AN IMPULSIVE NOISE ANALYSER USING AMPLITUDE PROBABILITY DISTRIBUTION (APD) FOR BROADBAND WIRED COMMUNICATION

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A thesis submitted in
fulfilment of the requirements for the award of the
Degree of Master of Electrical Engineering

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OCTOBER 2011

ABSTRACT

Electromagnetic interference or noise which is of impulsive nature is known to affect data communication performance. It is useful to correlate the characteristics of the noise with the bit error probability (BEP). The amplitude probability distribution (APD) has been proposed within CISPR for characterisation of the impulsive noise. However, there is no analyser available to perform direct measurement of the noise within the bandwidth of asymmetric digital subscriber line (ADSL2+) communication. This research presents a novel development of APD analyser for measurements of impulsive noise emission and its impact on ADSL2+ communication. A unique noise APD pattern is obtained from each measurement of noise emission from different electrical and electronic appliances. It is vital to have correct measurement set-up, signal power level, sampling rate, sample points and filter characterisation in order to acquire accurate data representation of the noise patterns. The APD graph is generated by the analyser using the APD algorithm method which employs the envelope sampling technique from actual probability. The noises are characterised using α-stable distribution which exhibits its own distinct APD parameters. The APD curve can be related with the single modulation scheme communication channel performance for estimation of bit error probability. The analyser has been developed successfully with dynamic range of 70 dB higher than the 60 dB CISPR 16 requirement, 0.02 dB amplitude resolution compared to 0.25 dB CISPR 16 requirement and 0.59 dB amplitude accuracy compared with the CISPR 16 standard of +/- 2.7 dB. In addition, the limits for noise in copper cable have been proposed for estimating the severity of the interference towards digital communication performance in ADSL2+ system. An advantage of the analyser is its ability to not only record the noise but the ability to regenerate back the noise which can be used for further analysis. In conclusion, the analyser can provide a comprehensive platform for impulsive noise interference verification towards ADSL2+ communication performance.

ABSTRAK

Gangguan elektromagnet atau hingar merupakan sifat dedenyut asli diketahui berupaya menjejaskan prestasi data komunikasi. Adalah amat berguna untuk mengaitkan ciri-ciri hingar dengan keberangkalian ralat bit (BEP). Keberangkalian agihan amplitud (APD) telah dicadangkan di dalam CISPR sebagai salah satu cara pengukuran pancaran hingar elektromagnet. Bagaimanapun, tidak terdapat penganalisis yang mampu mengukur hingar didalam lebar jalur komunikasi talian digit elektronik (ADSL2+). Penyelidikan yang dijalankan membentangkan hasil untuk memajukan alatan penganalisis APD bagi pengukuran terus pancaran dedenyut hingar dan hentaman terhadap komunikasi ADSL2+. Pelbagai corak unik ganguan akan didapati daripada setiap pengukuran pelbagai jenis peralatan elektik dan elektronik. Adalah amat penting semasa di dalam proses pengukuran penentuan cara pengukuran yang betul, kadar kuasa isyarat, kadar sampel, takat sampel dan ciri penapis elektronik di dalam mendapatkan hasil data tepat yang mewakili corak-corak hingar. Hasil graf APD didapati daripada alatan penganalisis APD yang menggunakan algoritma APD dimana sampel liputan pancaran hingar dikira daripada kebarangkalian sebenar. Ciri-ciri gelombang radiasi akan mengunakan kaedah taburan $\alpha-$stable yang mepunyai parameter-parameter tersendiri. Lengkung APD yang terhasil boleh dikaitkan dengan skema komunikasi modulatan tunggal dan kadar anggaran pretasi kebarangkalian ralat bit. Penganalisis telah berjaya dimajukan dengan julat dinamik 70 dB tinggi dari 60 dB spesifikasi CISPR 16, 0.02 dB peleraian amplitud berbanding 0.25 dB keperluan CISPR 16 dan 0.59 dB ketepatan amplitud berbanding +/- 2.7 dB piawai CISPR 16. Tambahan, had hingar pada kabel tembaga telah dicadangkan bagi anggaran keterukan gangguan pada pretasi digit komunikasi sistem ADSL2+. Satu kelebihan penganalisis APD bukan hanya boleh mengukur hingar tetapi berupaya menghasilkan semula pancaran hingar yang telah diukur bagi tujuan menganalisa dengan lebih mendalam. Dalam kesimpulan,

penganalisis ini akan menjadi satu pelantar bagi pengesahan gangguan pancaran hingar buatan manusia terhadap pretasi komunikasi ADSL2+.

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γ	-	Dispersion Parameter
α	-	Impulsiveness Parameter
β	-	Beta Constant Parameter
ADC	-	Analog to Digital Converter
AC	-	Alternate Current
APD	-	Amplitude Probability Distribution
AM	-	Amplitude Modulation
ADSL	-	Asymmetric Digital Subscriber Line
AWGN	-	Additive White Gaussian Noise
AWG	-	Arbitrary Wave Generator
BPSK	-	Binary Phase Shift Keying
BEP	-	Bit Error Probability
BER	-	Bit Error Rate
CDF	-	Cumulative Density Function
CISPR	-	Comité International Spécial des Perturbations Radioélectriques
CW	-	Continuous Wave
DC	-	Direct Current
DSL	-	Digital Subscriber Line
DSP	-	Digital Signal Processing
DSLAM	-	Digital Subscriber Line Access Multiplexer
DMT	-	Discrete Multi Tone
EMC	-	Electromagnetic Compatibility
EMI	-	Electromagnetic Interference
ESM	-	Equivalent Static Noise Model

EUT - Equipment Under Test
EN - Européen de Normalisation
FCC - Federal Communication Comission
FFT - Fast Fourier Transform
FIR - Finite Impulse Response
FPGA - Field Programmable Gate Array
GPS - Global Positioning System
GHZ - Giga Hertz
HSBB - High Speed Broadband
HDF - Hierarchical Data Format
HWS - Hierarchical Waveform Storage
HZ - Hertz
IEC - International Electrotechnical Commission
ISO - International Organization for Standardization
IF - Intermediate Frequency
IFD - Instantaneous Frequency Distribution
ITU - International Telecommunication Union
KHz - Kilo Hertz
LABVIEW - Laboratory Virtual Instrumentation Engineering Workbench
MHZ - Mega Hertz
MATLAB - Matrix Laboratory
OSP - On-board Signal Processing
PDF - Probability Density Function
PSD - Power Spectral Density
PSK - Phase Shift Keying
PXI - Modular Instrumentation Platform Designed for Measurement and Automation
PAM - Phase Amplitude Modulation
POTS - Plain Telephone Service
QAM - Quadrate Amplitude Modulation
RAM - Random Access Memory
RDSLAM - Remote Subscriber Line Access Multiplier

RMS - Root Mean Square

RF - Radio Frequency

SMC - Synchronization and Memory Core

SNR - Signal to Noise Ratio

UMTS - Universal Mobile Telecommunications System

VDSL - Very High Bit Rate Digital Subscriber Line

VCCI - Voluntary Control Council for Interference by Information Technology Equipment

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CHAPTER 1

INTRODUCTION

1.1 General

The technology of digital electronic systems and appliances are rapidly evolving for many applications. A household today has more electrical appliances than it did for the past ten years. Therefore the unintentional electromagnetic radiations from modern electronic systems have become increasingly difficult to control. Electromagnetic compatibility (EMC) has emerged as a branch of science and engineering concern to fulfill the needs of studying the relation between the immunity of electrical and electronic appliances toward electromagnetic interference and at the same time ensuring equipment to generate interference within specified limits.

Nowadays, the use of digital radio communication has become essential in human life. It has become a cultural necessity of an innovative lifestyle and entertainment tools. For example, devices like GPS navigator is equipped in middle - end and high-end modeled vehicles. Besides that the internet is an important tool for a global system of interconnected computer networks of academic, business and government networks are accessible by using medium of communication through copper wires, fiber-optic cables, wireless connections and other technologies. Understanding on the relations between the interference of electronic or electrical equipments and digital communication have become essential since the interference affect the communication system's capacity, robustness, reliability and availability. The interference phenomenon is called intersystem interference and is an inevitable in reality.

Current EMC standards cover all areas of interference and immunity in terms of radiation or conduction. All these standards and measurement set-up are well defined and illustrated in international standards (IEC, ISO, CISPR) and national standards (FCC, EN, VCCI). However, question arises whether current standards do consider the perspective of digital communication which mainly concerns the bit error probability of data received. The existing emission limits and requirements have been developed to protect analog amplitude modulated radio services. These limits are defined as the maximum allowable level of the measured peak and quasi-peak values of the radiated emission from the interference sources. However, the levels measured by the peak and quasi-peak detectors do not correlate with the impact of the interference source on a digital radio system [1]. The reason is that both detectors have been developed during the era of analog systems. Consequently, current electromagnetic compatibility analysers use these two detectors, which originally simulate human hearing perception of the disturbances on analog radio receivers [2].

The electromagnetic noises are the main elements to be studied in this research. The well known noise is called Additive White Gaussian Noise (AWGN), which exhibits an instantaneous level that varies following a normal random process of mean zero and variance equal to its mean power. Samples from this AWGN are independent, and they have a plain power spectrum with the same contributions in all the frequencies. AWGN does not represent a major problem in digital communication systems, as long as the mean power of the desired received signal is higher compared with the mean power of the noise itself. The other type of noise is called impulsive noise. This noise is not easily traceable. This noise is appearing unexpectedly as pulses of high amplitude. Typically the impulsive noises can be classified according to its origin such as natural noise and man-made noise. Most of the man-made noise originated from various electrical or electronic devices. These electrical or electronic devices are commonly co-located to the digital equipment communications system. As for digital communications, the impulsive noise is harmful because each pulse may causes bursts of bit errors and loss of synchronization. As the occurrence of noise pulses and its amplitude is so unpredictable, it makes it difficult to build digital communication systems that can avoid the effects of impulsive noise [3]. David Middleton [4]-[11] has divided the impulsive noise into three categories of bandwidth as listed below. Impulsive emissions mostly fall in Class B category.

(i) Class A: Impulsive noise with a bandwidth smaller than that of the receiver.

(ii) Class B: Impulsive noise with a bandwidth larger than that of the receiver.

(ii) Class C: A case that comprises Class A and Class B.

Two of the most popular and promising methods which presented a connection between the interferences and the performance of digital communication systems in term of bit error probability (BEP) are root mean square (RMS) detector, which uses existing standard detector [12]-[15], and amplitude probability distribution (APD), in which the information about the noise envelope statistics is obtained from the IF-filter. Both techniques successfully presented a connection between the interferences with the performance of digital communication and suggested possible new radiated emission standards. The BEP is the probability that the digital receiver makes an error in the decision of what kind of data bit that has been received.

1.2 Problem Statement

The digital subscriber line (DSL) technology has been widely used in Malaysia for accessing the broadband Internet. The DSL technology uses the existing local telephone network for transmitting high speed digital data. Service providers are able to provide the service at affordable service price since there is no cost of new cable layout. The DSL communication which is specifically a system that uses symmetric digital subscriber line (ADSL2+) system has covered almost 98% of broadband connections [16]. The unshielded nature of twisted telephone pair causes the ADSL2+ system to be vulnerable from electromagnetic interference of the man made noise [17]. As observed in Figure 1.1, around 30% of customers have lodged complains on the quality of ADSL2+ services. Up to now, there is no equipment available in the market that is able to analyze the interference within the bandwidth of ADSL2+ systems. This is because existing equipment manufacturers such as Rohde & Schwarz, Agilent and Anritsu are developing the test equipment for wireless and fiber communication system which have high potential market demands compared to ADSL2+ system. Therefore the ADSL service provider such as Telekom Malaysia needs to develop their own methodology and test equipment to fulfill their operation needs. The challenges to fulfill these requirements are to develop reliable and accurate test equipment which is useful in troubleshooting current problems. Many problems which are currently faced by the ADSL service provider cannot be answered which eventually lead to unsolved problems. Furthermore, these unsolved problems eventually affect the service quality performance of ADSL2+ system. Everyday complains are lodged by the customer service center and service providers are struggling to solve the current problems with limited tools capability. It is clear that there is an urgent need for an analyser which is able to characterise the noise that affect the performance services.

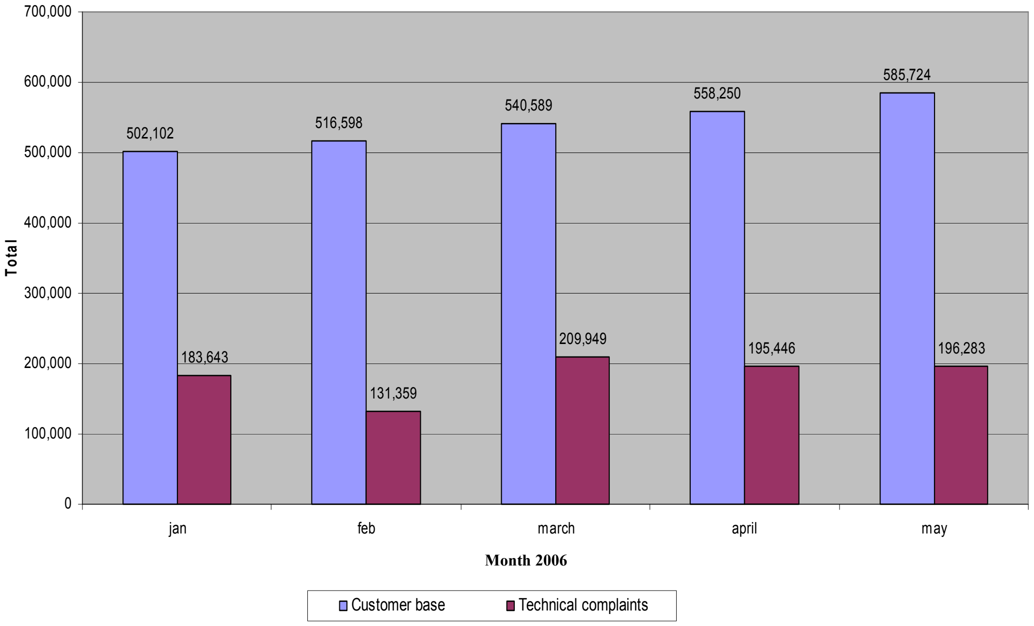

Figure 1.1: The ADSL2+ customer base and technical complains [18]

1.3 Aim of Research

The aim of this research is to develop and verify an amplitude probability distribution (APD) analyser to characterize the impulsive noise generated by various interference sources for evaluation of the bit error probability (BEP) for an asymmetric digital subscriber line (ADSL2+) system.

1.4 Objectives of Research

The objectives of this research are as follows:

(i) To develop a technique for impulsive noise interference measurement within the bandwidth of ADSL2+ system.

(ii) To assess the impact of impulsive noise on the quality of ADSL2+ communication in terms of bit error probability (BEP).

(iii) To calibrate and verify the performance of an ADSL2+ APD analyser based on international standard CISPR16-1-1 APD requirements.

(iv) To propose new limits threshold level for the impulsive noise that is being coupled to the copper cable.

1.5 Research Scope and Limitations

This research cover three important aspects of work namely measurement of impulsive noise, software development to analyse the noise and verification of the analyser performance based on requirements outline in CISPR 16-1-1 APD requirements [19]. The scopes and limitations of this research are given as follows.

(i) The research used an amplitude probability distribution (APD) methodology to measure electromagnetic noise emissions within ADSL2+ communication frequency bandwidth and verification of its impact towards digital communication. APD is chosen as the methodology because it can be related with the basic modulations schemes for single channel carrier analysis. Other types of communication system apart from ADSL2+ are not considered in this research.

(ii) The interference noises are characterized by using the α-distributions statistical parameters alpha (α) that represent the impulsiveness and gamma (γ) that represent the dispersion. Other types of statistical distributions are not considered in this research.

(iii) The analyser is verified according to the CISPR 16-1-1 APD requirements.

(iv) The hardware of analyser is consisting of on-shelf digitiser module, arbitrary wave generator (AWG) module and modular instrumentation platform based on PXI module.

1.6 Contributions

The Malaysian telecommunications market has expanded rapidly and the country is moving forward with the implementation of High Speed Broadband (HSBB) service. The ADSL2+ usage is expected to be the main application for broadband access. Thus, the need for ADSL2+ performance assessment tool is crucial for the service provider to provide optimal service performance. Copper access transmission systems such as ADSL2+ are required to operate in harsh physical and electromagnetic environments that are limited by variety of performance-limiting impairments. These impairments can be broadly classified as intrinsic or extrinsic noise impairments [20]. Examples of intrinsic noise impairments are thermal noise, echoes and reflections while extrinsic noise impairments are impulsive noise from man-made equipments, electric fences, power lines, switches, electrical appliances, and so forth. Moreover, copper cables cannot be screened and are often hung from poles. Therefore it has the capacity to act as an antenna. This implies that it can pick up radiated emissions which may be the sources of interference to ADSL2+ systems. It is vital that both of these possibilities are well understood and their impact controlled in this research. The outcome of this research is expected to provide the service provider with the analyser that has the capability to analyse the electromagnetic interference noise within frequency bandwidth of ADSL2+ receiver. This analyser will have the capability to measure the interference and relate with multiple type of communication modulations performance. Currently there are no other types of analysers that have this capability in the market.

1.7 Organisation of the Thesis

This thesis aims to outline the research and development of new APD analyser for ADSL2+ communication and the verification method to verify the developed analyser following the CISPR 16-1-1 APD requirements. The outlines of the thesis are as follows.

Chapter 2 presents summary of the important works in development of digital communication interference analyser and measurement methods. It starts by outlining the fundamental characteristics and concepts of ADSL2+ fixed line communication system, APD methodology and α-stable distribution principles. The review of important research works related to the concept of APD methodology and BEP is then presented. The previous works on development the method of analysing electromagnetic interference impact with digital communication is also explained in detail. The current available developed analyser limitation and urgent need on a new type of analyser for fixed lined communication are eventually triggered the aims and purpose of the research works. The efforts to develop the ADSL2+ APD analyser are highlighted in Chapter 3.

Chapter 3 describes the methodology used to develop the APD analyser and its measurement methods which begin with the review of measurement procedures. The analyser development can be divided into two parts, which are the concept of hardware design and software design. The hardware design starts with the concept of digitiser based on modular instrumentation platform designed for measurement and automation (PXI). The anti aliasing filter is explained as the front end filter of APD analyser. The analyser software system architerature are divided into five main modules, which are Data Acquisition Module, Statistical Analysis Module, Frequency Analysis Module, Bit Error Probability (BEP) Analysis Module and Noise Generation Module are explained in detail.

In Chapter 4, the developed analyser is measured and verified according to the international standard CISPR16-1-1 APD requirements. All specifications in the standard are measured and the results are compared to verify the analyser accuracy. The results of laboratory and field site measurements are also presented in this chapter in order to explain the usefulness of the invention.

Finally, in Chapter 5, the conclusions and impact of the analyser invention are summarised and suggestions for the future work are presented.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

In this chapter, the explanation concept of DSL system, amplitude probability distribution (APD) methodology, α-stable distribution principle and bit error probability (BEP) are described. The reviews of the works to study the APD are presented since early 1970 until recently. The limitations of the previous works are also highlighted with the improvements that will be implemented in this thesis. Finally, this research works is put in context with current research activities.

2.2 Explanation on DSL System

The digital subscriber line (DSL) is a form of digital data communications technology that enables faster data transmission over copper telephone lines which utilises frequencies that are not used by a voice telephone call. DSL service is introduced in 1995 [21] and the most used broadband internet delivery method for residential customer in the world and Malaysia specifically [16]. Deliveries of DSL services require a single copper pair configuration of a standard voice with a DSL modem at each of the line. This creates three information channels separated at different frequency bands which are plain telephone service (POTS) channel for voice, upstream channel for communication from the end user to the telephone central office and downstream channel for communicating the central office and the end user. There are numerous DSL standards, but in this research the focus is on ADSL2+ because of it world wide popularity and widely used in Telekom Malaysia fixed line network. ADSL2+ is standardized in ITU G.992.5, which uses discrete multi tone (DMT) modulation. In the standard, the frequency band from 25.875 kHz to 138 kHz is used for upstream communication, while 138 kHz – 2200 kHz is used for downstream communication. Each of these is further divided into smaller frequency sub channels of 4.3125 kHz. The ADSL2+ frequency plan is shown in Figure 2.1.

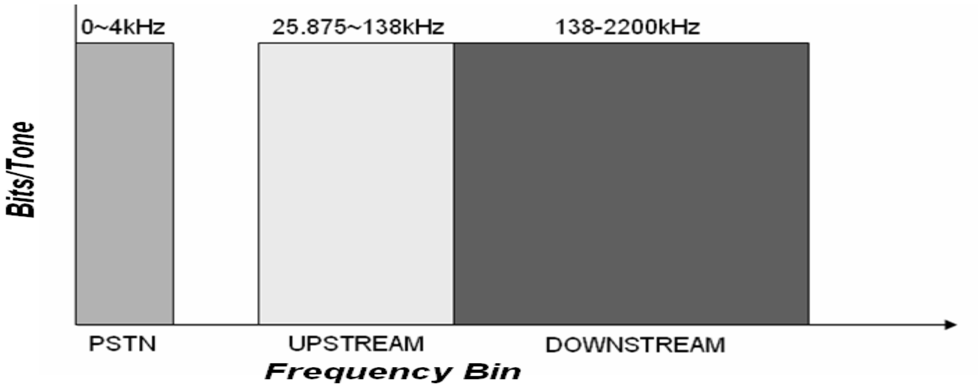

Figure 2.1: The frequency plan for ADSL2+ system based on ITU G.992.5

The data rates for downstream can be as high as 24 Mbps and 1.4 Mbps for upstream depending on the distance from the digital subscriber line access multiplexer (DSLAM) to customer home. Higher downstream bit rates are achieved via transmission asymmetry, using a wider bandwidth downstream transmission and a narrower bandwidth for upstream transmission. The ADSL2+ uses the discrete multi tone technique (DMT) which is a multi-carrier modulation technique. The basic idea of DMT is to divide the available bandwidth into parallel sub channels or tones. The incoming serial bit streams are divided into parallel stream which are used in QAM (quadrature amplitude modulation) or PSK (phase shift keying). The ADSL2+ usually provides fixed quality bit error probability (BEP) of 10^{-7} or less [21]. In particular, ADSL2+ uses variable constellation sizes and sophisticated bit allocation algorithms in order to best determine where to distribute energy in the usable bandwidth. This includes the operation of initialisation and steady state adaptation. Before steady transmission can occur, the modems on either side of a line must execute a coordinated initialisation procedure. A key step during the initialisation procedure is the training process in which the transceiver evaluates the quality of the line by measuring the attenuation or gain and signal to noise ratio (SNR) per tone. The low-constellation training signal will decide the constellation size and the maximum data rate sustainable to the copper loop with BEP of 10^{-7} or less. During initial training, the ADSL2+ modem tests each of the bins to establish the signal-to-noise ratio at each bin's frequency. Cable attenuation, interference on the copper wire such as amplitude modulation (AM) radio stations and electrical interference noise at the customer premises are the causes of poor frequencies propagation. A poor signal-to-noise ratio measured at certain frequencies unable those bins to be used, thus resulting slow speed connection of actual throughput receive by the ADSL2+ user. At this stage, the APD analyser developed in this research is crucial to identify the sources of noise causing the performance degradation of ADSL2+ system. The ADSL2+ modem will be able to make a plan on how to exploit each of the bins which is known as "bits per tone" allocation. Those tones that have good signal to noise ratio (SNR) will be chosen to transmit signals from a greater number of possibilities encoded in each main clock cycle. The number of possibilities must not be so large that the receiver might miscalculate the intended tones in the presence of noise. The channel with higher noise level may only be required to carry few bits and it can be as low as one bit per tone in the case of ADSL2+. In a worst case, noisy sub channel will not to be used at all [22]. The pattern of noise will be varying time to time and the DSL modem can alter the bits per tone allocations by a process known as “bit swap”. During this process, sub channels which are noisy will be adjusted to carry fewer bits and other sub channels with higher SNR will be chosen to carry higher bits allocation. Therefore the data transfer capacity of ADSL2+ modem will change from time to time because it depended on the total bits per-tone allocations of all the combined sub channels. In other words higher SNR ratios of overall ADSL2+ sub channels will provide a higher total link capacity and vice versa.

2.2 Amplitude Probability Distribution (APD) Principle

The APD function is used in EMC engineering to describe signal amplitude statistics. Today many EMC engineers are unfamiliar with APD and its applications because most modern receivers are designed to operate in frequency band where AWGN dominates and completely characterised by the average noise power statistic alone. On contrary, APD approach is used to characterise the amplitude statistics of non-Gaussian noise produced from man-made electrical equipment or appliance.

The noise signal s(t) captured by a receiver can be expressed mathematically as [23]:

$$s(t) = X(t)\cos(2\pi f_c + \theta(t)) \tag{2.1}$$

where $X(t)$ is the baseband envelope, $\theta(t)$ is the baseband phase and f_C is the carrier frequency. The amplitude X which is the absolute positive values appears as a random variable with the set of sampling $\{X_0, X_1, \ldots. X_m\}$. The percentage of noise envelope time existence at certain threshold level, phase and frequency bandwidth will be measured in order to obtain the probability of the noise amplitude, as shown in Figure 2.2. The probability density function (PDF) which expresses the probability of existing random variable X_m for the m number of samples of sampling is obtained during the measurement. PDF values are positive and area under PDF graph is equal to one. The discrete PDF can be estimated from histogram plot. The discrete value of cumulative density function (CDF) is obtained by integrating the discrete PDF and vice versa for all X_i, where values for i is less than or equal to m. Since EMC engineers are more concerned about how the noise envelop exceeds certain level; they prefer to use the complementary of the cumulative distribution function (CDF) which is known as APD. The discrete APD can be obtained by subtracting the discrete CDF value starting from value one until it becomes zero again. Figure 2.2 shows the percentage of time where the noise envelope exceeds a threshold level and can be represented in APD Equation 2.2.

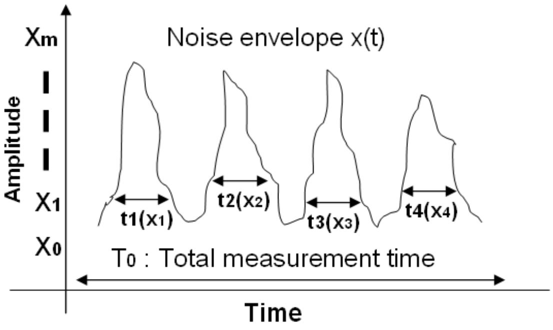

Figure 2.2: The APD graph probability concept [1]

$$APD(X_m) = \sum_{i=1}^{m} t_i(x_i) / T_0 \tag{2.2}$$

It is well explained in [24] that in order to plot the APD graph, probability of time for the amplitude occurrence is on y axis and log scale of the amplitude is on x axis. An example of APD graph is shown in Figure 2.3. Equation 2.2 is differentiated in order to obtain the probability distribution function PDF as given in Equation 2.3. The PDF function which is represented by f_{X_m} can be calculated for each interference source.

$$f_{X_m} = -\frac{d}{dx} APD(X_m) \tag{2.3}$$

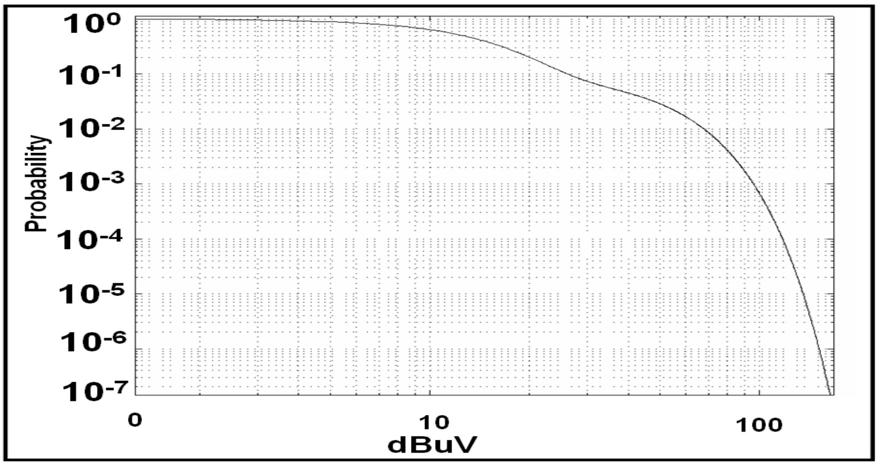

Figure 2.3: The example of APD graph [1]

Typically during the measurement for obtaining f_{X_m} the system noise floor should be lower than the measured envelope of impulsive noise. f_{X_m} has normally been accepted to follow the Rayleigh's function by most EMC engineers to represent the noise amplitude probability distribution [25]. However, from the view point of digital communication research community, the symmetric α-stable distribution has a more comprehensive statistical representation of impulsive phenomena towards signal processing and communication [26]-[27].

2.4 α-Stable Distribution Principle

The α-stable distribution is an important statistical tool to evaluate the characteristics of impulsive noise, which has received growing interest from the research community as statistical models for a broad range of impulsive phenomenon. In addition to its appealing analytical properties, the α-stable model provides physical insight into the noise generation process and is found to agree very well with the measured data of a variety of man made and natural noise [21] and [26]-]27]. A random variable is α-stable if the Fourier transform of its density function follows the form as in Equation 2.4 [21]:

$$\varphi(t) = \exp(-\gamma|t|^{\alpha}) \tag{2.4}$$

Alpha (0<α<2) is a shape parameter that control the impulsiveness and gamma (γ) parameter, which is also known as the scale parameter, controls the dispersion. Unfortunately, no closed form expression exist for general stable density except for some limiting cases such as the Gaussian (α=2) and Cauchy (α=1). In general α-stable distributions have heavier tails than the Gaussian model and constitute a very flexible modeling tool because the parameter α allows simulation of noise with continuous range of impulsiveness. A smaller α represents higher impulsiveness, while a value of α close to 2 represents a Gaussian type of behavior. The α-stable is appropriate especially for characterizing and capturing the multi shape noise distribution. In the case that X is α-stable with dispersion γ and impulsiveness α , its APD can be calculated as in Equation 2.5 with t respect to time [21]:

$$P(|X|>x)=1-\frac{2}{\pi}\int_0^\infty \frac{\sin tx}{t}\exp\left(-\gamma t^\alpha\right)dt \qquad (2.5)$$

The APD of α-stable noise can further be represented for various ranges of α as given in Equation 2.6 [21].

$$P(|X|>x)=\begin{cases} \dfrac{2}{\pi\alpha}\displaystyle\sum_{k=1}^{\infty}\frac{(-1)^{k-1}}{k!k}\Gamma(\alpha k+1)\sin\left(\frac{k\alpha\pi}{2}\right)\left(\frac{|x|}{\gamma^{1/\alpha}}\right)^{-\alpha k}, & 0<\alpha<1 \\ 1-\dfrac{2}{\pi}\arctan(x/\gamma),\ \alpha=1 & \\ 1-\dfrac{2}{\pi\alpha}\displaystyle\sum_{k=0}^{\infty}\frac{(-1)^{k-1}}{(2k+1)!}\Gamma\left(\frac{2k+1}{\alpha}\right)\left(\frac{x}{\gamma^{1/\alpha}}\right)^{2k+1}, & 1<\alpha<2 \\ 1-\operatorname{erf}\left(\dfrac{x}{2\sqrt{\gamma}}\right),\ \alpha=2 & \end{cases} \qquad (2.6)$$

where $\Gamma(x)=\int_0^\infty t^{x-1}e^t dt$ is the gamma function and erf(x) is the standard error function.

2.5 Relationship between APD and Bit Error Probability (BEP)

Kia Wiklund [1] shows that APD can be related to the performance degradation of a digital data communications. The impulsive noise is initially measured within the communications bandwidth, digitized and analysed to produce the APD graph. The BEP is then calculated for estimating the impact of the impulsive noise towards communication performance degradation. The main issue for determining the impact of an interfering signal is the envelope and phase of the resultant signal when the decision is made at the detector. As an example, when it is assumed that the “+1” is transmitted in coherent binary phase shift keying (BPSK) modulation, the decision variable at the receiver is described in Equation 2.7 and illustrated in Figure 2.4. r is a bit amplitude vector which represents the combination between bit energy E_b and additive white Gaussian noise n. n has zero mean and variance σ^2. The vector r can fall into correct decision “1” region or incorrect decision “0” region depending on the contribution of the noise component n.

$$r = \pm\sqrt{E_b} + n \tag{2.7}$$

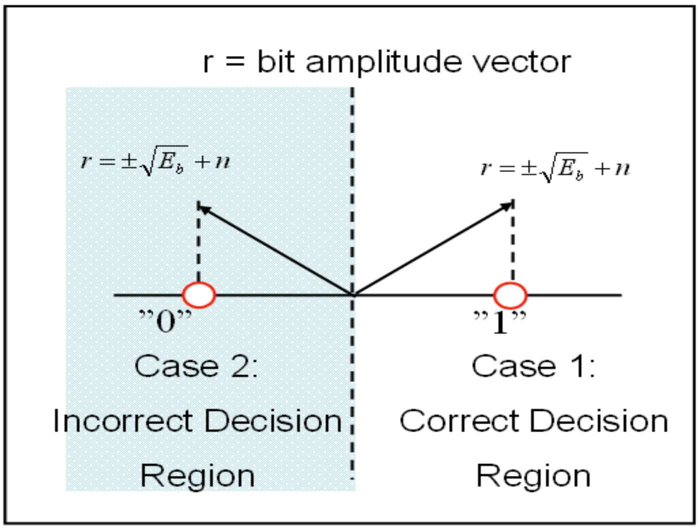

Figure 2.4: The decision status for vector r

The BEP (P_b) can be derived as given in Equation 2.8; where Q function is the area under Gaussian PDF represented by Equation 2.9 and illustrated in Figure 2.5.

$$P_b = Q\left(\frac{\sqrt{E_b}}{\sigma}\right) \tag{2.8}$$

$$Q(v) = \frac{1}{\sqrt{2\pi}}\int_v^\infty \exp\left(\frac{-x^2}{2}\right)dx \tag{2.9}$$

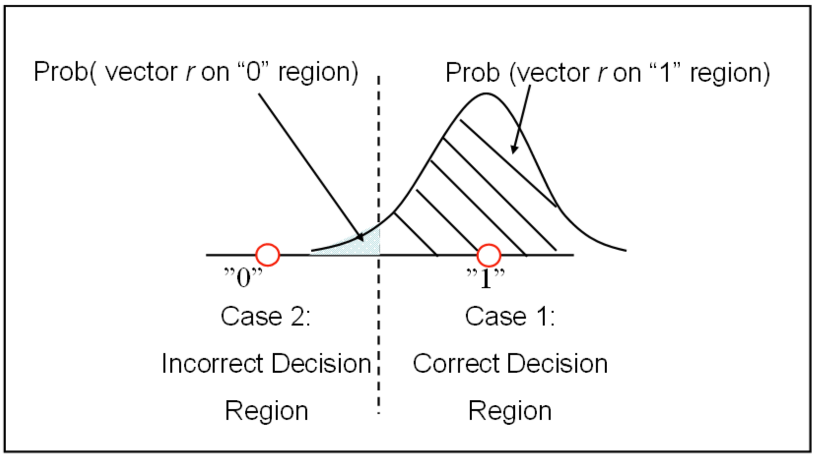

Figure 2.5: The illusration of BEP in BPSK

In the case of BPSK, the bit amplitude vector is r_1 with impulsive interfering signal $r_i \cos\varphi$ represented by $r_1 = \pm\sqrt{E_b} + r_i \cos\varphi$. r_i is the incoming interference envelope and φ denotes the phase. Thus, the substitution of E_b with r_1 in Equation 2.8 has results in conditional error probability adjusted for the interfering signal, as shown in Equation 2.10. Figure 2.6 illustrates the effect of incoming impulsive interference on BEP.

$$\Pr_1\left[biterror \mid r_i, \varphi\right] = Q\left(\frac{\sqrt{E_b} + r_i \cos\varphi}{\sigma}\right) \tag{2.10}$$

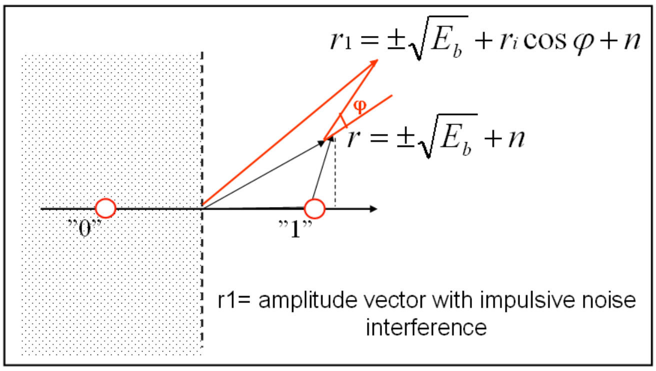

Figure 2.6: The illustration of bit amplitude vector with impulsive interference

The total bit error probability $\Pr[biterror \mid r_1]$ is represented in Equation 2.11 [1]. Substitution Equation 2.10 into Equation 2.11 and assuming that the phase at the moment of decision is uniformly distributed over [0, 2π], will yield the bit error probability (*Pb*) as shown in Equation 2.12. The probability density function of the envelope, $f_R(r_i)$ which is obtained from APD analyser, is added into Equation 2.12 to represent the probability of envelope interference.

$$\Pr[biterror \mid r_1] = \int_0^{\infty} \Pr_1[biterror \mid r_i, \varphi] dr_i \qquad (2.11)$$

$$P_b = \frac{1}{2\pi} \int_0^{2\pi} \int_0^{\infty} Q\left(\frac{\sqrt{E_b} + r_i \cos\varphi}{\sigma} \right) f_R(r_i).dr_i.d\psi \qquad (2.12)$$

Equation 2.12 shows that the APD can provide estimation of interference signal influence towards degradation on a digital communication with the additional $f_R(r_i)$ function and probability of amplitude vector r_1. Therefore this equation could be manipulated to yield the results to restrict the maximum allowed APD which eventually will cause the undesired results of BEP.

Equation 2.12 can further be simplified by neglecting the presence of AWGN. This is because the AWGN characterisation is understand and easily predicted during development of data coding. The impulsive noise instead is unpredictable, has high amplitude and key factors that contribute towards higher BEP [28]. Therefore the probability of interference r_1 is only to be considered for estimation of BEP. In this thesis, BPSK modulation technique is chosen to illustrate the relation between BEP and APD in order to proceed with the general approach. For coherent BPSK receiver without AWGN, decision variable is represented by $r_1 = \pm\sqrt{E_b} + r_i \cos\varphi$ for "+1" transmitted bit. The conditional error probability on certain phase φ is represented by Equation 2.13 [1] in which the probability of bit becoming "0" is given. Equation 2.13 is equal to the integration of the PDF function $f_R(r_i)$ that represents the probability of impulsive interference. This is equal to the value of APD function at bit energy $\sqrt{E_b}/(\cos\varphi)$. Figure 2.7 shows the possibility of making the wrong decision due to impulsive noise if the transmitted bit is “+1”.

$$\Pr[biterror|\varphi] = \Pr[\pm\sqrt{E_b} + r_i\cos\varphi < 0|\varphi : \pi/2 \le \varphi \le 3\pi/2] \tag{2.13}$$

$$= \int_{\sqrt{E_b}/\cos\varphi}^{\infty} f_R(r_i)dr_i = APD\left(-\frac{\sqrt{E_b}}{\cos\varphi}\right)$$

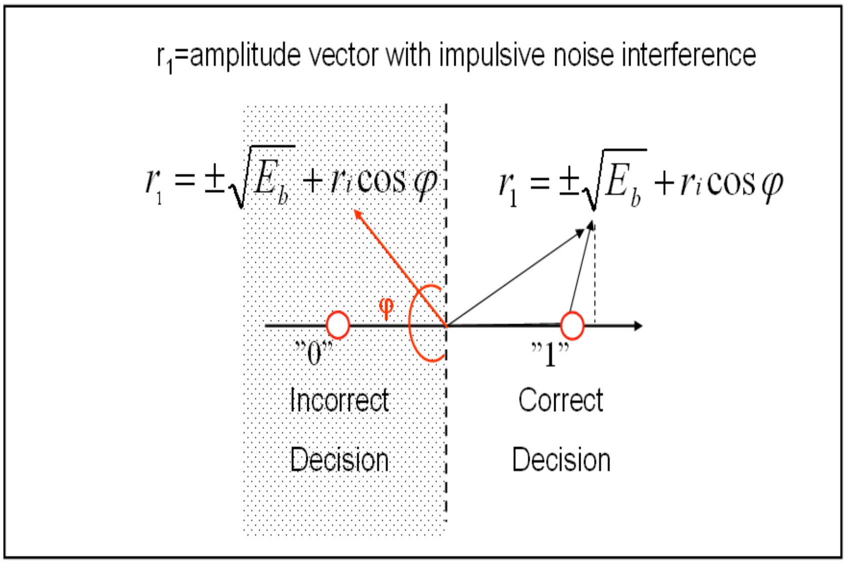

Figure 2.7: The illustration of bit amplitude correct and incorrect decision in BPSK

Equation 2.13 shows that the value of APD is directly correlated to the conditional error probability $\Pr[biterror|\varphi]$. By assuming the worst possible phase value of $\varphi = \pi$ (cos(π)= -1), a relation between the maximum bit error probability and the APD is obtained as represented by Equation 2.14.

$$P_{b,\max} = \Pr\left\lfloor\sqrt{E_b} - r_1 < 0\right\rfloor = APD\ (\sqrt{E_b}) \tag{2.14}$$

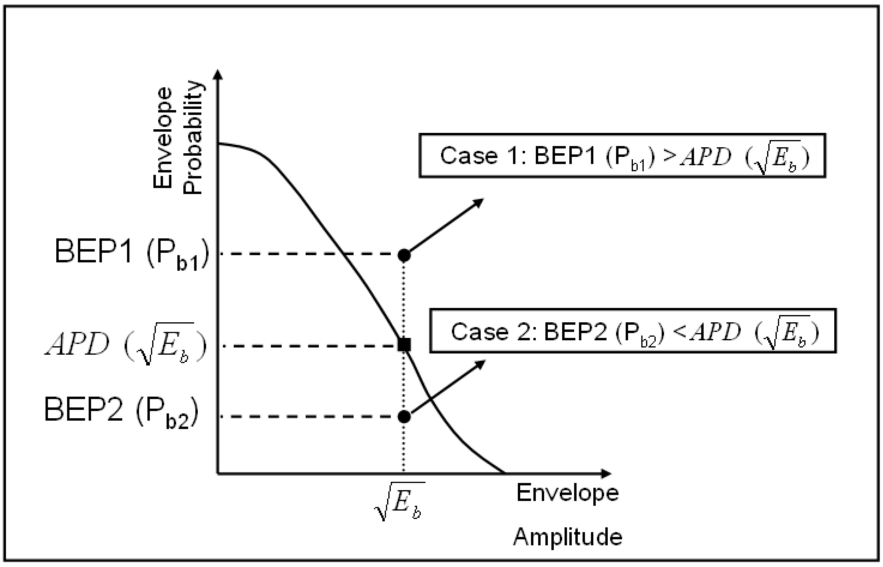

Figure 2.8: The illustration of calculated BEP (P_b) vs APD for define $\sqrt{E_b}$.

Figure 2.8 illustrated that the APD graph of a measured interference source for a certain $\sqrt{E_b}$, must not exceed the BEP requirement in order for the digital communication to transmit the data. In case 1, the BEP1 requirement is more than the APD of impulsive noise. Case 1 indicates that impulsive noise does not affect the performance of data communication. Case 2 is the opposite of case 1.

The relations between BEP and APD can be extended to other modulation schemes by studying the probability of symbol error. Previously it was explained that in the case of BPSK, the maximum BEP occurred when $\varphi=\pi$. In probability of symbol error, the value of the noise contribution towards the incorrect signal will caused error if the noise contribution vector exceeds half of the distance between the two signals which is shown as d_{min} in Figure 2.9.

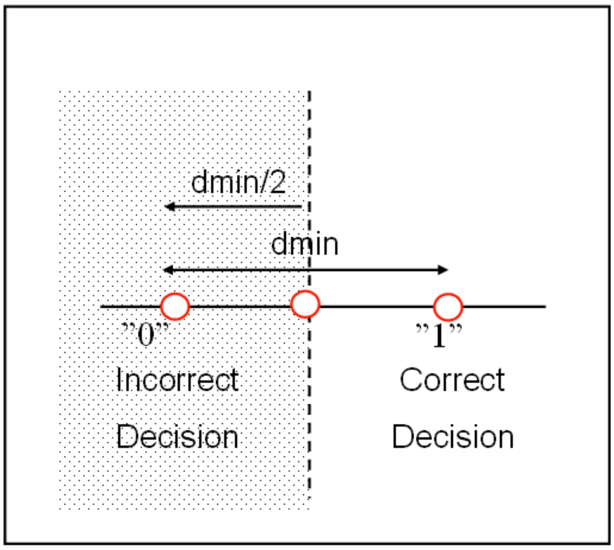

Figure 2.9: The probability symbol decision based on distance between two symbols.

In a worst case, a symbol error occurs when the envelope of the interference exceeds $d_{min}/2$ to the incorrect decision region. This is because the border decision in a conventional coherent receiver is located in the middle between two symbols. Therefore, the symbol error probability Pr[symbol error] for a worst case can be obtained from Equation 2.15.

$$\Pr[\text{symbol error}] = \Pr\left[r > \frac{d_{\min}}{2}\right] = \int_{\sqrt{d_{\min}/2}}^{\infty} f_R(r)\,dr = \text{APD}\left(\frac{d_{\min}}{2}\right) \qquad (2.15)$$

Equation 2.15 shows that the symbol error probability is always less than or equal to the APD value for certain value of decision in signal constellation.

Equation 2.15 can be rewritten as $\Pr[\text{symbol error}]_{\max} = \text{APD}(\beta\sqrt{E_b})$, where β are values depending on the modulation scheme. The d_{min} can be represented by Equation 2.16 for M-PSK (phase shift keying) signal where M denotes the number of symbols.

The d_{min} for M-PSK signal is [1]

$$d_{\min} = \sqrt{2\log_2(M)E_b\left[1-\cos\left(\frac{2\pi}{M}\right)\right]} \tag{2.16}$$

where β can be related to d_{min} by Equation 2.17 as follow:

$$\beta = \frac{d_{\min}}{2\sqrt{E_b}} = \sqrt{\frac{\log_2(M)}{M}\left[1-\cos\left(\frac{2\pi}{M}\right)\right]} \tag{2.17}$$

In Equation 2.17, M denotes the number of symbols and $M=2^k$, where k is the number of bits per symbol. As an example, the case of $M=8$ will yield the value of $\beta=0.66$. Considering the number of bits that constitute a symbol, the relation of *APD* vs maximum *BEP* (P_B) can be summarised in Table 2.1 for various modulation schemes for the estimation of BEP for a single carrier system.

Figure 2.10 shows the population plot for all the modulation schemes listed in Table 2.1. Each modulation scheme has its own specific point based on the required BEP and transmits bit energy E_b. The APD graph will be obtained from the measurement of the APD analyser.

Table 2.1: Summary of the relation between APD and P_B max [1].

Mod.	β	Pr[symbol error]	Relation between BEP (P_b) and APD
BPSK	1	Pr[symbol error]	$P_b \approx APD(\sqrt{E_b})$
QPSK	1	1/2* Pr[symbol error]	$P_b \approx (\frac{1}{2})APD(\sqrt{E_b})$
8-PSK	0.66	1/3*Pr[symbol error]	$P_b \approx (\frac{1}{3})APD(0.66\sqrt{E_b})$
16-PSK	0.39	1/4*Pr[symbol error]	$P_b \approx (\frac{1}{4})APD(0.39\sqrt{E_b})$
4-PAM	0.63	1/2*Pr[symbol error]	$P_b \approx (\frac{1}{2})APD(0.63\sqrt{E_b})$
8-PAM	0.37	1/3*Pr[symbol error]	$P_b \approx (\frac{1}{3})APD(0.37\sqrt{E_b})$
16-QAM	0.63	1/4*Pr[symbol error]	$P_b \approx (\frac{1}{4})APD(0.63\sqrt{E_b})$
64-QAM	0.38	1/6*Pr[symbol error]	$P_b \approx (\frac{1}{6})APD(0.38\sqrt{E_b})$
2-FSK	0.71	Pr[symbol error]	$P_b \approx APD(0.71\sqrt{E_b})$
4-FSK	1	Pr[symbol error]	$P_b \approx (\frac{2}{3})APD(\sqrt{E_b})$

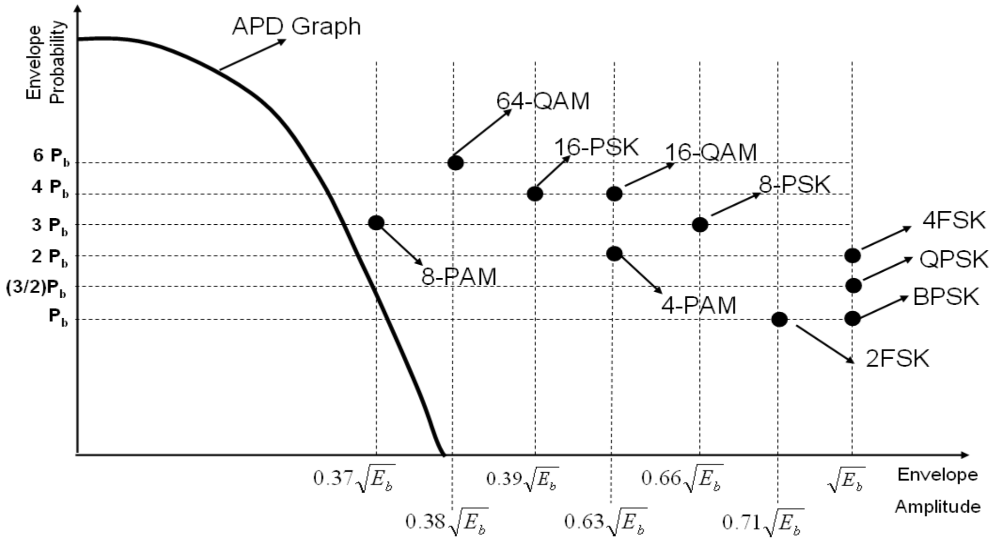

Figure 2.10: The example population plot of APD vs $\sqrt{E_b}$ for 10 modulations scheme

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