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SERIES K: PROTECTION AGAINST INTERFERENCE

Electromagnetic characterization of the radiated environment in the 2.4 GHz ISM band

Recommendation ITU-T K.79

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Summary

The rapid adoption of the unlicensed 2.4 GHz industrial, scientific and medical (ISM) band for various radio telecommunication services has created a complex electromagnetic environment in which interference between services may occur. Examples of such services are the IEEE 802.11 wireless LAN system and digital cordless phones. Appendix I discusses the 2.4 GHz ISM band environment in more detail.

Recommendation ITU-T K.79 characterizes the typical 2.4 GHz ISM band radiated EM environments for home, office and commercial locations. The environmental analysis uses both theoretical prediction and real measurements. The analysis includes multipath evaluation and the different modulation effects of the radio systems. Based on this analysis, proposals are made for interference levels and specific electronic equipment susceptibility levels.

Source

Recommendation ITU-T K.79 was approved on 13 June 2009 by ITU-T Study Group 5 (2009-2012) under Recommendation ITU-T A.8 procedures.

FOREWORD

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Electromagnetic characterization of the radiated environment in the 2.4 GHz ISM band

1 Scope

This Recommendation analyses the electromagnetic environment characteristics of the 2.4 GHz industrial, scientific and medical (ISM) band used by new radio service systems. Examples of these radio services are: the IEEE 802.11 wireless LAN system, the IEEE 802.16 system, the IEEE 802.15 system and digital cordless phone systems. The definition and relevant information about this frequency band can be found in [ITU-T Radio Regulations]. The equipment emission level and the susceptibility level are the key parameters analysed.

This Recommendation only considers indoor applications of the 2.4 GHz ISM band for the analysis of the band electromagnetic environment and for determining acceptable equipment emission levels and susceptibility levels.

2 References

The following ITU-T Recommendations and other references contain provisions which, through reference in this text, constitute provisions of this Recommendation. At the time of publication, the editions indicated were valid. All Recommendations and other references are subject to revision; users of this Recommendation are therefore encouraged to investigate the possibility of applying the most recent edition of the Recommendations and other references listed below. A list of the currently valid ITU-T Recommendations is regularly published. The reference to a document within this Recommendation does not give it, as a stand-alone document, the status of a Recommendation.

[ITU-R P.525-2] Recommendation ITU-R P.525-2 (1994), *Calculation of free-space attenuation*.

[ITU-R P.1238-4] Recommendation ITU-R P.1238-4 (2005), *Propagation data and prediction methods for the planning of indoor radiocommunication systems and radio local area networks in the frequency range 900 MHz to 100 GHz*.

[ITU-R SM.329-10] Recommendation ITU-R SM.329-10 (2003), *Unwanted emissions in the spurious domain*.

[CISPR 16-1-4] CISPR 16-1-4 Edition 2.1 (2008), *Specification for radio disturbance and immunity measuring apparatus and methods – Part 1-4: Radio disturbance and immunity measuring apparatus – Ancillary equipment – Radiated disturbances*.

[IEEE 802.11] IEEE 802.11 (2007), *IEEE Standard for Information technology – Telecommunications and information exchange between systems – Local and metropolitan area networks – Specific requirements – Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications*.

[IEEE 802.15.x] IEEE 802.15.x (2005), *IEEE Standard for Information technology – Telecommunications and information exchange between systems – Local and metropolitan area networks – Specific requirements – Part 15.x: Wireless medium access control (MAC) and physical layer (PHY) specifications*.

[IEEE 802.16]	IEEE 802.16 (2004), *IEEE Standard for Local and Metropolitan Area Networks – Part 16: Air Interface for Fixed Broadband Wireless Access Systems*.
[ITU Radio Regulations]	ITU Radio Regulations (2008), *Radio Regulations*.

3 Definitions

This Recommendation uses the following terms defined elsewhere:

3.1 access point (AP) [IEEE 802.11]: Any entity that has station (STA) functionality and provides access to the distribution services, via the wireless medium (WM) for associated STAs.

3.2 continuous disturbance [b-IEC 60050-161]: Electromagnetic disturbance whose effects on a particular device or piece of equipment cannot be resolved into a succession of distinct effects.

3.3 discontinuous interference [b-IEC 60050-161]: Electromagnetic interference occurring during certain time intervals separated by interference-free intervals.

3.4 electromagnetic interference [b-IEC 60050-161]: Any electromagnetic phenomenon that may degrade the performance of a device, equipment or system, or adversely affect living or inert matter.

3.5 equivalent isotropic radiated power (EIRP) [b-ITU-R BS.561-2]: The product of the power supplied to the antenna and the antenna gain G_i in a given direction relative to an isotropic antenna (absolute or isotropic gain).

NOTE – Indicates the power that would have to be radiated by a theoretical isotropic radiator substituted in place of the equipment under test (EUT) to produce the same field level at a given point in space. It is equivalent to the power measured at the test equipment receiver, corrected for the range calibration path loss between the EUT and test equipment receiver.

3.6 (electromagnetic) emission [b-IEC 60050-161]: The phenomenon by which electromagnetic energy emanates from a source.

3.7 integral antenna [b-ITU-T K.48]: Antenna which may not be removed during the tests, according to the manufacturer's statement.

3.8 (electromagnetic) susceptibility [b-IEC 60050-161]: The inability of a device, equipment or system to perform without degradation in the presence of an electromagnetic disturbance.

NOTE – Susceptibility is the lack of immunity of a device, equipment, or system, the degree to which it is subject to malfunction or failure under the influence of an electromagnetic emission.

3.9 port [b-ITU-T K.48]: Particular interface of the specified equipment with the external electromagnetic environment.

3.10 radio communications equipment [b-ITU-T K.48]: Telecommunications equipment which includes one or more radio transmitters and/or receivers and/or parts thereof for use in a fixed, mobile or portable application. It can be operated with ancillary equipment but if so, is not dependent on it for basic functionality.

3.11 radio frequency (RF) [b-ITU-T K.48]: The frequency range above 9 kHz.

3.12 radio (frequency) disturbance [b-IEC 60050-161]: Electromagnetic disturbance having components within the radio frequency range.

3.13 station (STA) [IEEE 802.11]: Any device that contains an IEEE 802.11-conformant medium access control (MAC) and physical layer (PHY) interface to the wireless medium (WM).

3.14 unwanted emission [b-IEC 60050-161]: A signal that may impair the reception of a wanted (radio) signal.

4 Abbreviations and acronyms

This Recommendation uses the following abbreviations and acronyms:

2D	Two Dimensional
3D	Three Dimensional
ACK	Acknowledgement
AF	Antenna Factor
AP	Access Point
BPSK	Binary Phase Shift Keying
CCK	Corporate Control Key
DBPSK	Differential Binary Phase Shift Keying
DQPSK	Differential Quadrature Phase Shift Keying
DSSS	Direct Sequence Spread Spectrum
EIRP	Equivalent Isotropic Radiated Power
EM	Electromagnetic
EMC	Electromagnetic Compatibility
ERP	Equivalent Radiated Power
EUT	Equipment Under Test
FAR	Fully Anechoic Room
FDTD	Finite-Difference Time Domain
FHSS	Frequency Hopping Spread System
GSM	Global System for Mobile communications
ISM	Industrial, Scientific and Medical
IT	Information Technology
LAN	Local Area Network
MIMO	Multiple-Input Multiple-Output
MOM	Method of Moments
OATS	Open Area Test Site
OFDM	Orthogonal Frequency Division Multiplexing
PML	Perfectly Matched Layer
QAM	Quadrature Amplitude Modulation
QPSK	Quadrature Phase Shift Keying
RF	Radio Frequency
RSE	Radiated Spurious Emission
STA	Station
STB	Set-top box
TIRP	Total Isotropic Radiated Power
TV	Television

WLAN Wireless Local Area Network

5 Different radiated EM environments

More and more radio technology services have emerged in recent years due to the unlicensed nature of the 2.4 GHz frequency band, which is also used by some home appliances, such as the microwave oven. These radio and non-radio equipments simultaneously using the 2.4 GHz frequency band create a complex radiated EM environment. EMC research is needed and guidelines established to ensure the operability of these radio services. This Recommendation analyses the electromagnetic environment in the 2.4 GHz unlicensed ISM band in different environments. The equipment EMC emission level and the susceptibility level are the key parameters analysed.

This clause analyses the radiated EM environments of the single home, multi-home, office, airport and coffee bar locations. Both theoretical analysis and *in situ* practical measurements are used to establish acceptable interference levels and susceptibility levels for the electronic equipment used in these location environments.

In the following clauses, the general configuration of each environment is described. Theoretical analysis is then used to predict the radiated EM environment. After that, site measurement establishes the actual radiated EM environment. The emission level and the susceptibility level proposals for an environment are based on the predicted and measured values.

The detailed evaluation procedures used in this clause are described in clause 6.

5.1 Home environment

The home is one of the most common locations for 2.4 GHz radio equipment applications. The 2.4 GHz wireless technologies give more freedom to the users. The occupants can simultaneous log on to the Internet with their computers through one IEEE 802.11 AP, avoiding complex wiring layouts. The 2.4 GHz wireless cordless telephone allows people to make telephone calls from anywhere in the house. Thus, a home may contain many items of 2.4 GHz wireless equipment. In this clause, the single home and multi-home environments are analysed separately.

5.1.1 Detached home environment

Usually there will be several 2.4 GHz ISM band radio devices located within the home and operating simultaneously: examples include wireless LAN devices (including both a single IEEE 802.11 AP and potentially multiple IEEE 802.11 STAs), cordless telephones, wireless video systems and amateur radio equipment. Some home appliances may also work in the same frequency band, such as the microwave oven. If the working frequency of the radio equipment falls into the working frequency of the microwave oven, the microwave oven emissions may interfere with the radio equipment.

The detached home environment that was studied had the following features:

1) Different items of radio equipment located in different rooms.
2) Each room had the dimensions of about 4 x 5 m.
3) Two or three different equipment items located in each room. These equipments may be wireless LAN equipments, IEEE 802.15 equipments or wireless cordless phones.
4) The different rooms are separated by walls that offer little attenuation within the 2.4 GHz ISM band. Hence, interference may occur between nearby rooms.

A typical single home sample is shown as Figure 1. First, the theoretical method is used to analyse the radiated EM environment and then the EM site survey method is also used to evaluate the EM characteristic of this environment.

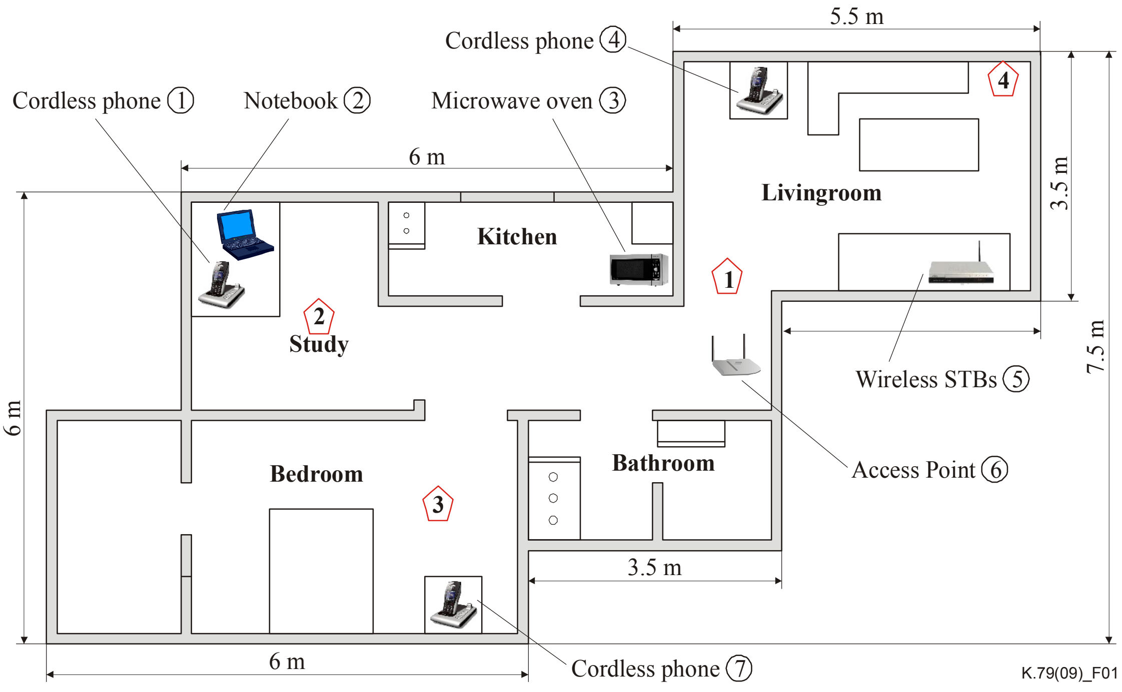

Figure 1 – Typical single home layout

The items of 2.4 GHz radio equipment are marked on Figure 1. Position ⑥ is an IEEE 802.11 AP. There are two IEEE 802.11 STAs located in positions ② and ⑤ and also there are three cordless phones located in positions, ①, ④ and ⑦. There is a 2.4 GHz microwave oven in the kitchen in position ③. IEEE 802.11 STA ② and the cordless phone ① were placed on a desk in the study at a height of 0.8 m. Other equipments in this room were all at a height of 0.4 m.

The EIRPs of the different equipments were measured in accordance with the test procedures presented in clause 6.2.3. The results are presented in Table 1.

Table 1 – EIRP of the different equipment

Equipment	**IEEE 802.11 AP ⑥**	**Station ②**	**Station ⑤**	**Cordless Phone ①**	**Cordless Phone ④**	**Cordless Phone ⑦**
EIRP (dBm)	22.14	19.32	19.49	19.74	19.63	19.71

The overall EM environment (obtained from the theoretical analysis procedure presented in clause 6.2.4) in the area of Figure 1 is shown in Figure 2. The red colour indicates the highest radiated level and the blue colour indicates the lowest radiated level.

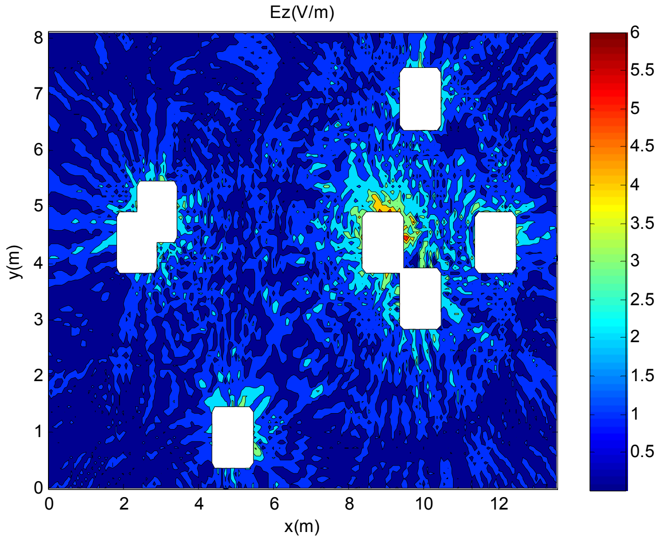

Figure 2 – Theoretical analysis result for the detached home environment

After the theoretical analysis, *in situ* measurements are performed. The measurement points are selected according to the guidelines of clause A.4.

1) The test is performed at the height of 0.8 m.

2) A corner location is measured.

3) Some of the centre locations are measured.

The four measurement points are marked in Figure 1 as numbers within pentagons. Measurement point 1 is 1.5 m away from both the IEEE 802.11 AP and the microwave oven. The result at measurement point 1 is shown in Figure 3 and the maximum emission was –29.90 dBm. The maximum emission level at 0.5 m distance was 122.32 dBμV/m using the computation method explained in clause 6.2.4, which means 1.31 V/m of the susceptibility level.

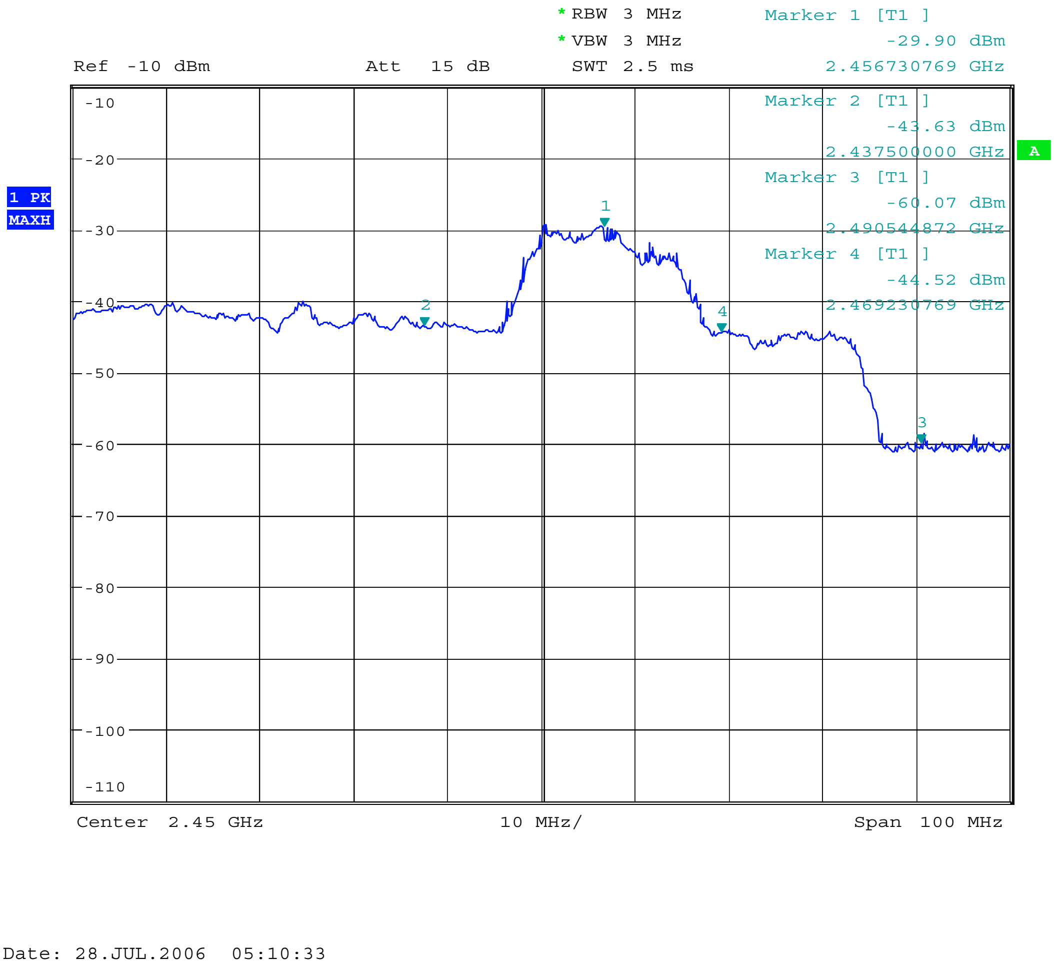

Figure 3 – Measurement result at point 1

The test results on the other measurement points are summarized in Table 2. All the results are converted to a measurement distance of 0.5 m.

Table 2 – Measurement results in Figure 1

Measurement point	1	2	3	4
Emission level (dBμV/m)	122.32	120.15	119.63	115.64
Susceptibility level (V/m)	1.31	1.01	0.96	0.61

5.1.2 Multi-home environment

The multi-home model is based on the single home model presented in clause 5.1.1. Two kinds of models are considered: the first considers all homes to be on the same floor; the second considers the homes to be on different floors.

Homes located on different floors will be separated by a ceiling or floor, making the EM interference between floors less likely to happen because a ceiling or floor introduces typically 20 to 30 dB of attenuation (see penetration loss Table 6). For the EM environment characterization, considering a more than 20 dB attenuation of the inter-floor emission, the impact of the radio equipments from homes on other floors can be ignored. The radiated EM environment characterization will be the same as the single home environment.

For those homes on the same floor, the distances between these homes are typically relatively small. Usually, these homes are only separated by a thin wall with an attenuation no greater than 10 dB. The distance between electronic equipment is usually less than 3 metres for interference between the equipments to occur. Hence, the radiated EM environment characterization can be done using the single home model which means that the radiated EM environment result is still dominated by those radio equipments in the same room.

5.2 Commercial environment

It is common for public commercial places to provide wireless Internet access using equipment that operates within the 2.4 GHz ISM band. Such places are said to offer 'hot spots'. An airport and a coffee bar are two examples of such commercial environments. These are analysed in the following clauses.

5.2.1 Airport environment

Many airports now provide wireless Internet access services in designated areas. The airport environment usually has the following features:

1) The typical dimension is about 30 x 20 m.
2) It usually contains a single IEEE 802.11 AP/IEEE 802.11 STA.
3) The distance between the IEEE 802.11 STAs is relatively great.
4) The area is 'open plan', i.e., without physical barriers that may attenuate the signals between the IEEE 802.11 AP and the IEEE 802.11 STAs.

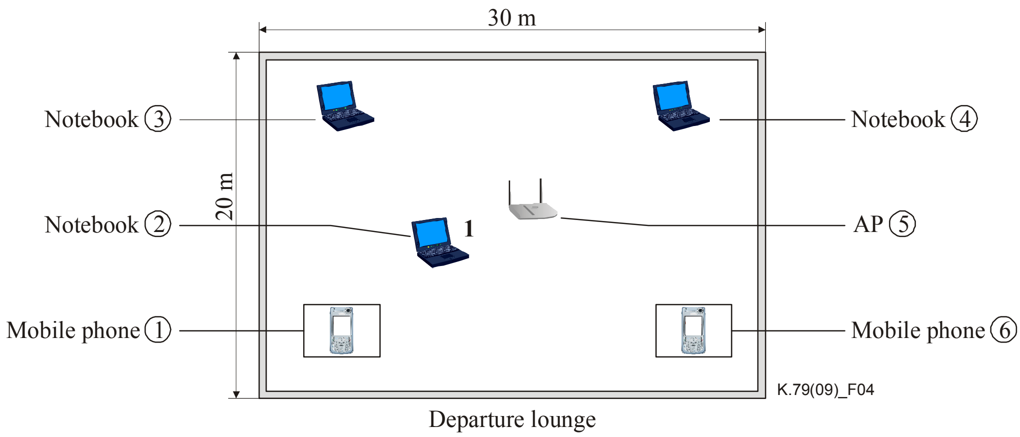

Figure 4 – Typical airport departure lounge environment

Figure 4 shows the 30 x 20 m airport departure lounge to be analysed in this clause. An IEEE 802.11 AP is located at the centre of this area and five IEEE 802.11 STAs are scattered around this IEEE 802.11 AP. There are two mobile phones (① and ⑥) that have a wireless LAN chipset. Three laptops (②, ③ and ④) are around the IEEE 802.11 AP. The IEEE 802.11 AP ⑤ is located on the ceiling at a height of 5 m and the other IEEE 802.11 STAs have heights of 0.5 m.

The lounge emission level at a height of 0.8 m is shown in Figure 5 using the theoretical analysis method of clause 6.2.4.

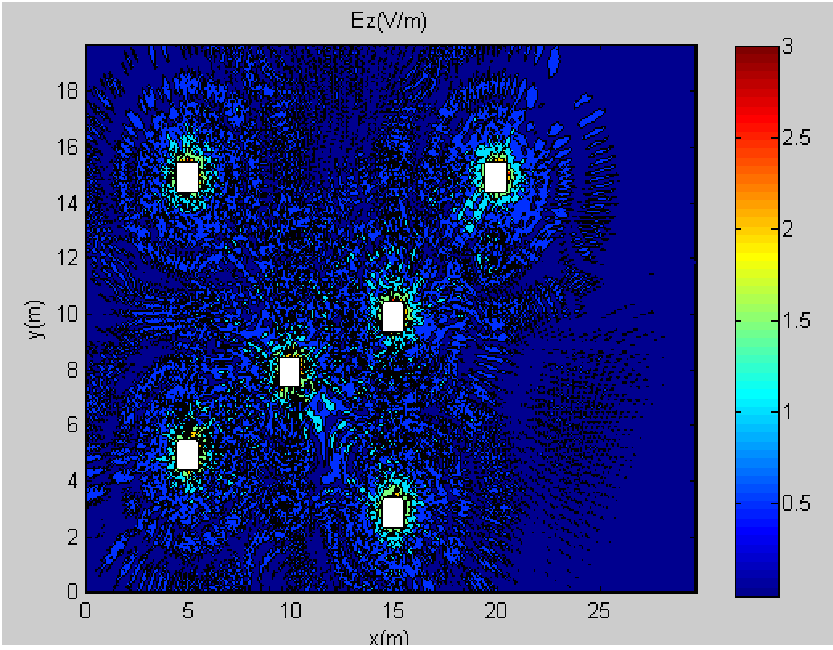

Figure 5 – Theoretical analysis result of the departure lounge

An EM site survey was performed in the environment of Figure 5. The test point is measurement point 1. It is 1 m away from notebook ② and 6 m away from the IEEE 802.11 AP ⑤. All the equipment in this environment was transmitting at their maximum radiating powers. The result of measurement point 1 is shown in Figure 6.

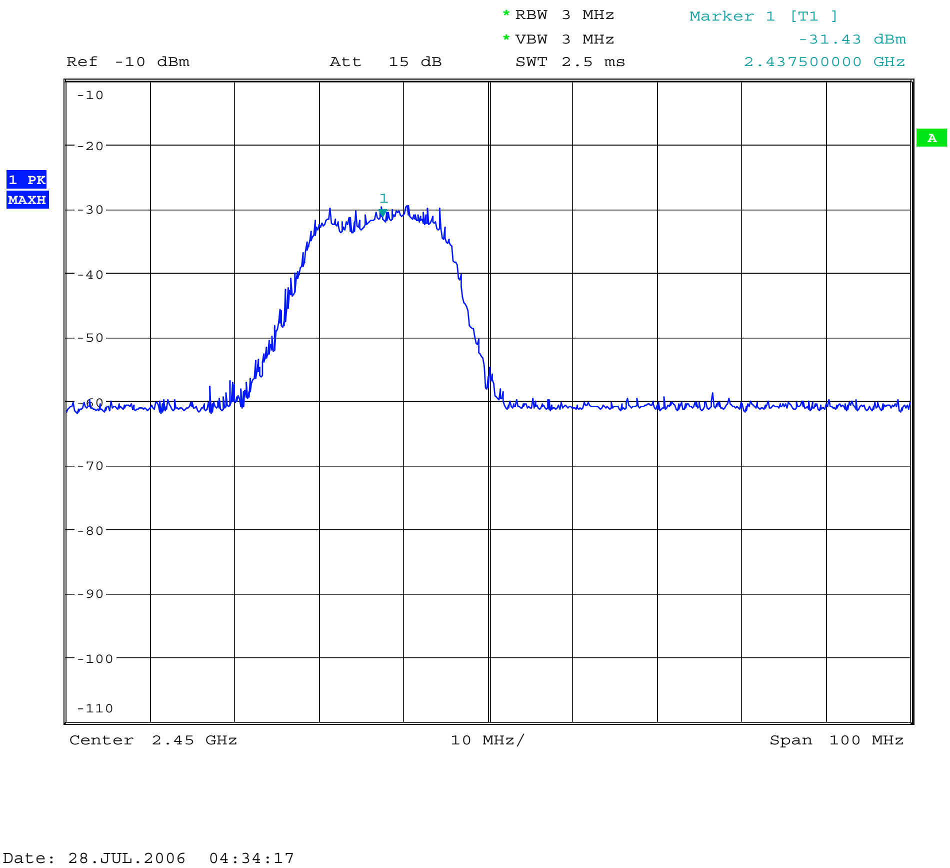

Figure 6 – Measurement result of point 1 of the departure lounge

The maximum emission at measurement point 1 is –31.43 dBm. The maximum emission level at 0.5 m distance is 117.23 dBµV/m (0.73 V/m) using the analysis method of clause 6.2.5.

All the equipments are relatively far away from each other in the airport environment. The maximum emission level is relatively low compared with other environments. So if the configuration of the IEEE 802.11 AP and IEEE 802.11 STAs is well planned and properly implemented, the EM interference situation is not so severe as other environments.

5.2.2 Coffee bar environment

Another typical commercial environment is the coffee bar environment. It is very common for the coffee bars to supply free wireless Internet access.

The coffee bar environment usually has the following features:

1) The typical dimension is about 10 x 6 m. Compared with the other typical commercial environment, the airport departure lounge, this is a relatively small area.

2) The most common equipment is wireless LAN, it usually consists of one or two IEEE 802.11 APs and several IEEE 802.11 STAs randomly located in the area.

3) Due to the limited space, these radio equipments are relatively close to each other without any separating walls or barriers.

4) There is usually a microwave oven in the room.

The coffee bar layout is shown in Figure 7. The area is 10 x 6 m. One IEEE 802.11 AP (④) is installed at the ceiling centre. Two mobile phones (⑤ and ⑦) that have the wireless LAN chipset and three notebooks (②, ③ and ⑥) are scattered around the coffee bar. One microwave oven (①) is on a desk in this room. The height of the IEEE 802.11 AP (④) is 3 m. The other equipments are at the 0.8 m desk height.

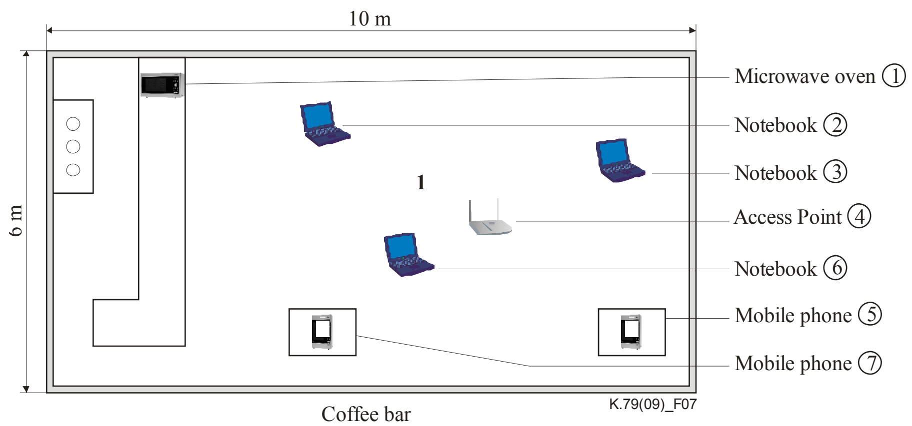

Figure 7 – Typical coffee bar environment

Interference will result if the working frequency of the microwave oven and the IEEE 802.11 AP are similar. The transmission rate of the wireless LAN system will be affected greatly in this situation.

The result of the EM theoretical analysis is shown in Figure 8.

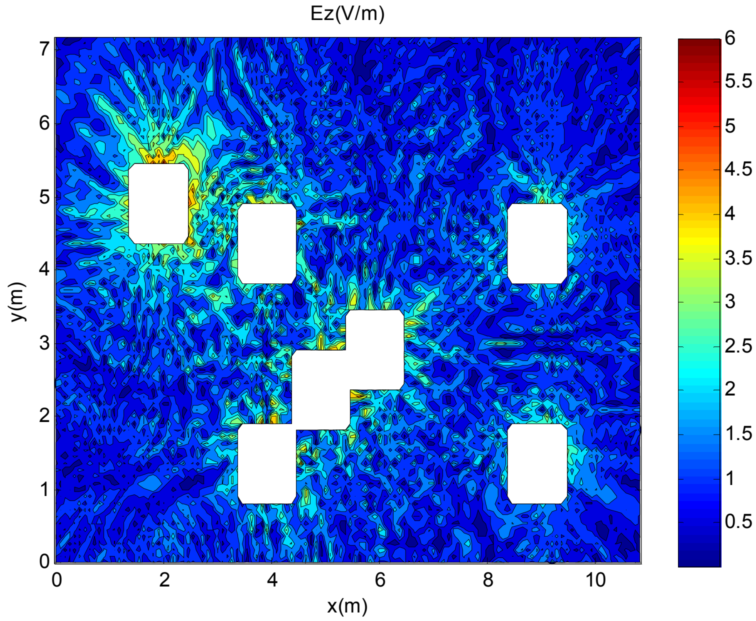

Figure 8 – EM theoretical analysis result of the coffee bar

After that, the EM site survey method is used to measure the radiated EM environment. Two kinds of tests are performed: one with only the IEEE 802.11 AP and IEEE 802.11 STAs working, and the other with the microwave oven in operation, to investigate whether this affects the radiated EM environment.

In the first case, only the IEEE 802.11 AP and the IEEE 802.11 STAs are working and there is no other telecommunication equipment present. The IEEE 802.11 AP is set to channel 6 and all 5 of the IEEE 802.11 STAs are exchanging data with the IEEE 802.11 AP. The test point 1 is 2 m away from both the IEEE 802.11 AP ④ and IEEE 802.11 STA ② and all the equipments are transmitting at their maximum radiated power. The result of measurement point 1 is shown in Figure 9.

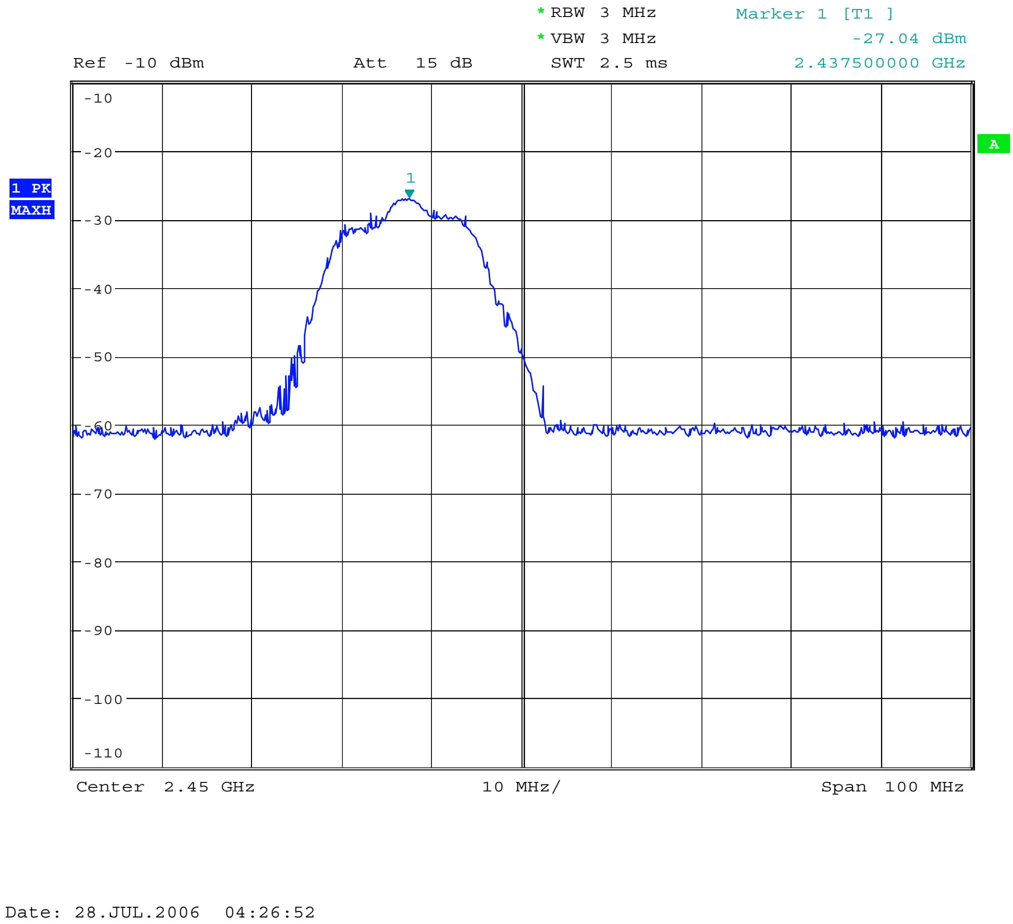

Figure 9 – Measurement result of point 1 in coffee bar environment

The maximum emission at measurement point 1 is –27.04 dBm. The maximum emission level at 0.5 m distance is 127.62 dBµV/m (the susceptibility level of 2.40 V/m) with the analysis method in clause 6.2.5.

In the second case, the microwave oven is in operation. Two kinds of test are performed. First, with the IEEE 802.11 AP and the other five IEEE 802.11 STAs are set the same as the previous non-microwave test. The test result is recorded in Figure 10. This shows that the emission spectrum of the wireless LAN system is from 2 425 MHz to 2 450 MHz with centre frequency of 2 437 MHz, and the emission spectrum of the microwave oven is from 2 453 MHz to 2 465 MHz with centre frequency of 2 459 MHz.

Then the IEEE 802.11 AP channel is reset to channel IEEE 802.11 AP10, such that the emission spectrum of the wireless LAN system is from 2 445 MHz to 2 480 MHz with centre frequency of 2 457 MHz. The EM emission result is shown in Figure 11.

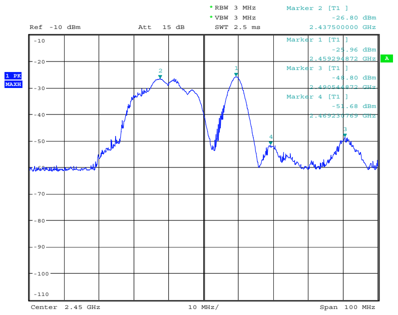

Figure 10 – IEEE 802.11 AP channel and microwave oven at different frequencies

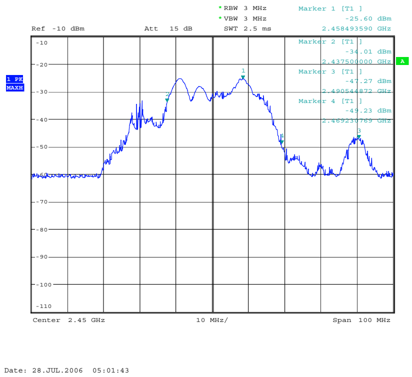

Figure 11 – IEEE 802.11 AP channel and microwave oven at overlapping frequencies

From the result of Figure 10, the IEEE 802.11 AP and all five other IEEE 802.11 STAs are working on channel 6 and the microwave oven is working on 2 459 MHz, which has an emission level of about –25.96 dBm. The emission level is 128.7 dBμV/m with the susceptibility level of 2.72 V/m converting the result to 0.5 m away. Under this environment, the data transfer rate is about 22 Mbit/s.

After changing the IEEE 802.11 AP setting to channel 10 with a working frequency of 2 457 MHz, the transmission rate is reduced to less than 10 Mbit/s, while the radiated EM environment is varied a little compared with the channel 6 situation. The emission level is –25.60 dBm converting the result to 0.5 m away, which is a little higher than the previous test. The emission level is 129.06 dBμV/m with the susceptibility level of 2.83 V/m.

5.3 Office environment

Many companies use wireless technology in the workplace. Use of wireless LAN and 2.4 GHz cordless telephones removes the need for complex fixed wiring layouts and enables employees to move about freely. In most cases, due to the small area of the office, each employee has only a small working area, which means that they are close to each other. This situation leads to a high deployment density of 2.4 GHz wireless equipment and produces a complex radiated EM environment.

The typical office environment usually has the following features:

1) The typical dimension of the office environment will usually be 30 x 20 m.

2) Depending on the number of employees, it will usually have 2 or 3 IEEE 802.11 APs for coverage. The IEEE 802.11 AP channel separation is usually being set to 5 or greater to avoid co-interference.

3) Each employee will have a working desk. Normally, there are one or two IEEE 802.11 STAs and a cordless phone on the desk. The IEEE 802.11 STA could be a notebook or a mobile phone that has a wireless LAN chipset.

4) These working desks are very close to each other. Equipment spacing is about 0.5 m or even closer.

5) There are no walls or other barriers between these radio equipments.

6) Sometimes there will be some IEEE 802.15 equipments.

Figure 12 – Typical office environment

Figure 12 shows a typical office environment. The office room size is 30 × 24 m. There are three rows of working desks arranged across the 24 m width of the office, with each row accommodating two workers. Each desk is 6 m long and the two aisles are 3 m wide. There are two IEEE 802.11 APs on the ceiling. Each worker has an IEEE 802.11 STA and a 2.4 GHz cordless telephone. The IEEE 802.11 STA is a laptop or a converged mobile phone with a wireless LAN chipset. The two IEEE 802.11 APs are set to have a 5-channel separation. The left IEEE 802.11 AP is set to channel 5 and the right IEEE 802.11 AP is set to channel 10. The left IEEE 802.11 AP has five IEEE 802.11 STAs associated with it and the right has four IEEE 802.11 STAs. There are also a few cordless telephones working in this environment

The EM theoretical analysis method gave the result shown in Figure 13.

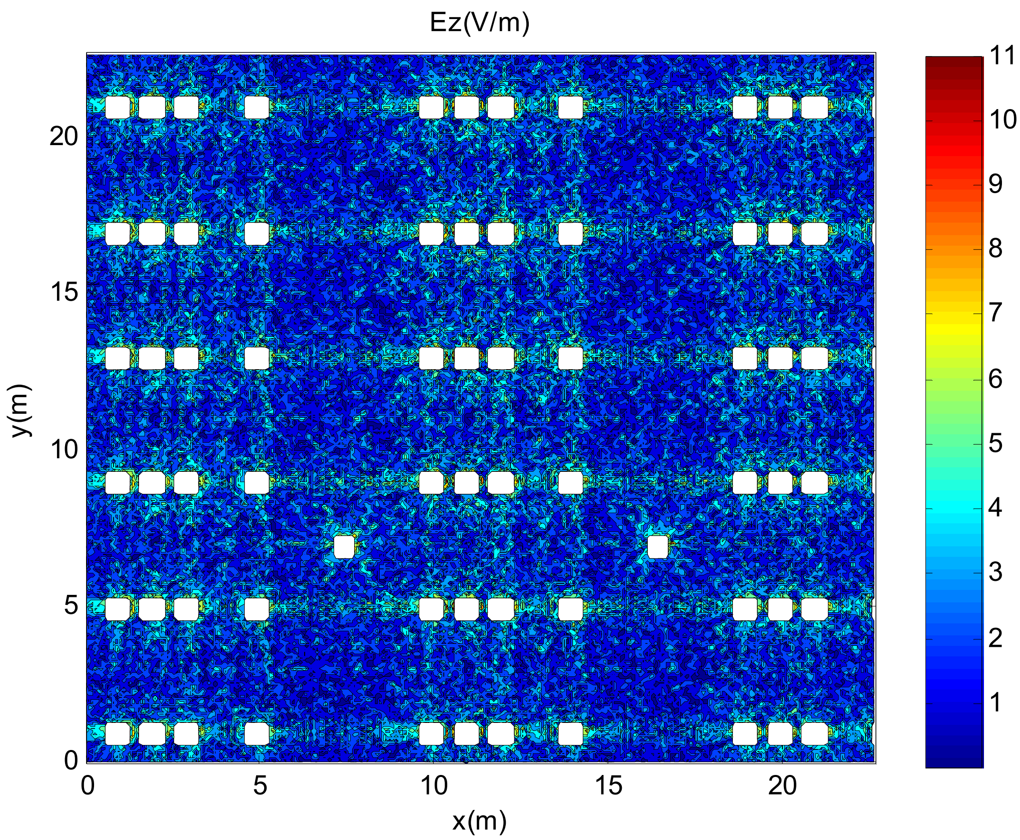

Figure 13 – EM theoretical analysis result of the office environment

Due to the symmetry of this environment, location 1 on Figure 12 is chosen as the measurement point for the EM site survey. This point is at the centre of the left aisle. The distance to the nearest equipment is about 3 m.

The measurement result at location 1 is shown in Figure 14. The maximum radiated power is –27.01 dBm using the method of clause 6.2.5. The emission level was 130.16 dBμV/m with the susceptibility level of 3.22 V/m converting to a distance of 0.5 m.

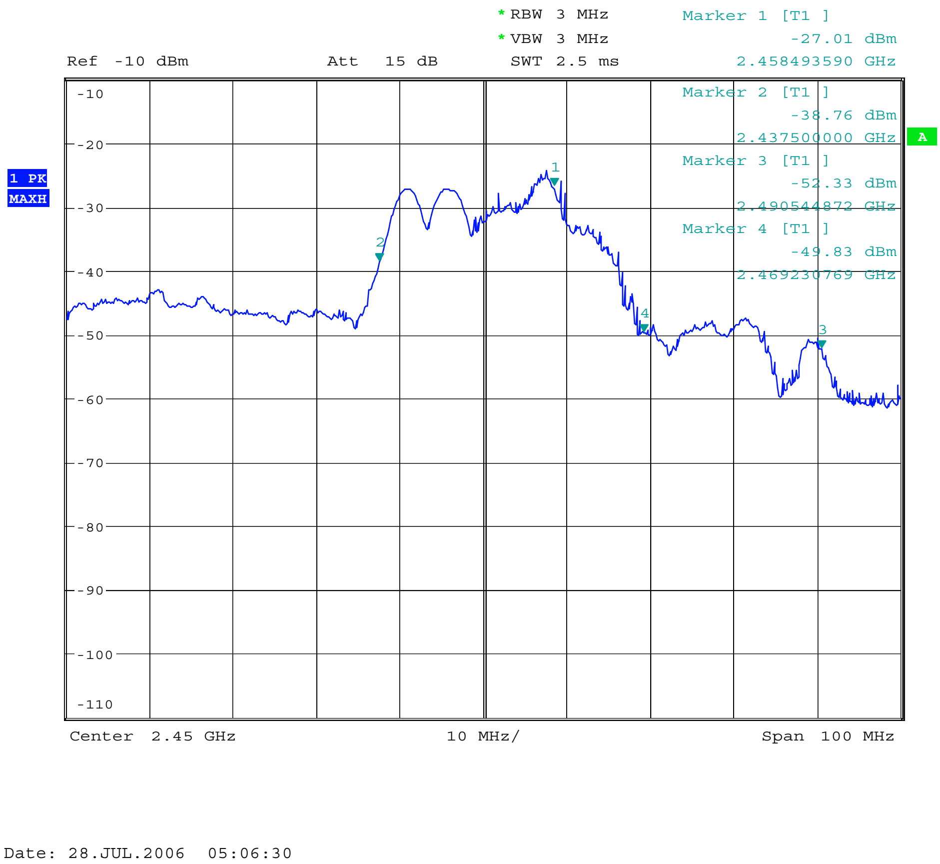

Figure 14 – Measurement result of point 1 at office environment

To make space for the measuring equipment, the number of transmitting equipments is reduced and spaced relatively far apart. The distance from one desk to another is relatively short in a real office and the density of the equipment will be higher. More IEEE 802.11 APs and IEEE 802.11 STAs could produce higher emission levels, and the maximum emission level of the office environment could be as high as 6 V/m to 7 V/m.

5.4 Conclusion

The characteristics for environments considered are summarized in Table 3 based on the above theoretical and measured values. These emission and susceptibility values are only indicators of the possible levels at one point in the different environments. The distance from this reference point to the various radiating equipments is normally between 10 cm and 10 m. In actual environments, the levels may be higher or lower than those listed in Table 3.

Table 3 – Various environment emission and susceptibility ranges

	Home environment		Commercial environment		Office environment
	Single home	Multi-home	Airport	Coffee bar	
Frequency range (MHz)	2400-2497	2400-2497	2400-2497	2400-2497	2400-2497
Emission level (dBµV/m)	60~130	60~135	60~130	60~135	70~140
Susceptibility level (V/m)	0.001~3	0.001~5	0.001~3	0.001~5	0.003~8
NOTE – The lower and higher value is based on the measured and theoretical results.					

6 2.4 GHz electromagnetic environment evaluation procedure

6.1 EM evaluation model

There are many methods used to analyse the EM environment in different frequency bands. Annex A briefly describes the EM site survey, the 2D test method, the theoretical analysis method and the 3D test method. These methods are different from each other and none can give a suitable result without using the results of other methods. This clause gives instructions on how to use these methods. Annex A describes generic methods, this clause explains how to use them in the 2.4 GHz band.

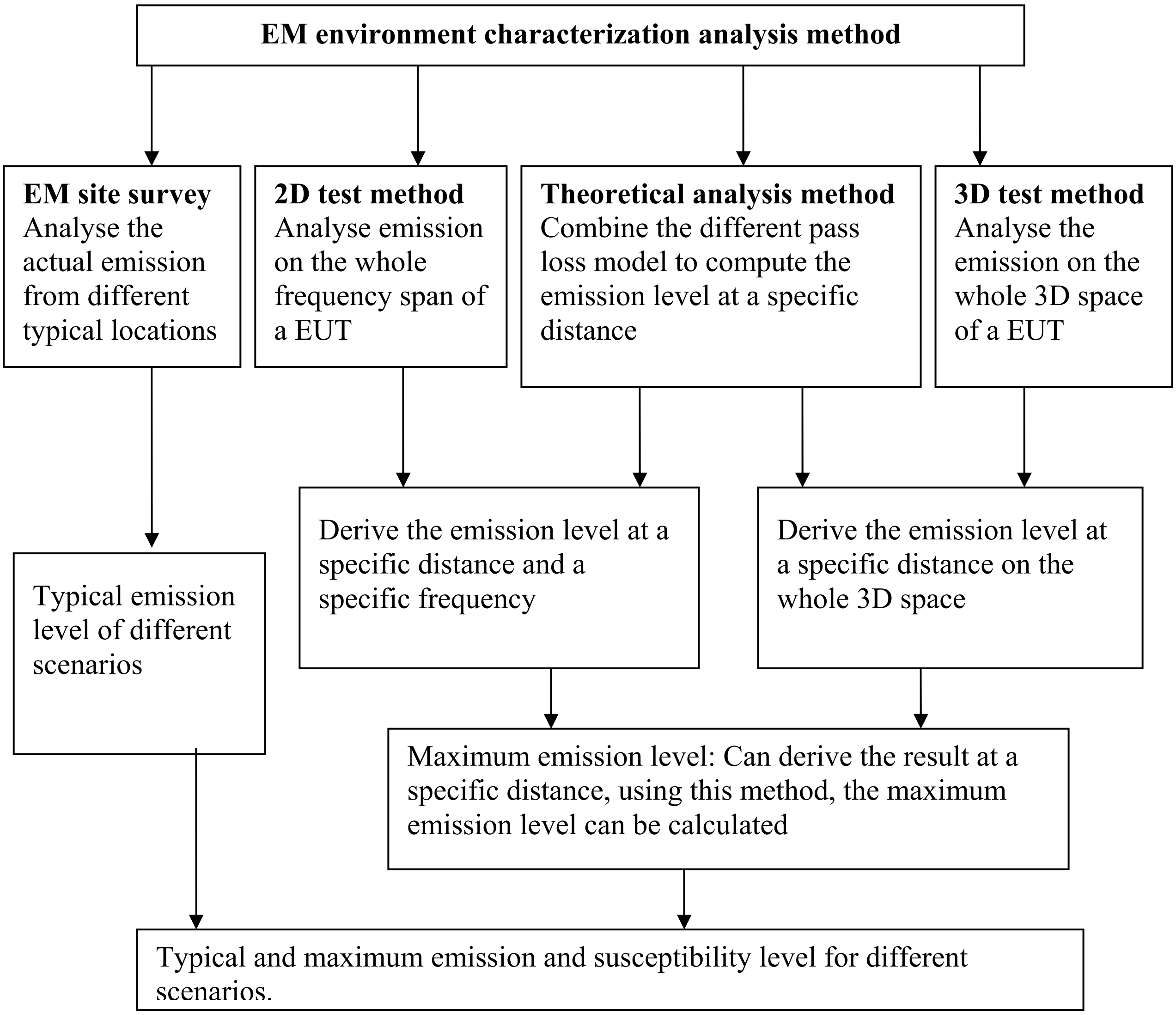

Figure 15 – Flowchart of the application of different EM analysis methods

Figure 15 is a flowchart that presents the relationship of the different EM analysis methods. These methods are divided into two flows: the practical EM site survey method and the theoretical analysis methods. The theoretical methods depend on the 2D and 3D measurement methods to provide the emission information of the radio or non-radio equipment in the environment to be studied. The radiated EM environment for the whole space can be evaluated with the addition of the space transmission model derived from the theoretical analysis.

The EM site survey method is one of the effective methods to evaluate the electromagnetic characteristics of different locations. This is needed when the environment is too complex to be analysed by the theoretical analysis method. The EM site survey can also be used as a validation of the theoretical analysis method results. The typical value can be measured through the EM site survey method. If the maximum EM emission is required, a combination of the EM site survey method, 2D test method, 3D test method and the theoretical analysis method shall be applied.

The 2D and 3D test methods also have other capabilities such as the restriction of the emission level from different radio equipments. Once the whole radiated EM environment characterization is done, the emission level and the susceptibility level can be determined. All emission level types from the radio equipment should be qualified. The 2D and 3D methods could be used for certification testing of equipments during a type-approval process.

The following is an example giving a detailed explanation of the application of these methods.

Figure 16 is an overview of the example room. The dimensions of the room are 6 × 5 m. There is a door on the east wall and a table against each of the other three walls. All the tables are 0.8 m high and all the radio equipments are at tabletop height. The room contains one GSM850 mobile phone, two notebook IEEE 802.11 STAs, one IEEE 802.15 adapter, one IEEE 802.11 AP and three cordless phones. The detailed evaluation procedure is explained in clause 6.2 with this model.

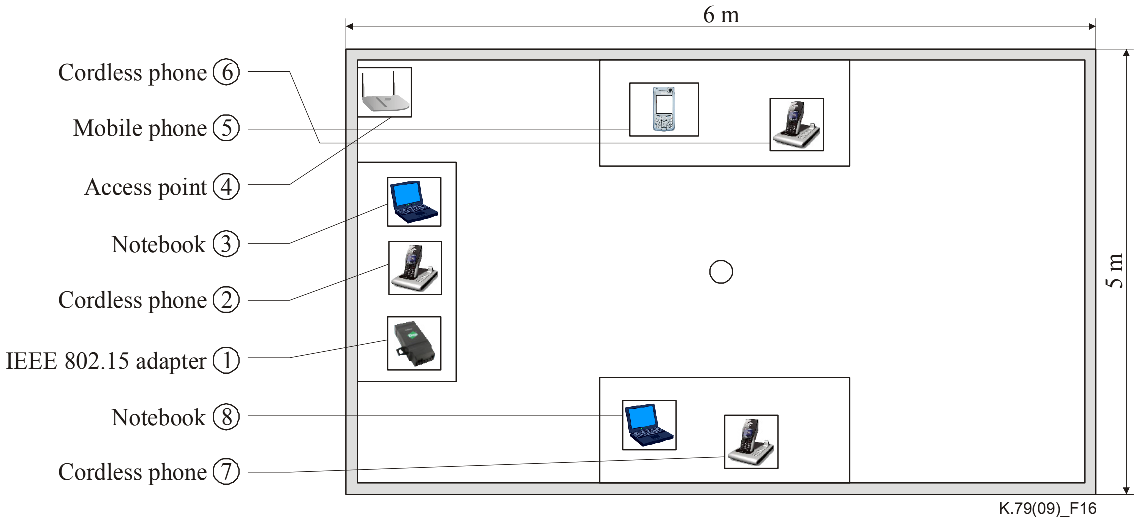

Figure 16 – Typical environment illustration evaluated in clause 6.2

6.2 Different environment evaluation

6.2.1 Different technology specification summation

It is useful to have an understanding of the commonly used 2.4 GHz radio technologies before starting a detailed analysis of the Figure 16 environment. This knowledge will help set the evaluation procedure.

Table 4 is a brief summary of the characteristics of these equipments. The parameters include the frequency range, the nominal output power, modulation, necessary bandwidth and also the manufacture's indication of distance coverage.

Table 4 – 2.4 GHz equipment characteristics

Emission equipment	Function	Frequency range (GHz)	Output power (dBm)	Modulation type	Necessary bandwidth (MHz)	Distance coverage
IEEE 802.11 AP	Radio	2.4-2.4835	20	DSSS/ OFDM	22	150 m
IEEE 802.11 STA	Radio	2.4-2.4835	20	DSSS/ OFDM	22	100 m
2.4 GHz cordless telephone	Radio	2.4-2.4835	20	FHSS	1.8	30 m

Table 4 – 2.4 GHz equipment characteristics

Emission equipment	Function	Frequency range (GHz)	Output power (dBm)	Modulation type	Necessary bandwidth (MHz)	Distance coverage
IEEE 802.15 equipment	Radio	2.4-2.4835	4~20 (Note)	FHSS	1	10~100 m
Microwave oven	Non-radio	2.453-2.467	N/A	N/A	About 10	N/A
NOTE – Usually, the output power for IEEE 802.15.3 equipment is under 4 dBm. When the output power is higher than that, additional power control settings are required.						

6.2.2 2D analysis procedure

The 2D test method is used to analyse the in-band EIRP test and the out-of-band emission test. The in-band EIRP also can be done through the 3D EIRP test method presented in clause 6.2.3 and can give a more accurate result. The 2D method is still widely used for those who do not have the 3D test environment. Also, some radio equipment may have a higher spurious emission level located in the 2.4 GHz band. A typical example is the GSM850 system, whose third harmonic (i.e., 2 550 MHz) falls within the 2.4 GHz band.

The 2D EIRP, and the spurious emission of the GSM850 mobile phone, were measured, as shown in Figure 17. The third harmonic at 2.4 GHz is nearly –43 dBm. This low spurious emission actually does not have a significant effect of the electromagnetic environment compared with radio equipment having an EIRP of about 20 dBm.

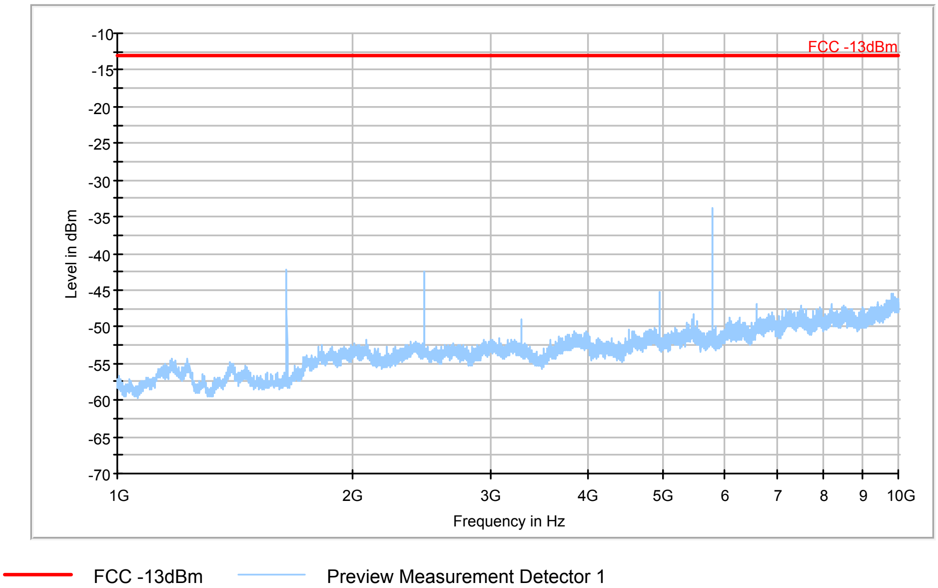

Figure 17 – Radiated emission of GSM850 equipment from 1~10 GHz

The 2D test method can also detect the spurious emission of the 2.4 GHz radio equipments. Figure 18 shows the spurious emission of wireless LAN station notebook ③ in Figure 16. The second harmonic emission is about –45 dBm.

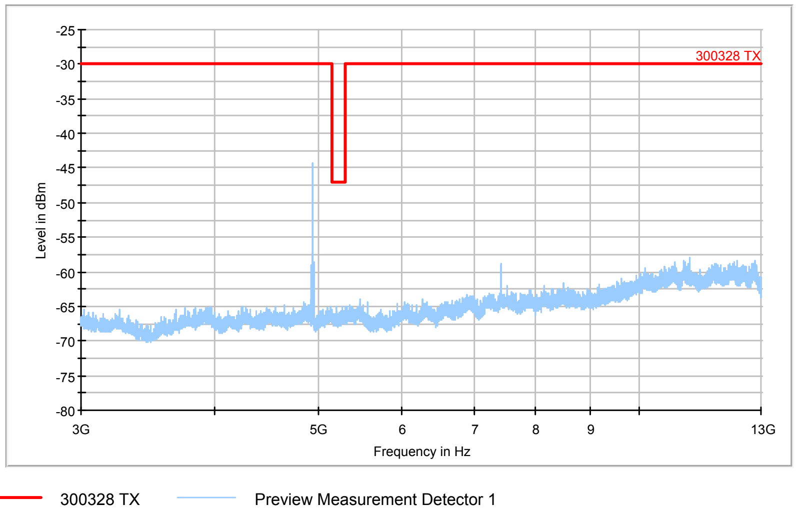

Figure 18 – Radiated emission of WLAN station ③ from 3~13 GHz

These results indicate that the spurious emissions contribute little to the whole radiated EM environment and are a relatively small problem to the in-band transmitters. Harmonic emissions only dominate the radiated EM environments where there are no radio transmitters.

6.2.3 3D analysis procedure

A brief introduction of the 3D emission test is given in clause A.3. The 3D emission test is used to determine the radiated emission of the EUT in all directions although it is not possible to include all the radiated emissions in the different directions as in the theoretical analysis model. The test can simply get the maximum radiated emission level instead.

Checks are needed to confirm that the test site measurement distance provides a far-field condition before using this method. The three far-field criteria are explained in Annex A. The far-field criterion on 2.4 GHz is listed in Table 5.

Table 5 – Minimum measurement distance in metres for the 2.4 GHz ISM band

Band	Lower frequency (MHz)	Upper frequency (MHz)	λ_L	λ_U	$R > \frac{2D^2}{\lambda_U}$	$R > 3D$	$R > 3\lambda_L$	R
2.4 GHz ISM band	2400	2497	0.13	0.12	1.5	0.90	0.39	1.50

In which:

D is the dimension of the radiator (m);

λ_L is the free-space wavelength at the lowest frequency of interest band (m);

λ_U is the free-space wavelength at the highest frequency of interest band (m);

R is the minimum measurement distance required for the far-field measurement (m).

The maximum radiated emission from different equipments in this environment can be derived one by one according to the test method proposed in clauses A.3.1 and A.3.2 while the EUT is cellular/wireless LAN equipment and IEEE 802.15 converged equipment.

6.2.3.1 Emission level of wireless LAN equipment

The cellular mode of this associated device is turned off while the wireless LAN module is transmitting the maximum power to disable the power save mode during the test. The test configuration is shown in Figure 19. The test results from different axis views are shown in Figures 20 to 22. The peak EIRP over the 3D surface is 19.86 dBm at theta = 30, phi = 150.

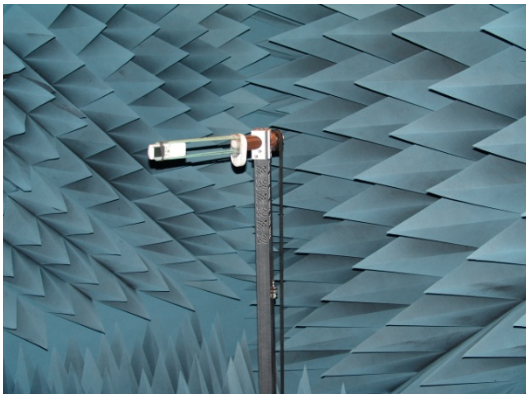

Figure 19 – 3D test configuration of the IEEE 802.11 STA

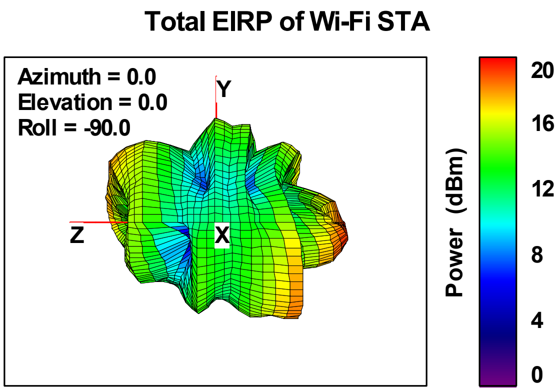

Figure 20 – 3D test result IEEE 802.11 STA from X axis

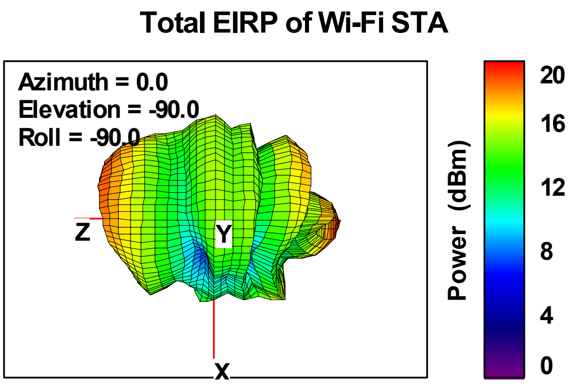

Figure 21 – 3D test result IEEE 802.11 STA from Y axis

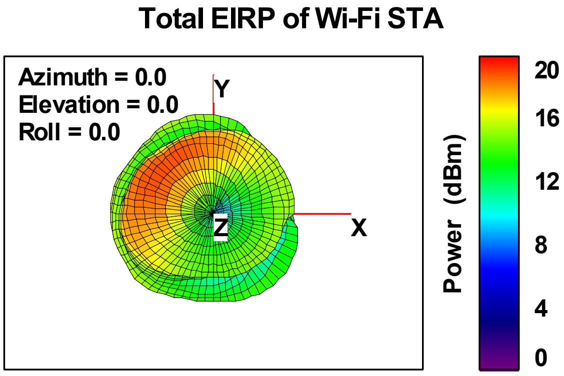

Figure 22 – 3D test result IEEE 802.11 STA from Z axis

6.2.3.2 Emission level of IEEE 802.15 equipment

The IEEE 802.15 equipment is set to test mode (maximum power output) with frequency hopping disabled. Channel 39 (2 439 MHz) is used as the working frequency. The test configuration and test results are shown in Figures 23 to 26.

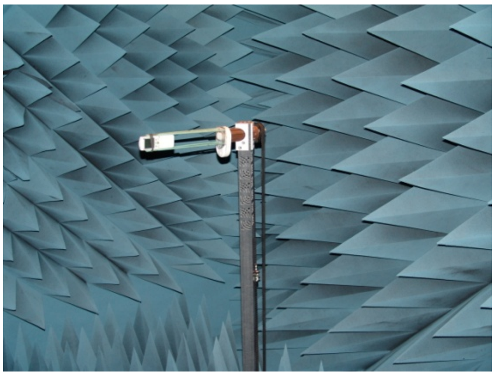

Figure 23 – 3D test configuration of the IEEE 802.11 STA

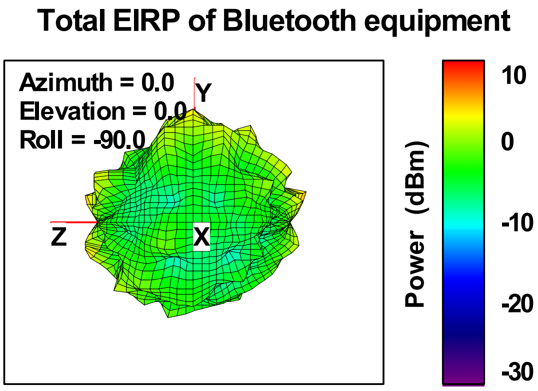

Figure 24 – 3D test result from X axis

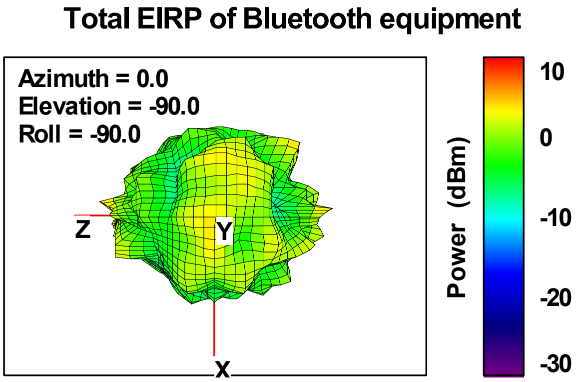

Figure 25 – 3D test result from Y axis

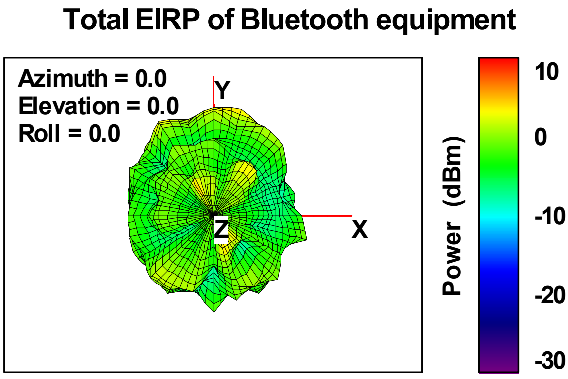

Figure 26 – 3D test result from Z axis

The peak EIRP over the 3D surface was 5.61 dBm at theta = 90, phi = 30. This is much lower than the wireless LAN peak power of 19.86 dBm.

6.2.4 Theoretical analysis procedure

The methods of MOM and FDTD, described in Annex A, are usually used to compute the accurate result. These methods are complex and will use considerable computing time to get the result. These methods can be simplified to provide useful tools, and these are used in this Recommendation. These simple models include the free space transmission model, the OATS transmission model and the indoor transmission model. The OATS and the indoor model are particularly useful to analyse the radiated EM environment.

6.2.4.1 Radiated power in free space

If the radiated power in any direction of the EUT is known, the radiated field strength at any distance from the EUT and in any direction in free space can be calculated. The key parameter of interest is the free space transmission loss L_{bf} that is expressed as [ITU-R P.525-2]:

$$L_{bf} = 32.4 + 20 \log_{10} f + 20 \log_{10} d \quad \text{(dB)} \tag{1}$$

where:

f is the frequency (MHz);

d is the separation distance between the source point and the destination point (km).

Then, the radiated power at any destination point in the free space can be calculated with the following formula:

$$P_r = P_{(\theta,\varphi)} - L_{bf} \tag{2}$$

where:

P_r is the radiated power at destination point;

$P_{(\theta,\varphi)}$ is the power at electromagnetic source point;

θ is the elevation angle of the source point;

ϕ is the azimuth angle of the source point.

With the equation, the field strength at the destination point can be derived:

$$P_r = \frac{3.12 \times 10^{-11} \times E_0{}^2}{F_{MHz}{}^2} \tag{3}$$

where:

E_0 is the field strength at destination point.

6.2.4.2 Radiated power at an OATS

The OATS transmission model is another model that is often used. The OATS transmission model assumes that the ground is an ideal reflecting plane. It is more suitable to analysis of the radiated EM environment in real life than the free space model.

The transmission routes from the source point to the destination point are the direct route via free-space and the indirect route via the reflecting ground plane.

Assuming that:

1) the height of the source and receiver are h_t and h_r respectively;
2) the separation distance between them is d;
3) $h_t << d$;
4) $h_r << d$;
5) Δd is the difference in length between the (longer) indirect and (shorter) direct route;

then it is possible to write:

$$\Delta d = \sqrt{(h_t + h_r)^2 + d^2} - \sqrt{(h_t - h_r)^2 + d^2} \approx \frac{2h_t h_r}{d}$$

The difference in the propagation distance between the direct and indirect routes means that there is a phase difference, $\Delta\varphi$, at the destination point given by:

$$\Delta\varphi = \frac{2\pi\Delta d}{\lambda} = \frac{4\pi h_t h_r}{d\lambda}$$

Having established the deviation of both the amplitude and the phase, the receive power at the receiver can be expressed as:

$$P_r = \log(P_t G_t G_r) + 2\log(h_t) + 2\log(h_r) - 4\log(d)$$

where:

P_r is the receive power at the receiver;

P_t is the transmit power at the source;

G_t is the gain of the transmit antenna;

G_r is the gain of the receive antenna.

6.2.4.3 Radiated power in indoor environment

The attenuation L_{total} for indoor path loss is given by (see [ITU-R P.1238-4]):

$$L_{total} = 20 \log_{10} f + N \log_{10} d + L_f(n) - 28 \text{ dB} \quad (4)$$

Where:

N is the distance power loss coefficient;

f is the frequency (MHz);

d is the separation distance (m) between the base station and portable terminal (where $d > 1$ m);

L_f is the floor penetration loss factor (dB);

n is the number of floors between the base station and the portable terminal ($n \geq 1$).

Besides door penetration loss, there are many other losses that need to be taken into account for the indoor environment to get more accurate results. The typical penetration loss of other objects at 2.4 GHz is listed in Table 6.

Table 6 – Object penetration loss at 2.4 GHz

Material/obstruction	Typical penetration loss (dB)	Material/obstruction	Typical penetration loss (dB)
Free space	0	Floor/ceiling (thick, not hollow)	20-25
Window (without metal)	3	Window in a brick wall	2
Window (metal)	5-8	Wall (glass) with metal window	6
Thin wall (dry)	5-8	Office wall	6
Medium wall (wood)	10	Office door (metal)	6
Thick wall (not hollow)	15-20	Wall (brick)	4
Very thick wall (not hollow)	20-25	Door (metal) in a brick wall	12.4
Floor/ceiling (not hollow)	15-20	Wall (brick) near a metal door	3
Door (wood)	3-5	–	–

6.2.4.4 Theoretical analysis result

Using the above methods, combined with the EIRP test results and the radiated spurious emission results from clauses 6.2.2 and 6.2.3, the theoretical analysis model can be established by the methods of clauses A.1 and 6.2.4. The analysis result of the Figure 16 environment is shown in Figure 27.

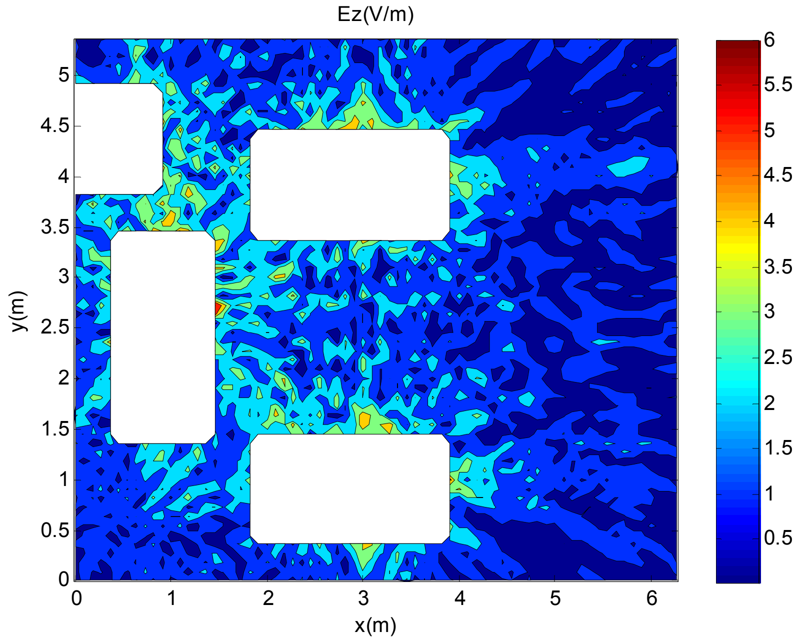

Figure 27 – EM theoretical analysis result of Figure 16

6.2.5 EM site survey method

The EM site survey is an efficient method when the environment is too complex to be analysed by mathematical methods. It also has another important function of validating the theoretical analysis results.

The EM site survey is performed according to the method detailed in clause A.4 to measure the radiated EM environment shown in Figure 16. The measurement equipment used during the evaluation include:

- spectrum analyser from 3 Hz to 26.5 GHz;
- precision sleeve dipole of 2.4 GHz;
- RF pre-amplifier;
- Ancillary items: High frequency RF cables, attenuators, filters, etc.

6.2.5.1 Emission level of cordless telephones

There is a cordless telephone on each of the three tables in Figure 16. The distance from each phone to the room centre is 2 m and the height of a table is 0.8 m.

The cordless telephone emission is measured with a precision sleeve dipole mounted at the same height as the tabletops (0.8 m).

Two kinds of measurement are performed. First, the emission level from a cordless phone is recorded. After that, it is investigated whether the number of the cordless phones could make the whole radiated EM environment more severe. The three cordless phones are put into service together and the result recorded.

First, the No. 1 2.4 GHz cordless phone is powered and put into service at its maximum radiated power. Figure 28 shows the EM emission from this cordless phone. The emission mask covers the whole frequency band of 2.4 to 2.4835 GHz. This 2.4 GHz cordless phone uses FHSS technology that has 95 separate channels from 2.4 to 2.4835 GHz (refer to Table 4). The channel separation is 0.864 MHz.

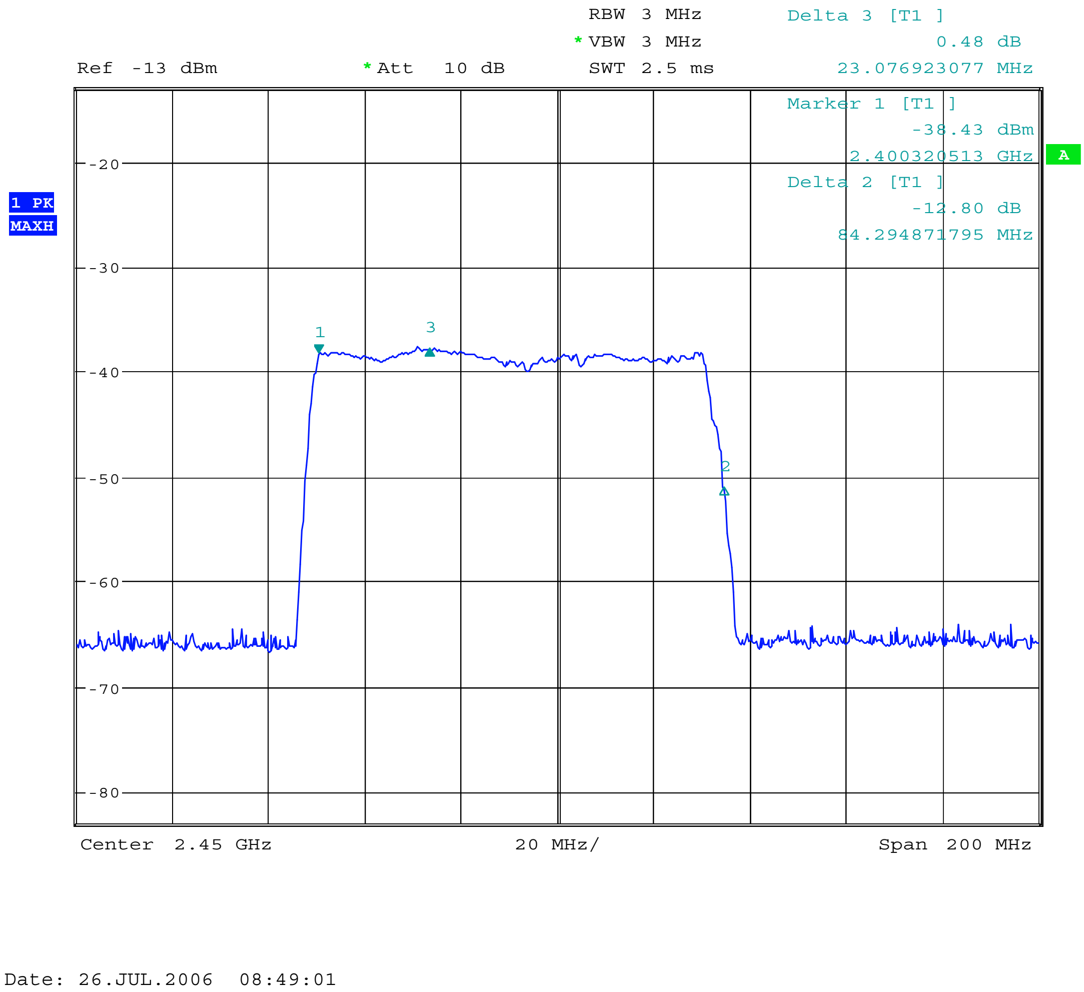

Figure 28 – EM test result of one cordless phone

The maximum emission level is about –38 dBm from Figure 28. The following equations can be used to convert the P (dBm) to E (dBμV/m) taking the whole system as 50 Ohms.

$$P(\text{dBm}) = E\ (\text{dB}\mu\text{V}) - 107 \tag{5}$$

$$E\ (\text{dB}\mu\text{V/m}) = E\ (\text{dB}\mu\text{V}) + AF(\text{dB/m}) \tag{6}$$

$$G\ (\text{dBi}) = 20\log_{10}(F(\text{MHz})) - AF(\text{dB/m}) - 29.79 \tag{7}$$

where:

- F is the measurement frequency;
- AF is the antenna factor of the measuring antenna. The measurement antenna is a precision sleeve dipole in this Recommendation, which has a gain, G, of 2.15 dBi. The AF can be calculated with equation 7, which is 35.66 dB/m at 2.4 GHz.

The relationship between the E (dBμV/m) and P (dBm) is given in equation 8 using the results from equations 5, 6 and 7.

$$E\ (\text{dB}\mu\text{V/m}) = P\ (\text{dBm}) + 20\log_{10}(F\ (\text{MHz})) - G(\text{dBi}) + 77.21 \tag{8}$$

The emission level at 2 m for one cordless phone will be 104.66 dBμV/m, which is 0.17 V/m.

Figure 29 shows the test result of No. 1 and No. 2 cordless telephones working simultaneously. Figure 30 shows the result for all three cordless telephones working simultaneously.

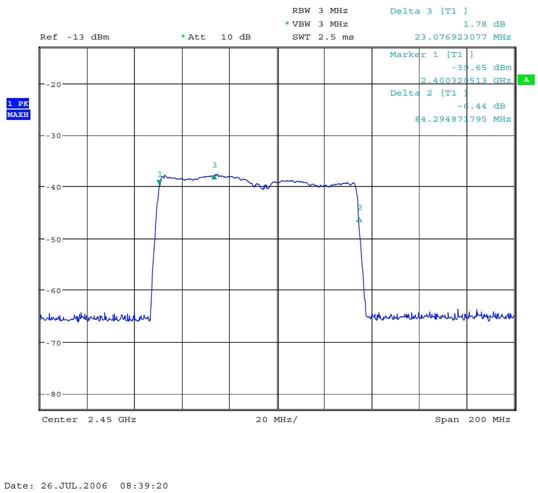

Figure 29 – Measurement of two cordless phones

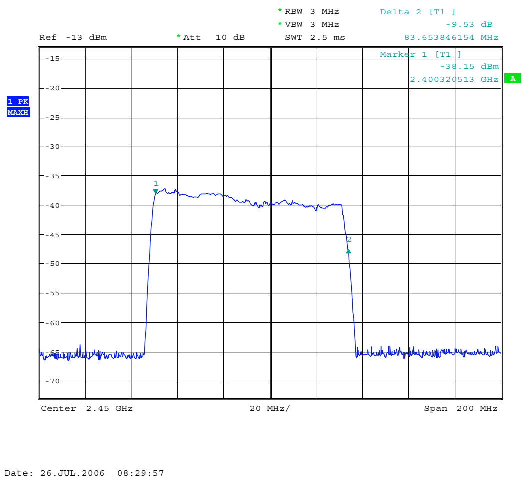

Figure 30 – Measurement result of three cordless phones

The measured emission level for two and three cordless telephones working are almost the same at about –38 dBm. These cordless phones are using the same adaptive FHSS technology used by most IEEE 802.15 equipment. This technology will automatically avoid using those channels already used by the other cordless telephones. Before the second cordless phone begins to work, it will check the status of all 95 channels and record which channel(s) could be used. It automatically avoids using the channels currently used by other telephones. The cordless telephone changes its channel use rapidly but only on the available channels.

The radiated EM environment due to the cordless phones is almost independent of the number of phones in use.

6.2.5.2 Emission level of wireless LAN equipments

There are four wireless LAN equipments in Figure 16. This clause covers the Wireless LAN equipment emissions.

Emission levels for data transfer and no data transfer conditions between the IEEE 802.11 AP and the IEEE 802.11 STAs are compared. How the number of IEEE 802.11 APs and IEEE 802.11 STAs will affect the radiated EM environment is also evaluated.

The emission level difference of data transfer and no data transfer between the IEEE 802.11 AP and the IEEE 802.11 STAs are measured first. IEEE 802.11 STA 1 was turned on and associated with the IEEE 802.11 AP. Figure 31 shows the measured emissions for no data exchange between the IEEE 802.11 AP and the IEEE 802.11 STA. The maximum emission with no data transfer is –31.43 dBm and with data transfer it is –30.94 dBm, as shown in Figure 32.

Then the other two IEEE 802.11 STAs are associated with the IEEE 802.11 AP. Figure 33 shows the emission level is –28.67 dBm when normal data transfer occurs between the IEEE 802.11 AP and the three IEEE 802.11 STAs. The level is about 2 dB higher than the previous one. As the number of the associated IEEE 802.11 STAs increases, the emission level will increase accordingly.

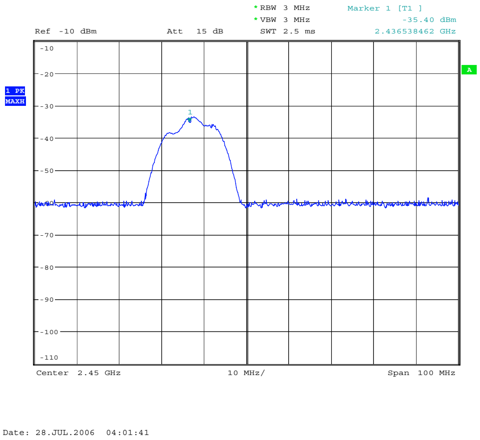

Figure 31 – One IEEE 802.11 AP and one IEEE 802.11 STA without data transfer

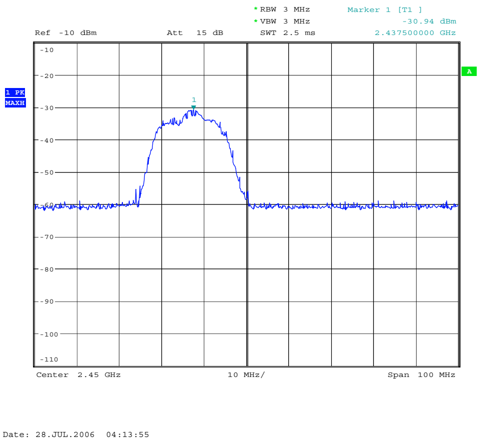

Figure 32 – One IEEE 802.11 AP and one IEEE 802.11 STA with data transfer

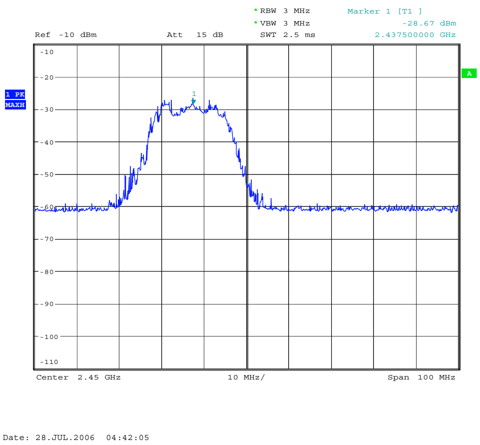

Figure 33 – One IEEE 802.11 AP and three IEEE 802.11 STAs with data transfer

Usually, one IEEE 802.11 AP has the capability of associating with 7 to 10 IEEE 802.11 STAs, depending on the circumstances. More than 10 IEEE 802.11 STAs would affect the EM level dramatically.

The last area of study is the influence of the number of IEEE 802.11 APs and their operating channels on the radiated EM environment. Two configurations were tested. The first configuration had one IEEE 802.11 AP set to channel 10 and the second IEEE 802.11 AP set to channel 5 – a channel separation of 5. Each IEEE 802.11 AP had 5 IEEE 802.11 STAs associated with it. The test result shown in Figure 34 is for data transfer between the two IEEE 802.11 APs and the IEEE 802.11 STAs. The second configuration had one IEEE 802.11 AP set to channel 10 and the second IEEE 802.11 AP set to channel 9 – a channel separation of 1. The test results are shown in Figure 35.

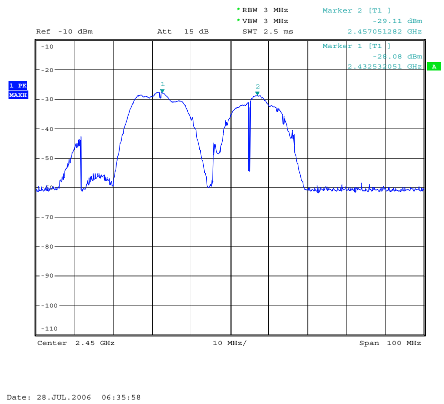

Figure 34 – Test results of two IEEE 802.11 APs with a separation of 5 channels

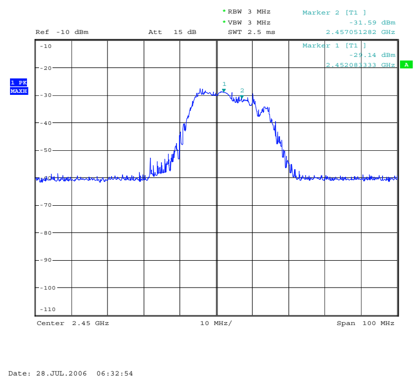

Figure 35 – Test results of two IEEE 802.11 APs with a separation of 1 channel

The transfer data rate was substantially reduced from 21 Mbit/s to about 10 Mbit/s after the channel separation was changed from 5 to only 1. The maximum emission level is changed from –28.5 dBm to about –28 dBm. It is about 0.5 dB higher than the previous one. The electric field strength is about 6 V/m, counting the measurement distance and the antenna factor.

The measurements were done with 5 IEEE 802.11 STAs associated with each IEEE 802.11 AP. As a single IEEE 802.11 AP can typically associate with 7 to 10 IEEE 802.11 STAs, one would expect the radiated EM environment to become more severe as additional IEEE 802.11 STAs are associated with the IEEE 802.11 AP.

Test results show that emission levels increase as more IEEE 802.11 STAs associate with an IEEE 802.11 AP. The radiated EM environment could be even more complex when these radio equipments are installed in a limited area such as in a typical office. The electric field strength could be very high in some places with such a situation.

6.3 Different modulation resolution

The wireless LAN, IEEE 802.15 adapter and digital cordless phone use different modulation resolutions resulting in each having a different environmental impact and resistance to electromagnetic interference.

The direct sequence spread spectrum (DSSS) system uses DBPSK, DQPSK or CCK modulations in different situations for different signal transmit rates. The necessary bandwidth for [IEEE 802.11] is 22 MHz and the signal is similar to white noise, so it has a strong ability to resist RF interference. The WLAN system can have a big influence on a frequency-hopping system such as [IEEE 802.15.x] due to its wideband characteristics. The IEEE 802.11 22 MHz bandwidth will overlap a lot of IEEE 802.15 equipment channels, especially if there are many wireless LAN equipments nearby. The DSSS system occupies a wide frequency band and has a significant influence on other communication systems.

For the orthogonal frequency-division multiplexing (OFDM) system, the WLAN uses BPSK, QPSK, 16QAM or 64QAM in different situations for different transmit rates. This system can adjust to use different modulation types to maximize the signal quality. The system will use BPSK or QPSK when the transmit channel is bad to ensure the signal/noise quality. When the channel quality is good or the EUT is near the base station, it will use the 16QAM or 64QAM modulation to improve the spectral efficiency.

The benefits of OFDM are high spectral efficiency and resistance to RF reflections and interferences. The orthogonal nature of OFDM allows sub-channels to overlap, which has a positive effect on spectral efficiency. The sub-carriers transporting information are just far enough apart from each other to theoretically avoid interference.

This parallel form of transmission over multiple sub-channels enables OFDM-based wireless LANs to operate at higher aggregate data rates up to 54 Mbit/s with IEEE 802.11a-compliant implementations. In addition, interfering RF signals will only destroy the portion of the OFDM transmitted signal related to the frequency of the interfering signal.

6.4 Multi-path evaluation

DSSS transmission multiplies the data by a higher-frequency pseudo-random digital "noise" signal. In theory, it requires a signal with white noise characteristics, such as the DSSS signal, to affect the multi-path attenuation. The code width is very narrow and the rate is very high in DSSS systems. DSSS performs well in the multi-path situations.

OFDM transmission exhibits lower multi-path distortion (delay spread) because the high-speed composite's sub-signals are sent at lower symbol rates. Multi-path-based delays are not nearly such a significant factor as they are with a single-channel high-rate system.

The information content of a narrow-band signal can be completely lost at the receiver if the multi-path distortion causes the frequency response to have a null at the transmission frequency. The usage of the multi-carrier OFDM significantly reduces this problem. An OFDM system variant is the multiple-input and multiple-output (MIMO) system which uses multiple antennas to get higher data transmission rates.

Annex A

Electromagnetic environment analysis method

(This annex forms an integral part of this Recommendation)

More and more new radio services make use of the unlicensed ISM 2.4 GHz frequency band, such as: IEEE 802.11 Wireless LAN systems, IEEE 802.16 systems, IEEE 802.15 systems and digital cordless phones. Multiple systems and installations can result in a very complex electromagnetic environment for this frequency band, resulting in interference and a reduction in service. Some typical interference situations are given in Appendix I.

This annex describes some methods to evaluate an electromagnetic environment. Some methods can be used separately while some methods should be used in combination.

A.1 Electromagnetic environment theoretical analysis method

This clause discusses two theoretical analysis methods; finite difference time domain (FDTD) and method of moments (MOM). Both methods have been extensively used and there are enhanced versions available.

A.1.1 FDTD method

A.1.1.1 Basic algorithm

The Maxwell's curl equations for an isotropic medium are:

$$\Delta\times\vec{E} = -\mu\frac{\partial\vec{H}}{\partial t} \tag{A.1}$$

$$\Delta\times\vec{H} = \delta\vec{E} + \varepsilon\frac{\partial\vec{E}}{\partial t} \tag{A.2}$$

These can be written as six scalar equations in Cartesian coordinates:

$$\frac{\partial H_x}{\partial t} = \frac{1}{\mu}\left(\frac{\partial E_y}{\partial z} - \frac{\partial E_z}{\partial y}\right) \tag{A.3}$$

$$\frac{\partial H_y}{\partial t} = \frac{1}{\mu}\left(\frac{\partial E_z}{\partial x} - \frac{\partial E_x}{\partial z}\right) \tag{A.4}$$

$$\frac{\partial H_z}{\partial t} = \frac{1}{\mu}\left(\frac{\partial E_x}{\partial y} - \frac{\partial E_y}{\partial x}\right) \tag{A.5}$$

$$\frac{\partial E_x}{\partial t} = \frac{1}{\varepsilon}\left(\frac{\partial H_z}{\partial y} - \frac{\partial H_y}{\partial z} - \delta E_x\right) \tag{A.6}$$

$$\frac{\partial E_y}{\partial t} = \frac{1}{\varepsilon}\left(\frac{\partial H_x}{\partial z} - \frac{\partial H_z}{\partial x} - \delta E_y\right) \tag{A.7}$$

$$\frac{\partial E_z}{\partial t} = \frac{1}{\varepsilon}\left(\frac{\partial H_y}{\partial x} - \frac{\partial H_x}{\partial y} - \delta E_z\right) \tag{A.8}$$

Where (i,j,k) is defined as:

$$(i,j,k)=(i\Delta x, j\Delta y, k\Delta z) \tag{A.9}$$

Where Δx, Δy and Δz are the actual grid separations.

Any function of space and time can be written as:

$$F^n(i,j,k)=F(i\Delta x, j\Delta y, k\Delta z, \Delta t) \tag{A.10}$$

Where Δt is the time increment and n is the time index. The spatial and temporal derivatives of F are written using central finite difference approximations as:

$$\begin{aligned}\frac{\partial F^n(i,j,k)}{\partial x}&=\frac{F^n\left(i+\frac{1}{2},j,k\right)-F^n\left(i-\frac{1}{2},j,k\right)}{\Delta x}+O\left(\Delta x^2\right)\\ \frac{\partial F^n(i,j,k)}{\partial t}&=\frac{F^{n+1/2}(i,j,k)-F^{n-1/2}(i,j,k)}{\Delta t}+O\left(\Delta t^2\right)\end{aligned} \tag{A.11}$$

Equations A.11 can be applied to the six scalar equations A.3 to A.8, resulting in six coupled explicit finite difference equations:

$$\begin{aligned}E_x^{n+1}(i+1/2,j,k)&=\frac{\varepsilon/\Delta t-\sigma/2}{\varepsilon/\Delta t+\sigma/2}E_x^n(i+1/2,j,k)+\frac{1}{\varepsilon/\Delta t+\sigma/2}\{[H_z^{n+1/2}(i+1/2,j+1/2,k)\\ &-H_z^{n+1/2}(i+1/2,j-1/2,k)]/\Delta y-[H_y^{n+1/2}(i+1/2,j,k+1/2)-H_y^{n+1/2}(i+1/2,j,k-1/2)]/\Delta z\}\end{aligned} \tag{A.12}$$

$$\begin{aligned}E_y^{n+1}(i,j+1/2,k)&=\frac{\varepsilon/\Delta t-\sigma/2}{\varepsilon/\Delta t+\sigma/2}E_y^n(i,j+1/2,k)+\frac{1}{\varepsilon/\Delta t+\sigma/2}\{[H_x^{n+1/2}(i,j+1/2,k+1/2)\\ &-H_x^{n+1/2}(i,j+1/2,k-1/2)]/\Delta z-[H_z^{n+1/2}(i+1/2,j+1/2,k)-H_z^{n+1/2}(i-1/2,j+1/2,k)]/\Delta x\}\end{aligned} \tag{A.13}$$

$$\begin{aligned}E_z^{n+1}(i,j,k+1/2)&=\frac{\varepsilon/\Delta t-\sigma/2}{\varepsilon/\Delta t+\sigma/2}E_z^n(i,j,k+1/2)+\frac{1}{\varepsilon/\Delta t+\sigma/2}\{[H_y^{n+1/2}(i+1/2,j,k+1/2)\\ &-H_y^{n+1/2}(i-1/2,j,k+1/2)]/\Delta x-[H_x^{n+1/2}(i,j+1/2,k+1/2)-H_x^{n+1/2}(i,j-1/2,k+1/2)]/\Delta y\}\end{aligned} \tag{A.14}$$

$$\begin{aligned}H_x^{n+1/2}(i,j+1/2,k+1/2)&=H_x^{n-1/2}(i,j+1/2,k+1/2)+\frac{\Delta t}{\mu\Delta z}[E_y^n(i,j+1/2,k+1)\\ &-E_y^n(i,j+1/2,k)]-\frac{\Delta t}{\mu\Delta y}[E_z^n(i,j+1,k+1/2)-E_z^n(i,j,k+1/2)]\end{aligned} \tag{A.15}$$

$$\begin{aligned}H_y^{n+1/2}(i+1/2,j,k+1/2)&=H_y^{n-1/2}(i+1/2,j,k+1/2)+\frac{\Delta t}{\mu\Delta x}[E_z^n(i+1,j,k+1/2)\\ &-E_z^n(i,j,k+1/2)]-\frac{\Delta t}{\mu\Delta z}[E_x^n(i+1/2,j,k+1)-E_x^n(i+1/2,j,k)]\end{aligned} \tag{A.16}$$

$$\begin{aligned}H_z^{n+1/2}(i+1/2,j+1/2,k)&=H_z^{n-1/2}(i+1/2,j+1/2,k)+\frac{\Delta t}{\mu\Delta y}[E_x^n(i+1/2,j+1,k)\\ &-E_x^n(i+1/2,j,k)]-\frac{\Delta t}{\mu\Delta x}[E_y^n(i+1,j+1/2,k)-E_y^n(i,j+1/2,k)]\end{aligned} \tag{A.17}$$

In all of the finite difference equations, the components of $\vec{E}$ and $\vec{H}$ are located within a single unit cell of the three-dimensional lattice depicted in Figure A.1.

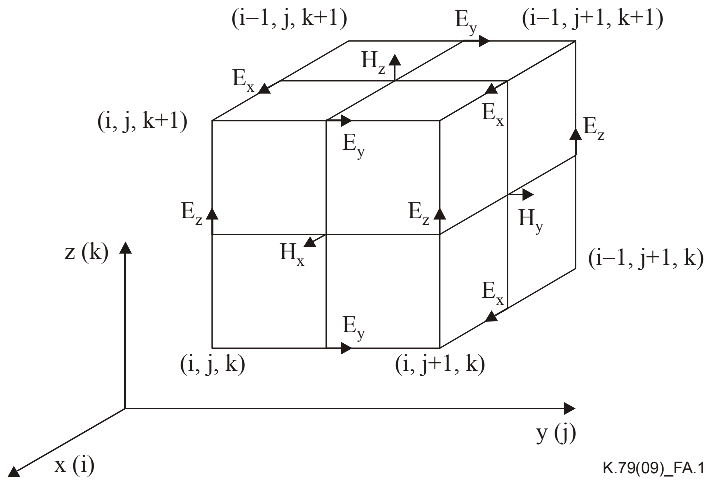

Figure A.1 – Cell demonstrating the arrangement of field components within a cubical grid

$\vec{E}$ and $\vec{H}$ are evaluated at alternate half time steps, using equations A.12 to A.17, such that all field components are calculated in each time step Δt.

A.1.1.2 Grid and geometry

To yield accurate results, the grid spacing in the finite difference simulation must be less than the wavelength, usually less than $\lambda/10$. The stability condition relating the spatial and temporal step size is

$$\Delta t \leq \frac{1}{v_{\max}\sqrt{\frac{1}{\Delta x^2}+\frac{1}{\Delta y^2}+\frac{1}{\Delta z^2}}} \tag{A.18}$$

Where $v_{\max}$ is the maximum velocity of the wave.

A.1.1.3 Sources

A number of different sources can be used to find the scattered fields including Gaussian pulse plane wave, sinusoidal pulse and sinusoidal plane wave. The incident fields described by Gaussian pulse are:

$$E^{inc} = E_0 e^{-(x-x_0)2} \big/ \omega^2 \tag{A.19}$$

This source, however, is not a single frequency or monochromatic plane wave.

A single frequency source is modelled with either a sinusoidal pulse or a continuous wave source. In either case, the incident field is of the form of:

$$E^{inc}(x,y,z) = E_0(x,y,z)\sin(\omega t) \tag{A.20}$$

In the case of a pulse, the incident field is turned off after a specified number of time steps. The discrete form for a uniform plane wave incident field of frequency *f* is

$$E^{inc}(i+1/2,j,k) = E_0(i+1/2,j,k)\sin(2\pi f n \delta t) \tag{A.21}$$

A.1.1.4 Boundary conditions

Because of the finite computational domain, the values of the fields at the boundaries must be defined such that the solution region appears to extend infinitely in all directions. Without truncation conditions, the scattered waves will be artificially reflected at the boundaries leading to inaccurate results.

A number of boundary conditions have been proposed for finite difference simulation of Maxwell's equations, including the Mur absorbing boundary condition [b-Mur] and PML boundary condition.

The Mur absorbing boundary condition simulates the propagation of an outward-going wave at the boundary. All of the field components satisfy the three-dimensional scalar wave equation,

$$\nabla^2\psi + \frac{1}{u^2}\frac{\partial^2\psi}{\partial t^2} = 0 \tag{A.22}$$

Where ψ is any field component and u is the velocity of the wave.

As an example of the Mur absorbing boundary condition, consider the E_z component at $x = 0$. The finite difference form of the first order Mur absorbing boundary condition is

$$E^{n+1}{}_z(0, j, k+1/2) = E^n{}_z(1, j, k+1/2) + \frac{c\Delta t - \delta}{c\Delta t + \delta}\left[E^{n+1}{}_z(1, j, k+1/2) - E^n{}_z(0, j, k+1/2)\right] \tag{A.23}$$

where c is the speed of light.

A more accurate solution is obtained when second order finite differences are used.

The boundary condition called the perfectly matched layer (PML) provides several orders of magnitude improvement over the Mur absorbing boundary conditions. In the PML boundary condition, an artificial material region surrounding the scatterer is created which has both electrical and magnetic conductivities. Each field component is split into two parts, resulting in a total of 12 field components in this region.

A.1.2 MOM

A.1.2.1 Basic algorithm

Consider the inhomogeneous equation:

$$L(f) = g \tag{A.24}$$

Where L is a linear operator, g is known and f is to be determined. We shall now perform the two essential steps.

Let f be expanded in a series of functions:

$$f = \sum_n \alpha_n f_n \tag{A.25}$$

Where α_n are constant. The set f_n is called the expansion function, or basis functions.

Note that for an exact solution, the summation should be taken to ∞, but it has to be truncated in practice.

It is assumed that a suitable inner product has been defined for the problem. Now, we define a set of weighting functions, or testing functions, $w_1, w_2, ..., w_N$ in the range of L, and take the inner product of the previous equation with w_m:

$$\sum_n \alpha_n < w_m, Lf_n > = < w_m, g > \tag{A.26}$$

The system can now be written in matrix form as:

$$[A_{mn}][\alpha_n] = [g_m] \tag{A.27}$$

where

$$[A_{mn}] = \begin{pmatrix} < w_1, \mathcal{L}f_1 > & < w_1, \mathcal{L}f_2 > & \dots \\ < w_2, \mathcal{L}f_1 > & < w_2, \mathcal{L}f_2 > & \dots \\ \vdots & \vdots & \ddots \end{pmatrix}, \quad [\alpha_n] = \begin{pmatrix} \alpha_1 \\ \alpha_2 \\ \vdots \end{pmatrix}, \quad [g_m] = \begin{pmatrix} < w_1, g > \\ < w_2, g > \\ \vdots \end{pmatrix}. \tag{A.28}$$

If the matrix $[A_{mn}]$ is not singular, the unknowns α_n are simply given by:

$$[\alpha_n] = [A_{mn}]^{-1}[g_m] \tag{A.29}$$

Generalize the following definitions. The basis functions used previously are defined as follows.

Pulse basis functions:

$$f_n = \begin{cases} 1 & \text{if } x \text{ belongs to the interval } n \\ 0 & \text{otherwise} \end{cases} \tag{A.30}$$

The testing function (or weighting functions):

Point matching = taking Dirac δ function as testing functions

The advantage of the MOM over purely numerical methods is that there is still a large part that remains analytical. Yet, it remains a numerical method based on a matrix inversion technique and therefore, convergence issues need to be examined.

A.1.2.2 Basis and testing functions

The convergence of the MOM is closely related to the choice of basic functions and testing functions. There are essentially two families of basic functions.

Entire domain basis functions

Using these functions to expand the unknowns is analogous to a Fourier expansion or to a modal expansion. These types of functions yield a good convergence of the method but are not versatile since the geometry need be regular in order to have the modes defined. Note that in this case, there is no use to mesh the geometry.

Sub-domain basis functions

These rely on a proper meshing of the geometry, which can be rectangular, triangular, etc. The choice of basic functions here is very wide.

Dirac δ function:

$$B_0(x) = \delta(x - x_0) \tag{A.31}$$

Pulse or piecewise-constant function:

$$B_1(x) = p(x, x_1, x_2) = \begin{cases} 1, x_1 < x < x_2 \\ \\ 0, \textit{otherwise} \end{cases} \tag{A.32}$$

Sub-sectional triangle function

$$B_2(x) = t(x, x_1, x_2, x_3) = \begin{cases} \dfrac{x - x_3}{x_4 - x_3}, x_3 < x < x_4 \\ \\ \dfrac{x_5 - x}{x_5 - x_4}, x_4 < x < x_5 \end{cases} \quad \text{(A.33)}$$

In addition, there are still the quadratic spline function, the lagrangian interpolation polynomials function and many other functions.

Finally, note that point matching, which is easy to grasp and straightforward to implement, may not yield an optimal convergence. In most of the applications, the Galerkin technique is better, which consists of choosing the same testing functions as the basis functions. This applies to both sub-domain and entire domain functions.

A.2 2D electromagnetic emission measurement method

The 2D electromagnetic emission measurement method is the most common technique to be used today. It is efficient to analyse the emission from the EUT in the whole frequency span. Normally, the test is divided into two parts: assigned frequency band measurement – EIRP test, and spurious emission measurement – RSE test. The emissions from EUT at a specific frequency can be measured with the above two methods and it can be used to analyse the whole electromagnetic environment. It can use the EIRP test method to analyse radiated power, which transmits at 2.4 GHz. Some other radio services, such as GSM850, have a harmonic emission that falls within this frequency and that will be analysed by the RSE method.

A.2.1 Assigned frequency band measurement – EIRP test

The assigned frequency band test is the EM power from the working frequency band of the radio service. When the radio equipment is working, this EM power will be present to the other wireless/wire equipments.

Normally, the emission level will be the power radiated from the EUT, which is the power from the amplifier of the equipment and the antenna directivity. If the power from the amplifier port is known, the conductive test method by using a spectrum analyser or power meter can be used to measure it. If the antenna gain is not known or the EUT has an integrated antenna, the radiated measurement method can be used. The maximum equivalent isotropic radiated power (EIRP) is defined as the maximum radiated power from the EUT in any direction.

If the RF power of the EUT is adjustable, then all the measurements should be performed under the condition of highest power level.

The radiated test should be performed in a fully anechoic room (FAR), which should comply with the requirements of the specified frequency range and performance to be tested. A suitable measurement distance is normally greater than 3 metres to ensure a far-field test. Usually, a wideband spectrum analyser is used as the receiver.

The procedure is:

1) In an anechoic room, a half-wave dipole of 2.4 GHz is placed at the reference centre of the room. An RF signal generator, which can produce the signal of the frequency band of interest, is connected to the dipole via a ferrite cable. A known (measured) power (P_{in}) is applied to the input of the dipole, and the power received (P_r) at the room's probe antenna is recorded.
2) A "reference path loss" is established as $P_{in} + 2.15 - P_r$.

3) The EUT is substituted for the dipole at the reference centre of the room and a scan is performed to obtain the radiation pattern.

4) From the radiation pattern, the coordinates where the maximum antenna gain occurs are identified.

5) The EUT is set to its maximum power, the receiving antenna is placed at the coordinates determined in step 4 to determine the maximum output power.

6) This value is EIRP since the measurement is calibrated using a half-wave dipole antenna of known gain (2.15 dBi) and known input power (P_{in}).

NOTE – Equivalent radiated power (ERP) refers to the radiation of a half-wave tuned dipole instead of an isotropic antenna. There is a constant difference of 2.15 dB between EIRP and ERP:

ERP (dBm) = EIRP (dBm) – 2.15 (see [ITU-R SM.329-10])

A.2.2 Spurious emission measurement – RSE test

Spurious emission is the emission on a frequency, or frequencies, which are outside the necessary transmission bandwidth. The spurious emission levels can be limited or controlled below a certain level without affecting the corresponding transmission of information.

A.2.2.1 Measurement configurations

The equipment shall be tested under normal test conditions and the test configuration shall be as close as possible to normal usage.

If the equipment is part of a system, or should be connected to ancillary equipments, then it should be tested with the minimum configuration of ancillary equipments necessary to exercise the ports.

Ports, which in normal operation are connected with cables, shall be connected to ancillary equipment or to a representative piece of cable correctly terminated to simulate the input/output characteristics of the ancillary equipment; radio frequency (RF) input/output ports shall be correctly terminated.

Ports that are not connected to cables during normal operation, e.g., service connectors, programming connectors, temporary connectors, etc., shall not be connected to any cables for the purpose of EMC testing. Where cables have to be connected to these ports, or interconnecting cables have to be extended in length in order to exercise the EUT, precautions shall be taken to ensure that the evaluation of the EUT is not affected by the addition or extension of these cables.

The test conditions, test configuration and mode of operation shall be recorded in the test report.

A.2.2.2 Measurement method

Whenever possible, the site shall be a fully anechoic room (FAR) to simulate free-space conditions. The EUT shall be placed on a non-conducting table, see Figure A.2. The average power of any spurious components shall be detected by the test antenna and recorded by a measurement receiver (e.g., a spectrum analyser).

At each frequency at which a component is detected, the EUT shall be rotated to obtain the maximum response, and the equivalent radiated power (ERP) of that component determined by a substitution measurement, which shall be the reference method. Antenna-to-EUT polarization (horizontal and vertical) shall be varied during the measurements to find the maximum equivalent radiated power.

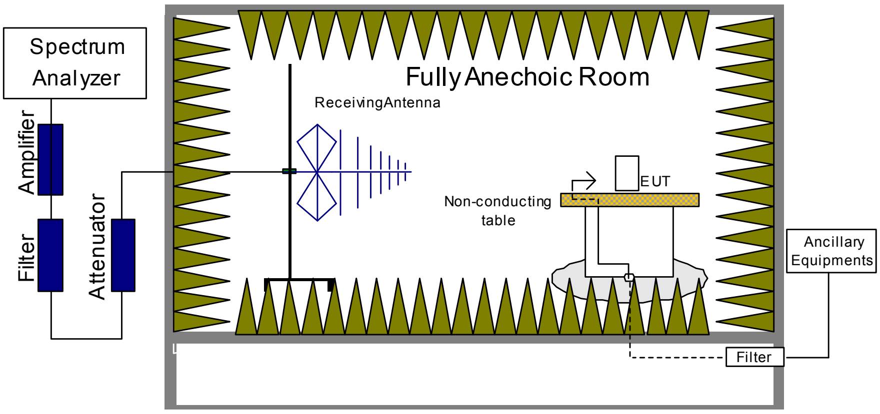

Figure A.2 – Radiated spurious emission measurement method

Measurements are made with a tuned dipole antenna or a reference antenna with a known gain referenced to an isotropic antenna.

If a different test site or method is used, this shall be stated in the test report. The results shall be converted to the reference method values and the validity of the conversion shall be demonstrated.

A.2.2.3 Measurement procedure

a) Configure the EUT according to clause A.2.2.1.

b) The measurement devices (e.g., measurement receiver, antenna, filter, etc.) and measurement site should be set up properly.

c) Adjust the height of the measurement antenna and the distance from the boundary of the EUT to a suitable distance.

d) Set the measurement bandwidth per Table A.1.

Table A.1 – Radiated spurious emission measurement bandwidth

Frequency range	Resolution bandwidth	Video bandwidth
30 to 1000 MHz	100 kHz	300 kHz
≥1 GHz	1 MHz	3 MHz

e) Starting measurement in the measurement frequency range, both horizontal results and vertical results should be recorded accordingly.

f) Record the measurement result.

A.3 3D electromagnetic environment measurement method

Clause A.2.1 gives the standard EIRP measurement method. Generally, peak EIRP is not a good indication of the electromagnetic radiation performance of equipment for two reasons. First, the value is only a two-dimension test result and may ignore the significant radiation in other directions. Second, the radiated pattern of other directions is not captured, making it difficult to randomly select a 2D cut to get the maximum EIRP, unless the radiated pattern of the EUT is known, for example, GSM mobile phones in the 900 MHz band. The EIRP test does not give a complete understanding of the EUT electromagnetic characteristics.

The 3D electromagnetic measurement method overcomes the limitation of the EIRP test. This Recommendation requires spherical equivalent isotropic radiated power (termed total isotropic radiated power, TIRP) to be measured.

The radiated RF performance of the EUT is measured by sampling the radiated transmitted power of the EUT at various locations surrounding it. A three-dimensional characterization of the 'transmit' performance of the EUT is pieced together by analysing the data from the spatially distributed measurements. Data points taken every 10 degrees in the theta (θ) and in the phi (Φ) axes are sufficient to adequately characterize the EUT's far-field radiation pattern.

A.3.1 Measurement method

The traditional spherical coordinate system is shown in Figure A.3. The phi axis is defined as being along the Z axis. Treating this as the coordinate system of the EUT is the equivalent of assuming that the EUT is mounted directly on the phi axis and rotates with it. As the phi axis rotates, the orientation of the theta axis varies with respect to the EUT.

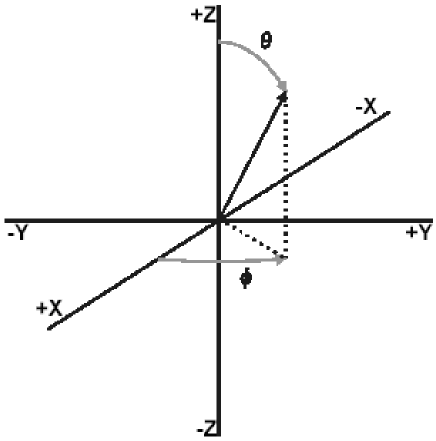

Figure A.3 – Spherical coordinate system

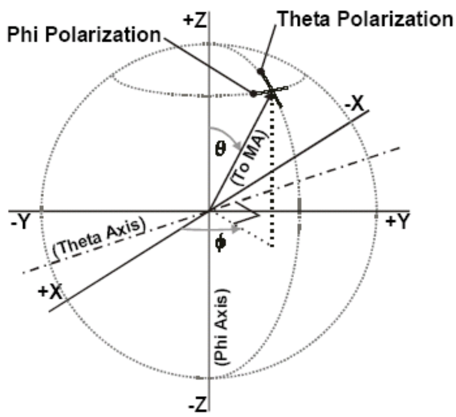

Figure A.4 – Measurement antenna polarizations

After defining the spherical coordinate system, it is necessary to define the two polarizations to be used for measuring the EM field at each point. The two polarizations are identified in terms of the two rotational axes, such that the phi polarization is along the direction of motion when the phi axis rotates and the theta polarization is along the direction of motion when the theta axis rotates (see Figure A.4).

It is assumed that the EUT is supported by some sort of structure along the –Z axis, which is likely to obstruct the measurement of the data point at θ = 180°. The resulting spherical coverage required for a pattern test (based on 10 degree steps) is one where the whole 3D surface is included in the testing, with the exception of the area for which θ > 170°. The method used to perform the 3D test is shown in Figure A.5.

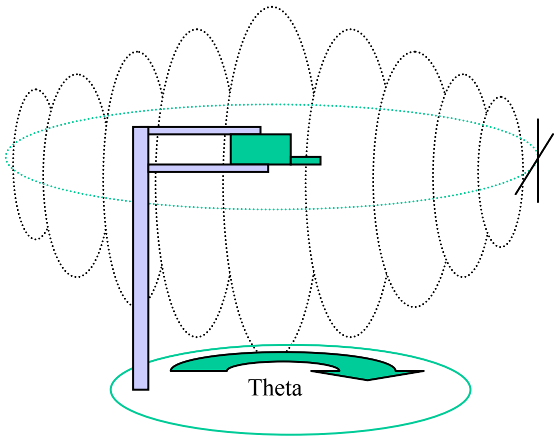

Figure A.5 – 3D measurement method illustration

The site shall be a fully anechoic room (FAR) to simulate free-space conditions. The FAR shall cover the required frequency range and be adequate for the expected performance levels. The EUT holder used must be capable of securely holding the EUT. The hardware and positioner used must be made of a material that is substantially transparent to RF. Average power shall be detected by the test antenna and connected via a low loss cable to the measurement receiver (e.g., a spectrum analyser). In addition to the theta axis rotation, the EUT will have to be rotated about the Z axis (phi rotation) in order to perform the full spherical scans.

The test site shall allow at least the specified minimum measurement distance for all tests in this Recommendation.

These distances are the minimum required to facilitate measurement in the far field for the purposes of this Recommendation. They are based on selecting the strictest of the three conventional far field criteria within each band. These criteria state that the measurement distance should be greater than the largest value of 2D2/λ (the phase uncertainty limit), 3D (the amplitude uncertainty limit), and 3λ (the reactive near-field limit), in which:

D is the dimension of the radiator (m);

λ is the free-space wavelength at the frequency of interest band (m);

R is the minimum measurement distance required for the far-field measurement (m).

A.3.2 Measurement procedure

The radiated EM characteristics of the EUT is measured by sampling the radiated transmit power of the EUT at various locations surrounding it.

The radiated EM characteristics of the EUT shall be measured using a calibrated and accurate RF measuring instrument (e.g., spectrum analyser/measurement receiver/power meter). Ideally, the power measurement will be performed with the same instrumentation in an equivalent configuration as used during calibration in order to minimize the measurement uncertainty involved.

According to the test result above, the radiated power in any direction for different radio equipments can be measured by this method, when applying this result to the theoretical model established in clause A.1, the radiated power at any place of the 3D free space and OATS can be calculated.

A.4 Electromagnetic environment site survey

When there are many radiators, the electromagnetic model becomes complex and it becomes difficult to predict the interference by numerical methods. It is then important to have a practical EM site survey method to measure a complex radiated EM environment.

A.4.1 Measuring equipments and receivers

The recommended instruments and their connections are shown in Figure A.6. This measuring instrument consists of an appropriately selected antenna attached to a variable attenuator. A band-pass filter coupling to the input of a pre-amplifier normally follows the attenuator; the pre-amplifier being used for weak signals. The pre-amplifier must be in a shielded enclosure to reduce the measurement errors. Following the preamplifier is a main receiver that has a detector of chosen function and characteristics.

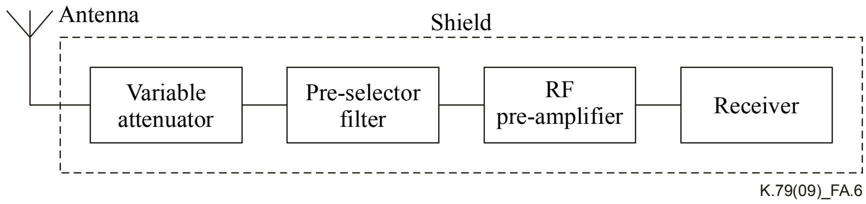

Figure A.6 – EM site survey measurement receiver

Sometimes, the antenna can be connected to the receiver directly with the receiver's own attenuator providing the required reduction of the input signal. It is important not to overload the receiver signal processing circuits as this can result in inter-modulation and spurious signal generation. Broadband, high dynamic range pre-amplifiers are used to improve system sensitivity for noise measurements by reducing the system noise figure. The attenuators used must be suitable for use at the radio frequencies being measured.

A.4.2 Site survey procedure

Electromagnetic site surveys may be grouped into two general classifications: interior and exterior. Interior locations consist of sites within buildings and all man-made inhabitable structures (including mines), while all other sites fall into the exterior category. For accurate measurements, it is important that the measuring and monitoring equipments do not affect the existing electromagnetic fields.

A spectrum analyser is the most common measurement instrument used for testing. The spectrum analyser frequency sweep, whether automatic or manual, should have upper and lower sweep band limits set to 10% below and above the frequency range of interest. Before testing, the spectrum noise floor of the site should be recorded and, during testing, should be done with a signal that is at least 6 dB higher than the noise floor.

A.4.2.1 Exterior location considerations

The measurement result can be affected if man-made noise is present. If the man-made noise is likely to produce radio performance degradation at the survey site, comparison measurements should be done at a quiet reference site remote from any possible noise source.

A.4.2.2 Interior location considerations

Interior measurements are more difficult than exterior open field measurements. Conducting materials will affect the result if they are close to the measurement antenna and measurement area. Mutual coupling between the antenna, metal objects and the instruments may also affect the result. Hence, interior measurements may display larger variations than exterior measurements.

Before making interior measurements, establish what metal objects are present, then select a measurement point as far away from these metal objects as possible. Empty rooms without permanent equipment are the easiest to measure in.

Several site selections should be included in the survey:

1) The four quadrants of the building floor.

2) All floors of the building including the basements.

3) Various distances from the walls, both interior and exterior, and the centre of the occupied area.

4) Window areas and doorways.

Due to possible effects on the antenna impedance and pattern, the antennas should be placed as far as possible from all metal objects:

1) In general, the antenna should be located in the centre of the room.

2) In large rooms, the antenna should be placed at least 0.8 m above the ground.

3) Sometimes, the metal objects in the room will create a standing wave in the room. When measuring high frequency signals in these conditions, the antenna position should be varied in small steps to maximize the signal.

Appendix I

Electromagnetic interference examples

(This appendix does not form an integral part of this Recommendation)

Modern society greatly relies on IT systems for information and mobility. New radio services, such as wireless LAN (WLAN) and the cordless telephone make communication possible anywhere. However, public areas that use WLAN systems, such as airports, railway stations and underground shopping malls, can have a complex electromagnetic environment when these communication systems are used. In such environments, these services may interfere with each other and lower the service quality.

This appendix describes some typical interference problems for radio services in the 2.4~5 GHz band. Most of the examples are concerned with the IEEE 802.11 WLAN system.

I.1 Interference between IEEE 802.11 APs

When a multiple IEEE 802.11 AP system is installed, such as in a hospital, the location and configuration of the IEEE 802.11 APs needs to be carefully planned. Inappropriate location and IEEE 802.11 AP configuration can make it difficult for some wireless terminals in certain areas to associate with an IEEE 802.11 AP. Figure I.1 shows an analysis of an IEEE 802.11 AP arrangement.

To understand the association failure problem, the electromagnetic spectrum of the WLAN band was measured at specific locations. The spectrum result is shown in Figure I.2. This figure shows that the whole 2.4 to 2.48 GHz frequency band was fully occupied, making it difficult to distinguish different IEEE 802.11 APs.

This problem is mainly caused by:

1) Too many installed IEEE 802.11 APs.
2) Inappropriate IEEE 802.11 AP channel configuration (the IEEE 802.11 AP channel selections are too close together and overlap).

To fix this problem, some IEEE 802.11 APs were removed, and using a channel difference of 4 for nearby IEEE 802.11 APs optimized the channel separation of the remaining IEEE 802.11 AP channels. Figure I.3 shows the result, now the different IEEE 802.11 AP channels are clearly separated, greatly reducing the interference between IEEE 802.11 APs. The configuration change removed the mutual interference between wireless terminals and IEEE 802.11 APs.

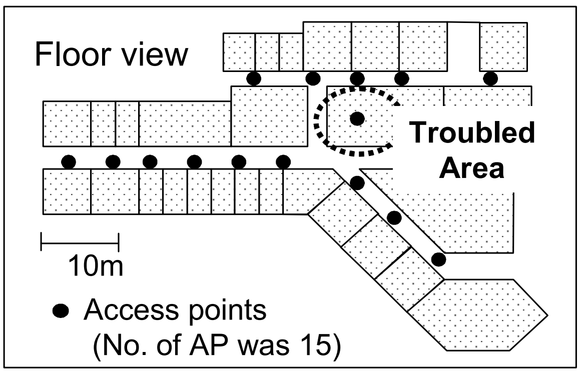

Figure I.1 – IEEE 802.11 AP location illustration

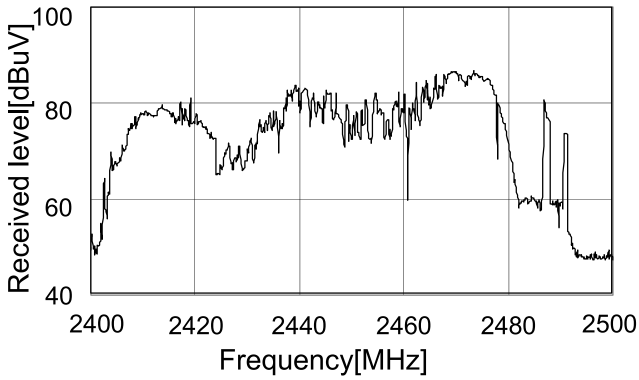

Figure I.2 – Spectrum measured before optimization

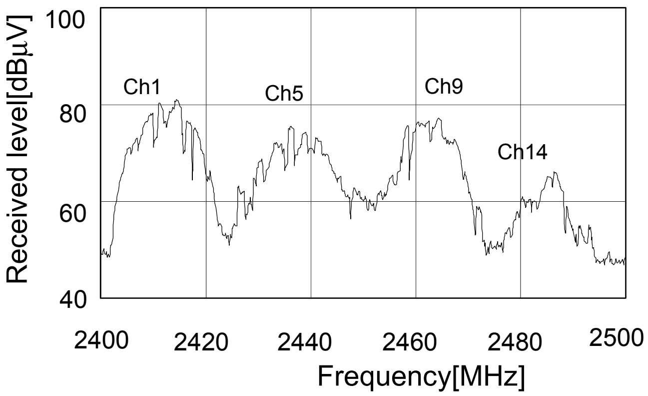

Figure I.3 – Spectrum measured after optimization

I.2 Interference between IEEE 802.11 APs and other wireless systems

This example concerns an electronic goods shop. The installed WLAN system had a very low throughput (about 300 kbit/s) and sometimes the IEEE 802.11 STA could not connect to the IEEE 802.11 AP.

Figure I.4 shows the installation configuration. The shop frequency spectrum measurement is shown in Figure I.5. The black and grey lines are the frequency spectrum with the IEEE 802.11 AP turned on and off, respectively. This figure shows that there are other systems in the shop in the same frequency band. After investigation, it was found that a wireless TV and a wireless speaker system produced the interference.

Once the interference sources were found, the WLAN provider and shop owner needed to work together to fix the interference problem. Changing the working frequencies of the WLAN, the wireless TV and wireless speaker system, to avoid interference, could solve the WLAN problem.

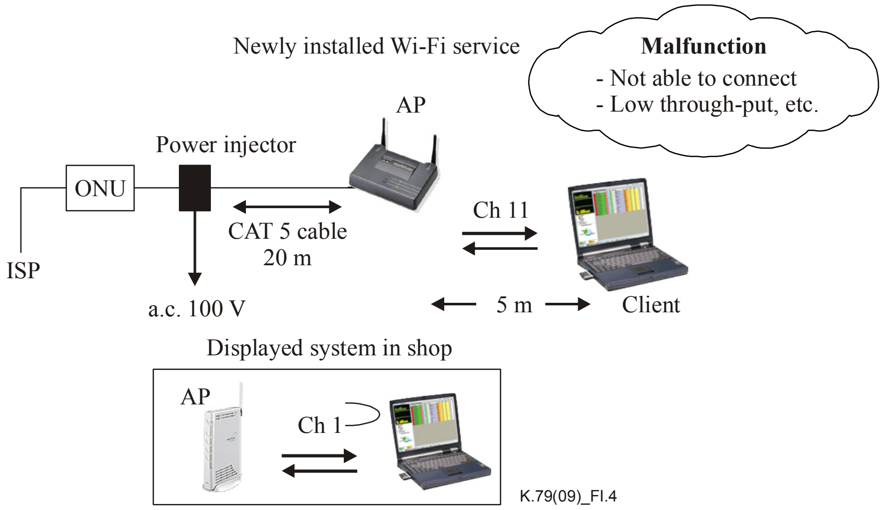

Figure I.4 – Configuration of WLAN system

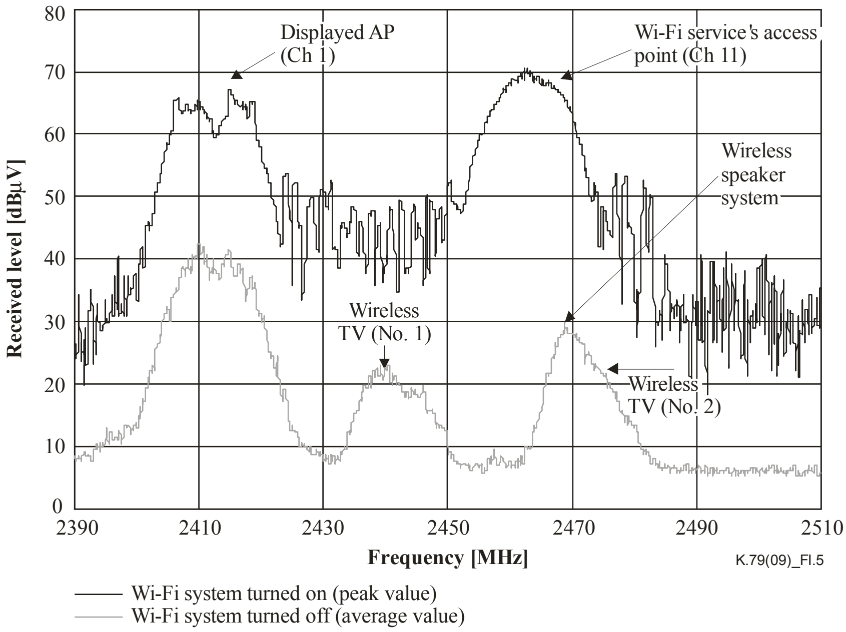

Figure I.5 – Measured frequency spectrum

I.3 Interference between radio services and other unintentional emissions

Unintentional emissions can dramatically interfere with the quality of a radio service, causing such things as dropped connections and low data transfer rates.

In this example, sometimes an IEEE 802.11 AP to IEEE 802.11 STA connection could not be established until the operating channel of an office WLAN system was changed from channel 9 to channel 1. Figure I.6 shows the measured electromagnetic spectrum in the office. The figure shows a disturbance in the frequency range from 2 423 MHz to 2 458 MHz, which is created by the operation of a microwave oven.

Figure I.7 shows an example of the interference between the WLAN signal on channel 9 and the electromagnetic emission from the microwave oven.

The microwave oven emitted a disturbance in channels 5 to 11 of the WLAN band. Changing the WLAN operating frequency from channel 9 to channel 1 avoided an overlap with the microwave oven emissions.

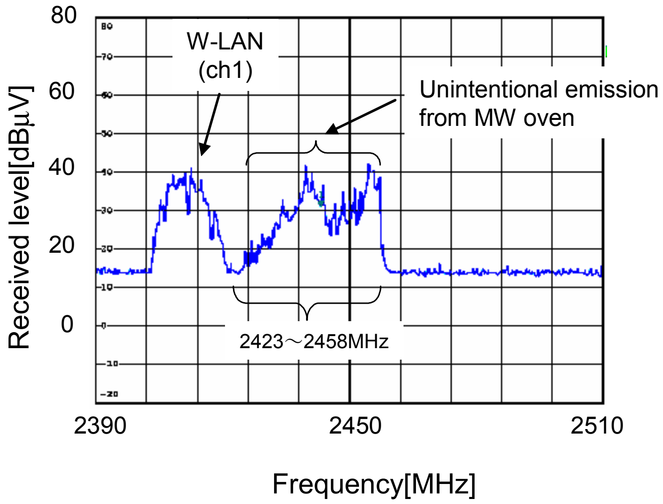

Figure I.6 – Measured spectrum when malfunction occurred

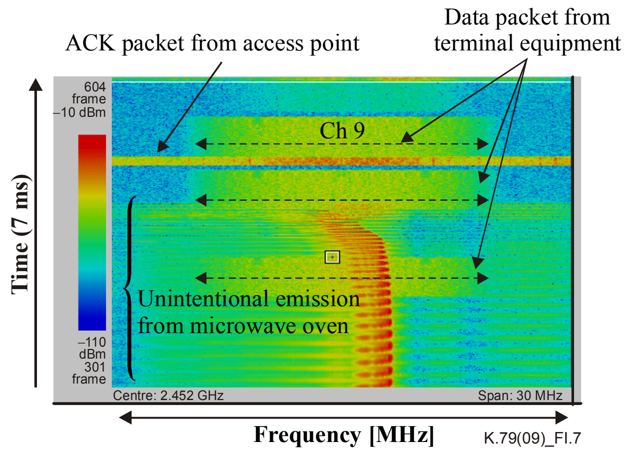

Figure I.7 – Measured spectrum

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