average data bandwidth measurement.

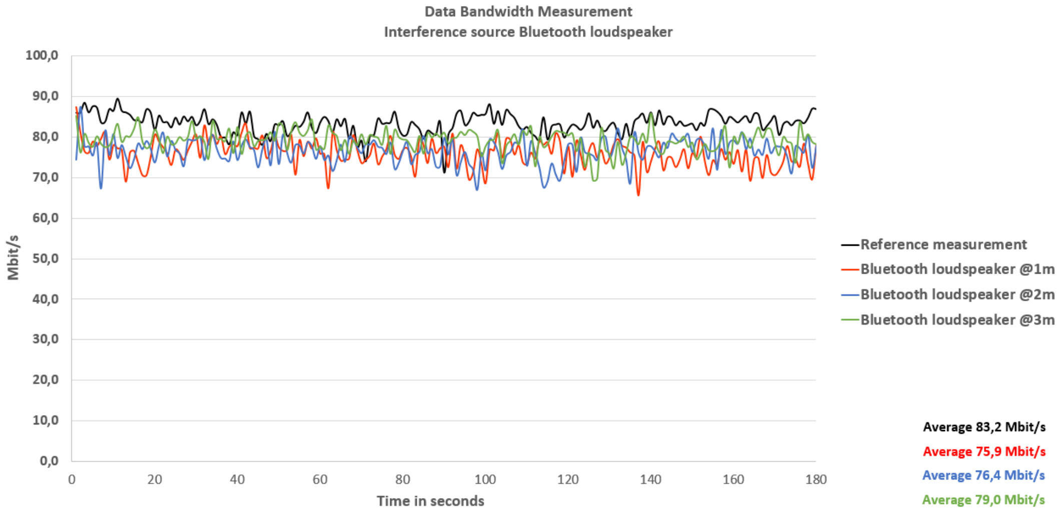


Figure 50. Test results for average data bandwidth measurements under Bluetooth loudspeaker interference signal.

As shown in figure 50 by the red, green and blue traces, the average data bandwidth between the server and the client computer was slightly reduced from the reference value of 83.2 Mbit/s to 75.9 Mbit/s–79,0 Mbit/s after the Bluetooth loudspeaker was activated. The closer the loudspeaker was placed towards the experimental WLAN access point, the lower were the data bandwidth values recorded. All recorded traces were quite flat, no large spikes were observed during the Bluetooth loudspeaker data bandwidth measurements.

4.4 Analysis of measured data

4.4.1 External RF-interference signals

In this chapter, the final test results for the microwave oven and Bluetooth loudspeaker RF-interference signal measurements are shown and analyzed. The spectrum analyzer measurements for physical layer interference signals were performed in swept tuned and real time modes in order to illustrate the typical differences between these two measurement technologies. During the measurements, the antenna was placed in the back wall of the storage room. As a general rule, an antenna has to be placed under the far field condition of measured electromagnetic wave in order to get reliable measurement results. The wavelength of 2.4 GHz ISM frequency band signals in free space is approximately 12 centimeters. As the physical dimension of the Aerial measurement antenna panel was significantly larger compared to the wave length, the distance between the measurement antenna and the interference signal sources was chosen to be between 2–5 meters in order to meet the far field condition in all measurement positions.

The physical layer connection of WLAN devices is based on the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) technique. Devices are transmitting for a short duration of time and only when the transmission channel is free, while no other transmissions are detected in the same channel. In the swept tuned mode, the spectrum analyzer is sweeping through the selected frequency span, thus resulting in certain overall sweep time depending on the selected frequency span, resolution and video bandwidth settings. In practice, the analyzer is not able to show reliable maximum power level readings for the WLAN signal source if wrong trace, sweep time, RBW or VBW settings are selected. In order to get clear trace readings, the max hold trace function, 1 MHz RBW, 10 MHz VBW and 1.01 ms sweep time settings were used during the swept tuned spectrum analyzer measurements.

The swept tuned measurement typically takes a long measurement time for catching short duration signals, such as fast transient spikes at the band edges of a wide band interference signal. During the 180 seconds of total measurement time, the swept tuned spectrum analyzer was only showing a 80 MHz bandwidth for microwave oven interferences, but in reality the bandwidth was 94 MHz wide as later measured in real time mode. It would have taken several tens of minutes or even hours of measurement time just to show the total bandwidth of 94 MHz interference signal in swept tuned mode. A conventional swept tuned spectrum analyzer is not the ideal measurement device for showing separate spectral components inside the measured frequency band of short duration signals such as spurious signals or Bluetooth device frequency hopping payload signals. In order to recognize the spectral signature of frequency hopping devices in swept tuned mode, the usage of spectrogram is highly recommended. Interference signals coming from frequency hopping devices can be identified as stripes, shown by the different colors in the spectrogram trace.

The most precise measurement technology for interference signal hunting is real time spectrum analysis. In real time mode, the spectrum analyzer captures the bandwidth of 800 MHz signal at once and calculates the spectrum with the aid of FFT algorithms inside powerful and fast Field Programmable Gate Array (FPGA) circuits. Real time spectrum analyzer is capable of showing measurement results within few micro seconds of time in the display of the analyzer. It is also capable of showing short duration signals and separate spectral components inside the entire measured frequency span. The spectrum signature of frequency hopping devices such as Bluetooth signal payload and other narrow and wideband external interferences can be easily displayed in the real time persistence spectrum.

Three separate real time interference measurements for both the microwave oven and the Bluetooth loudspeaker were performed in six different frequency points in the 2.4 GHz ISM frequency band. Figure 51 shows summary test results for the microwave oven's real time peak power interference measurements.

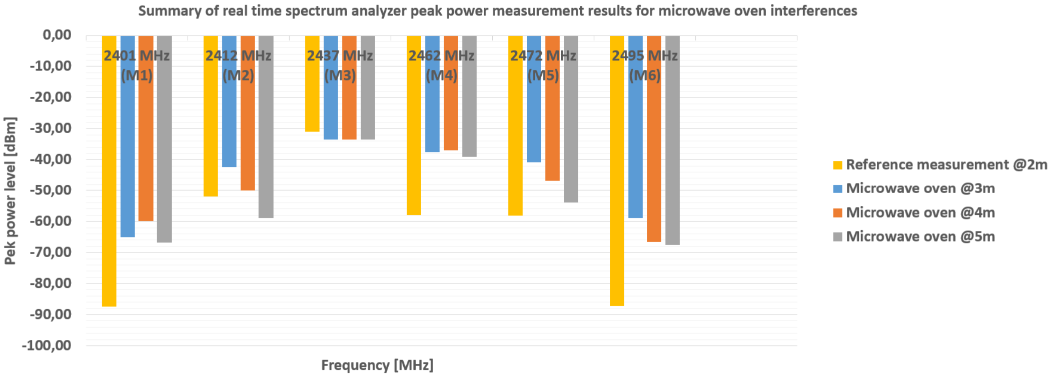


Figure 51. Summary of real time spectrum analyzer peak power measurement results for microwave oven interferences.

In figure 51, the x-axis shows the measured frequency in Megahertz and the y-axis the signal peak power level in dBm value at a specific frequency point. Every frequency point contains four bars indicating measurements performed in different distances and the measurement marker used during the measurement procedure. The yellow bar represents the reference measurement performed for the experimental WLAN access point, positioned two meters away from measurement antenna. The blue, orange and grey bars represent external interference signal measurements for the microwave oven, positioned three, four and five meters away from the measurement antenna. The highest peak power levels for reference measurement were found in frequencies 2412 MHz, 2437 MHz, 2462 MHz and 2472 MHz as shown by the yellow bars in figure 51. The peak power level was very low in band edges 2401 MHz and 2495 MHz frequencies during reference measurement. The bandwidth for the microwave oven interference signal was 94 MHz wide, covering all WLAN channels in the 2.4 GHz ISM frequency band.

The measured peak power level in the center frequency of 2437 MHz was almost constant in all distances as shown by the blue, orange and grey bars in figure 51. The interference signal coming from the microwave oven was strongest in a measurement distance of three meters away from the measurement antenna, as shown by blue bars in most of the frequency points. When the distance between the microwave oven and the measurement antenna increased, the measured peak power level decreased in all frequency points except center frequency 2437 MHz. The microwave oven created less interference with the WLAN access point physical layer signal when the oven was moved further away from the access point.

Figure 52 shows the summary test results for the Bluetooth loudspeaker’s real time peak power interference measurements.

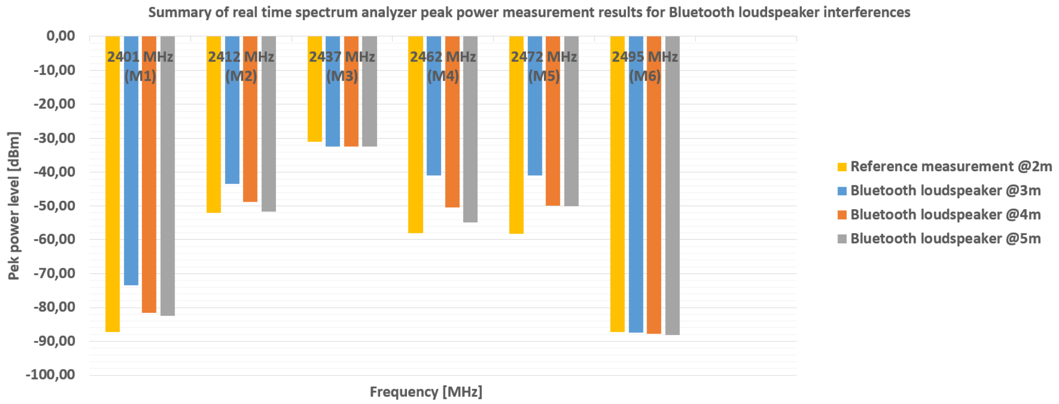


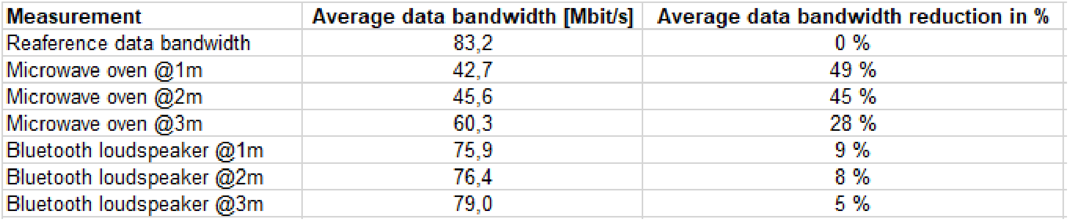
Figure 52. Summary of real time spectrum analyzer peak power measurement results for Bluetooth loudspeaker interferences.

The reference measurement results of the Bluetooth loudspeaker were exactly the same as described in the case of the microwave oven. As shown in figure 52 by the blue, orange and gray bars, the peak power level for the Bluetooth interference signal was very low in band edge frequencies 2401 MHz and 2495 MHz. The bandwidth of the Bluetooth interference signal was 80 MHz wide. The measured peak power level in the center frequency of 2437 MHz was almost constant in all distances. As shown by the blue bars in all frequency points in figure 52, the strongest peak power level for the Bluetooth interference signal was detected in a measurement distance of three meters away from the measurement antenna. The orange and grey bars show that the measured peak power level decreased in all frequency points except frequency 2437 MHz, while the distance between the Bluetooth loudspeaker and the measurement antenna increased. In practice, the Bluetooth loudspeaker created less interference with the WLAN access point physical layer signal when it was moved further away from the access point.

4.4.2 WLAN network data bandwidth

This chapter shows the final results of the WLAN network data bandwidth measurements and describes the main reasons for the reduction of data bandwidth under the presence of microwave oven and Bluetooth loudspeaker RF-interference signals. Table 3 shows an overall summary of test results for the measured data bandwidth values performed during the different measurement tasks.

Table 3. Summary of test results for measured data bandwidth values.



Measurement	Average data bandwidth [Mbit/s]	Average data bandwidth reduction in %
Reaference data bandwidth	83,2	0 %
Microwave oven @1m	42,7	49 %
Microwave oven @2m	45,6	45 %
Microwave oven @3m	60,3	28 %
Bluetooth loudspeaker @1m	75,9	9 %
Bluetooth loudspeaker @2m	76,4	8 %
Bluetooth loudspeaker @3m	79,0	5 %

As can be seen from table 3, the average data bandwidth was dramatically reduced when the microwave oven was switched on. When the microwave oven was placed one and two meters away from the WLAN access point, the average bandwidth was reduced between 45%–49% from the reference value. At a distance of three meters, the bandwidth was reduced by 28% from the reference value. These recorded data bandwidth values correlate well with the spectrum analyzer RF-interference measurement results.

The microwave oven was transmitting a wide band interference signal similar to noise at a high power level. The microwave oven RF-interference signal was attenuating as the physical distance between the oven and WLAN access point was increasing. When the oven was moved further away from the WLAN access point, the power level of the microwave interference signal was reduced, thus creating less interference with the physical layer connection between the WLAN access point and the client computer. If the microwave oven had been placed four or five meters away from the WLAN access point, more reduced readings in the average data bandwidth values would have been expected. Unfortunately, it was not possible to test this due to lack of physical space in the storage room.

A similar behavior was observed with the Bluetooth interference source. The average measured data bandwidth under Bluetooth interference was only slightly reduced, thus the loudspeaker was not creating serious problems for the WLAN access point physical layer connection. In distances of one and two meters between the Bluetooth device and the WLAN access point, the data bandwidth was reduced between 5%–9% from the reference value. At a distance of three meters, the data bandwidth was only reduced by 5% from the reference value. RF-interference signals coming from the Bluetooth device were also attenuating as the physical distance between the loudspeaker and the WLAN access point was increasing. When the loudspeaker was moved further away from the WLAN access point, the power level of the Bluetooth interference signal was reduced, thus interfering less with WLAN access point physical layer connection.

Bluetooth devices are operating in ISM frequency band between frequencies 2400 MHz–2485 MHz. The bandwidth for Bluetooth payload signal is typically 80 MHz wide, depending on the used device type. Bluetooth devices are using Frequency Hopping Spread Spectrum (FHSS) technology, usually at a rate of 1600 hops per second. Bluetooth transmission is spread over 79 separate sub-channels, the bandwidth for each channel is 1 MHz wide. As a consequence, Bluetooth devises are creating less RF-interferences for WLAN devices operating in same ISM frequency band. The maximum power level of each designated sub-channels is only present for a short period of time in the frequency spectrum and the bandwidth of one sub-channel is quite narrow. Modern WLAN access points are capable of handling short time physical layer RF-interferences quite well.

5 Practical implications for hospital WLAN network environment

Setting up a WLAN network in the hospital building, network administrators need to consider few basic preparation steps before actual network is deployed to a fully functional state. The minimum recommended five steps for designing and building a hospital WLAN network are described below.

- Proper site survey
- Frequency planning for the WLAN access points and selection of enterprise controller
- Setting up the network
- Network security planning
- Network testing

In the first step, it is very important to perform a proper site survey for the hospital building before network deployment. The person in charge must ensure effective WLAN coverage and excellent Quality of Service (QoS) and minimize harm of RF interferences, which could be causing problems for the network performance. A site surveyor must use up-to-date blueprints to optimize the network efficiency in all areas of the building. [16; p.4]

The second step is frequency planning for the WLAN access points and selection of the enterprise controller. Modern technology WLAN access points can be configured to broadcast at 2.4 GHz or 5 GHz frequency bands. The 2.4 GHz frequency band is more crowded because of the volume of devices using that band. The cell size is smaller in the 5 GHz frequency band due to the shorter wave length and higher RF signal attenuation. Any clinical device that is not transmitting life critical network traffic should be designed to operate in the 2.4 GHz frequency band. All devices that are transmitting life critical network traffic should be placed in operation on the 5 GHz frequency band in order to enable a higher data rate in a less congested frequency band. [16; p.6]

Sensitive data is frequently transmitted in hospitals, therefore an enterprise grade network infrastructure must be used. Enterprise graded WLAN access points offer better security features, centralized user control and a larger set of different technical features than normal home and business office access points. Also redundancy and self healing capabilities are important features for life critical wireless medical network devices. [16; p.6]

The third step is setting up the network. A separation of different data traffic on multiple Virtual Local Area Networks (VLAN) ensures important and secure network communications and network segmentation. Proper VLAN access control measures must be used in order to control the devices and user access for different areas of local area network. Separate VLANs should be configured for hospital staff, private personal devices, guests and clinical and medical devices in order to enhance network security. The most important security feature is to separate guests from sensitive medical and clinical information data. [16; p.6]

All personal wireless devices of guests and the hospital staff should be configured to operate in the 2.4 GHz frequency band in order to assure high quality and high data throughput for important life-critical wireless medical devices. Uninterrupted connection is a key factor for life-critical and clinical wireless devices. Consumer devices, such as smart phones, microwave ovens, Bluetooth devices, laptops and tablets, are all operating in the 2.4 GHz ISM band. All of these devices are potential RF interference sources for medical devices operating in same frequency band. [16; p.6]

All life-critical hospital wireless devices should be placed in operation to the less congested 5 GHz frequency band in order to secure robust transmission of secured data. It is not recommended to use Dynamic Frequency Selection (DFS) functionality in hospital 5 GHz WLAN access points. DFS could be causing up to two seconds loss in life critical medical device data transmission every time when an access point is scanning for a new available RF channel. [16; p.6]

Modern hospital WLAN networks must also be able to transmit robust voice and video data. Quality of Service (QoS) settings allows hierarchy and prioritization to be set for specified traffic. QoS is typically implemented in VLAN level to improve throughput of the system. Four levels of QoS packet prioritization is typically used when planning the network. These are in order of significance Voice, Video, Best effort and Background network traffic. Best effort is usually the default setting in WLAN hotspots, whereas background priority is normally used for maintenance purposes. The manager in charge must decide which VLAN traffic is most important and has the highest priority to be processed first. It is recommended to switch off the QoS packet prioritization for guest VLANs. All guest data connections should be treated as equal and to be handled by using the first-in first-out principle for the network access. [16; p.7]

Planning and optimizing device roaming is an important part when setting up the network. As a general rule, a roaming plan for 5 GHz band should be optimized first and then set the transmit power of the 2.4 GHz WLAN hotspots to match the 5 GHz hotspot cell size. It is highly recommended that WLAN devices used in hospitals should support customization for roaming settings. This ability allows setting to be set in device level in order to improve connectivity to the network. Typical customizable settings are low signal threshold, positive change in signal strength and minimum period of time before a devise can roam back to previous access point. As a general rule, a mobile WLAN device should be able to roam faster than stationary devises. Every hospital has unique physical environment and Information Technology (IT) requirements, therefore each settings has to be planned at an individual device level, according to hospital IT policy. [16; p.8]

The fourth step is network security planning. When transmitting sensitive data in a hospital WLAN network, security settings must be set at a strong level. It is highly recommended to use a high level of security protocols and encryption, such as Wi-Fi Protected Access II with advanced Encryption Standard (WPA2-AES). In addition to WPA2-AES, an Extensible Authentication Protocol (EAP), i.e. authentication with certificates should be in use. This requires the user to provide credentials before accessing the network. In order to gain more security to network, separate VLANs need to be set for guest access, staff devices and life-critical devices or sensitive information. [16; p.9]

The fifth step is network testing, which is recommend to be performed when initially setting up the network, a new device is added, a physical attribute of the original site survey has changed or a new version of firmware code is installed into the WLAN devices. Minimum recommended test procedures should include tests for channel overlap, measurements for WLAN coverage and testing the wireless devices against security breaches. When the hospital network is set up initially, a proper site survey has to be performed. Access points are placed in the building according to results of the site survey. A used case of each specific wireless devices should be carefully planned, and tested in its intended normal operating environment and defined parameters. [16; p.10]

A usage of a spectrum analyzer is highly recommended in order to find sources of external RF-interferences. When an interference source is located, it should be plotted in the blueprint, and the WLAN channels affected by the interference should be noted. Based on the spectrum analysis findings, a placement of access points can begin and planning of optimized cell size and data throughput can be performed. For difficult indoor areas, specialized antennas can be used in order to maximize required coverage requirements. [16; p.4]

6 Proposed actions and suggestions

The detection of external interference signals and their sources is an essential phase in WLAN network design when planning and monitoring network Quality of Service (QoS) parameters. Data bandwidth measurement alone does not reveal the overall condition of the network. The physical layer signals also need to be verified in order to get a full picture of the network performance. The best tool for performing physical layer RF-signal measurements is a spectrum analyzer. There are many commercial applications and devices available for this purpose. It is highly recommended to make a solid plan for performing spectrum analyzer measurements in WLAN network. Some of the basic steps for such a plan are listed below.

- Physical environment survey
- Selection of proper measurement equipment
- Identifying interference sources
- Creating measurement report, containing traceable measurement results

A physical environment survey helps to identify possible sources of external and internal WLAN network interferences. It is necessary to examine the physical layout of the office space in order to understand how WLAN access points and possible sources of external interference signals, such as industrial machines, household machines and cellular base stations, are deployed inside the building. It is also important to take into consideration office furnishing and building materials. For example, metal walls, metal ceilings and office furniture inside the office room could be reflecting or attenuating RF-signals, causing multipath propagation, fading effects and other interferences for WLAN network.

The selection of proper measurement equipment is very important for detecting and identifying interference signal sources. The most important basic RF-characteristics for selecting a spectrum analyzer are frequency range, dynamics and phase noise. The frequency range of the spectrum analyzer should cover at least 2.4 GHz ISM and 5 GHz frequency bands. It is highly recommended to select a spectrum analyzer that can be used for measuring interference signals beyond 5 GHz, so that harmonic and spurious signals of 2.4 GHz and 5 GHz WLAN access point can be detected and measured. In practice, the frequency range of spectrum analyzer should be at least between 9 kHz–13 GHz. If the spectrum analyzer does not possess good dynamics and phase noise characteristics, the analyzer cannot be reliably used for detecting the low level WLAN access point and interference signals.

The next important thing is to select between the swept tuned or real time spectrum analyzer technology. Both technologies have their advantages and disadvantages. A swept tuned spectrum analyzer is usually much cheaper in price than a real time analyzer. One disadvantage of the swept tuned spectrum analyzer is the long measurement time for detecting periodical spurious interference signals and in-band spectral components. For the interference measurements, it is highly recommended to select a swept tuned spectrum analyzer with spectrogram functionality. Periodical interferences and frequency hopping devices, such as Bluetooth, can be identified with the help of the spectrogram. A real time spectrum analyzer is the best tool for interference measurements. It can detect, measure and display periodical spurious signals and in-band spectral components in real time, but a disadvantage is its price. Real time spectrum analyzers are usually much more expensive than conventional swept tuned analyzers.

The selection of the measurement antenna has to be done according to the measurement task at hand. Usually a directive antenna, such as yagi, log-period or ultra wideband antenna, is used for interference hunting. The most important parameters are frequency range, 3 dB beam width and gain. The frequency range of an antenna has to match 2.4 GHz ISM and 5 GHz frequency bands. Narrow E-plane and H-plane 3 dB beam width values lead to high directivity and antenna gain. A highly directive antenna can be used for detecting low level interference signals and pinpointing physical location of interferer sources inside the WLAN network.

Identifying interference sources can be a tricky task. WLAN network access points can interfere with each other without proper coverage and channel planning, this is known as co-channel and adjacent channel interference. External interference sources can create narrow and wideband interference signals for a WLAN network physical layer. Every interferer leaves a unique spectral signature, and therefore it is highly recommend to study the typical characteristics of interference signals in theory before practical measurements are performed on-site. This helps to identify different sources of interferences during different measurement tasks.

Finally, when all interference signals are measured and identified, proper test report should be created. The test report should contain information at least from the detected interference source, device type, physical location, measured interference signal power level, measured interference signal frequency and bandwidth. Recorded measurement results should be traceable in order to review them after a few years if needed for some reason.

7 Conclusions

This study aims to help hospitals to ensure that their WLAN networks function without interference. To address this issue, this study adds to the knowledge of how to detect and measure interference signals from external sources. The precise objective of this study was to identify and determine the characteristics of microwave oven and Bluetooth loudspeaker device interference signals that are causing problems in the WLAN network physical layer and suggest what kind of measurement equipment can be used for interference measurement. The measurement results and theoretical considerations of this study can be universally applied in numerous environments such as hospitals or normal business offices. In practice, there were some challenges that posed a problem to data gathering in a hospital environment due to confidentiality requirements and practical measurement setup arrangements. Therefore, an experimental WLAN network was built in a normal business office environment for interference and WLAN network data bandwidth measurement purposes.

The physical layer RF-interference signals coming out of the microwave oven and Bluetooth loudspeaker were measured and characterized with a modern spectrum analyzer in swept tuned and real time modes. In addition, the WLAN network data bandwidth was measured with a network performance software tool in order to find out how external interference signals are affecting the network performance and quality of service. During the WLAN network interference and data bandwidth measurement, it was discovered that a microwave oven can cause serious interference with the network physical layer connection, dramatically decreasing its quality of service and performance. The microwave oven was transmitting high power level interference signals with a bandwidth of 94 MHz when it was operated at its maximum power level of 900 W. The Bluetooth loudspeaker was transmitting high power level signals with a bandwidth of 80 MHz during its normal operation. The impact of the Bluetooth payload signal for the WLAN network physical layer connection, quality of service and network performance was not so severe.

The analyzed data bandwidth measurement results show that the experimental WLAN network data bandwidth was decreased between 28%–49% from the reference value of 83,2 Mbit/s when the microwave oven was activated. In case of the Bluetooth loudspeaker, the network data bandwidth was decreased between 5%–9% from the reference value when the Bluetooth device was operational. The closer the external interference sources were placed towards the experimental WLAN network access point, the lower were the network data bandwidth values recorded. The peak power level of RF-interference signals for both external interferer sources decreased as the distance between the measurement antenna and the interferer source increased. The reason for this is that the power level of RF-interference signals attenuates when they are traveling away from the point of their origin.

The measurement setup used during this study is not practical for on-site measurement purposes inside office buildings because the physical size of measurement equipment was large and heavy. It is highly recommend to use a light portable spectrum analyzer and measurement antenna for example inside hospital buildings when performing interference measurements. Comparison of traditional swept tuned and real time spectrum analyzer technologies show that a real time spectrum analyzer is the best tool for interference measurements. It can be efficiently used for detecting and measuring wideband signals, narrowband signals, periodical spurious signals and in-band spectral components in real time without losing important information. A highly directive measurement antenna should be used for interference measurement in order to measure low level signals and effectively locate the actual physical location of interference sources inside the WLAN network coverage area.

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Spectrum analyzer measurement results for microwave oven RF-interference signals in swept tuned and real time modes.

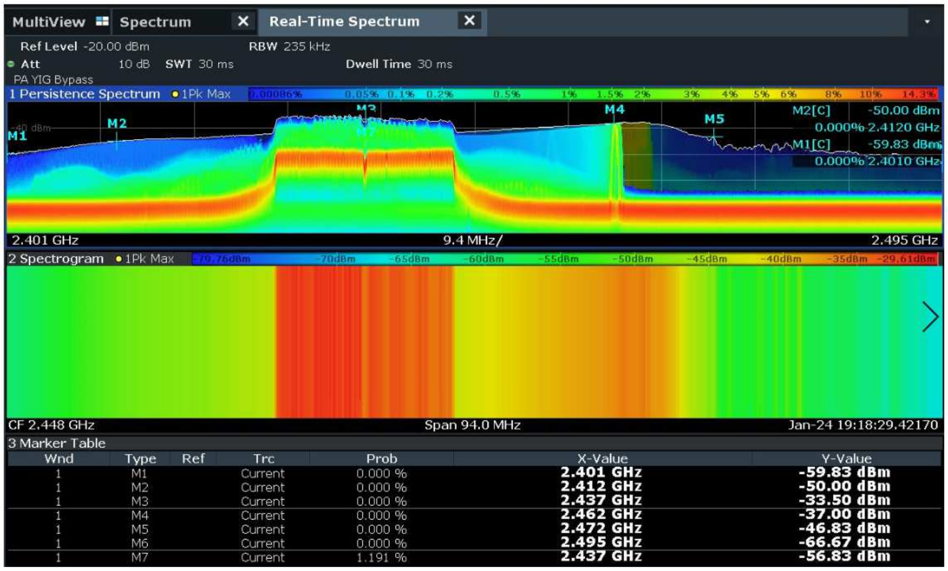
Ref Level -20.00 dBm RBW 1 MHz
Att 10 dB SWT 1.01 ms VBW 10 MHz Mode Auto Sweep

M6[1] -73.04 dBm
#0 2.4950000 GHz
M1[1] -72.02 dBm
#0 2.4010000 GHz

3 Marker Table

Type	Ref	Trc	Frame	X-Value	Y-Value	Function	Function Result
M1		1	0	**2.401 GHz**	**-72.02 dBm**		
M2		1	0	**2.412 GHz**	**-49.13 dBm**		
M3		1	0	**2.437 GHz**	**-31.22 dBm**		
M4		1	0	**2.462 GHz**	**-36.43 dBm**		
M5		1	0	**2.472 GHz**	**-40.90 dBm**		
M6		1	0	**2.495 GHz**	**-73.04 dBm**		

Figure 53. Second swept tuned spectrum analyzer measurement results for microwave oven interference signals. Four meters distance between measurement antenna and microwave oven.



Ref Level -20.00 dBm RBW 235 kHz
Att 10 dB SWT 30 ms Dwell Time 30 ms
PA YIG Bypass

M2[C] -50.00 dBm
0.000% 2.4120 GHz
M1[C] -59.83 dBm
0.000% 2.4010 GHz

3 Marker Table

Wnd	Type	Ref	Trc	Prob	X-Value	Y-Value
1	M1		Current	0.000 %	**2.401 GHz**	**-59.83 dBm**
1	M2		Current	0.000 %	**2.412 GHz**	**-50.00 dBm**
1	M3		Current	0.000 %	**2.437 GHz**	**-33.50 dBm**
1	M4		Current	0.000 %	**2.462 GHz**	**-37.00 dBm**
1	M5		Current	0.000 %	**2.472 GHz**	**-46.83 dBm**
1	M6		Current	0.000 %	**2.495 GHz**	**-66.67 dBm**
1	M7		Current	1.191 %	**2.437 GHz**	**-56.83 dBm**

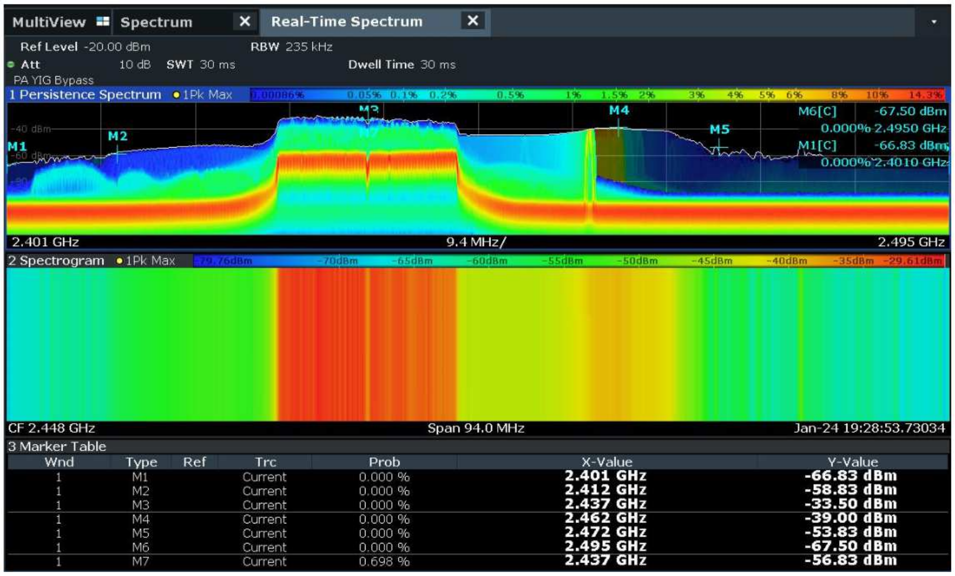
Figure 54. Second real time spectrum analyzer measurement results for microwave oven interference signals. Four meters distance between measurement antenna and microwave oven.

Ref Level -20.00 dBm RBW 1 MHz
Att 10 dB SWT 1.01 ms VBW 10 MHz Mode Auto Sweep

3 Marker Table

Type	Ref	Trc	Frame	X-Value	Y-Value	Function	Function Result
M1		1	0	**2.401 GHz**	**-72.19 dBm**		
M2		1	0	**2.412 GHz**	**-49.29 dBm**		
M3		1	0	**2.437 GHz**	**-31.11 dBm**		
M4		1	0	**2.462 GHz**	**-47.41 dBm**		
M5		1	0	**2.472 GHz**	**-53.47 dBm**		
M6		1	0	**2.495 GHz**	**-72.37 dBm**		

Figure 55. Third swept tuned spectrum analyzer measurement results for microwave oven interference signals. Five meters distance between measurement antenna and microwave oven.



Ref Level -20.00 dBm RBW 235 kHz
Att 10 dB SWT 30 ms Dwell Time 30 ms
PA YIG Bypass

3 Marker Table

Wnd	Type	Ref	Trc	Prob	X-Value	Y-Value
1	M1		Current	0.000 %	**2.401 GHz**	**-66.83 dBm**
1	M2		Current	0.000 %	**2.412 GHz**	**-58.83 dBm**
1	M3		Current	0.000 %	**2.437 GHz**	**-33.50 dBm**
1	M4		Current	0.000 %	**2.462 GHz**	**-39.00 dBm**
1	M5		Current	0.000 %	**2.472 GHz**	**-53.83 dBm**
1	M6		Current	0.000 %	**2.495 GHz**	**-67.50 dBm**
1	M7		Current	0.698 %	**2.437 GHz**	**-56.83 dBm**

Figure 56. Third real time spectrum analyzer measurement results for microwave oven interference signals. Five meters distance between measurement antenna and microwave oven.

Spectrum analyzer measurement results for Bluetooth loudspeaker RF-interference signals in swept tuned and real time modes.

Ref Level -10.00 dBm
RBW 1 MHz
Att 30 dB
SWT 1.01 ms
VBW 10 MHz
Mode Auto Sweep
PA

D7[1] -17.99 dB
#0 80.5000 MHz
M1[1] -48.22 dBm
#0 2.4010000 GHz

3 Marker Table

Type	Ref	Trc	Frame	X-Value	Y-Value	Function	Function Result
M1		1	0	2.401 GHz	-48.22 dBm		
M2		1	0	2.412 GHz	-43.95 dBm		
M3		1	0	2.437 GHz	-31.20 dBm		
M4		1	0	2.462 GHz	-38.65 dBm		
M5		1	0	2.472 GHz	-41.20 dBm		
M6		1	0	2.495 GHz	-69.83 dBm		
D7	M1	1	0	80.5 MHz	-17.99 dB		

Figure 57. Second swept tuned spectrum analyzer measurement results for Bluetooth loudspeaker interference signals. Four meters distance between measurement antenna and Bluetooth loudspeaker.

Ref Level -20.00 dBm
RBW 235 kHz
Att 10 dB
SWT 30 ms
Dwell Time 30 ms
PA YIG Bypass

M5[C] -50.00 dBm
0.021% 2.4720 GHz
M1[C] -81.50 dBm
0.000% 2.4010 GHz

3 Marker Table

Wnd	Type	Ref	Trc	Prob	X-Value	Y-Value
1	M1		Current	0.000 %	2.401 GHz	-81.50 dBm
1	M2		Current	0.021 %	2.412 GHz	-48.67 dBm
1	M3		Current	0.000 %	2.437 GHz	-32.33 dBm
1	M4		Current	0.006 %	2.462 GHz	-50.50 dBm
1	M5		Current	0.011 %	2.472 GHz	-50.00 dBm
1	M6		Current	0.000 %	2.495 GHz	-87.83 dBm
1	D7	M1	Current	9.594 %	80.5 MHz	-26.83 dB

Figure 58. Second real time spectrum analyzer measurement results for Bluetooth loudspeaker interference signals. Four meters distance between measurement antenna and Bluetooth loudspeaker.

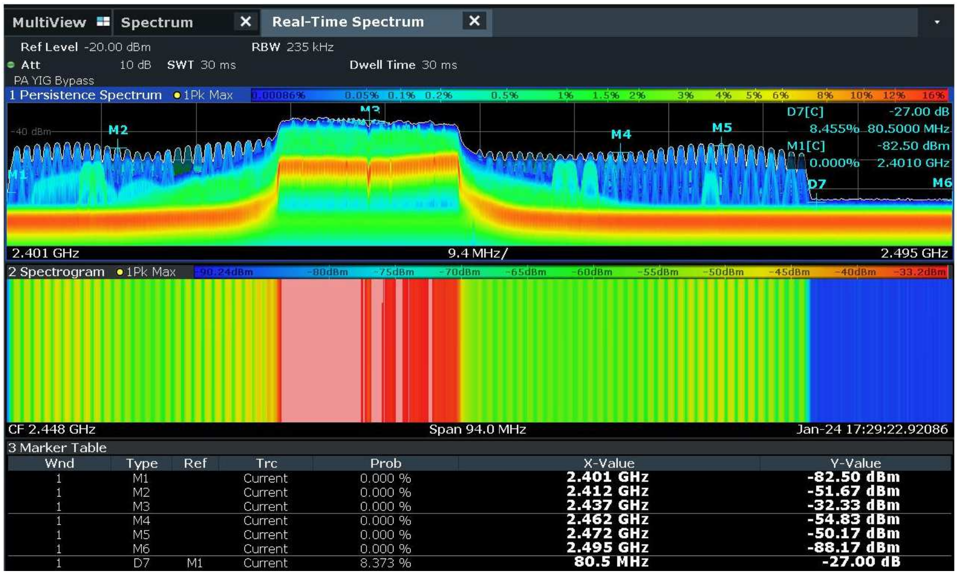
Ref Level -10.00 dBm RBW 1 MHz
Att 30 dB SWT 1.01 ms VBW 10 MHz Mode Auto Sweep
PA

D7[1] -21.33 dB
#0 80.5000 MHz
M1[1] -48.95 dBm
#0 2.4010000 GHz

3 Marker Table

Type	Ref	Trc	Frame	X-Value	Y-Value	Function	Function Result
M1		1	0	2.401 GHz	-48.95 dBm		
M2		1	0	2.412 GHz	-44.94 dBm		
M3		1	0	2.437 GHz	-31.53 dBm		
M4		1	0	2.462 GHz	-54.06 dBm		
M5		1	0	2.472 GHz	-54.66 dBm		
M6		1	0	2.495 GHz	-71.15 dBm		
D7	M1	1	0	80.5 MHz	-21.33 dB		

Figure 59. Third swept tuned spectrum analyzer measurement results for Bluetooth loudspeaker interference signals. Five meters distance between measurement antenna and Bluetooth loudspeaker.



Ref Level -20.00 dBm RBW 235 kHz
Att 10 dB SWT 30 ms Dwell Time 30 ms
PA YIG Bypass

D7[C] -27.00 dB
8.455% 80.5000 MHz
M1[C] -82.50 dBm
0.000% 2.4010 GHz

3 Marker Table

Wnd	Type	Ref	Trc	Prob	X-Value	Y-Value
1	M1		Current	0.000 %	2.401 GHz	-82.50 dBm
1	M2		Current	0.000 %	2.412 GHz	-51.67 dBm
1	M3		Current	0.000 %	2.437 GHz	-32.33 dBm
1	M4		Current	0.000 %	2.462 GHz	-54.83 dBm
1	M5		Current	0.000 %	2.472 GHz	-50.17 dBm
1	M6		Current	0.000 %	2.495 GHz	-88.17 dBm
1	D7	M1	Current	8.373 %	80.5 MHz	-27.00 dB

Figure 60. Third real time spectrum analyzer measurement results for Bluetooth loudspeaker interference signals. Five meters distance between measurement antenna and Bluetooth loudspeaker.