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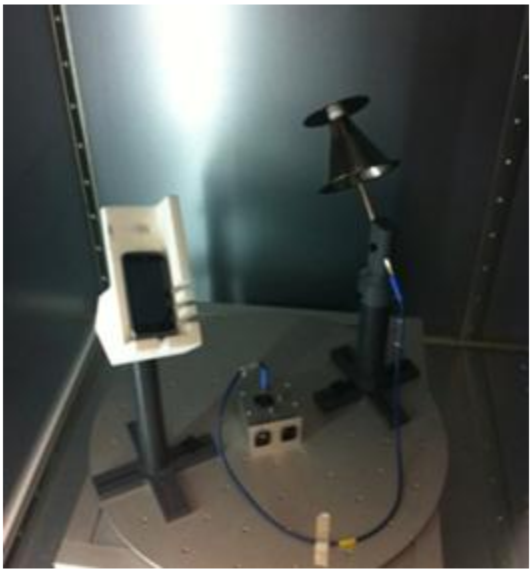

Methods for Measuring the Impact of Interference on Wireless Devices in a Reverberation Test System

Master's Thesis in the Wireless Photonics and Space engineering program

Weiming Dong

Department of Signals and Systems
Antenna Group
Chalmers University of Technology
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NAME WEIMING DONG

Department of Signals and Systems
Chalmers University of Technology
SE-412 96 Gothenburg
Sweden
Telephone + 46 (0)31-7721000

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Weiming Dong

List of Contents

List of Figures

Abstract

With the development of modern communication systems, the interference causes a series of problems. Interference is generated by different factors such as inter-cell traffic, external noise source, adjacent cell congestion etc. In addition, different communication standards have their own properties which will impact on other systems e.g. the tablet is connecting with a Bluetooth mouse and Wi-Fi transmits in low data rate although the sign strength is in full bars; the phone suffers a strong interference during the voice conversation. Therefore, understanding interference among different standards is essential. In this thesis, it has been proposed that several interference scenarios based on modern communication standards measured in reverberation chamber. This thesis mainly focuses on investigating inter-cell co-channel interference based on WCDMA standard. The idea of using AWGN noise to represent the real interference was measured in the reverberation chamber and the comparison among results is listed in the thesis. Other standards were measured in reverberation chamber like LTE, Wi-Fi and Bluetooth etc.

Chapter 1 Introduction to reverberation chamber

1.1 Background

Reverberation chamber is a metal cavity used for testing electromagnetic compatibility (EMC) and small wireless devices characteristics. Its application has a history of more than 40 years and the reverberation chamber has been developed more and more accurate to test small antennas and wireless terminals. The basic theory of reverberation chamber is simulating the condition of small antennas and wireless terminals through Rayleigh fading, to achieve uniform distribution of Electromagnetic field by shifting the conductive plates or some other ways. 3GPP TR 25.914 V7.0.0 [1] includes measurement procedure details of UMTS terminals in reverberation chamber as an alternative method testing in anechoic chamber. In the middle of 2008, generally followed standards of measuring MIMO capacity and throughput are not published. The reverberation chamber supplies a suitable testing environment which has repeatable and high reliability with accurate result.

Bluetest AB is continuously dedicated to develop the reverberation chamber with high speed and high accuracy measurement performance. Bluetest and Chalmers University of Technology are working closely for many years to improve the reverberation chamber. For key technologies as LTE, WLAN and WIMAX etc, Bluetest always follows the pace of technological progress, [2] [3] [4] has been published to prove the accuracy and repeatable measurement can be tested in the reverberation chamber.

1.2 Multipath environment in reverberation chamber

Reverberation chamber is used for testing over-the-air (OTA) performance of small antennas and wireless devices in multipath environment. The basic structure of reverberation chamber is a metallic shield cavity with two mechanical plate stirrers, one rotatable platform and one fixed antennas with three ports [5]. It also includes a blocking plate to separate the fixed antenna and Antenna under Test (DUT). The reverberation chamber can be considered as a volume enclosed by conductive surface which excites several numbers of resonate modes [6] with three-dimensional standing wave patterns at the frequency of radiation. Reverberation chamber could be treated as a variable volume rectangular resonator with high Q factor, by moving the two plates to change the boundary condition for each excited mode in the chamber. It's theoretically proved that for rectangular shaped object like reverberation chamber, the real and imaginary part of electric and magnetic fields follow Gaussian distribution independently [6]. Assume a rectangular cavity with width a, height b and length d. For the nml^{th} TE mode, propagation constant can be expressed as

$$\beta_{nm}^2 = k_0^2 - (\frac{n\pi}{a})^2 - (\frac{m\pi}{b})^2 \tag{1.1}$$

Where $k_0 = 2\pi f_0 / c$, c is the velocity of light. And if $k_0=k_{nml}$, where k_{nml} can be expressed as

$$k_{nml}^2 = [(\frac{n\pi}{a})^2 + (\frac{m\pi}{b})^2 + (\frac{l\pi}{d})^2]^{1/2} \tag{1.2}$$

Only if equation (2) is fulfilled, equation (1) will be satisfied. So that resonant frequency of rectangular cavity can be expressed as

$$f_{nml} = \frac{k_{nml}c}{2\pi} = c[(\frac{n}{a})^2 + (\frac{m}{b})^2 + (\frac{l}{d})^2]^{1/2} \tag{1.3}$$

It's necessary to point that there is more than one excited solution for one resonant frequency, also note that the excited mode depends on the size of chamber, and so that enlarge the size of reverberation chamber enhances the performance of chamber due to more resonate frequencies are excited, i.e. assume lowest resonant frequency TE_{101} mode. The electric and magnetic fields of resonant mode TE_{nml} can be expressed as:

$$f_{101} = \frac{k_{101}c}{2\pi} = c[(\frac{n}{a})^2 + (\frac{l}{d})^2]^{1/2} \tag{1.4}$$

$$E_y = E_0 \sin\frac{n\pi x}{a}\cos\frac{m\pi y}{b}\sin\frac{l\pi z}{d} \tag{1.5}$$

$$H_x = -\frac{iE_0}{Z_{TE_{nml}}}\sin\frac{n\pi x}{a}\sin\frac{m\pi y}{b}\cos\frac{l\pi z}{d} \tag{1.6}$$

$$H_z = \frac{i\pi E_0}{k\eta a}\cos\frac{n\pi x}{a}\cos\frac{m\pi y}{b}\sin\frac{l\pi z}{d} \tag{1.7}$$

Where Z_{TE} is the wave impedance for *nm*'s mode. Use the Euler's equation, transfer magnet field in *z* direction to complex exponential function, equation (1.7) is given by

$$H_z = \frac{i\pi E_0}{k\eta a}\cos\frac{n\pi x}{a}\cos\frac{m\pi y}{b}\sin\frac{l\pi z}{d} = \frac{i\pi E_0}{k\eta a}\sum_{K=1}^{8} e^{\pm i\frac{n\pi x}{a}\pm i\frac{m\pi y}{b}\pm i\frac{l\pi z}{d}} \tag{1.8}$$

Equation (1.8) shows waves propagate along z direction depending on the propagation medium and the size of reverberation chamber. As mentioned before, amplitudes of waves can be seen as constant. Wave phase factor varies in three directions, in other words, each resonate mode corresponds to 8 plane waves [6].

Typically speaking, antennas are designed in the environment of Line-of-sight (LOS) between ports, so that antennas are characterized equivalently as a free space environment, which can be measured in the anechoic chamber. But in the real environment, communication link propagation environment is more complicated. When the signal is transmitting from the base station to user equipment (UE) in multipath, it will go through different paths reaching the receiver, smooth objects like mirrors will cause reflection, the irregular object will cause scattering and the object edge will cause diffraction [7]. So the received signal is the sum of all radio waves from transmitter in different amplitudes and phases. The distance between transmitter and receiver is fixed, but the path length is a function of time. Therefore received

signal contributions add up at receiver. Multipath propagation can be characterized as the independent incoming waves reaching the receiver port by more than two paths. Independent means every single wave's amplitude, phase and polarization are not relating to each other.
The Angle of Arrival (AoA) distribution of incoming waves towards the DUT is uniform. It's normally assumed that antennas are placed arbitrarily in reverberation chamber, but the electromagnetic fields in azimuth plane and horizon plane are uniform distribution. But in real environment, the way of holding wireless devices are always preferred to be of vertical-direction than horizon-direction because of the design of devices, and most of the base stations are designed to transmit signal in vertical polarization. But with the development of the antenna technology, the antennas are designed as vertical and horizontal polarization with +/- 45 degree and the performance of latter is better than former one. Therefore, reverberation chamber simulates the near-real environment and shows the repeatable results of the performance. In a nutshell, multipath environment inside reverberation chamber corresponds to rich isotropic environment with uniform distribution in both azimuth and elevation for the AoA of waves [8].

1.3 **Mode stirring**

As mentioned before, theoretically, electrical and magnetic fields in the reverberation chamber have uniform distribution, but simulation results show spatial distribution of fields is inhomogeneous, for the purpose of compensating inhomogeneous fields, mode stirrers are introduced from [8]. The metallic plates are moving along the walls in different orientations to reflect radio waves to achieve different boundary condition, which is called mechanical stirring. The other effective way of mode stirring is named as platform stirring, a rotatable table is placed in the chamber and the DUT is placed on the table. During the test, antenna under testing moves along with rotate table. The third mode stirring is called polarization stirring. Use the fixed antenna with multiple ports to emit the radio waves in the chamber which are aimed for balance polarization.

1.4 **Friis equation, Rayleigh fading and Racian fading**

Rayleigh fading is a common mathematical statistical model for simulating the effect of propagating waves' properties, widely used in wireless system testing. Basically, Rayleigh fading is caused by multipath reflection, scattering and terminals motion, the emitted radio waves add up at the received antenna in amplitude and phase independently, which is called multipath effect [9].

In wireless communication system, analysis and simulation via using statistical characteristics to model multipath effect, various types of literatures [10] [11] [12] have proposed numerous of channel models. Generally speaking, impact on the wireless channel could be divided into three main parts:

1. Propagation path loss model: this model is often used in wireless system, in general, received power and propagation path loss can be seen as random variations. Path loss model describes average received signal power or average propagation path loss, the received power decrease with increasing distance; in other word, propagation path loss

will increase with increasing distance.

2. Small-scale fading model: small-scale fading is defined as if distance between transmitter and receiver is smaller than half wavelength or in a short time interval, which leads to attenuation of the signal due to strong fluctuation in amplitude and phase [9].

3. Large-scale fading model: the distance between transistor and receiver is larger than hundreds or thousands of meters, the signal attenuation increases with increasing distance, define this fading situation as large-scale fading. In this model, transistor and receiver are often set as a given distance. The received signal power will vary as a random variable. This model is often used to estimate the radio waves coverage area [10].

It's important to point out three impairments model could be existed simultaneously. But in theoretical analysis, three models are less using at the same time due to computation complexity. Most of scenarios only use propagation path loss model and large-scale fading model since channel capacity, handover as well as system stability are related to signal power. If study objective focuses on power control, three models may be used at the same time, which depends on what kind of problem need to be solved. Details of multipath fading model will be discussed in next sections.

1.5 S-parameter transfer function in the reverberation chamber

S-parameters are used to describe the power transfer function between antennas of transmitter and receiver in reverberation chamber. The power transfer function consists of two contributions [8]: first contribution is the direct coupling, in other word, signal propagates in free space amidst two antennas and another contribution is the power loss in the chamber. Using mathematical expression of the power transfer function:

$$S_{21}^{tot} = \frac{1}{N}\sum_{n=1}^{N}(S_{21}^{FS} + S_{21}^{chamber}) \tag{1.9}$$

Contributions of the chamber loss is the dominating factor as the result of mode stirrers in reverberation chamber and average received power follows complex Gaussian distribution. In the normal measurement, the fixed antenna and DUT are separated by the blocking board, so that the direct coupling between two antennas can be neglected in equation (1.9).

1.6 Free space propagation model

Free space propagation model indicates the signal radiates from transmitter to receiver in LOS with no obstacles between them, which means the signal propagates in shortest distance between two antennas. Assume transmitter is connected to an isotropic antenna and the far-field function of received power in a unit sphere can be expressed as:

$$P_r = \frac{P_t}{4\pi r^2} \tag{1.10}$$

Assume transmit antenna gain as G_t, corresponding to power density of receive antenna is given by

$$P_r = \frac{P_t}{4\pi r^2} G_t \tag{1.11}$$

Also, received power is related to receiver cross section, which means received power has relation with effective aperture is given by：

$$A_{cross} = \frac{\lambda^2}{4\pi} G_t \tag{1.12}$$

$$P_r = P_t \frac{\lambda^2}{(4\pi r)^2} G_t G_r \tag{1.13}$$

The equation (1.13) is the Friis transmission formula. Where P_t and P_r is transmitting and received power respectively, G_t is transmit gain, G_r is receive gain, λ is the wavelength and d is the distance between two antennas, $(\frac{\lambda}{4\pi d})^2$ is free space loss factor.

1.7 Average transfer function of reverberation chamber

The power transfer function between transmitter and receiver in reverberation chamber can be presented by Hill's transmission formula from [13]. The equation is only valid if the direct coupling can be ignored and the reverberation chamber is excited with more than two modes. The Hill's formula can be quoted as reference chamber transfer function as follows [8]:

$$G_{chamber} = |S_{21}^{chamber}| = \frac{\lambda^3 Q}{16\pi^2 V} = \frac{c^3 e_{rad1} e_{rad2}}{16\pi^2 V f^2 \Delta f} \tag{1.14}$$

Where

c is the speed of light

e_{rad1} and e_{rad2} is the radiation efficiency of the fixed antenna

f is the frequency

V is the chamber volume

Δf is average bandwidth mode

The average bandwidth mode Δf consists of four contributions due to the loss and leakage of the chamber through slots and antennas in the chamber, using mathematical equation can be expressed as follow:

$$\Delta f = \sum_{\substack{all\\walls}} \Delta f_{wall} + \sum_{\substack{all\\slots}} \Delta f_{leakage} + \sum_{\substack{all\\antennas}} \Delta f_{antenna} + \sum_{\substack{all\\lossy\\objects}} \Delta f_{objects} \tag{1.15}$$

With $\Delta f_{wall} = \frac{2A}{3V}\sqrt{\frac{c\rho f}{\pi\eta}}$; $\Delta f_{leakage} = \frac{\lambda \sigma_l}{4\pi V f}$;

$\Delta f_{antenna} = \frac{\lambda e_{rad}}{16\pi^2 V}$; $\Delta f_{objects} = \frac{\lambda}{2\pi V f}\sigma_d$

Where A is the conducting surface area, V is the chamber volume, ρ is the conductive surface area resistance, η is the free space impedance, σ_1 is cross section of leakage through narrow slot in the chamber wall, σ_a is the cross section with absorbers placed in the chamber.

Since the different volume and characteristics of reverberation chamber cause the variation of average mode bandwidth. It's hard to calculate the bandwidth mode which corresponds to high value of Q, especially in active measurement, the mode bandwidth should larger than the modulation bandwidth or the electromagnetic field should be uniform distribution.

1.8 Transfer function due to mismatch of the fixed antenna

Basically, the chamber transfer function is decided by the equation (1.14) by knowing the reference antenna radiation efficiency $e_{rad,fix.}$ The leakage of specific chamber can't be changed, e.g. chamber volume, conductive surface resistance, leakage etc. In practice, the mode bandwidth should be kept the same during the measurement to maintain the uniform distribution of electromagnetic fields in the chamber. Thus during the calibration and real measurement, it's important to put both the AUT and terminated reference antenna inside the chamber. The average chamber transfer function (1.14) can be summarized as a function of frequency. In order to boost the accuracy of the calibration measurement, the reflection coefficient of fixed antenna and AUT have to be considered as average complex S_{11} and S_{22}. The mismatch factor includes chamber transfer function [8] can be described as:

$$\mathrm{G}_{chamber} = \frac{1}{N}\sum_{\mathrm{i}=1}^{N}\frac{\left|S_{21}^{chamber}\right|^2}{\left(1-\left|\overline{S_{11}}\right|^2\right)\left(1-\left|\overline{S_{22}}\right|^2\right)} \tag{1.16}$$

Where N is the number of sample position.

1.9 Bluetest Reverberation Chamber parameters [14]

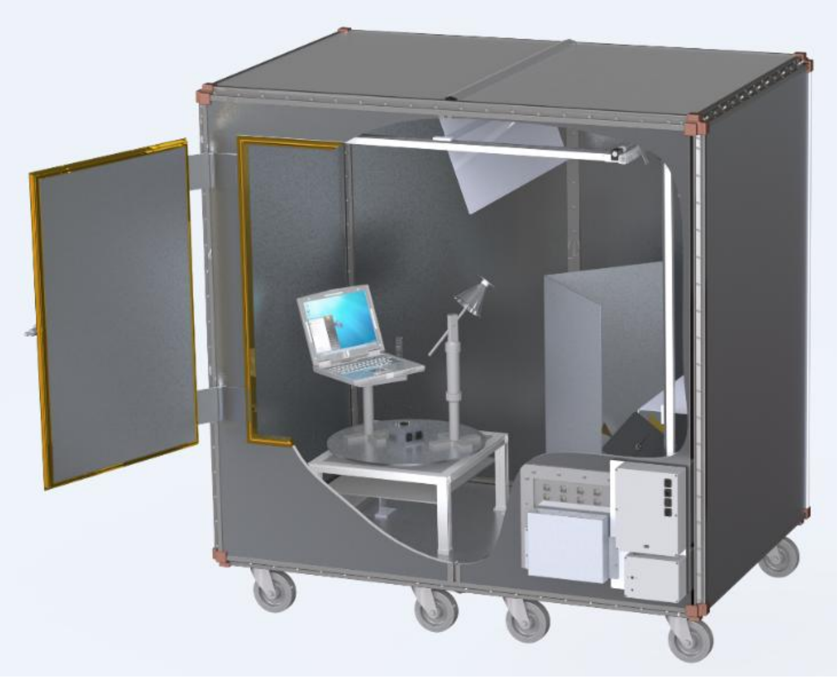


Figure 1. 1 Bluetest Reverberation chamber RTS 60

Bluetest reverberation chamber RTS 60 Specification:
Frequency range: 650-6000MHz
Isolation: >100dB
Dimension (length*Height*Depth): 1940*2000*1400 mm
Supported Communication Testers:
Bluetooth: Agilent N4010A
WLAN: Anritsu 8860/Bluetest TTS11
All Cellular Standards: Agilent 8960/PXT E6621; Anritsu MT8815/8820, R&S CMU200/CMW500
Chamber support: Active 4*4 MIMO measurements

Figure 1. 2 Bluetest Reverberation chamber RTS 90

Bluetest reverberation chamber RTS 90 Specification:
Frequency range: 400-6000MHz
Isolation: >100dB
Dimension (length*Height*Depth): 3340*2610*4240 mm
Supported Communication Testers:
Bluetooth: Agilent N4010A
WLAN: Anritsu 8860/Bluetest TTS11
All Cellular Standards: Agilent 8960/PXT E6621; Anritsu MT8815/8820, R&S CMU200/CMW500
Chamber support: active 4*4 MIMO measurements

Chapter 2 Interference and types of interference

2.1 Introduction

Radio frequency interference induces a series of problems when wireless system is disturbed by electromagnetic radiation or other external sources. Although regular standards define that wireless terminals must operate in specific frequency bands, but the conflict between different standards may impact the performance, e.g. both Bluetooth and WLAN work in the same band and the interference occurs if the two systems are transmitting in same frequency band. The phenomenal explosion in wireless communication has stressed the radio frequency spectrum. Dropped calls or limited transmitting data rate between wirelesses terminals is the most direct indicator of interference which may be observed due to background noise at the receiver. Interference in e.g. Bluetooth can lead to limited distance between terminals for successful communication. Therefore using the spectrum analyzer to check the interference level is an effective way, the most intuitive manifestation in spectrum analyzer is high noise floor or high power strength like pulse signal in both uplink and downlink at the frequency of reception. The main point is that interference signal may not be on the receiver channel but maybe only on the receiver bandwidth to cause the interference e.g. adjacent channel interference. In other words, if the interference signal passes through the receiver's channel filter, the system will be influenced by the interference [15].

In urban area, more than 1000 licensed radio channels, 600 cell sites and 100 broadcasters are used, plus the mix of military, emergency services, frequency spectrum are exploited efficiently [15]. If we consider the technology expanding, ageing or reusing, the interference will become a serious issue evidently due to the reason that radio frequency was not occupied 20 years ago as nowadays. For instance, analog systems as AM and FM [15] interference shows in several ways: hiss, hum or voice from other channel can be heard. For digital transmission, interference results in a low communication data rate, short distance link, dropped calls etc. The waterfall sound indicates poor reception and high data error in the link. All these phenomena indicate the effects of interference on the performance of communication links.

2.2 Definition of interference

Interference has been widely mentioned in communication system, in both wired and wireless system. While for accurate explanation, the term of interference refers to signal impairment due to the properties of channel propagation, other external sources and noise. Interference severely affects the ability of decoding the payload at the receiver, results an increase of confliction and retransmission. The question comes along with how to quantitative evaluate the properties of interference. Signal to interference ratio has been extensively used to quantitatively describe the relative power level of interference. Since the performance is tied to the structure of system, which is unique for different terminals, the signal to interference ratio is not the only standard to evaluate the performance of system.

The most basic model of interference is that interference source has the identical parameters as interested system. As we all known, modulation, detect threshold of the receiver and other properties are important to weigh the impact of interference. In chapter 4, this thesis will list several cases to highlight the effects of interference on different standards.

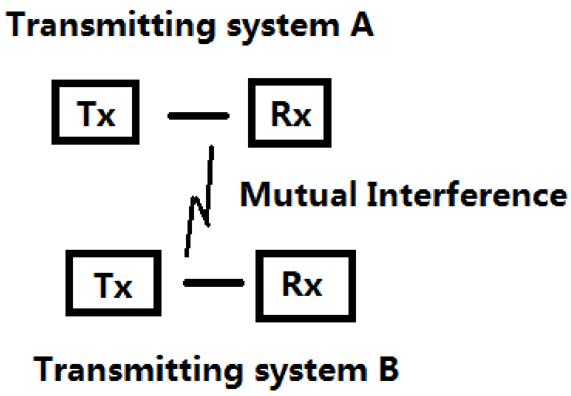


Figure 2. 1 Model of mutual interference between two wireless systems

In general, defining two independent communication systems have mutual interference as basic model as illustrated in figure 2.1. As figure shows, both of two communication systems have at least one transmitter and one receiver. Defining the transmit system A as victim system (interested signal) and the transmit system B as interference system. The assumption in this model is that system A doesn't communicate directly to system B since the crosstalk between different wireless standards is not possible. Due to interaction between two independent systems, any system might be seen as a victim and an interference system. It depends on which system is the target standard under investigating. Consider one system as interference system and another one is regarded as victim system. In this thesis, the measurements of Bluetooth and WLAN in chapter 4 can be modeled as mutual interference.

2.3 Definition of decibel and signal-to-noise ratio

The decibel is a logarithmic unit to compress the universe into small scale value. Decibel is often expressed the absolute value of gain or attenuation. The equation is described as follows:

$$\text{Decibel}=10\log_{10} P_{(w)} \tag{2.1}$$

In communication system, the power ratio of the power refers to one mill watt (mW). Technically, dBm is a convenient expression which is capable to stand for both large and small values.

$$P_{(mW)} = 1_{mW} * 10^{(P_{(dBm)}/10)} \tag{2.2}$$

Signal-to-noise ratio is the ratio of average received signal to noise level, also known as carrier-to-noise ratio, the unit of signal to noise ratio can be expressed in dB or W.

$$SNR=P_{rec}/P_{noise} \ \ (W) \tag{2.3}$$

2.4 Definition of throughput, delay and packet loss

Basically, the performance of the system can be quantified with different formats [17], e.g. how many packets are transmitting successfully from the end to end and how many errors are occurred during the transmission etc. The data unit can be described by packets, blocks or bits. The details of throughput, delay and packet loss are included as follows:

a) Throughput: defining average successfully received bits (packets or blocks) divide by time over a physical or logical link. The unit of throughput usually describes as kbps or bit/s, blocks/s sometimes. Good throughput defines as average received bits per second expect overhead bits during the transmission.

b) Latency: latency is also written as delay, measure of how long to receive a complete packet from the end to end. The unit of delay is seconds. Delay may different even if the signal is transmitting in same communication channel, which depends on specific standard and background environment. The concept of delay can separates into several components: transmission delay is related to the length of packet and transmission bit rate; access delay, scheduling time before a packet transmits over the channel; retransmission delay, the time to retransmit the packet if the connection is dropped or the packet the lost.

c) Packet loss: defining as how many packets are lost during the propagation. Packet loss ratio is a normal expression of the ratio of lost packets divided by total transmission packets.

All of these terms as mentioned can be applied to the layer above the physical layer, e.g. packet loss is used to describe the quality of transmission and reception in MAC layer, but it also can be applied in network layer. The effect of packet loss is obviously which generates the errors in data transmitting. In video conference, the packet loss causes the jitter; in television broadcast, screen will have flakes and noise. The factors of packet loss contributes to signal strength as a function of the distance, interference, coding and modulation of the system, more than one factors are involved in propagation channel. High packet loss ratio also limits the performance of the communication link. With improvement of the system, error correction is introduced to the packet, but if a single error is found in a packet, the whole packet is judged as an error which leads to discard the packet.

2.5 Related effect performance elements

The elements to affect the performance of the system are diversity including modulation, packet size, error correction, transmitting power etc. Other elements can be classified as interaction between victim system and interference system.

Spectrum spreading [17] is the technology of transporting signal in a particular bandwidth and sending out the signal in wider bandwidth modulation with pseudo-random code. The advantage of this technology achieves stable communication link, boosts the resistance of external interference, jitter and interception. Besides, frequency hopping technology is a basic modulation technology while the signal is transmitting in a spread spectrum. And now Spectrum spread technology is widely applied in multiple standards as CDMA and IEEE802.11 series. There are two representative spectrum spreading modulation patterns: Direct-sequence Spread Spectrum (DSSS) and Frequency-hopping Spread Spectrum (FHSS). DSSS modulation technology accounts for more bandwidth than original signal and the carrier occurs over full bandwidth at channel frequency. FHSS emits radio waves by fast switching between available frequency channels.

Traffic is a key point to affect the performance of the system, discussing about interference analysis refers to traffic without exception. The base station in idle status indicates no packets are transmitting to the terminal, the transmitting time indicates the interval in time domain between the terminals. If two systems are transmitting packets overlap in same time slot means interference occurs since the victim system may be detected the signal of interference system. Thus, changing the length of packets or time interval for transmitting scheme improves the performance against interference. Retransmission is another alternative solution that can be used to avoid the collision of data reception while errors are detected. The packet interval is also related to packet size and data rate. Generally, decrease the packet length reduces the probability of packet loss ratio. To some extent, use adaptive packet length makes the system prone to resist the interference between the systems.

Power plays an important role in communication system as the large radiation power from interference system leads to reduce the signal to noise ratio at victim system receiver. In fact, high interference power leads to higher packet loss in victim system. By the way, received victim system's signal is also related to the distance between two systems. For a certain distance between victim system and interference system, transmit power should be controlled, high output power doesn't stand for high transmission rate, it interferes the neighbor cells communication link instead. Therefore, reducing the transmission power promotes the network coexistence, but transmitting at appropriate output power still keeps the stable link.

2.6 **Co-channel interference**

Co-channel interference [18] can be understood literately as interactions between two cells transmit radio waves at identical frequency. Take some examples of co-channel interference: frequency spectrum is assigned to distinct standards with non-overlapping in cellular mobile communication system; the frequency band will be re-used after certain geographical distance since the topology of network. Interested signal and co-channel interference can be collected at the same receiver while the interference signal can be radiated from other cells at same frequency band, see in figure 2.2. Some co-channel interference is caused by the bad cellular planning, but this phenomenon is rare in realistic, but sometimes it happens since the geographical terrain restriction. The solution of solving the co-channel interference caused by frequency re-using is control radio resource management.

With the growing demand of wireless communication market, frequency reuse is recommended to enhance the frequency spectrum utilization. When surrounding environment and coverage area are known, with certain system topology, received signal can be calculated over known distance. With the assistant of this information, the relation between signals to interference could be found easily for a given system. In order to achieve high spectrum efficiency, with limited coverage area and close cell planning, frequency reuse of signal carrier leads into mobile cell planning to solve the co-channel interference issues. Distance and power between cells at identical frequency determine the mutual interference power level. The quality of system communication performance can be measured as signal to interference ratio. For some standards, the desired signal can be detected in high power level of interference. But if the radius of the cell is very big plus the user locates at the edge of the cell and only one interference cell is considered, as a result of that, the co-channel interference and channel capacity will reduce simultaneously. Thus, set the optimal radiation power and separation between cells for acceptable co-channel interference level at receiver. In this thesis, the device to device co-channel interference has been explored in section4.3 based on WCDMA inter-cell co-channel interference, and in section 4.6 corresponding to Bluetooth and WLAN interference. WCDMA inter-cell co-channel interference scenario based on frequency re-used technology and power control is an important step to keep S/N ratio as a constant.

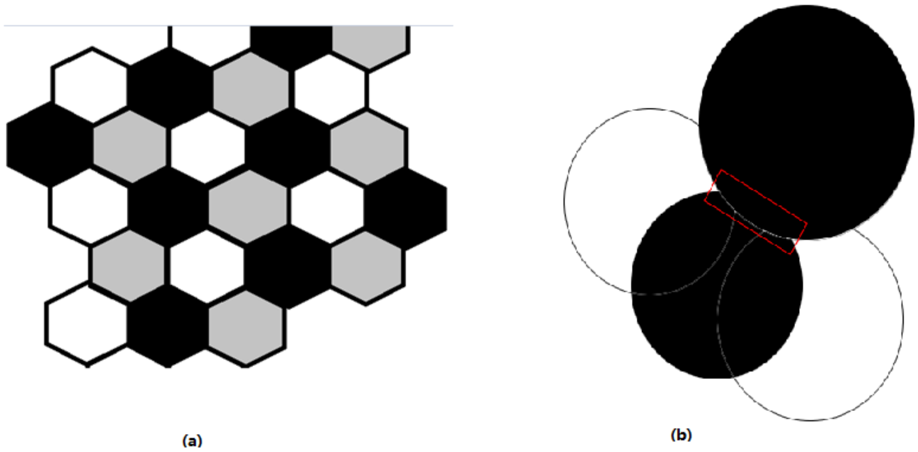


figure 2. 2 The figure (a) shows the ideal cell planning, figure (b) shows the co-channel interference happens in the reality frequency re-use planning.

2.7 Adjacent channel interference

Adjacent channel interference [19] is defined as signal impairment by another signal at nearby frequency. Adjacent channel interference occurs when adjacent frequency signal leaks into imperfect channel filter of the receiver. Although the channel filter is designed to minimize the adjacent channel interference, but the side lobe of adjacent channel interference signal will leak into the channel filter of the receiver, if the signal power of side lobe of adjacent channel is strong enough compare to desired signal, the adjacent signal will dominate the noise floor of communication channel. The adjacent channel leakage ratio is presented for the sum of undesired emission from adjacent channel divided by wanted receiver. The growing trend in wireless industry shows that millions of wireless devices are flooding into ISM band which is the unlicensed band, the similar frequency are using repeatedly. The best solution to avoid the adjacent channel interference is using the well designed channel filter at receiver.

2.8 Intra-cell interference

The definition of intra-cell interference is the users are interfered by same cellular users which can affect the quality of communication in both uplink and downlink. This issue has been solved with development of modulation technology, like OFDM, OFDM-TDMA and OFDM-CDMA etc. In the most cases, literate studies focus on the downlink intra-cell interference because the base station broadcasts the signal in a wide area, the user is easily interfered by other users if the signal frequency is close to interference or the interference power level is relatively high. The uplink is designed to feedback the connection information which has less interference. Thus, the intra-cell interference in uplink draws less attention compares to downlink intra-cell interference.

Since the 4th generation system has became the mainstream technology in modern wireless communication, which uses unique OFDMA modulation scheme, cancels the intra-cell interference between users and achieves high spectrum efficiency. The user's information hosts in different mutually orthogonal sub-carriers, so that OFDMA technology can effectively against frequency selective fading. As for the cell edge users, the interference from other cells is relatively high due to the adjacent cell probably occupies the same frequency carrier resource plus the cell edge users are far away from centre base station, resulting the cell edge users have poor quality of communication service and low throughput.

In this thesis, there isn't any simulation or measurement based on intra-cell interference, the inter-cell interference becomes the main topic in the latter measurement.

2.9 Inter-cell interference

Because of Orthogonal frequency division multiplexing (OFDM) has high spectral efficiency, and it effectively solves the broadband wireless communication inter-symbol interference. Thus, OFDM has been widely accepted as the main modulation scheme in future wireless broadband communication system. Inter-cell interference presents a great challenge that limits the performance of the system, especially for the cell edge users' wide utility function like throughput etc.

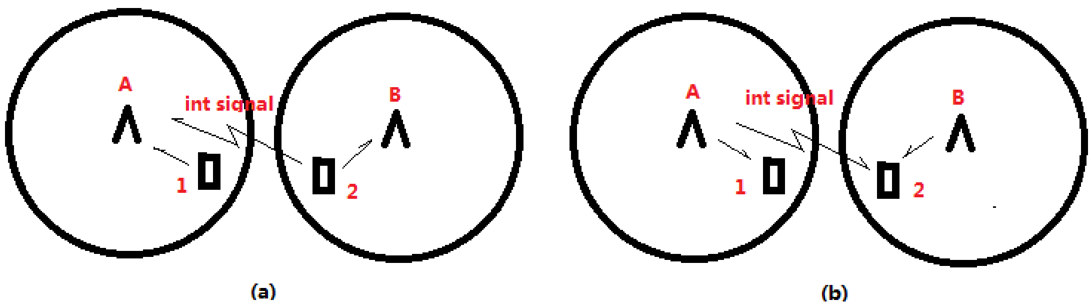


Figure 2. 3 inter-cell interference model

As figure 2.3 (a) illustrated inter-cell interference in uplink. Generally, User 1 and User 2 transmit the same sub-carriers signal to the base station A and base station B simultaneously. So that user 2 is the interference for base station A. When the user 1 and user 2 locate in the junction of area A and B, the base station A receives interested signal and interference signal strength considerably, which means received signal SINR (SINR) at base station A reduced dramatically. Inter-cell interference may leads the information from users 1 cannot be correctly demodulated, and even more, the user 1 has the transmit power restriction problem.

In figure 2.3 (b) shows inter-cell interference in downlink, the user 2 receives signal from base station B. This signal will be affected by signal from base station A which uses same frequency sub-carrier. When the user 1 and user 2 locate in the junction of area A and B, the base station A receives interested signal and interference signal strength equally, such interference will be a serious problem and the communication quality will be drastically reduced.

Uplink intra-cell interference has not been part of this study, but inter-cell interference in downlink has been explored in both WCDMA and LTE system.

Chapter 3 Passive and active measurement in reverberation chamber

3.1 Introduction

Introduction to passive & active measurement and the configuration in reverberation chamber, describing the process of operating passive and active measurement, including reference measurement, radiation efficiency, diversity gain, Total Radiation Power, Total Isotropic Sensitivity, Throughput etc. The measurement is over the air testing within reverberation chamber in free space environment, what's over the air (OTA) testing? It's different to conductive connection. Basically, the connection between DUT and the instrument via cables is called conductive connection, the drawbacks of this connection is limited by particular measurement and complex connection. Over the Air testing is to connect DUT with the instrument via radio waves and to simulate the radio waves performance in real environment, which ensures the accuracy of the measurement. The basic passive and active measurement will be introduced in next paragraphs.

3.2 Reference Measurement

The most important and necessary step is to calibrate the average received power in reverberation chamber during one complete stirrer period. In other words, signal strength through the chamber attenuates since the loss of chamber. As we all known, for a single calibration measurement, a reference antenna with known radiation efficiency must be used. If the configuration and connection inside the chamber are the same, the loss of the chamber should be a constant number at specific frequency. The preferable reference antenna efficiency should be as high as possible, therefore, reference antenna mounted on a low loss dielectric stand. In this thesis, type C disk-cone antenna with working frequency range of 0.65-3.5 GHz is the standard reference antenna. Disk-cone antenna is suitable for wideband measurement as a reference antenna in reverberation chamber. In order to respect the boundary condition and to establish free space environment, it's extremely important that do not place the reference antenna and AUT less than half wavelength from metal object and it should be at least 0.7 wavelengths away from any lossy objects [7].

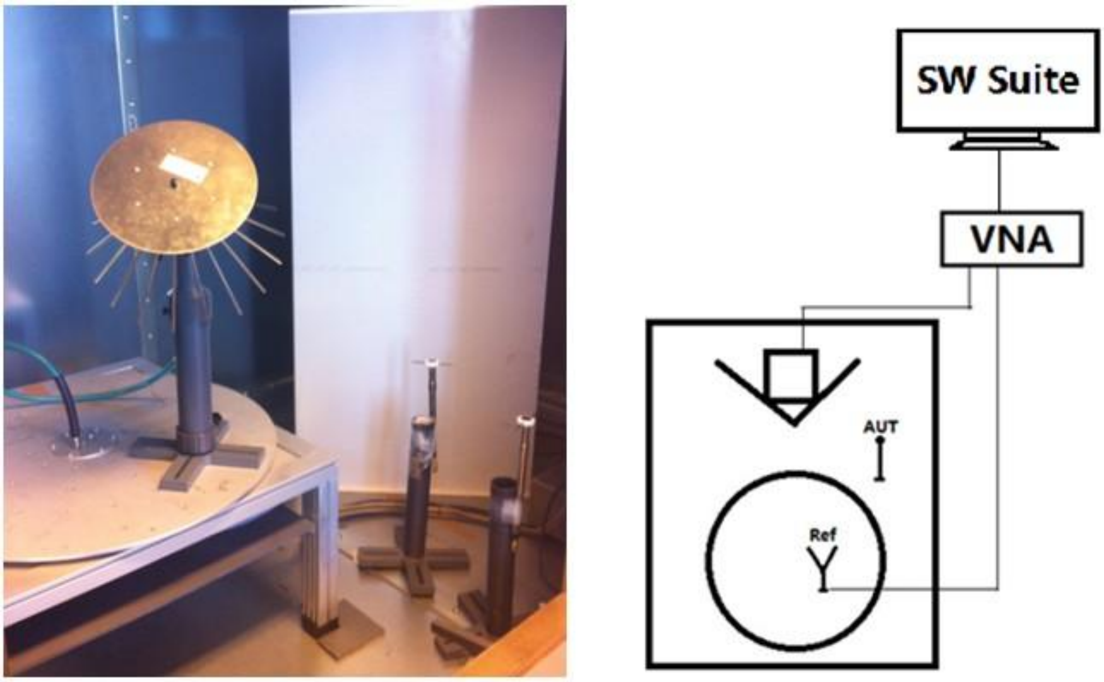


Figure 3. 1 Configuration and scheme of two dipole antennas calibration measurement

3.2.1 Measurement Setup

Vector Network Analyzer
Reference antenna
Antenna under Test

The reference antenna should be placed in the rotatable table in the chamber and far away from chamber walls, reflection absorbers, as well as stirrer plates, resemble as a free space environment as mentioned above. Vector network analyzer is needed during calibration measurement, Agilent E5071C is chosen as the vector network analyzer in this thesis. The computer is used to control the stirrer mode and collect measured data from the vector network analyzer. To be specific, port 1 of network analyzer should connects to the fixed antenna of reverberation chamber, port 2 connects to reference antenna to emit radio signal and performs the efficiency measurement. Therefore, the AUT should be terminated with 50 ohm load and placed on the floor in the chamber, see as figure 3-1. The reference measurement procedure will be introduced in following steps:

1. Establish all the objects are configuring rightly and placed in the chamber. Keep the rule of separation as mentioned before.
2. Calibrate the chamber loss with vector network analyzer with two-port calibration so that eliminate the cable loss and connector loss between network analyzer and fixed antenna, enhance the accuracy of calibration.
3. Choose measurement frequency band and load reference antenna radiation data, measure S parameters of antenna for one stirrer mode.
4. Load average received power from fixed antenna. Calculate the power transfer function

of the chamber.

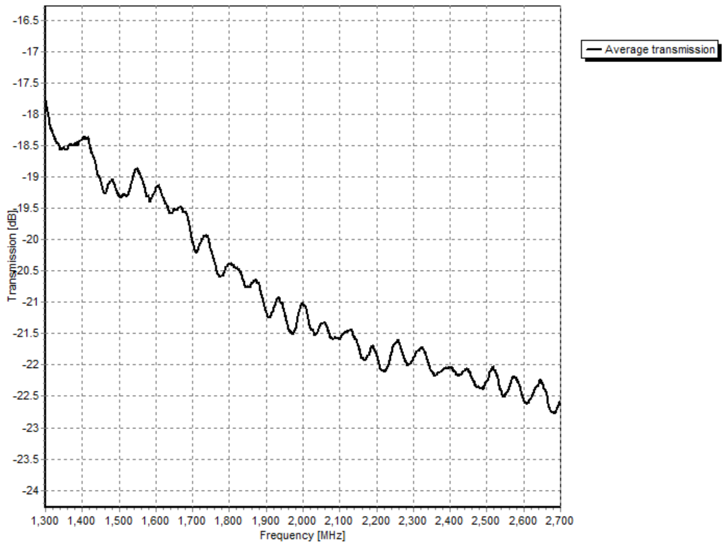


Figure 3. 2 reference measurement at frequency range from 1300 MHz to 2700 MHz

3.2.2 Summary

For passive measurement of two dipole antennas in Bluetest RTS 60 chamber, at frequency of 1300 MHz, the power transfer function via chamber is around -18 dBm with no absorbers inside the chamber; at 2700 MHz, the power transfer function via chamber is around -22.5 dBm with no absorbers inside the chamber. The chamber loss increases along with increasing frequency. The reason of that is the reference antenna radiation efficiency is reduced with raising frequency, which will lead to the fixed antenna receiving power dropped. Repeat measurement prone to enhance the accuracy of the calibration measurement result.

3.3 Radiation Efficiency Measurement

For any type of antennas, radiation efficiency is an important metric, e.g. antenna gain is determined by antenna directivity and radiation efficiency. Radiation efficiency is defined as ratio of total radiated power divided by power received at the terminal over a stirrer sequence at specific frequency. Another term is called total radiation efficiency, used to describe the efficiency of radiation power including mismatch loss of antenna. Total radiation efficiency is defined as ratio of total radiated power over received power accepted at the terminal antenna port at specific frequency. In a word, radiation efficiency is average received power for antenna under test divided by average received power of reference antenna with fixed efficiency. The efficiency can be expressed as a percentage with frequency dependent and it’s always less than 100 percent in real world.

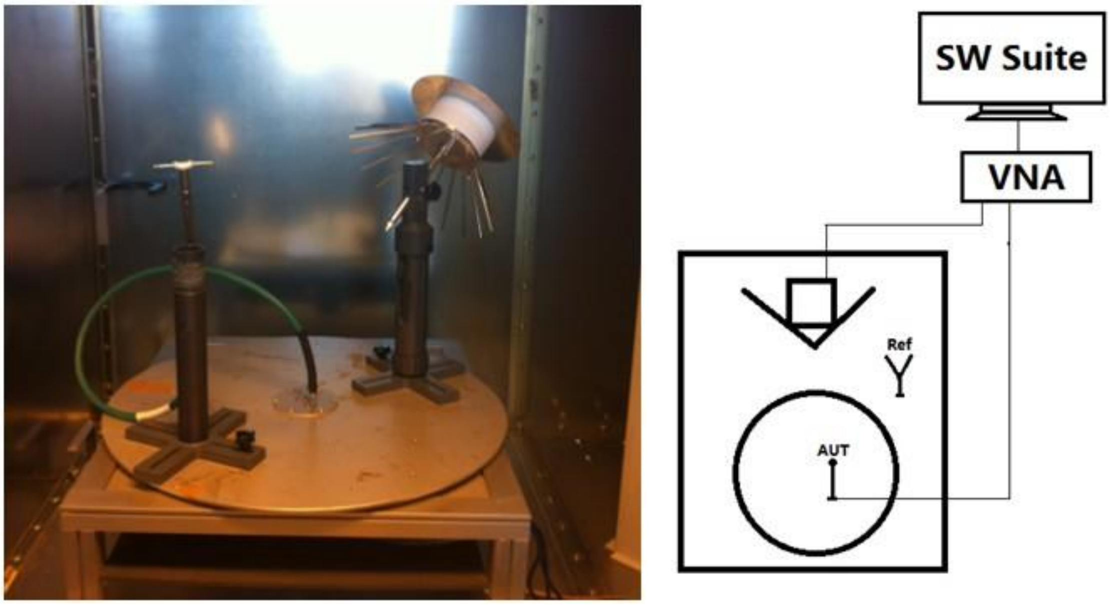


Figure 3. 3 Configuration and scheme of radiation reference in reverberation chamber

3.3.1 Setup

The required equipments for measurement:
Vector Network Analyzer
Reference antenna
Antenna under Test

The connection between VNA and chamber is same as calibration measurement, in the chamber, switch the position of two loads, terminated reference antenna with 50 ohm and placed it on the rotatable table, connects port 2 with under test antenna. In this case, a dipole antenna is under testing, see in figure 3-3. The procedure of radiation efficiency measurement is quite similar to calibration measurement and details can be listed as follow:

1. Perform the two ports calibration measurement as mentioned, including chamber calibration measurement; if it's done, skip step one.
2. Switch the connection of reference antenna and under test antenna: terminated reference antenna with 50 ohm and connects AUT with VNA, place both AUT and reference antenna on the rotate table.
3. Calculate the power transfer function for radiation efficiency and total radiation efficiency.

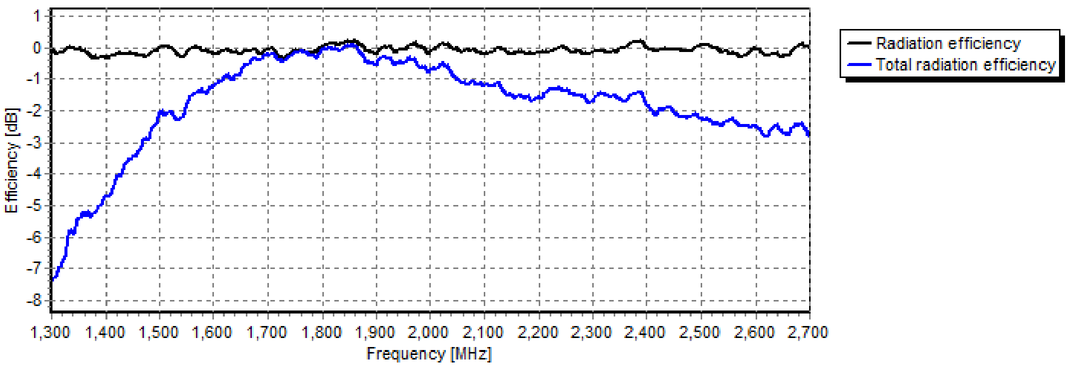


Figure 3. 4 Radiation efficiency and total radiation efficiency of dipole antenna at 1800 MHz

3.3.2 Summary

This experiment measured half-wavelength dipole antenna efficiency in Bluetest RTS 60. The dipole antenna is working at 1800 MHz, which means length of dipole antenna is 8.3 cm. It also can be proved by the below figure 3.4, reflection coefficient S_{11} is low enough at 1800 MHz. The only difference between radiation efficiency and total radiation efficiency is mismatch factor, which means two factors are close in low reflection coefficient at working frequency. But at out band frequency, total radiation efficiency is lower than radiation efficiency since mismatch factor of fixed antenna [7]. The formula can be list as:

$$\eta_{total}=\eta(1-|S_{11}|^2)$$

It also can observe that at frequency of 1800 MHz, the antenna efficiency is highest. The efficiency drops when the frequency is lower than 1800 MHz, frequency is higher than 1800 MHz, efficiency is not decreased so obviously, but that do not present that dipole antenna can be used while frequency is higher than 1800 MHz.

3.4 Antenna Diversity Gain Measurement

Diversity gain is defined as power difference between combined antennas selection at 1% CDF reference level. Although with the configuration of combined antennas in very close distance, strong coupling occurred between the separate antennas and it presented as radiation efficiency drops. With MIMO configuration, multiple antennas configuration, signal will through different fading environment, which is the main reason why MIMO system has more diversity gain in the real environment. The problem is whether the environment changes or the configuration of antenna causes increased gain, one of the solutions is measuring the antenna separately in anechoic chamber to simulate the fading environment, but the disadvantage of anechoic chamber is it takes quite a long time. An alternative solution is measure the diversity gain in the reverberation chamber since reverberation chamber could perfectly simulate Rayleigh fading environment, repeating the measurement to establish the antennas through same fading environment, to prove MIMO configuration have higher diversity gain and improve the performance of communication system, it will help antenna designer to change the position of MIMO antennas in an effective way.

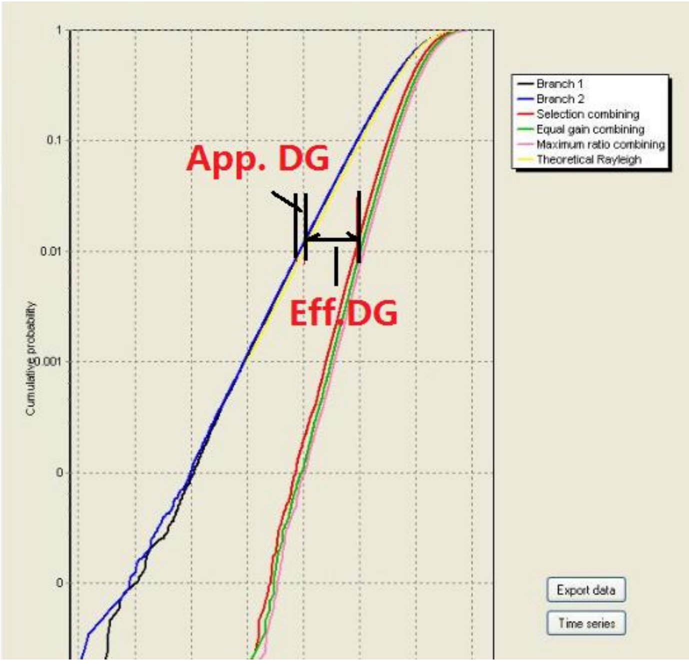


Figure 3. 5 Cumulative probability of diversity gain of two parallel dipole antennas at distance of 65 cm at 1800 MHz

Some concepts will be introduced in the thesis. The cumulative distribution function (CDF) describes the probability of a real random variable at a given probability distribution and diversity gain is based on CDF. At a certain CDF level, the diversity gain is difference between selection combined CDF and theoretical CDF, basically choose 1% CDF probability as reference level. The reference antenna with ideal radiation efficiency follows the theoretical Rayleigh distribution, which implies the reverberation chamber have rich isotropic environment. But in real environment, every antenna has loss in radiation efficiency. In theoretical, branch 1 and 2 should also follows the Rayleigh fading distribution, but the relative power level is decreased since each branch have lower total radiation efficiency. The spacing difference between two curves is called as apparent radiation efficiency [1], see in figure 3-5. In this case, apparent radiation efficiency is quite high as the distance between two dipole antennas is much bigger than wavelength so that each dipole antenna is close to theoretical Rayleigh fading line. The apparent radiation efficiency is defined as efficiency when signal at antenna port have largest radiate power. When two antennas are selection combining, slope of the curve is changing. At 1% CDF level, if apply selection combining of two ports of antennas, improved CDF curve is presented. The spacing between theoretical Rayleigh reference and selection combining is called effective diversity gain. And total radiation efficiency plus effective diversity is equal to diversity gain in unit of dB.

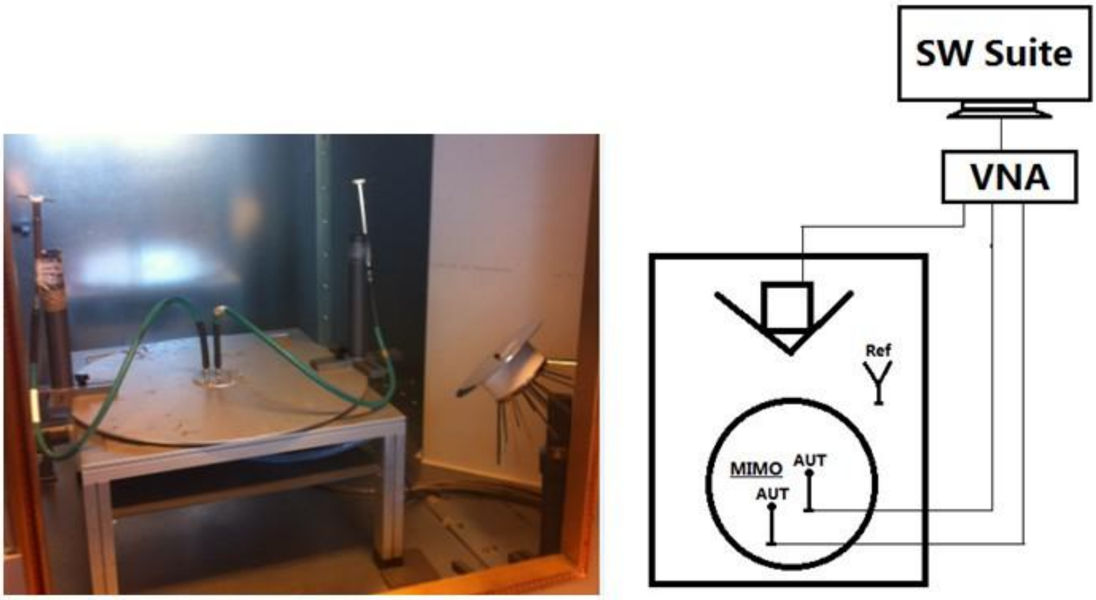


Figure 3. 6 Configuration and scheme of diversity gain measurement

3.4.1 Setup

The required equipments for measurement:
Vector Network Analyzer
Reference antenna
Antenna under Test (MIMO Configuration)

In Figure 3-6, two 1800 MHz dipole antennas are presented in Bluetest reverberation chamber RTS 60 with a vector network analyzer. Make a connection between VNA with two dipole antennas separately, terminated reference antenna with 50 ohm and put it on the ground. The procedure of measuring diversity gain is listed as follows:

1. Perform the two port calibration measurement as mentioned, including chamber calibration measurement; if it's done, skip step one.
2. Placed two dipole antennas on the rotatable table in certain distance with relative height and angle.
3. Sample the diversity gain of the DUT by VNA for each position of mode stirrer.
4. Choose frequency band and calculate the power transfer function for diversity gain.

3.4.2 Summary

Relative angle (deg)	Distance (mm)	Diversity Gain (dB)	Radiation efficiency(dB)

0	65	9.8	-0.3
0	15	9.4	-0.5
90	15	9.6	-0.4

Table 3-1 Function of distance and relative angle between two dipole antennas for Diversity Gain, Radiation efficiency at 1% CDF

In table 3-1, it does apparently observe that reduced distance makes the dipole antenna have lower diversity gain, but radiation efficiency increased since the mutual coupling. Keep the distance of two antennas hold, increase two dipole antennas' relative angle, and diversity gain robust slightly and radiation efficiency drops which is still affected by mutual coupling, the correlation is quite high when relative angle is small.

3.5 Total Radiated Power Measurement

With the rapid development of mobile terminals, they update with never-ending transformation and improvement. Technological competition between the products has been everywhere and that will bring a great change to our fast-paced life. Total radiated power (TRP) is an important property to evaluate the performance of the mobile phones. As the name implies, total radiated power means the total output power from the terminal, which is related to output power of the mobile station and radiation efficiency of antenna. TRP is an active measurement, which is defined as when the transmitter emits the radio signal, total received power in far field is calculated by total radiated power. Thus, the procedure of TRP measurement is similar to the passive measurement of radiation efficiency, but the network analyzer is substituted by power meter and base station simulator. Base station simulator is most important part of active measurement since base station simulator is used to control the power, establish the connection between active terminals and base station simulator. The power meter is used to measure the electric power at specific frequency in the reverberation chamber. It could be seen as a wide bandwidth spectrum analyzer.

3.5.1 Setup

The required equipments for measurement:
Base Station Simulator
Reference antenna
Wireless Terminal
Simulate Absorbing Objects (Head and Phantom etc.)

The characteristic of rich isotropic environment inside the reverberation chamber establishes the uniform distribution of the fields no matter how to place the DUT. As long as it follows the rule of any metallic objects should not be placed less than half wavelength and at least 0.7 wavelengths away from any lossy objects. The procedure of TRP measurement can be list as follows:

1. Perform the calibration measurement as mentioned before, including chamber calibration measurement; if it's done, skip step one.

2. Measure the loss of cable connecting base station simulator and fixed antenna in reverberation chamber.
3. Set up the uplink frequency, place the DUT in the reverberation chamber in interested position and orientation, connect the DUT in loopback mode and enable the BER measurement.
4. If head or phantom is under testing, put the DUT with head or phantom in related position and orientation, if not, skip step four.
5. Page the test unit; connect between base station simulator and the test unit in maximum output power and specific traffic channel.
6. Sample the output power of the test unit by power meter for each position of mode stirrer.
7. Calculate the average TRP valve.

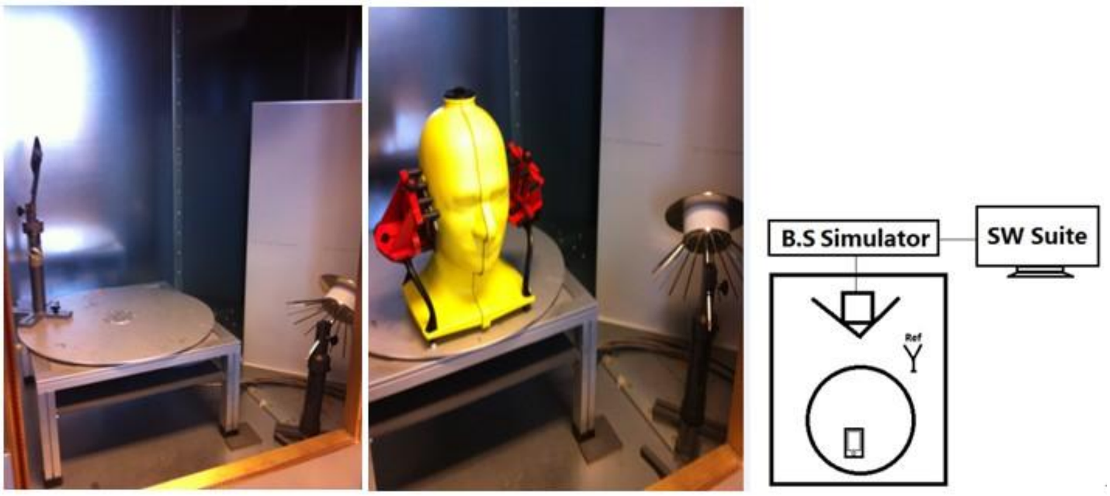


Figure 3. 7 Configuration and scheme of TRP measurement, set up for WCDMA measurement (left); testing TRP value of WCDMA with phantom (middle)

3.5.2 Summary

UL Freq. (MHz)	Channel		Without Phantom	With Phantom
1950	9750	TRP (dBm)	19.91	13.68

Table 3-2 Total radiated power of HTC Radar c110e in different case

This measurement is a standard active measurement in reverberation chamber and it's an important characteristic to weigh the wireless terminal. For this measurement, HTC radar c110e is tested and the standard is WCDMA. This cell phone supports the frequency band of 900/2100 MHz, at specific uplink frequency band as shown above. Total radiated power of this cell phone is 19.91 dBm. Measure total radiated power of the cell phone with the phantom as 13.68 dBm. The difference between two values is the phantom absorbs the energy. If changing the position of cell phone related to the phantom or change the tilt angle of cell phone, TRP will be performance differently slightly. This thesis is mainly focused on interference study, other experiments will not into details.

3.6 Measurement of Total Isotropic Sensitivity

Like total radiated power, total isotropic sensitivity is another important parameter to evaluate the unit downlink performance, which is also depending on antenna and the receiver structure. TIS depends on the antenna radiation pattern in root of total isotropic sensitivity defined as the average receive sensitivity of mobile station in integral valve of spherical surface in three-dimension space, reflect the receive characteristic of mobile station in all direction and orientation. The receiver sensitivity is the lowest power that can be detected to maintain the communication reliable link. In real environment, TIS of receiver is easily affected by noise and interference.

TIS describes as the mobile station minimum received power at downlink frequency in particular channel while the bit error rate is smaller than certain threshold value. The TIS measurement in Bluetest reverberation chamber is based on Cellular Telecommunication & Internet Association (CTIA) standardized the measuring procedure, and configuration in the chamber is similar to TRP measurement. Before the measurement, cell output power should define a method of convergence so that the BER of EUT falls into a nearby segment. Since the sensitivity of the mobile station is unknown, the starting point of the measurement cannot be determined. If set the output power improper will cause the problem of unable to connect base station simulator to the mobile station or easily drop the connection.

3.6.1 Setup

The required equipments for measurement:
Base Station Simulator
Reference antenna
Wireless Terminal
Simulate Absorbing Objects (Head and Phantom etc.)

TIS measurement is a static measurement, which means mode stirrers should be hold at each sample point. The delay spread of the reverberation chamber will cause variation as the result of BER. Way of avoiding bit errors is that increases the initial output power of base station simulator to have a higher SNR at mobile station. The configuration of TIS measurement is similar to TRP measurement. The procedure of TIS measurement can be described as below:

1. Perform the calibration measurement as mentioned before, including chamber calibration measurement; if it’s done, skip step one.
2. Measure the loss of cable connecting base station simulator and fixed antenna in reverberation chamber.
3. Set up the downlink frequency, place the DUT in the reverberation chamber in interested position and orientation, connect it in loopback mode and set the certain BER measurement.
4. If head or phantom is under testing, put the DUT with head or phantom in related position and orientation, if not, skip step four.
5. Page the test unit, connect between base station simulator and the test unit, and adjust the

output power of base station in specific traffic channel.

6. Repeat step 5 until searching the decent output power so that BER meets required BER threshold for each position of mode stirrer.
7. Calculate the power transfer function of TIS.

3.6.2 Summary

For same wireless standard, TIS varies between devices over same frequency. In this case, the total isotropic sensitivity of HTC radar c110e is -106.4 dBm in UMTS Band I. Generally speaking, lower isotropic sensitivity is easier to receive the incoming radio waves. But every coin has two sides, when sensitivity is close enough to reach the background noise, in other words, the signal noise ratio at receiver is too low so that the receiver won't be able to subtract the signal from noisy background environment, that will affect the quality of communication system and the link between base station and terminal will drop easily. In short, in an appropriate fluctuation scope, the lower sensitivity it is, the better performance of the receiver.

3.7 WCDMA Throughput Measurement

Nowadays, 3G has become an indispensable part of life. The advantage of 3G is providing wideband communication and high quality communication links between different types of applications and allowing global roaming. The high data rate offers the WCDMA standard unimpeded communication between different terminals. Along with the further development, the drawbacks are gradually revealing, transmission in high speed and quality data requires wider wireless resources to support the communication. The WCDMA signal transmits on a pair of 5 MHz band radio channels. High Speed Packet Access (HSPA) is an enhanced 3rd generation communication standard, which increases data transporting speed and channel capacity. For instance, HSDPA supports data speed in downlink of up to 42 Mbit/s, for the next generation of HSPA+, which boosts the speed up to 337 Mbit/s in theoretically. Coexistence between different standards has to be planned and the frequency reused technology is supported in WCDMA standard. The basic principle of overall network planning is maximizing the coverage and capacity between the cells, interference between different cells appears inevitably. The most common scenario is inter-cell co-channel interference, which can be perfectly simulated in the Bluetest reverberation chamber and the procedure of this measurement will show in the chapter 4.

3.7.1 Setup

The required equipments for measurement:
Base Station Simulator
Reference antenna

Wireless Terminal
Simulate Absorbing Objects (Head and Phantom etc.)

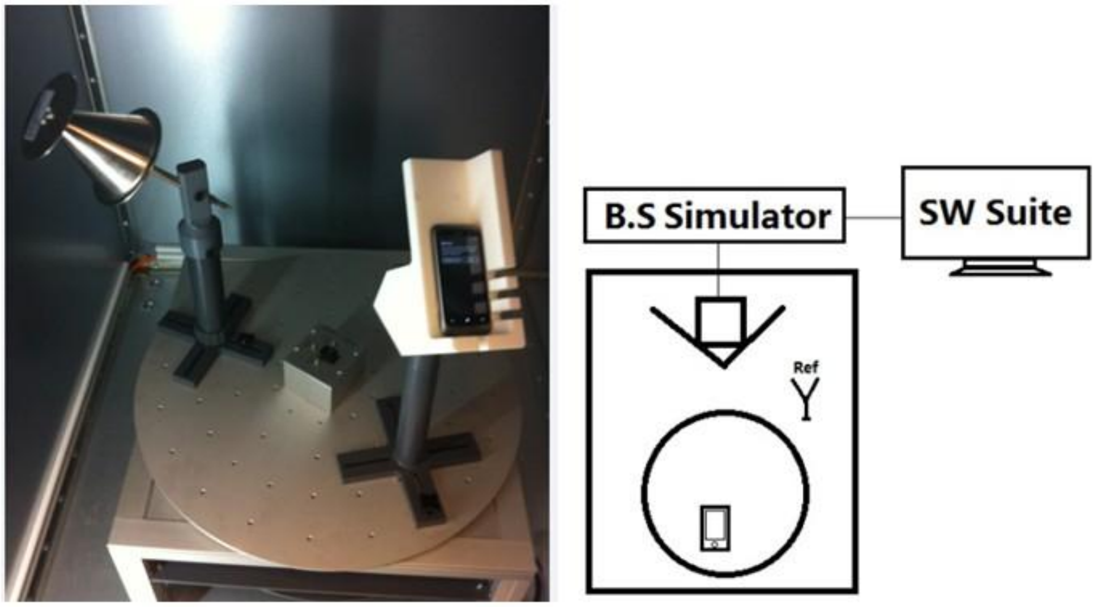


Figure 3. 8 Configuration and scheme of throughput measurement, test for HSPA as illustrate

The configuration of throughput measurement is same as TIS measurement. Details are present in figure 3-8. The procedure detail will be listed as below:

1. Perform the calibration measurement as mentioned before, including chamber calibration measurement; if it’s done, skip step one.
2. Measure the loss of cable connecting base station simulator and fixed antenna in reverberation chamber.
3. Switch the test mode to HSDPA or LTE (if MS supported) and set DL data rate at 12.2k, count for certain blocks and bits and connect it in loopback mode, enable the BER measurement.
4. If head or phantom is under test, put the DUT with head or phantom in related position and orientation, if not, skip step four.
5. Connect between base station simulator and the test unit, and adjust the output power from the base station under test.
6. Calculate the BER and throughput of the system.

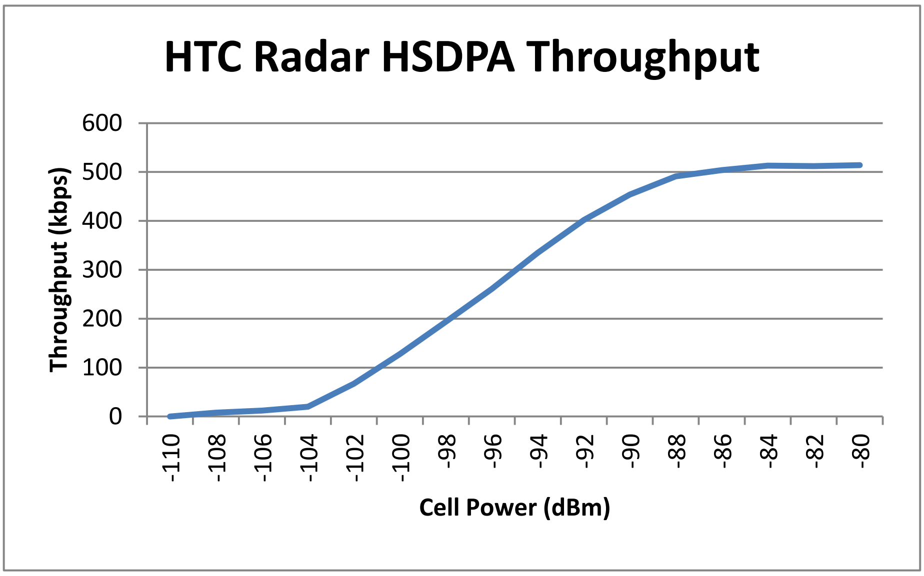


Figure 3. 9 HTC Radar c110e HSDPA Throughput measurement result

3.7.2 Summary

The unit of Throughput is bits per second (bps) and HTC Radar c110e is under testing in Bluetest reverberation chamber RTS 60. The throughput curve looks like a slant ”S”, the cell output power for testing is from -80 dBm to -110 dBm. In theoretical, maximum throughput is essentially related to channel capacity of the system. If BER is 0% at a certain received power, maximum throughput should be close to theoretical throughput. In this case, the maximum throughput is 508 kbps. When cell power is above -88 dBm, throughput is close to maximum throughput and it varies in small range. Maximum theoretical throughput takes to count overhead and redundancy in ideal atmosphere. The throughput starts to drop from -86 dBm, throughput begins to decrease while cell power decreased in almost linearly. Low throughput indicates the mobile station will easily drop the connection from the mobile station. Both TIS and throughput measurement can be used to evaluate the performance of the system which is related to packet loss and IC hardware consideration.

Chapter 4 Alternative interference source and real interference scenarios simulation in reverberation chamber

4.1 Background

Channel interference is the essential factor in the communication link which occurs on the same frequency or adjacent frequency band. In modern cellular mobile communication system, the performance of communication system depends on the coverage of the cellular and users' location in a network. In the meantime, several wireless devices could share the same frequency band due to frequency re-use planning. All of these interference uncertain factors impact on the system performance. For GSM standard, signal to noise ratio tolerances is 8 dB, assume power difference between unwanted signal and wanted signal is lower than the threshold, which will affect the communication link in variety of ways.

For example, government and commercial agencies monitor the broadcast television, TV, satellite frequency spectrum to establish the threaten interference won't have the influence on the signal of interested. Therefore, understanding the properties of different interference sources is extremely important. Initially, use alternative interference source to represent the real signal is a good way to understand interference issues.

4.2 TIS measurement of WCDMA terminal with VNA signal (as noise source) in LOS

Before get to the point of real signal interference, replace the real signal by constant signal generated by signal generator is a good choice, which is the simplest model to understand the effect of interference. Interference becomes a big issue when wireless system no longer operates as expected. For every communication system, the signal to noise ratio is limited. As mentioned of GSM standard before, the threshold of SNR of GSM system is 8 dB. The continuous waves generated by signal generator can be seen as background noise for wanted signal. Boost the interference power level will have an influence on receiving radio signal. When the interfering signal becomes relatively high while comparing to interested signal, interfere signal will ruin the communication system and probably lose the connection in communication link. The TIS measurement of WCDMA terminal with VNA as noise source can be treated as the basic interference scenario. The advantage of RF signal generator as interference source produces stable and constant power strength without modulated carriers, which will directly affect the wanted signal, and it's convenient to dismiss the interfere source by switch off the RF signal generator.

4.2.1 Setup

The required equipments for measurement:
Vector Network Analyzer (Agilent E5071B)
Vector Spectrum Analyzer (R&S FSV)

Reference antenna
Wireless terminal (HTC Radar c110e)
Base station Simulator (Agilent 8960)

Basic information:
Reverberation chamber: Bluetest RTS60
Frequency: UMTS Band I 2140 MHz
Bandwidth: 5 MHz
Delay spread: 117ns (No absorbers)

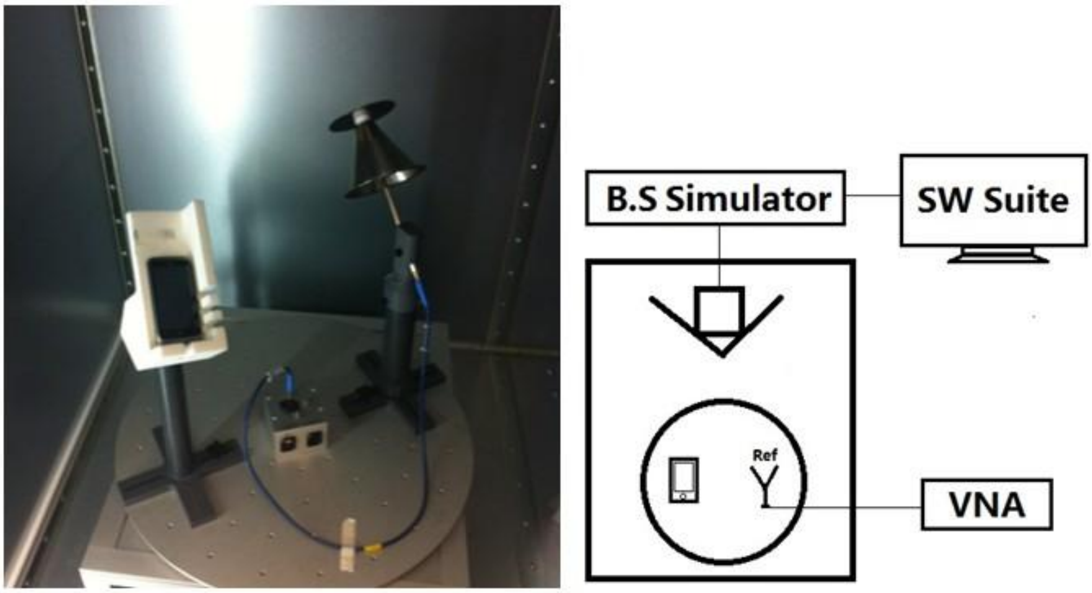


Figure 4. 1 Configuration and scheme of constant signal source interfered to WCDMA signal

The basic idea of this scenario is a constant in-band interference source is transmitting interference signal in LOS via reference antenna to interfere the WCDMA signal. The details of configuration are shown in figure 4-3. In this experiment, Agilent 8960 substitute of signal generator since VNA has an embedded signal generator inside. Connect the VNA with the reference antenna to emit the interference signal. Place both the mobile station and reference antenna on the rotatable table, and the distance between mobile station and reference antenna is fixed as 40 cm, then that the received interference strength is constant to interested WCDMA signal. In this test, the interference power sets on the VNA is -20 dBm, -30 dBm, -40 dBm and -55 dBm, individually. The cable loss between VNA and the reference antenna is 2.13dB totally at 2.14 GHz and radiation efficiency of reference antenna at 2.14GHz is -0.22dB. That means the noise power at the output point of reference antenna is -22.35, -32.35, -42.35 and -57.35 dBm, individually. Since both the reference antenna and mobile station are placed in rotatable table in LOS, the signal will go through both of free space propagation and multipath propagation according to the equation (1.9). But the received interference power level at mobile station can’t be accurate predicted, which indicates the interference power at receiver is hard to know. Meanwhile, regulate the bandwidth of interference signal by 500 kHz, 1 MHz and 5 MHz. The expected result is the total isotropic sensitivity drops with increasing interference power, while weak interference signal only influence the performance scantly. The procedure will be listed as follows:

1. Perform the calibration measurement as mentioned before, including chamber calibration measurement; if it's done, skip step one.
2 Set up the downlink frequency, place the DUT in the reverberation chamber in interested position and orientation, connect it in loopback mode and set the certain BER measurement.
3 Generate the interference signal with certain bandwidth and amplitude from VNA, connect it to reference antenna.
4 Page the test unit, connect between base station simulator and the test unit, and adjust the output power of base station in specific traffic channel.
5 Repeat step 4 until searching the decent output power so that BER meets required BER threshold for each position of mode stirrer.
6 Calculate the power transfer function of TIS.

TIS \ Int Pwr (dBm) / B	-20 dBm	-30 dBm	-40 dBm	-55 dBm
500 kHz	-104	-104.5	-105.3	-106.4
1 MHz	-103.9	-104.8	-105.3	-106.3
5 MHz	-104.6	-105.2	-105.8	-106.4

Table 4-1 Total isotropic sensitivity of WCDMA signal with constant signal interference, Int Pwr is the abbreviation of interference power from the VNA and B is the abbreviation of Bandwidth of the interference signal from the VNA.

4.2.2 Summary

The measurement is operating in the chamber RTS60 with 117 delay spread and sensitivity of HTC Radar c110e without external noise is -106.4 dBm at UMTS Band I. When the interference strength from the VNA is lower or equal to -55 dBm, the sensitivity of mobile terminal will not be affected. For a certain bandwidth of constant interference signal, increasing the power of interference leads to drop the sensitivity of system since increasing the interference signal power means increasing the noise floor level at receiver. In other words, the sensitivity drops with lower SNR of interested signal. Vector network analyzer generates the signal doesn't behavior as noise generator, the signal is scanned for every single frequency, which means change the bandwidth of signal won't affect the average noise power level if the power level of interference is constant. The difference is less than 0.7 dB which can be ignored due to the uncertain environment in the chamber. The result meets the previous expectation and constant interference signal power will drop the sensitivity of mobile station. Conclusion of this experiment is that this scenario is not the perfect model to simulate the interference noise since the power transfer function in free space propagation can't be estimate, so that the interference power at receiver can't be calculated to evaluate the affect of interference.

4.3 WCDMA inter-cell Co-channel Interference TIS measurement

Nowadays, WCDMA standard is widely used in modern communication system, since lack of frequency spectrum resources, coexistence between different terminals has to be planned and the frequency reuse technology is supported in WCDMA standard and the basic idea of overall network planning is maximizing the coverage and capacity between the cells. Inter-cell interference appears at the edge of cellular more often, the user will receive interference from other base stations. Therefore, the inter-cell co-channel interference can be the most common scenario to emulate, which can be perfectly simulated in the Bluetest reverberation chamber. In this chapter, the experiments compare the real WCDMA interfere with AWGN interference to verify that AWGN noise can be used for substitute for real co-channel interference.

4.3.1 Setup

The required equipments for measurement:
Interest WCDMA Base station simulator: Anritsu MT8820c
Interference WCDMA Base station simulator: R&S CMW500
Interest WCDMA Mobile station: HTC Radar c110e
Interference WCDMA Mobile station: Samsung Galaxy S
Reference antenna
Splitter

Basic information:
Reverberation chamber: Bluetest RTS 60
Frequency: UMTS Band I 2140 MH
Bandwidth: 5 MHz
Delay spread: 117ns (No absorbers)
Bits: 10000 Blocks: 200
DL data rate: 12.2k
Fixed ref. channel: H-set1 (QPSK)
Paging service: RB test mode

Figure 4. 2 The Configuration and scheme of inter-cell Co-channel interference based on WCDMA standard

In this scenario, inter-cell co-channel interference scenario is emulated via reverberation chamber. The goal of this model is to minimize the intra-cell communication between different users, only consider one interference source from out-cell base station which is working at the same frequency band. First step is to establish two base stations are using the same coding and modulation scheme at same frequency band. If place the interested mobile station and interference mobile station in the chamber simultaneously, the base station is hard to distinguish the target user since both interested and interference mobile station transmit the same property of WCDMA signal in same environment. Thus, the solution of this scenario is to attach the interference mobile station in conductive connecting and to place it outside the chamber. In such configuration, the chamber perfectly isolates the communication between interested and interference mobile station .Use the splitter to separate the interference base station signal into two directions, one way is constructing the link amidst the interference base station and user mobile in conductive connection and another way is connect base station to the fixed antenna of the chamber. The WCDMA signal from interested base station and interference signal will go through different Rayleigh fading path. Its worth to mention that the output power from the interference base station needs to be calibrated the loss of splitter, cables and chamber. The procedure can be listed as follows:

1. Perform the calibration measurement as mentioned before, including chamber calibration measurement; if it’s done, skip step one.
2. Measure the loss of cable connecting base station simulator to fixed antenna in reverberation chamber.
3. Place the interested mobile station in chamber which counts for certain blocks and bits. Connect it in loopback mode and enable the BER measurement.
4. Separate the interference signal into two outputs by splitter, one cable attaches with the interference base station and mobile station via conductive cables; another port attaches with one port of the fixed antennas of the chamber.
5. Estimate the emit interference power from interference base station by calculating power transfer function due to chamber, cables and splitter.
6. Calculate the BER and TIS of the system.

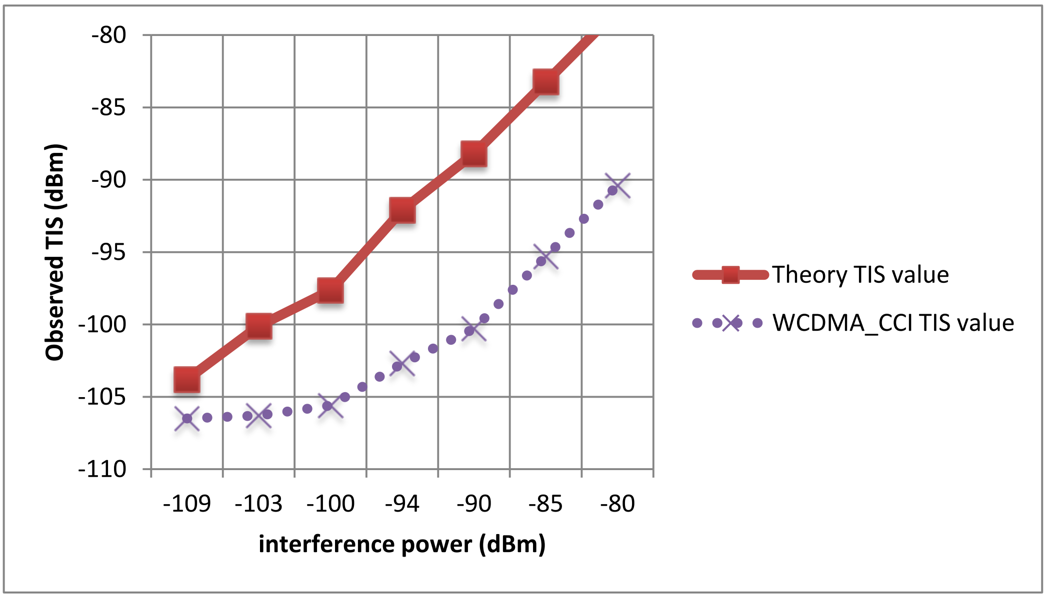


Figure 4. 3 TIS measurement based on WCDMA standard with co-channel interference

4.3.2 Summary

The measurement is tested in Bluetest reverberation chamber RTS 60. Increase the WCDMA inter-cell co-channel interference power results the observed interested WCDMA TIS decreased, details seen in figure 4-13. WCDMA TIS value result is 10dB difference compare with theory TIS value while interference power is larger than -92 dBm roughly. When the interference power is smaller than -94dBm, the difference between theoretical TIS value and measured TIS value with inter-cell interference is gradually narrowed since the WCDMA TIS value is limited by the sensitivity of the device. Is it possible to use the AWGN noise to represent the WCDMA interference which is more convenient? If that works, how much is the difference between two values? To answer the question, continuous TIS measurement with AWGN noise interference is under investigating.

4.4 Theoretical Proof

The Procedure of measuring Total Isotropic Sensitivity is to adjust the output power from base station as desired until the lowest output power establishes the DUT bit error rate lower than the specific target BER limit for each position of mode stirrers. Increase the number of samples and repeat for each position of mode stirrers can increase the accuracy of measurement result. The TIS [21] can be expressed as:

$$\mathrm{TIS} = \left(\frac{1}{N} \sum_{n=1}^{N} \frac{1}{P_{BS}(n)} \right)^{-1} \Big/ G_{chamber} R_{fix} G_{cable} \qquad (4.1)$$

Where $P_{BS}(n)$ is the appropriate output power from the base station simulator to specific BER in number of n samples of mode stirrers. $G_{chamber}$ is the calibration power transfer function of

the reverberation chamber; N is the samples of mode stirrer position; R_{fix} is the corresponding power correction factor of fixed antenna and G_{cable} is the loss of the cable which connects base station simulator and fixed antenna.
The signal power from base station at receiver can be expressed as:

$$P_{rec} = \frac{1}{N}\sum_{n=1}^{N} P_{Tx} G_{chamber} R_{fix} G_{cable} \tag{4.2}$$

Where P_{Tx} is output power from transmitter.
The chamber calibration is the power transfer function through the chamber. The signal emitted to the chamber is actually transformed among three fixed antennas to built isotropic environment and average received power. So the averaged power transfer function in the chamber can be expressed as:

$$G_{chamber} = \frac{1}{N}\sum_{n=1}^{N} \left| S_{21}^{(n)} \right|^2 \tag{4.3}$$

Correct the reference antenna efficiency, the reflection in fixed antenna and internal loss in the chamber, the complete averaged power transfer function [21] can be rewritten as:

$$G_{chamber} = \frac{1}{N}\sum_{n=1}^{N} \frac{\left| S_{21}^{(n)} \right|^2}{\left(1-\left|\overline{S_{11}}\right|^2\right)\left(1-\left|\overline{S_{22}}\right|^2\right) e_{eff}} \tag{4.4}$$

Where e_{eff} is the fixed antenna radiation efficiency, S_{11} is the reflection coefficient of the fixed antenna. The contribution of $1-|S_{11}|^2$ is signal transmits through the fixed antenna due to the mismatch factor of fixed antenna and the factor also can be expressed as R_{fix}.
The signal to noise ratio is used for measuring the power level of desired received signal over background noise. When an external noise source is added at the receiver, SNR can be expressed as:

$$\mathrm{SNR} = \frac{P_{TIS}}{N_0 + I_{ext}}$$

$$P_{TIS} = SNR_{(dB)} + 10\log(N_0 + I_{ext}) \tag{4.5}$$

Where P_{TIS} is the total isotropic sensitivity at the receiver. Basically, interference can be treated as two contributions [8]. One is interference signal propagates through free space and another contributes is interference signal after the Rayleigh fading environment via the chamber. In normal passive and active measurement in reverberation chamber, the signal propagates in NLOS dominates as the result of mode stirrers. The direct coupling can be expressed as free space formula as Friis free space equation:

$$S_{21} = S_{21}^{iso} + S_{21}^{\mathrm{dir}}$$

$$P_{rx} = P_{tx} G_{tx} G_{rx} \left(\frac{\lambda}{4\pi d}\right)^2 \tag{4.6}$$

Where P_{tx} is output power from transmitter, G_{tx} and G_{rx} is the antenna gain at transmitter and receiver, respectively, λ is the wavelength and d is the distance between the antennas. Reverberation chamber provides the isotropic reference environment in Rayleigh fading, so that direct coupling between DUT and interference power level should be as low as possible. Take mobile phone as an example, the radiation antenna is mounted at the backside of cell phone, so that ensure the antenna is not pointing towards to fixed antenna or interference source. The fixed antenna after the shield reduces the direct coupling as much as possible compare to the chamber contribution. Thus, the signal emit from fixed antenna could seen as null contributes from direct coupling.

Basically, the condition of ideal background noise is seen as the receiver with matched load in room temperature. Usually, the effective temperature of the device is near the room temperature of 290K. Thus, the background noise can be expressed as N_0=kTB, where k is Boltzmann's constant, T is receiver temperature and B is the bandwidth, here the background noise power in theory is equal to -108.13dBm if assume the room temperature as 270 k. The signal to noise ratio is related to the transmitting data rate and bandwidth, which can be expressed as:

$$\mathrm{SNR} = \frac{E_b}{N_0}\frac{f_D}{B} \tag{4.7}$$

Where E_b/N_0 is the equation of energy per bit to noise power density, f_D is the data rate in downlink stream, B is the channel bandwidth. In practice, the background noise is not only considered as ideal environment, instead, the temperature at receiver is determined by system temperature, ambient temperature and radiation efficiency of the receiver antenna which is difficult and inconvenient to calculate. The solution to calculate the background noise is to measure for two cases. First, processing the TIS measurement; then measure the TIS of specific power with incoherent AWGN noise, the difference between two TIS measurement and known incoherent AWGN noise power at receiver can deduced the background noise if the system and ambient environment is stable. The expression of calculating the background noise in decibel format can be written as below:

$$\mathrm{P}_{TIS}^{AWGN}{}_{(dB)} - P_{TIS\,(dB)} = 10\log[N_{0(W)} + N_{AWGN\,(W)}] - N_{0(dB)} \tag{4.8}$$

The derivation for predicted TIS with external noise power can be written as below:

$$\mathrm{constant}_{\mathrm{BER}=1.2\%} = \mathrm{SNR} = \frac{\mathrm{P_{TIS}}}{N_0 + I_{ext}} \tag{4.9}$$

$$\frac{P_{TIS}}{N_0} = \frac{P_{TIS}^{AWGN}}{N_0(1+\dfrac{N_{AWGN}}{N_0})} = cons \tag{4.10}$$

$$P_{TIS}^{AWGN}{}_{(dB)} = P_{TIS\,(dB)} + 10\log(1+\frac{N_{AWGN(W)}}{N_{0(W)}}) \tag{4.11}$$

Take WCDMA as an example, the signal is transmitting in DL with 12.2k data rate and the chip rate of WCDMA standard is 3.8 Mcps, so the processing gain which is the ratio between channel data rate and bandwidth is -25dB. The WCDMA standard stipulates the target BER ratio is 1.2%, according to the bit-error rate curves for QPSK modulation in AWGN channel, seen in figure 4-1, the limit of E_b/N_0 is around 4dB.

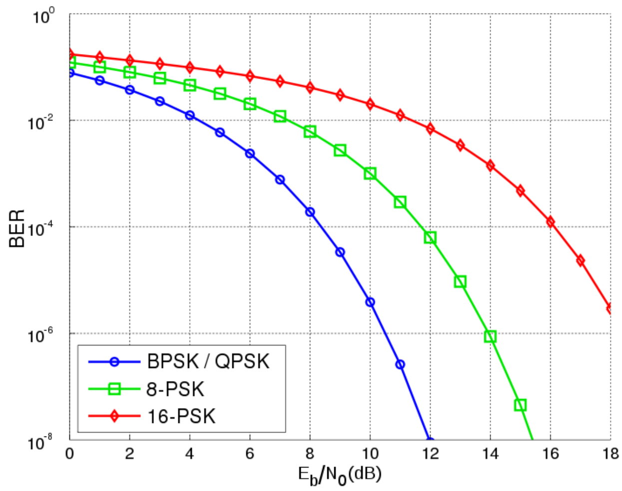


Figure 4. 4 BER vs Eb/N0 curves in different modulation in AWGN channel [21]

AWGN power at receiver (dBm)	No Added Noise	-80	-85	-90	-94	-100	-103	-109
TIS (dBm)	-106.4	89.9	94.8	-99.4	-102.2	-104.9	-105.8	-106.3

Table 4-2 Result of WCDMA TIS measurement with different incoherent AWNG power level

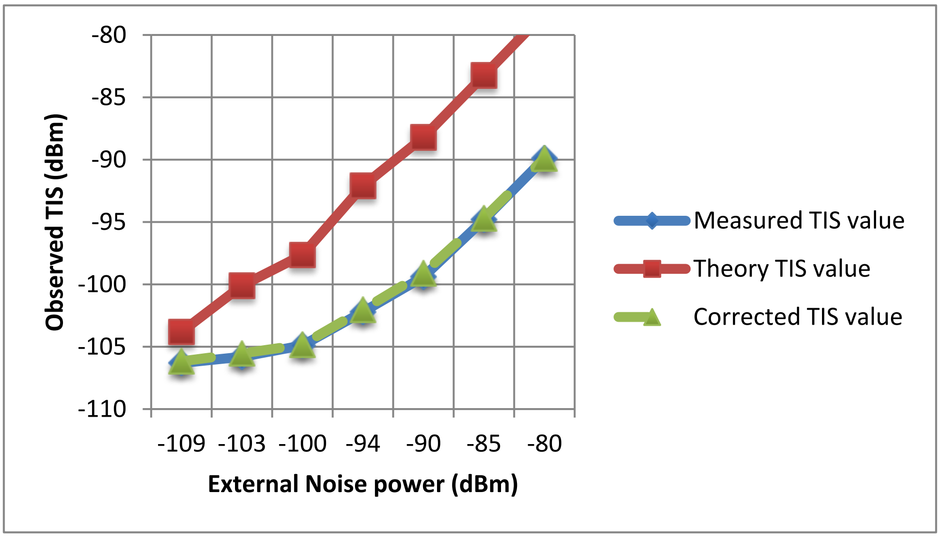


Figure 4. 5 Measured TIS value, theory TIS value and Corrected TIS value

The device of TIS measurement is HTC Radar c110e in Bluetest RTS 60 and the result is shown in the table 4-1. Pick up two random data and plug into equation (4.8) to calculate the background noise is -96.4 ±0.4dBm for this specific cell phone. Therefore, the total isotropic sensitivity can be easily predicted.

4.5 Interference amidst WCDMA standard and simulate the effect of interference

4.5.1 Noise generator presented for interference source

Additive White Gaussian Noise (AWGN) is the most typical channel model to simulate the impairment to the communication system. The basic characteristic of AWGN is linear addition of wideband white Gaussian noise and the amplitude of AWGN follows the Gaussian distribution. AWGN channel is the widely accepted model to simulate the real environment impairment. Normally, whether the signal is transmitted or not, additive noise is always exist at the receiver. More importantly, the AWGN is uniformly distributed over whole band spectrum, in other words, the power spectrum density of noise is constant. Intra-cell interference is commonly happened in one cellular, two similar devices transmit signals via shared channel (time slot and frequency) will cause interference. Generally speaking, intra-cell interference could be measured in reverberation chamber in an effective way. To be specifically, the configuration of the measurement is one base station connects to one mobile station with wanted signal and interference base station connects to another mobile station named as interference signal, and then checks the performance difference of interested signal. This scenario will be present later. But is it possible to model the interference signal with non-carrier AWGN noise, which is more convenient to build the scenario and evaluate the result in an effective way. The idea of this scenario is to produce the AWGN signal by noise generator to interference other sophisticated wireless communication standards and rank the performance of different scenarios. There are two ways to combine the AWGN and interested signal: Case one is to combine the WCDMA signal and AWGN by using a combiner, then connect the “mixed” signal to fixed antenna; Case two is to connect the WCDMA signal and AWGN to the different fixed antenna. Two cases are simulating different scenarios, case one is less normal, with constant power interference source besides the WCDMA mobile station in NLOS. Therefore, the signal to noise ratio is constant at receiver. Case two is more common in real environment, physical distance between interference sources and interested mobile station is constant, the surrounding environment is moving diversely, so that the signal to noise ratio at receiver is always changing. This section focuses on investigating the relation between two cases and real scenario.

4.5.1.1 Noise Generator

The noise generator is treated as Additional White Gaussian Noise (AWGN) in a narrow band. In this thesis, the noise generator is a simple analog circuit and working frequency is from 700MHz to 2700MHz, see in figure 4-12. With the bandwidth of 5 MHz of WCDMA standard, check the noise generator with spectrum analyzer (R&S, FSV signal analyzer) with resolution bandwidth of 5 kHz at frequency of 2.14 GHz, the output power is detected as -26.5 dBm in cold system, specifically. But the output power is -28.1 dBm in warm-up system. The best choice of noise generator is digital tunable noise generator, since the limitation of the measurement equipment, way of adjusting noise power via connecting the attenuators with the noise generator, which means the output power is probably not as accurate as digital noise generator. Another reasonable choice is utilizing the AWGN noise inside the base station instrument as Agilent 8960, Anritsu 8820c.

4.5.1.2 Noise Generator Measurements in the Reverberation Chamber

Firstly, check the output power from the noise generator by connecting noise generator to spectrum analyzer directly as mentioned before, the value is -28.1 dBm in warm-up system. Then detect the received noise power at receiver whether noise power agrees with Rayleigh fading as signal. The scheme of this configuration is shown in Figure 4-7.

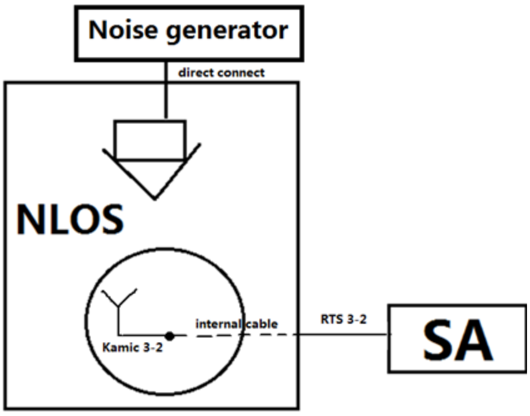


Figure 4. 6 Scheme of measuring received noise power at mobile station

Use a reference antenna to simulate the mobile station to receive the noise power. The noise power level at receiver can be shown in spectral analyzer, but cable loss and reference antenna efficiency need to be considered. According to the reference measurement of reverberation chamber RTS 60, the chamber loss is -23 dB at 2.14 GHz, the output power of noise generator is -28.1 dBm, so that calculate the received noise power should be around -51.1 dBm. Average 100 samples from the spectrum analyzer, which is -54.89 dBm, detail is shown in the table. The values from spectrum analyzer subtract three cable losses and the reference antenna efficiency is the real received noise power. In this case, three cable losses are 0.48 dB, 1.37 dB, 1.08 dB separately and the reference antenna efficiency is -0.22 dB at 2.14 GHz. Thus, the measured received noise power is -51.75 dBm. One thing worth to mention is that convert the logarithmic form to linear form while taking the average values of 100 samples to establish the accuracy of the results. This test proves that the AWGN noise power level at receiver needs to consider the loss of the chamber.

-54.31	-57.11	-56.63	-55.66	-57.45	-56.39	-55.51	-56.48	-55.47	-52.94
-54.73	-55.81	-55.86	-53.04	-57.17	-56	-52.29	-53.55	-52.34	-52.71
-56.05	-50.65	-57.27	-55.57	-58.21	-57.59	-54.08	-52.93	-53.44	-56.96
-54.14	-54.76	-52.9	-56.89	-51.46	-55.44	-57.57	-53.83	-58.47	-54.74
-58.27	-56.3	-56.26	-55.48	-53.32	-59.97	-54.27	-58.74	-53.25	-54.57
-57.12	-54.22	-56.47	-53.18	-55.85	-57.53	-56.94	-55.78	-57.81	-53.55

-57.41	-52.3	-54.72	-57.09	-55.45	-53.32	-54.77	-56.11	-55.3	-56.31
-54.61	-53.33	-53.73	-55.78	-56.97	-57.06	-53.8	-55.46	-58.09	-53.96
-58.88	-55.89	-51.73	-51.11	-55.78	-52.95	-55.44	-56	-56.35	-53.71
-53.7	-54.51	-56.66	-54.13	-54.23	-55.11	-53.46	-56.23	-58.51	-58.83

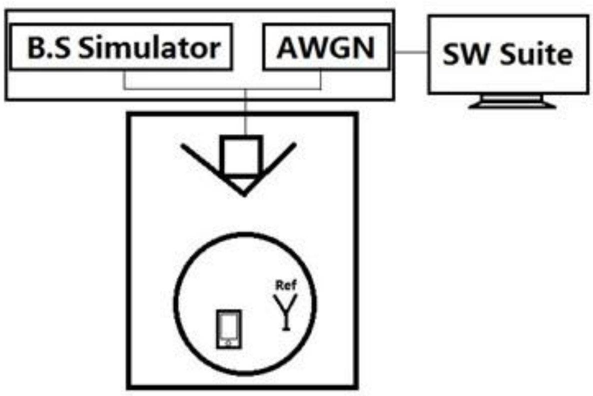
Table 4-3 power level read from spectrum analyzer for 100 samples

4.5.2 Simulate the performance of WCDMA signal with coherent AWGN noise

4.5.2.1 Setup

The required equipments for measurement:
Vector Spectrum Analyzer (R&S FSV)
Reference antenna
Wireless terminal (HTC Radar c110e)
Base station Simulator (Agilent 8960)
Noise generator

Basic information:
Reverberation chamber: Bluetest RTS 60
Frequency: UMTS Band I 2140 MHz
Bandwidth: 5 MHz
Delay spread: 117ns (No absorbers)
Bits: 10000   Blocks: 200
DL data rate: 12.2k
Fixed ref. channel: H-set1 (QPSK)
Paging service: RB test mode



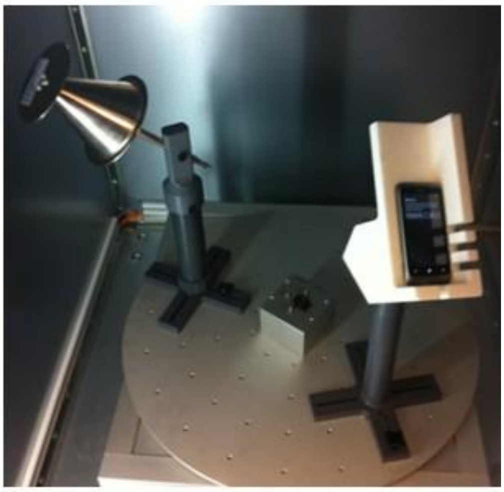


Figure 4. 7 Configuration and Scheme of WCDMA signal with coherent AWGN noise interference

In this case, the experiment injects combined WCDMA signal and AWGN noise into chamber, the “mixed” signal will go through same Rayleigh fading environment, so that the signal to noise ratio at receiver is always a constant. There are two ways to combine the base station signal and AWGN noise, first step is combine the noise power from the noise generator and base station signal with a combiner; the other way is to setup the AWGN noise level in the base station simulator and inject the AWGN noise with the wanted signal together. The latter solution is chosen in this measurement since the latter process of setup is more accurate, stable and convenient to operate. Transmit the combined WCDMA signal with AWGN noise to the fixed antenna, the AWGN noise tracks the fading environment as WCDMA signal, the relative amplitude and phase of AWGN noise compares to WCDMA signal is constant. This sort of interference scenario is uncommon in daily life but worth to understand. The procedure will be listed as follows:

1. Perform the calibration measurement as mentioned before, including chamber calibration measurement; if it’s done, skip step one.
2. Switch the test mode to HSDPA and DL data rate at 12.2k, count for certain blocks and bits; connect it in loopback mode and enable the BER measurement.
3. Set the AWGN noise level at the base station with certain power strength.
4. Connect base station simulator and the test unit. Adjust the output power from base station until BER reaches certain value.
5. Calculate the BER and throughput of the system.

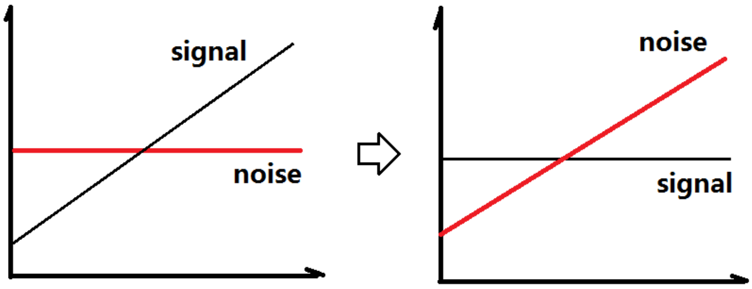
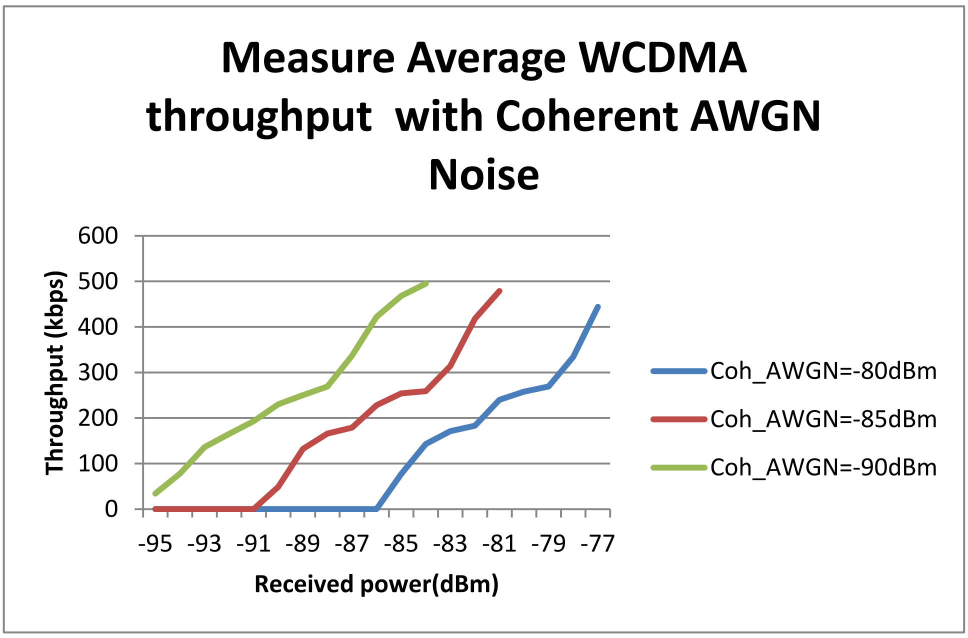


Figure 4. 8 two ways to change the signal to interference ratio at receiver



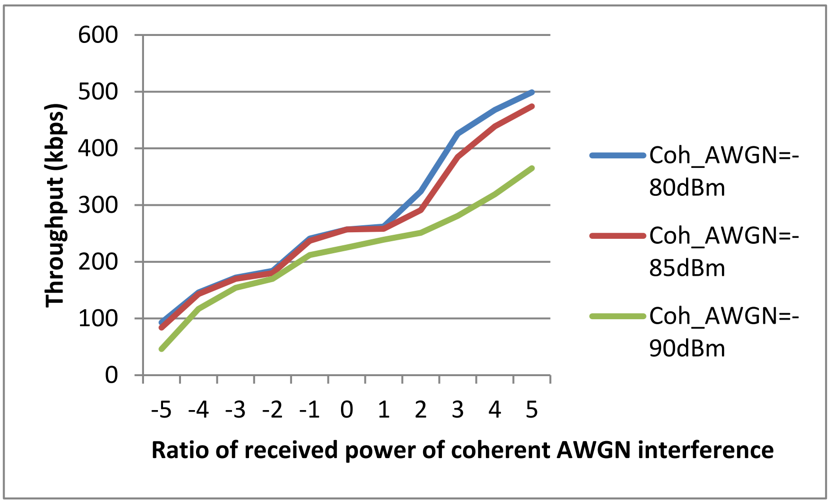
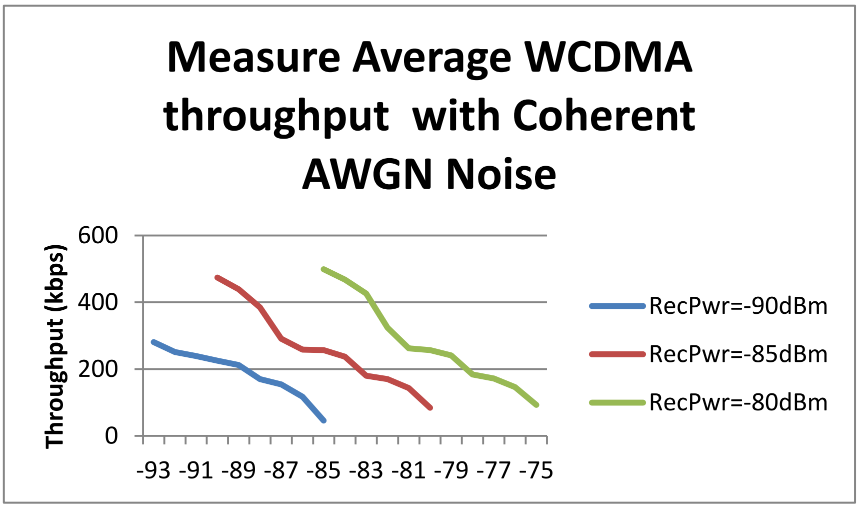


Figure 4. 9 Throughput measurement of WCDMA combined with different received AWGN power strength at mobile station, condition is change the SNR at receiver by adjusting the power level of WCDMA signal and keep the AWGN as constant value



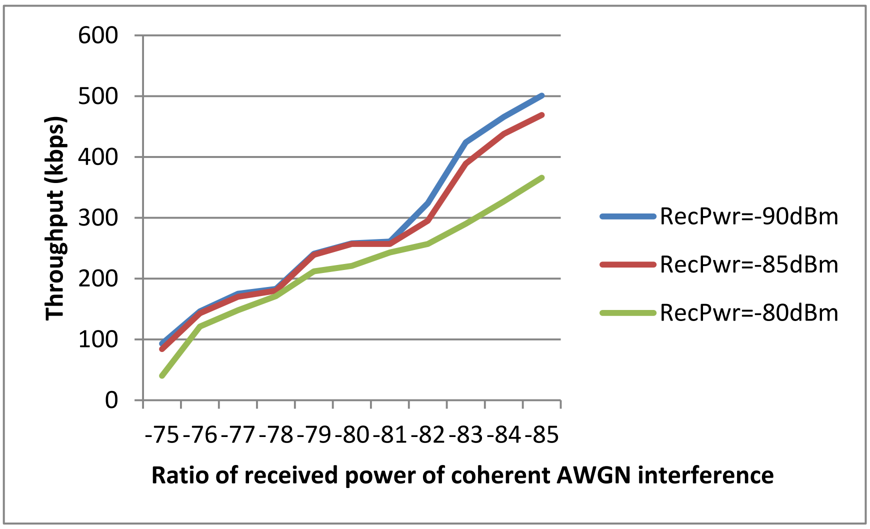


Figure 4. 10 Throughput measurement of WCDMA combined with different received AWGN power

strength at mobile station, condition is change the SNR at receiver by adjusting the power level of AWGN and keep the WCDMA signal as constant value

4.5.2.2 Summary

The measurement is tested in Bluetest reverberation chamber RTS 60. From the figure 4-10, it’s clear to see the result of throughput measurement with constant coherent AWGN noise interference. Increase the output power from base station boosts the throughput of the system. With strong AWGN noise power interference, average received power should be higher to reach same throughput level. With lower coherent AWGN noise interference, the ratio of received power to AWGN noise power is smaller at same throughput level since the lower AWGN noise power is close to the sensitivity of mobile station which will affect the result of throughput. Two ways of changing the ratio of received power to AWGN noise power at receiver: one is keep the coherent AWGN noise as a constant value, varies the received power to AWGN noise power ratio by adjusting the output power from the base station and vice verse, see in figure 4-6. The throughput measurement shows that the results are close to each other which mean that the way of adjusting ratio of received power to AWGN noise power at receiver won’t be affect the throughput measurement result.

4.5.3 Simulate the performance of WCDMA signal with incoherent AWGN signal

4.4.3.1 Setup

The required equipments for measurement:
Reference antenna
Wireless terminal (HTC Radar c110e)
Base station Simulator (Agilent 8960)
Noise generator
Attenuators

Basic information:
Reverberation chamber: Bluetest RTS 60
Frequency: UMTS Band I 2140 MH
Bandwidth: 5 MHz
Delay spread: 117ns (No absorbers)
Bits: 10000 Blocks: 200
DL data rate: 12.2k
Fixed ref. channel: H-set1 (QPSK)
Paging service: RB test mode

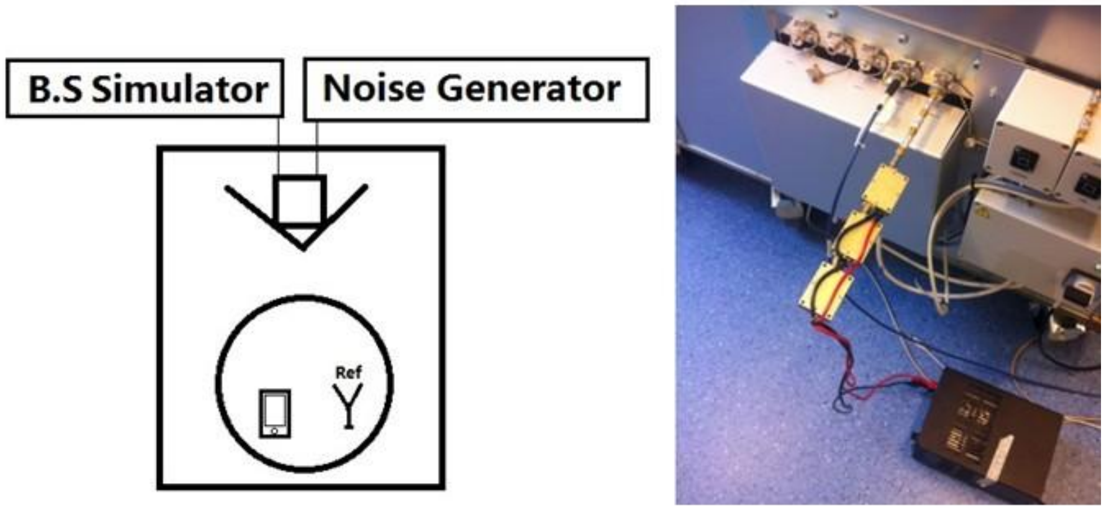


Figure 4. 11 Configuration and Scheme of WCDMA signal with incoherent AWGN noise

In this scenario, the base station emits the WCDMA signal with incoherent AWGN to the chamber, the WCDMA signal and AWGN noise will go through different fading patterns, which mean the SNR at receiver is always changing. As checked before, output power of noise generator is -28.1 dBm in warm-up system. One of the goals of this experiment is to compare incoherent throughput result to coherent AWGN. Add the attenuators at the output port of noise generator, which indicates the received power at mobile station is equal to -80dBm, -85dBm, -90dBm. Although the way of modify the output power of noise generator is not so accurate which has ±1dB deviation. In this case, the power transfer function through chamber is equal to -22.9dB at 2.14 GHz, which means the attenuation at the AWGN generator port should be equal to 29dB, 34dB and 39dB, individually. Connect noise generator with one port of the fixed antenna. The procedure will be listed as follows:

1. Perform the calibration measurement as mentioned before, including chamber calibration measurement; if it’s done, skip step one.
2. Measure the loss of cable connecting base station simulator and fixed antenna in reverberation chamber.
3. Estimate the received noise power at mobile station by calculating power transfer function of chamber and output power of noise generator. Connect the noise generator with certain attenuators to one port of the fixed antennas.
4. Connect between base station simulator and the test unit for certain blocks and bits connect it in loopback mode and enable the BER measurement.
5. Calculate the TIS and throughput of the system.

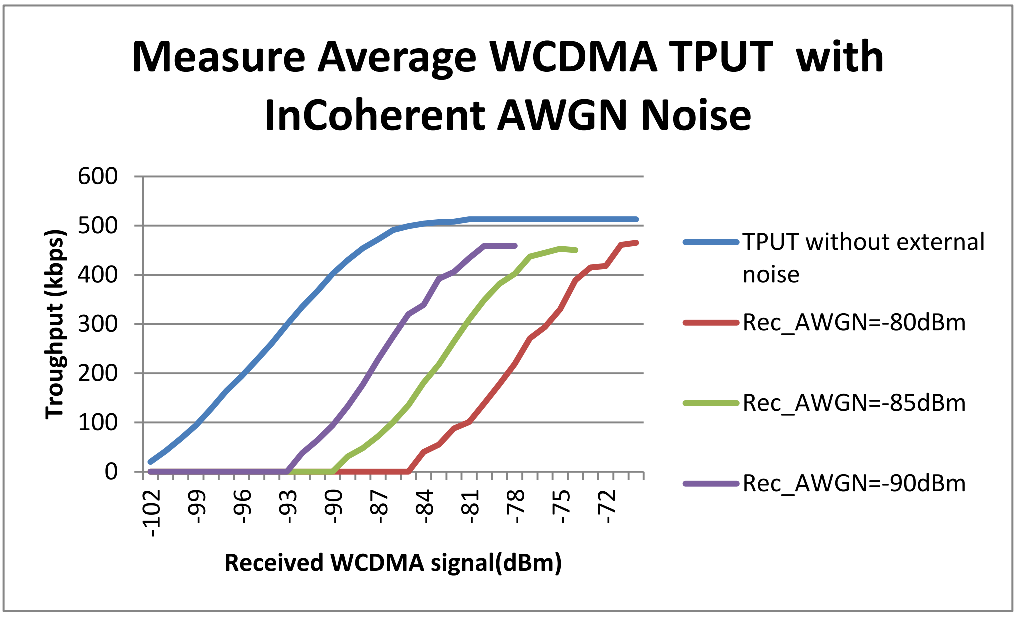


Figure 4. 12 Throughput measurement of WCDMA with different incoherent received AWGN power strength at mobile station and throughput of mobile station without external noise

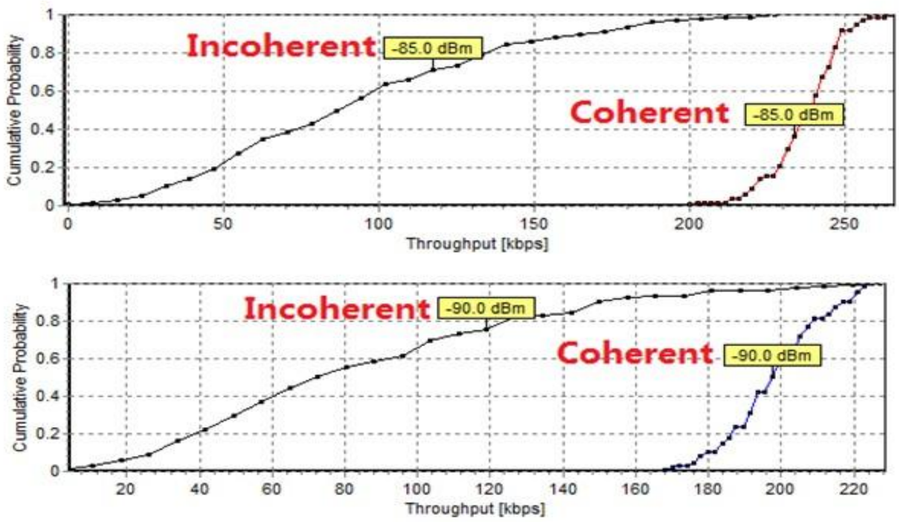


Figure 4. 13 CDF vs TPUT in different power with coherent and incoherent noise interference

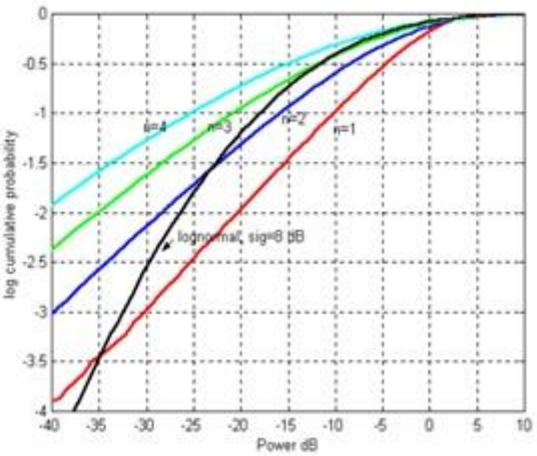


Figure 4. 14 CDF vs power for multiple Rayleigh distribution and a lognormal distribution for compassion [22]

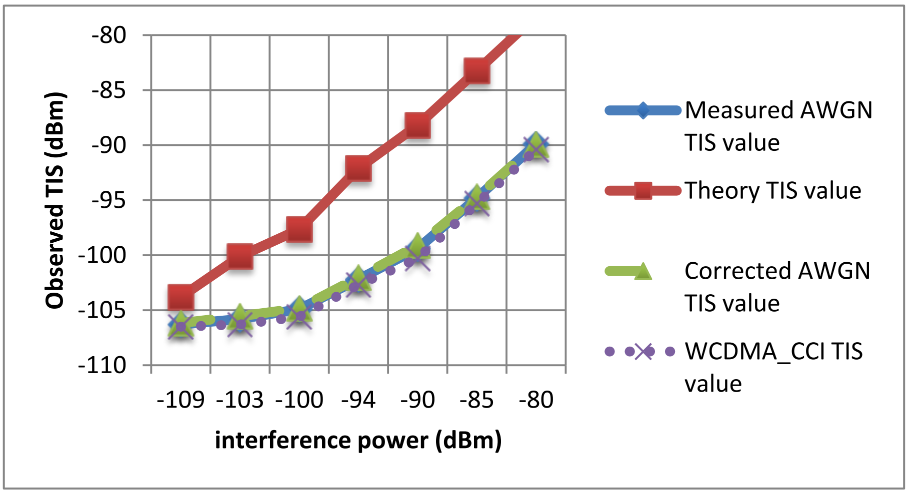


Figure 4. 15 TIS measurement with inter-cell co-channel interference and Corrected AWGN TIS value

4.5.3.2 Summary

The measurement is tested in Bluetest reverberation chamber RTS 60, seen from the figure 4-11. The measurement is under the condition of WCDMA signal with incoherent AWGN noise, the throughput of the system increases while boosting the base station power level. The slope of the curve is smoother compare to coherent AWGN interference and the slope of curve is similar to throughput measurement without external noise. But the throughput never reaches the maximum theoretically value. According to figure 4-14, with coherent AWGN noise interference, the slope of throughput cumulative probability is sharper; with incoherent AWGN noise interference, the cumulative probability of throughput distribution is more uniformly over whole power range since the interested signal and AWGN noise through different Rayleigh fading path, probability of received signal in lower power increased, so that the average received power and average throughput will reduce. Details are described in figure 4.14. The throughput always reaches 0 while with incoherent AWGN noise connection (no data exchange between base station and terminal), this phenomenon occurs even the average received power is much higher compare to received external noise power level. Compare TIS value with incoherent AWGN noise and inter-cell co-channel interference from figure 4.15, the TIS of two curves are close. It can be observed that interested WCDMA TIS value with incoherent AWGN interference and interested WCDMA TIS value with inter-cell co-channel WCDMA interference is almost overlapping, which means scenario of interested WCDMA TIS value with inter-cell co-channel WCDMA interference can be represented by interested WCDMA TIS value with incoherent AWGN interference. Conclusion can be written as the incoherent AWGN noise can be used for replacing the inter-cell co-channel WCDMA interference. The difference between TIS value of theory and with inter-cell co-channel is the reason of background noise is uncertain due to the IC structure of the devices.

4.6 Interference with LTE standard and simulate the effect of interference

4.6.1 Background

LTE is short for Long Term Evolution, which is the 4th generation communication standard. LTE supports high speed data and cell capacity for wireless terminals and mobile devices based on developing of 3GPP protocol. LTE meets the demand of telecommunication, radio, TV, internet, traditional information serves and so on. In order to penetrate to people's daily life, LTE design is based on all IP service provision capability, simplify network architecture, optimize performance of packet traffic, operation and interaction for better user experience. Specification of LTE supports downlink peak rate of 300 Mbit/s and uplink peak rate of 75 Mbit/s depending on 4*4 MIMO configuration using 20 MHz bandwidth. Ameliorate the cell boundary throughput [23] the network latency in radio access network less than 5 ms. LTE can able to handle multicast and broadcast streams. The carrier bandwidth can be choose from 1.4 MHz to 20 MHz and provide Frequency Division Duplexing (FDD) and Time Division Duplexing (TDD). The architecture of LTE network is designed to substitute GPRS network, support handover for both voice and data to base station and coexistence with older topology. LTE supports at least 200 active users in every 5 MHz cell and high rate mobility [24].

LTE CTIA 2*2 MIMO Open-loop standard parameters

- Measurement setup as CTIA MIMO Open-loop standard:
- Frequency: LTE Band 3 (mid-band):1842.5MHz
- UL&DL Bandwidth: 10MHz
- Duplex Mode: FDD
- Minimum Number of Subframe:20000
- DL Mod: 64 QAM
- DL subframe 1-4&6-9 TBS=18; subframe 0 TBS=17
- Transmission Mode: TM3(MIMO Open-loop)
- Number of DL Resource block:50
- DL Starting Resource block: 0
- UL Mode: QPSK
- UL TBS index: 6
- Number of UL Resource block: 50

- UL starting Resource block: 0
- Transmit power control: Tx power= constant
- PDSCH Power offset: Rho_a=-3dB Pho_b=-3dB

4.6.2 Simulate performance of LTE signal with incoherent AWGN noise

The success of MIMO technology arise the public enthusiasm in antenna industry, the Fourth Generation standard is continuously investigating in MIMO technology. More importantly, MIMO has become a mainstream technology since high throughput and low spread delay even at the cell edge, probably more and more wireless terminals and base station will utilize MIMO configuration antennas to enhance the performance of communication link in the future. Take an example, high quality data transmission protocols as HSPA, LTE and WiMax apply multiple antennas in both mobile station and base station. In a specific channel, property of packets successful delivered to receiver ratio is defined as Throughput. Moreover, data can be delivered over Mac layer and logical link layer, which is named Mac Throughput and IP Throughput, separately. MIMO system performance depends on characteristic of each antenna and channel circumstance. Unlike Single Input and Single Output measurement, more issues need to be considered. SISO measurement is built on uniform distribution field corresponding to 3D power forming and received sensitivity pattern measurement with an isotropic weighting. Therefore TIS measurement is no longer suit for MIMO measurement as channel characteristic is not considered in propagation model. To some extent, both throughput and receive sensitivity evaluate the performance of the system. However, throughput measurement is more suitable for multiple antennas configuration. The common point of TIS and throughput measurement is both of two measurements have to establish the BER measurement, the different of two measurements is TIS limited the link in certain BER threshold, but throughput measurement allows the BER variation range from 0 to 1. Throughput measurement could be operated in the anechoic chamber, but the time cost for single measurement explains this way of measurement isn’t a wise choose. Also, the complex configuration of MIMO measurement in anechoic chamber increases the difficulties [14]. Reverberation chamber fulfill the condition of Rayleigh fading environment with rich scattering, and perfect shielding room isolate the interference radio waves from outside, which can simulate the indoor and urban circumstance.

4.6.2.1 Setup

Experiment requirement:
LTE mobile station: LG P936
Base station simulator: R&S cmw500
Reference antenna (terminated)
Noise generator

Basic information:
Reverberation chamber: Bluetest 4*4 lab chamber
Delay spread: 84 ns (2 absorbers)

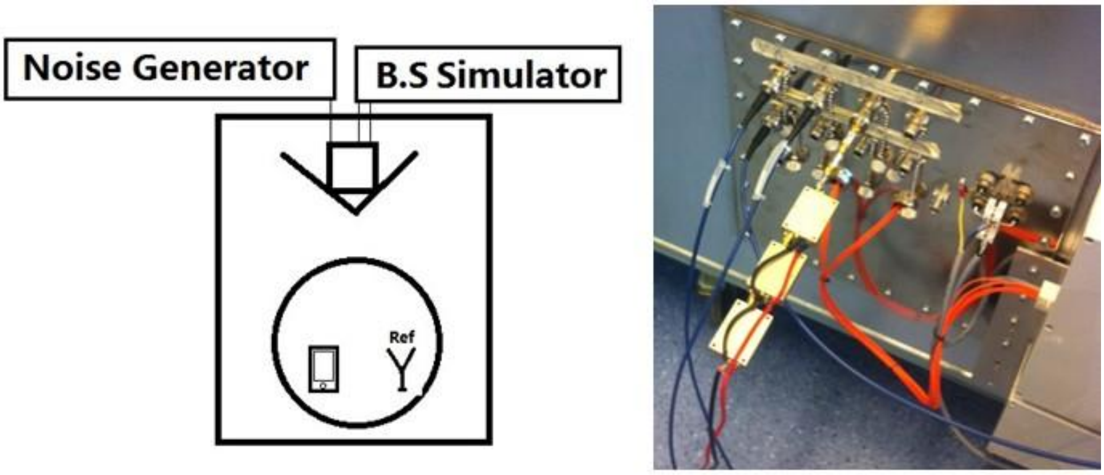


Figure 4. 16 Configuration and Scheme of LTE standard with incoherent AWGN noise

In this scenario, the base station emits the LTE signal with incoherent AWGN noise to the chamber, the LTE signal and AWGN will go through different fading patterns, which means the amplitude and phase at receiver are independently. Because the bandwidth of LTE, 10 MHz is chosen, is not same as WCDMA, output power of noise generator is -22.7 dBm in warm-up system. As measured, the TIS of LTE based on CTIA MIMO open-loop standard in LTE Band III are -78.1 dBm. The goals of this experiment is make a comparison to real LTE signal, so that add the attenuators at the output port of noise generator, which indicates the received power at mobile station should be equal to received real LTE signal. Although this way of modifying the output power of noise generator is not accurate, probably with ±1dB deviation. Connect noise generator with one port of the fixed antenna. Therefore, the base station signal and AWGN noise are transmitted through different Rayleigh fading to mobile station by switching the fixed antenna. The procedure will be listed as follows:

1. Perform the calibration measurement as mentioned before, including chamber calibration measurement; if it's done, skip step one.
2. Measure the loss of cable connecting base station simulator and fixed antenna in reverberation chamber.
3. Estimate the received noise power at mobile station by calculating power transfer function of chamber and noise generator. Connect the noise generator with certain attenuators to one of the port of the fixed antenna.
4. Connect between base station simulator and the test unit based on CTIA MIMO open-loop standard and enable the BER measurement.
5. Calculate the TIS and throughput of the system.

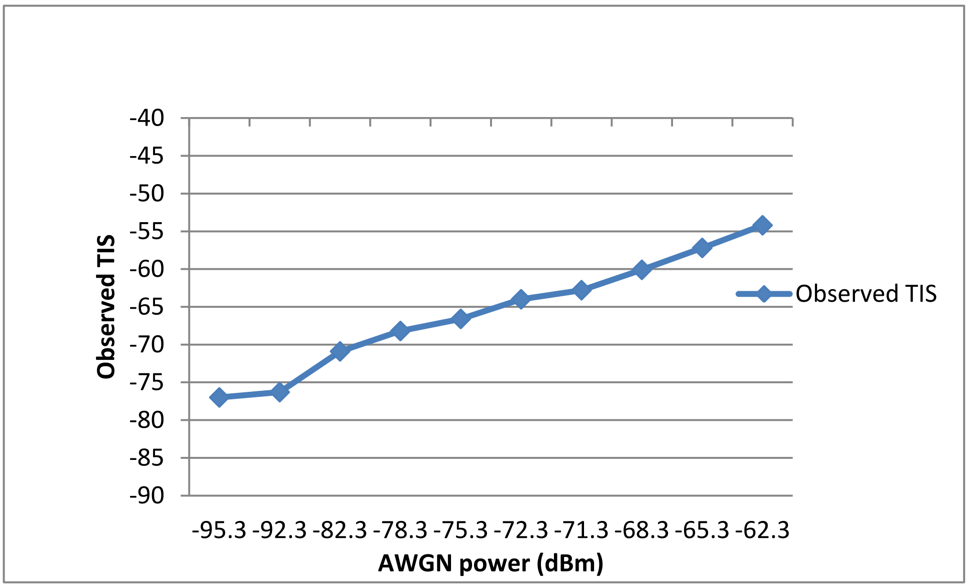


Figure 4. 17 LTE TIS measurement based on CTIA MIMO Open-loop standard with incoherent AWGN interference

4.6.2.2 Summary

The measurement is tested in Bluetest reverberation chamber Bluetest 4*4 lab chamber. Seen from the figure 4-16, with constant incoherent AWGN noise, increasing the incoherent AWGN power will reduce the TIS of the system. While the incoherent AWGN power is larger than -72.3 dBm, the ratio between observed TIS value to incoherent AWGN power is constant as 8dB. While the incoherent AWGN power is smaller than -72.3 dBm, the ratio between observed TIS value to incoherent AWGN power is increasing since the AWGN power reaches the sensitivity of mobile station. This phenomenon is similar to WCDMA TIS measurement with incoherent AWGN noise.

4.6.3 LTE TIS measurement with inter-cell Co-channel interference in SISO

Smart antenna system is a new technology use of multiple antennas to improve communication performance, and diversity technology is based on MIMO construction. As the name implies, MIMO means multiple input and multiple output. By choosing more than one antenna combined the transmit signal and receiving signal in multiple antennas, the diversity gain will be much higher than using one antenna in receiving system. Diversity gain is defined as power difference between combined antennas selection at 1% CDF reference level. Although with the configuration of combined antennas in very close distance, strong coupling occurred between the separate antennas and it presented as radiation efficiency drops. But it's also widely known that MIMO technology increases the system throughput significantly, so that MIMO draws high attention in wireless communication. In fourth generation communication standards (LTE), MIMO becomes a hot topic of discussion because MIMO combination improves the link reliability.

4.6.3.1 Setup

Measurement Setup:

Interested and interference base station simulator: R&S CMW 500
Interested mobile station: LG P936
Interference mobile station: SONY c503
Reference antenna
Circulator and Splitter

Basic information:
Reverberation chamber: Bluetest 4*4 lab chamber
Delay spread: 84 ns (2 absorbers)

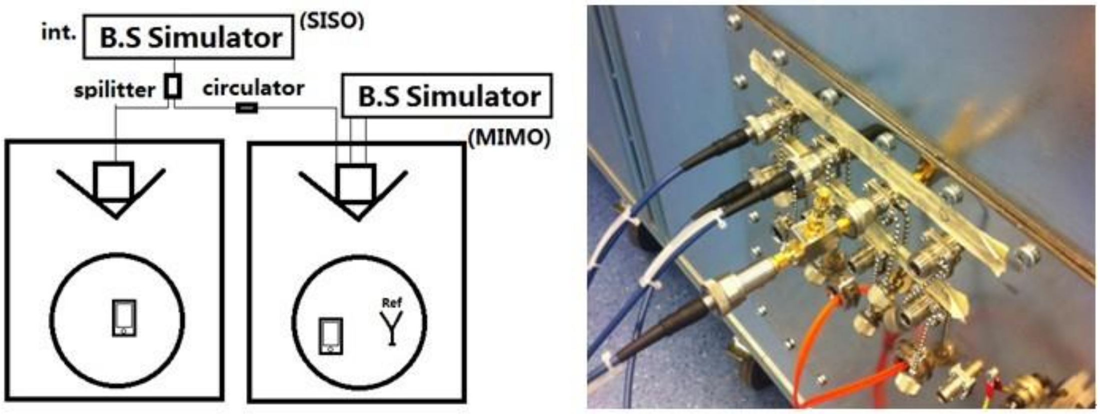


Figure 4. 18 Configuration and scheme of LTE signal with inter-cell co-channel LTE interference based on CTIA SISO Open-loop standard

The property of the circulator is listed as follows:

- Frequency: 1.7-2GHz
- Isolation: 20dB MIN
- VSWR:1:1.25 MAX
- Insertion loss: 0.5dB MAX

The aim of this measurement is to simulate the LTE interference and compare the result to incoherent AWGN noise to check if the AWGN noise can be represented for real LTE signal. It's been theoretically proved that AWGN can be represented for LTE signal in [30] [31] [32]. Since lack of the conductive cable to connect the interference DUT to base station, use an alternative solution as connecting the interference DUT in OTA. In this section, two chambers are ready for the measurement, one chamber is measurement chamber used for measuring the interested LTE status with interference, another chamber is used for building up the connection of interference DUT and base station, named as hook-up chamber. There is only one AWGN noise generator used in last experiment, therefore the connection of interference base station is LTE in SISO. Add the splitter at the output port of interference base station to separate the interference signal: one port of the splitter connects to the hook-up chamber; another port connects to one of the fixed antennas of the measurement chamber. The splitter is placed between the splitter and measurement chamber to isolate the interested LTE signal, so that the interested LTE signal doesn't flow back to destroy the link between interference base station and DUT. The procedure of this measurement can be listed as follows:

1. Perform the calibration measurement as mentioned before, including chamber calibration measurement; if it's done, skip step one.
2. Measure the loss of cable connecting base station simulator and fixed antenna in reverberation chamber.
3. Place the interference mobile station in hook-up chamber which based on CTIA MIMO open-loop standard and enable the BER measurement.
4. Separate the interference signal into two outputs by splitter, one cable attaches with the interference mobile station in hoop-up chamber; another port connects with one port of the fixed antennas of the measurement chamber. Add the circulator between splitter and measurement chamber.
5. Estimate the received noise power at mobile station by calculating power transfer function of chamber, splitter, circulator and noise generator. Connect the interference base station simulator and the interference DUT corresponds on CTIA MIMO open-loop standard and enable the BER measurement.
6. Connect between base station simulator and the test unit based on CTIA MIMO open-loop standard and enable the BER measurement.
7. Calculate the TIS and throughput of the system.

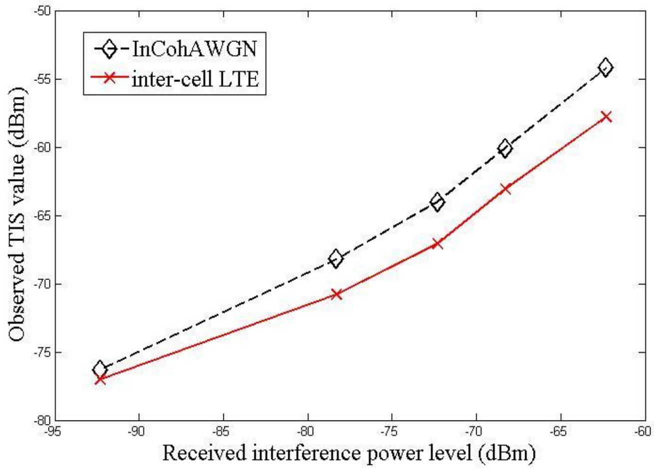


Figure 4. 19 TIS measurement of LTE inter-cell co-channel interference based on CTIA MIMO open-loop standard and incoherent AWGN noise interference

4.6.3.2 Summary

For specific frequency band with same standard, TIS value of different terminals are slightly different due to the structure of receiver. Observed from the figure 4.19, the TIS of LTE inter-cell co-channel interference based on CTIA MIMO open-loop standard is lower than incoherent AWGN interference. While the received power is below -92.3 dBm, the TIS value of incoherent AWGN noise is close to inter-cell LTE interference since the TIS value is approach to the sensitivity of the device. While the received power level is higher than -78.3 dBm, the difference between two TIS values is around 3 dB. Because of the limitation of the project time and accessing to the lab, no more measurements will be tested to explain the reason of 3 dB. Guess the 3 dB difference is on account of the CTIA standard setup, the power have to reduce 3 dB before the data transport in physical layer. For further work, do the same experiment except changing the physical layer parameter into 0 dB, or attaches the interference base station in MIMO configuration.

4.7 Coexistence between IEEE 802.11 WLAN and Bluetooth

4.7.1 Bluetooth Overview

Bluetooth technology is described as Wireless Personal Area Network (WPAN), widely accepted in modern terminals, used for cable replacement. WPAN is a standard of small-scale communication between digital assistant devices, mainstream technologies including Bluetooth, ZigBee, and Ultra-wideband etc, which are based on standard IEEE 802.15. Wireless PAN aims at interconnects communication devices and computer, probably covers a certain geographic area. Bluetooth, interconnecting among wireless devices over short distance, operates in globally unlicensed Industrial, Scientific and Medical (ISM) band at 2.4 GHz, bandwidth of each channel is 1 MHz and start from 2402 MHz to 2800 MHz, which means 79 Bluetooth channels are designed to transmit packet. Bluetooth uses 625 us slotted channel. Bluetooth is widely used in real-time isochronous connection such as headset, cordless cell-phone, but also Bluetooth supports for asynchronous connection for voice and data exchange in non real-time. A physical channel shares by two devices at least, which needs to be synchronized to same clock, Bluetooth master provides the synchronous reference, channel and phase, and other devices are treated as Bluetooth slaves. In one piconet communication network, one mater could exchange data up to seven slaves. Besides, device in one piconet could also play the role of master or slave.

Bluetooth utilizes Frequency-hopping Spread Spectrum (FHSS) [25] physical layer for transmitting radio signals by using a pseudorandom sequence, transmitter and receiver both know that, to swap signal carrier to other channels, each frame uses a single hop frequency for one timeslot. Such technology is highly resistant to narrow band interference and fading causes the limitation of the characteristic of Bluetooth. If the transmission environments is excellent, a single packet may allocated into several successive slots to enhance the bandwidth efficiency. Moreover, frequency hopping exists in both transmitting and receiving streams that means it fits the application of Time-Division Duplex (TDD) scheme. Gaussian Frequency Shift Keying (GFSK) is the modulation scheme of Bluetooth and maximum date rate of 1Mbit/s theoretically. In Bluetooth Version 2.0+ EDR, pi/4-DQPSK and 8DPSK modulation may be used, increasing data rate to 2Mbit/s.

4.7.2 Wi-Fi Overview

IEEE 802.11 standard is a specification for Wireless Local Area Networks (WLAN), [26] exchange information in unlicensed ISM band as Bluetooth. All the measurement of Wi-Fi standard is based on IEEE 802.11g as an extension of IEEE 802.11 specification, the maximum throughput is up to 54 Mbit/s with forward error correction technology. Standard IEEE802.11g and b works compatible in hardware, but the modulation of the standard g supports Orthogonal Frequency-Division Multiplexing (OFDM) which is different from the previous standard. The IEEE 802.11g working in the same frequency band as b, but it can provides high data rate since the modulation scheme. The bandwidth of 802.11g is 22 MHz and frequency range is from 2.401 GHz to 2.495 GHz and total number of channels is 14.

4.7.3 TIS measurement of Bluetooth with WLAN interference

4.7.3.1 Setup

Measurement setup:
Bluetooth simulator: Agilent N4010A
Bluetooth DUT: Samsung Galaxy S
WLAN simulator: Bluetooth TTS11
WLAN DUT: Samsung Galaxy S3LTE Golden device
Reference antenna

Measurement Specification:
Measurement Chamber: Bluetest RTS 60
Delay Spread: 137ns (without absorbers)
WLAN frequency: 802.11g Band I: 2412 MHz
WLAN Bandwidth: 22MHz
WLAN Modulation: OFDM
WLAN Packet count: 100
WLAN PER target limit: 10%
BT frequency: Band 10: 2412 MHz
Disabled Adaptive frequency-hopping
BT bits count: 10000
BT BER limit: 0.1%

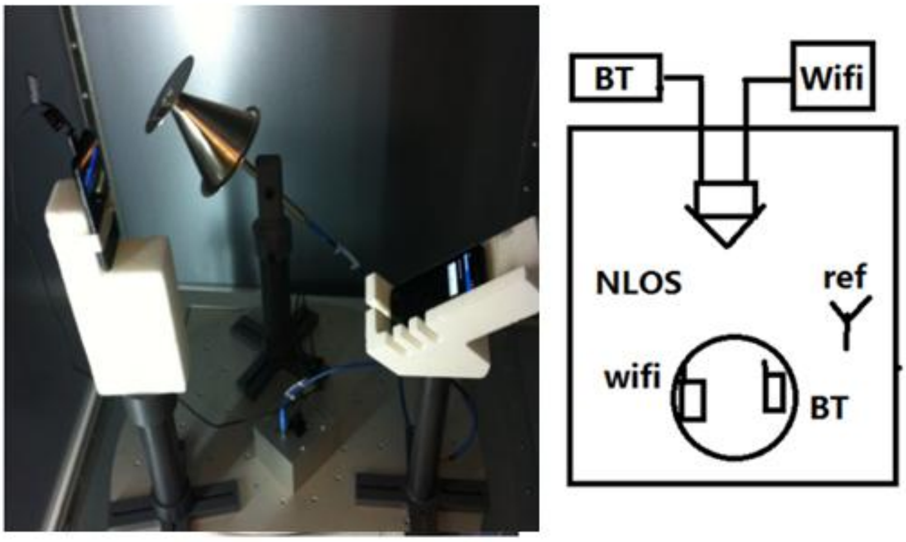


Figure 4. 20 Configuration and Scheme of Bluetooth TIS measurement with WLAN interference

According to IEEE 802.15 Working Group allows Bluetooth and 802.11 coexisting in the same atmosphere and has less influent with each other. The study shows that when the distance between interference source and interested system is less than 2m, the interference among Bluetooth and 802.11 will severely degrade the performance of each other [27] while the distance between interference source and interested system is larger than 2m, the interference among Bluetooth and WLAN will slightly degrade the performance of each other. It’s possible to coexistence between Bluetooth and 802.11 to decrease the mutual interference, but the prerequisite is two standards exist in different terminals [28].

The Bluetooth under testing device is Samsung series, the Bluetooth test mode can be settled by typing secret code. Since the Bluetooth technology is a short distance communication standard, it’s easily drop the connection with simulator when the output power is too low from the simulator or adds the external interference source besides the terminal. Repeat the TIS measurement of Bluetooth to investigate the result of 802.11 standard interference impacts. The TIS of Bluetooth on this specific device is -78.7 dBm without external interference.

Attach the WLAN DUT to base station simulator in static measurement. In other words, the mode stirrers are moving according to Bluetooth measurement. Transit the WLAN signal to DUT on 12 Mbps in downlink stream to stabilize the modulation [29], thus the output power from the WLAN simulator is constant. During the measurement, the power save mode of the device must be shut off. Does the throughput measurement of WLAN because the received power of WLAN signals (interference) can be estimated if the loss of chamber and cables connecting with simulator and chamber are known. A Key point of this measurement is the status between WLAN simulator and DUT should always be connected.

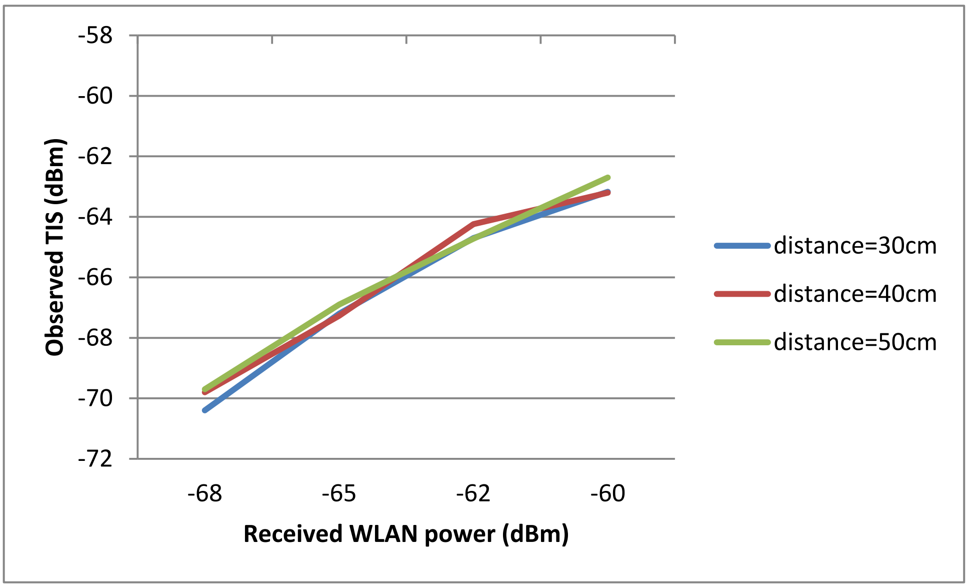


Figure 4. 21 TIS measurement of Bluetooth with WLAN interference in different distances

4.7.3.2 Summary

In order to guarantee the accuracy of the result, sequence of the measurement should ensure the successfully connection between the WLAN simulator and DUT before TIS measurement of Bluetooth. The estimated received WLAN signal is from -68 to -60 dBm, if decrease the received WLAN power continuously, the connection of WLAN is easily disconnect. For same reason, increase the received WLAN power to make it impossible to measure the Bluetooth TIS result. But if the interference power is too low compare to Bluetooth power, there won't be any varying in observed TIS value of Bluetooth. So that keep interference power in a certain range will increase the result accuracy. Increase the interference power level (WLAN), the Bluetooth TIS reduces and the increasing volume is almost linear. In this case, the WLAN signal transmits in LOS can be neglect since the direct coupling compare to chamber loss is low enough. Alter the distance between two DUTs in the chamber slightly changes the TIS value. Since the measurement is not based on device to device interference, change the distance between two devices won't affect the TIS value of Bluetooth. Although the WLAN is working in duplex mode, but the data transmits in the uplink is information correction which won't affect the Bluetooth performance. While increasing the WLAN power level, the observed TIS value of Bluetooth drops.

4.7.4 TIS measurement of WLAN with Bluetooth interference

4.7.4.1 Setup

Measurement setup:
Bluetooth simulator: Agilent N4010A
Bluetooth DUT: Huawei U8300 (standard)

WLAN simulator: Anritsu MT8860C
WLAN DUT: Samsung Galaxy LTE edition Golden device
Reference antenna

Measurement Specification:
Measurement Chamber: Bluetest RTS 60
Delay Spread: 137ns (without absorbers)
WLAN frequency: 802.11g Band I: 2412 MHz
WLAN Bandwidth: 22MHz
WLAN Modulation: OFDM
WLAN Packet count: 100
WLAN PER target limit: 10%
BT frequency: Band 6: 2408 MHz
Disabled Adaptive frequency-hopping
BT bits count: 10000
BT BER limit: 0.1%

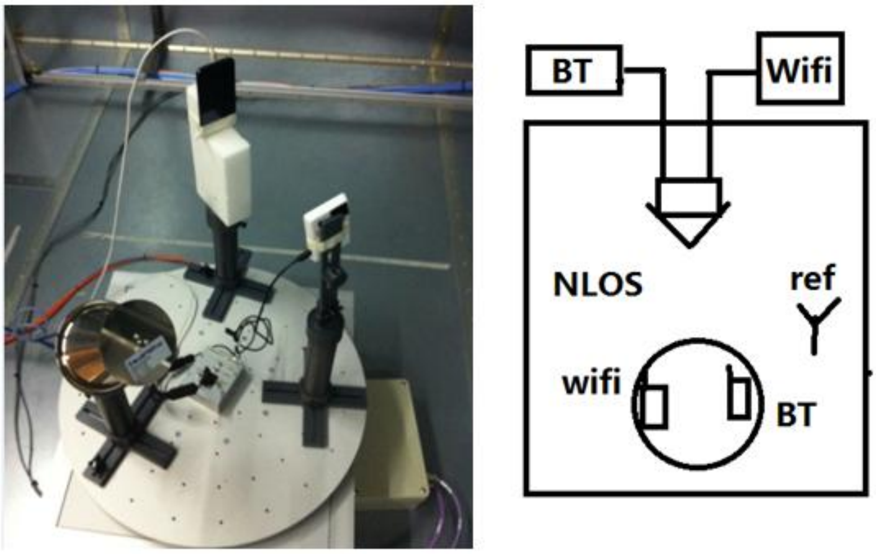


Figure 4. 22 Configuration and Scheme of 802.11 TIS measurement with Bluetooth interference

The Bluetooth under testing terminal is Huawei U8300 cell phone. It needs to be programmed to turn on the Bluetooth test mode to enable the measurement. In this case, the Bluetooth is measured for TRP because the scarcity of Bluetooth throughput measurement instrument. Attach the Bluetooth DUT to base station simulator in static measurement. In other words, the mode stirrers are moving according to WLAN measurement. The problem of this configuration is that the Bluetooth as interference source is transmitting in uplink at maximum power and Bluetooth is working on time division duplex, the interference effects on WLAN device is hard to calculate. The one provides the synchronization reference is marked as the Bluetooth master and other devices are known as slaves. In this case, the Huawei cell phone plays the role of Master and Bluetooth simulator as the slave. A Key point of this measurement is the status between WLAN simulator and DUT should always be connected. WLAN TIS result without interference is -91.6 dBm

Distance (cm)	20	30	40	50
TIS (dBm)	-79.7	-80.82	-81.63	-83.25

Table 4-4 802.11g standard TIS measurement in different distance with Bluetooth interference measured in TRP

4.7.4.2 Summary

The total radiated power of Bluetooth is stabilized at -11.4 dBm. Increase the distance between Bluetooth device and WLAN device, the impact from Bluetooth is decreased. The separation between two mobile stations increase for another additional 10cm, the TIS value of 802.11g reduces around 1 dB. This measurement is a device to device interference and it can be clearly seen that change the distance between devices affect the communication performance, especially the distance between devices is approaching.

Conclusion

In this thesis, it has been introduced the basic function of reverberation chamber and several interference scenarios are measured in reverberation chamber. The WCDMA inter-cell co-channel interference can be simulated in reverberation chamber. It's theoretically and experimentally proved that AWGN noise can be used to represent the WCDMA inter-cell co-channel interference via reverberation chamber. But there are 3 dB differences between real inter-cell co-channel interference and AWGN model based on LTE standard, since the limitation of the project time, the reason of that hasn't been figured out. Coexistence between WLAN and Bluetooth are measured in the reverberation chamber and both WLAN and Bluetooth interference can be modeled by AWGN noise.

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