Chapter 2
Introduction to Noise and its Applications

2.1 Overview

A random fluctuation also called "noise," is a characteristic of all physical systems in nature. In most of the scientific fields, noise is considered as apparently irregular or periodic chaotic. Since 1826, noise and fluctuation have been of interest to study Brownian motion which indirectly approves molecules and atoms existence. The recognizable measured noise or signal patterns express valuable information of a system [1].

2.2 Background and History of Noise

In 1826, Robert Brown, a Scottish botanist, carried out the first research about the noise. He observed periodic motion of pollen on a water film surface [2]. The origin of Brownian motion was the first noise problem which had been unsolved for almost 80 years. In 1905, the problem was finally solved and presented by considerable work of Von Smoluchowski [2] and [3], which indirectly confirmed the molecules and atoms existence. An obvious sign of continuum molecular bombardment belongs to the medium of liquid or gas, is Brownian motion's fluctuations [4]. Nowadays, noise and fluctuation analysis are areas of interest in different scientific fields such as physical, biological, and other systems. Effects of the noise can be varying due to the circumstance. In some cases, it can enhance the system performance (constructive), while it could be destructive [5]. Nevertheless, in nonlinear systems, noise has an essential characteristic due to the possibility of the performance optimization in the levels which noise is nonzero.

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The noise can be represented with considering the following factors:

- *Distribution of duration/Size in time or space*
- *Variance or Power spectrum which shows inverse power-law* [6].

Early attempts lead to recognition of some quantitative mathematical distributions which almost fit sets of data of a vast study range and scientific disciplines. Statistical normal distribution and power law distribution are the most well-known ones.

In 1733, a gambler's consultant and statistician who was Abraham de Moivre, discovered the first normal curve of error (or the bell curve because of its shape). Normal curve importance initiated from the fact that the distributions of many natural phenomena are at least approximately normally distributed. This normal distribution concept highlights how the experimental data have been analyzed over last two centuries [6, 7].

2.3 Noise in Electronic View

In electronic knowledge, an unwanted disturbance within an electrical signal is defined as noise. The noise generation in this category is the result of many different effects. So that these types of noise greatly vary.

2.4 Noise in Communication View

Noise in an undesired disturbance which is random, and it will be considered as error in communication systems. In general, noise in communication view is all type of disturbing and unwanted energy which its resource might be man-made or natural. There is a difference between the noise and interference, and it has to be distinguished about the definition. The difference between the noise and distortion is that the distortion usually is defined as systematic unwanted alteration of a signal (wave) generated by communication devices, so it's artificial noise [8]. Also the signal itself can generate interference, for instance if there is a conflict between subsequent symbols, or not perfect matching on a transmission line. Noise is everything that is not useful signal, so can be due to interference, temperature, impurities, gamma rays, moon phase or whatever. So interference is noise but the inverse is not true.

2.5 Different Types of Noise

There are different types of noise exist based on the characteristic and sources which is generating them. Although they are different about these aspects but for various type of them some of these characteristics are common. For instance, noise spreads

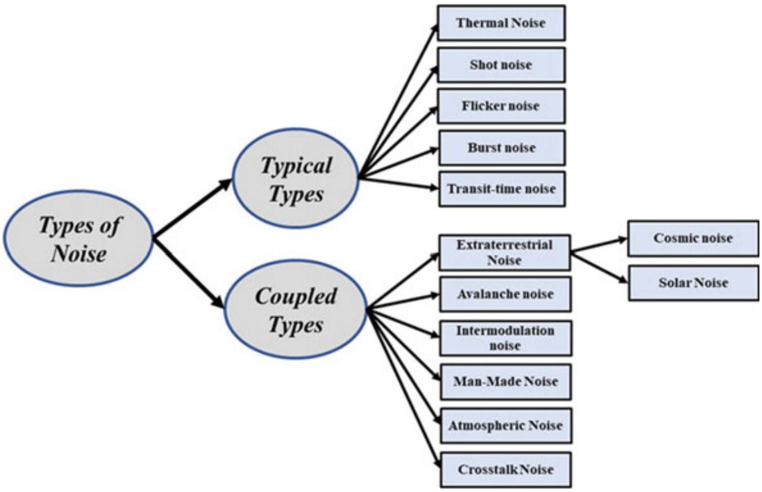

Fig. 2.1 Different types of noise categories

across the frequency spectrum, in some category the frequency are low and in some of them is high, but the amplitude of these noises might be the same (Fig. 2.1).

2.5.1 Typical Types of Noise

To categorise the different types of noise and the source which generating it, it is worthy to categorise them first based on their features. There are five main resources of noise which are common in real life and have different applications no matter as wanted or unwanted item. In order to cover all types of noises, the coupled category of noise has been distinguished from the typical types.

2.5.1.1 Thermal Noise

Molecular forces bounded many ions and electrons strongly in conductors. The vibration of ions around their average or normal position is a function of position. The source of resistance in conductors is the electrons' collision which is continuous and also the ions vibration. The collision of the electrons and vibration of ions generate continues transfer of energy between them and it is the reason of resistance in the conductors. Free electron movements create a pure random current which has average zero over the long time [9, 10].

2.5.1.2 Shot Noise

Nonlinearity in the transmitter, receiver, or intervening transmission system induces intermediation noise. These components usually react as linearly which the output is equal to the input times a constant. In a nonlinear system, the output is a more complex function of the input. The reason of nonlinearity can be the dysfunction of the component or excessive strong signal usage. Under this situation, the sum and difference terms happen [11].

2.5.1.3 Flicker Noise

Flicker noise exists in most of the electronic devices and can affect the system in different ways such as: impurities in a conductive channel, generation and recombination noise in a transistor due to base current, and many other effects. Due to the fluctuation of resistance during the transformation and fluctuation of current according to Ohm's Law, the flicker noise will be generated. As the mentioned items are the characteristics of the direct current (DC), this noise usually exists in this type of voltage. This type of noise is appearing in rotation rate of the earth, fluctuation of sand and hourglass flow and undersea currents as a low-frequency noise. The high-frequency noises are going to be considered as white noise. Nevertheless, noise with low frequency in oscillators might be diverse to frequencies close to the carrier which is going to generate oscillator phase noise. As in the all of the resistors there is carbon composition. The total noise will be increased to above thermal noise due to the flicker noise which is available in resistors, and it is named as excess noise [12].

In contrast, the least amount of flicker noise is in wire-wound resistors. Since flicker noise level is associated with DC level, at low current, thermal noise is prevailing effect in the resistor. The mentioned type of resistors might not influence the level of noise due to the frequency window [13].

2.5.1.4 Transit Time Noise

Transit time noise can be defined as the period of time which is the carrier of current. It can be considered like a hole for transport from input to output. It is important to know that the involved distances are unimportant because of the size of the devices, and the required time lasts for careering current to pass a short distance is restricted. This time is insignificant at low frequencies, whereas for the high operational frequencies the processed signal is the magnitude of the transit time. As a type of noise which is random in the system, transit time will be defined and it is proportional to the operational frequency directly [14].

2.5.1.5 Burst Noise

Burst noise is another type of electronic noise which presents in semiconductors . It is also known as random, bistable, telegraph, signal, popcorn, and impulse noise. It is immediate step-like offset among more than two current levels or discrete voltage, around hundred microvolts, at random times. Each voltage or current offset usually occurs between milliseconds to seconds and if it is connected to a speaker will sound like popcorn bursting [1].

The first witness of burst noise was in early point contact diodes, and after that it has been detected during one of the first semiconductor op-amps commercializing [15]. The single source of popcorn noise and its occurrences are not theoretically clear. However, the most frequent cause of that is charge transmit intermittent trapping and releasing in defect site in bulk semiconductor crystal or in thin film interfaces. In some circumstances where charges have a substantial effect on transistor performance, there is considerable signal output. The common cause of these defects is due to manufacturing process, for instance, heavy ion implantation or by unwanted side effects like surface contamination [16].

2.5.2 Coupled Type of Noise

With considering the mentioned description about the resources of noise within an electronic circuit, it is essential to mention the other type of noise which is couple noise. Couple noise is another noise resource which has different definition than the typical type of noise. Whenever additional noise energy is going to be coupled to the main noise resource into the electrical circuit, coupled noise will be generated. There are many types of noise energy can be coupled to the circuit, but most of them are from external environments. The following sections show different source of noise which are resulting to the coupled noise.

2.5.2.1 Atmospheric Noise

Lightning in the atmosphere induces discharges in the form of electrical disturbances , and it is known as atmospheric noise. Naturally, they are random electrical impulses. Consequently, the distribution of the energy is completely over the radio communication frequency spectrum [17]. Therefore, atmospheric noise creates fake radio signals with a wide range of frequency with distributed components. These fake radio signals consist propagated noise over the earth similar to the same frequency radio waves. Thus, a receiving antenna at a point picks up both signal and the static from all the thunderstorms, local or remote. The atmospheric noise strength nearly changes inversely with the frequency. The atmospheric noise which is very little will be generated in band of UHF and VHF and large one will be generated in broadcast bands which are low or medium bands. In addition, components of noise for VHF and UHF components are limited to less than 80 km propagation of line of sight. Therefore, at frequencies above 30 MHz, the atmospheric noise is less intense [18].

2.5.2.2 Crosstalk Noise

Crosstalk is a type of noise which might be experienced by anyone who had heard a secondary conversation while speaking on telephone. It is an undesirable signal paths coupling. It can happen by close twisted pair electrical coupling coax, cable lines and rarely, carrying multiple signals. In addition, when unsolicited signals are collected by microwave antennas, crosstalk can occur. Microwave energy distributes through the propagation despite being highly directional. Characteristically, crosstalk noise has less or same magnitude as thermal noise [19].

2.5.2.3 Interference Noise

It is the super position of two or more waves propagating through the same medium at same time without being disrupted. Depending on how maximum and minimum amplitude of the traveling waves overlapped, the resulting wave amplitude can be lower or higher compared with individual waves. When amplitudes of two interacting waves have the same sign, the amplitude of the sum wave is greater than that of the larger wave. This is known as constructive interference [20].

In contrast, when two waves interact with opposite amplitude in less than half the time, the stronger wave has bigger amplitude in comparison with the resulting wave. This interference is called destructive interference. However, it is possible that having two same waves with opposite amplitude which in destructive interference, they can cancel each other [21].

2.5.2.4 Intermodulation Noise

In a nonlinear system, including signals with two or more dissimilar frequencies, the modulation of the amplitude will be defined as intermodulation distortion or intermodulation. Additional signals will be formed between the components of each frequency during the intermodulation. These frequencies are at harmonic frequencies, summation and deference of the frequencies of the original frequencies, and also multiples of all of the mentioned frequencies [22, 23].

By considering the characteristic of the signal processing which probably is nonlinear, intermodulation can be defined as the result. In order to calculate the nonlinearity, Volterra series and Taylor series can be utilized [24].

Since intermodulation causes unfavorable spurious emissions usually in the form of sidebands, it is seldom favorable in radio or audio processing. Intermodulation augments the occupied bandwidth for radio transmissions causing interference in adjacent channel. Therefore, the range of the spectrum can be increased, and the quality of the audio can be reduced. The definition of the intermodulation is different than the musical application's harmonic distortion or intentional modulation in applications in which modulated signals show up as intentional nonlinear element.

The products of intermodulation in audio is related to the input frequency and they are not harmonic [24].

2.5.2.5 Man-Made Noise (Industrial Noise)

Another category of noises is man-made noise or industrial noise. Some examples of this type of noises are: electrical noise generated by ignition in aircrafts, vehicles with normal and electrical motors, different type of electrical machines which are heavy, fluorescent lights, and lines of high voltage. The noises in this category are generated in the mentioned systems and devised by the arc discharge while they are functioning. High intensity of these types of noises is localized in industrial and highly areas. The intensity of the noises from these areas is higher than all other sources and their frequency ranged between 1 and 600 MHz [25–27].

2.5.2.6 Extra-Terrestrial or Galactic Noise

The definition of this type of noise refers to the type of radio noise which its resource is out of the earth from the galaxy. This type of noise is known as galactical noise, and can be presented in some degree with all of the possible directions. It is important to know that it is mostly penetrating near to the galaxy plane and mainly in galactic center direction. This type of noise has a wide range of frequency between 1 and 1360 mc. The Extra-terrestrial noise mainly can be categorized to the solar noise and cosmic noise [28, 29].

Solar Noise

Solar noise is a type of electrical noise which its source is the sun. As the surface of the sun has the temperature of over 6000 °C, and it is a large object with the steady situation, it generates the steady radiation of noise. This noise is actually electrical energy which is radiating with the frequency which has a wide range. The solar noise spectrum is the same spectrum in radio communication. The noise produced by the sun has a time varying intensity. This noise cycle is 11 years. The noise generated by sun at the peak of the cycle induces great interference to radio signal, causing many unusable for communications. During the rest of cycle, the noises are at a minimum level [30, 31].

Cosmic Noise

Distant stars also have high temperature and emit noises like sun. The thermal noises (or black body noise) received from distant stars are distributed almost homogeneously over sky. As the other type of sources which can generate this type of noise, distant galaxies, centre of Milky Way and pulsars and quasars as virtual point sources can be mentioned [32, 33].

2.5.2.7 Avalanche Noise

At the beginning of the avalanche breakdown during a junction diode functioning, avalanche noise will be generated. The reason behind this noise generation is a semiconductor junction phenomenon. It carriers the voltage gradient which is high and developing adequate energy to dislodge additional carriers through physical impact [34].

2.5.2.8 Impulse Noise

This type of noise is defined as minor disturbance for analog data. As an example, crackles or short clicks can disrupt voice transmission with no effect on its intelligibility. In digital data communication, this type of noise is the main reason of errors [35].

2.5.3 Colored Noise in Signal Processing View

Noise in signal processing has different way of definition. In signal processing, noise will be categorized based on its statistical properties. These statistical properties are defined as noise color. It is difficult to differentiate the various types of noise. However, it is possible to differentiate the noises with color method. The noise colors arise from similarity to light and correspond to the content of frequency. For each noise, a color is defined in which some of them are related to the physical world and some are adopted for psychoacoustics field. These colors resemble the frequency power which is proportional to their spectrum see (Table 2.1) [15].

Table 2.1 Colored noise and frequencies [15]

Color	Frequency content
Purple/Violet	f^2
Blue	f
White	1
Pink	1/f
Red/Brown	$1/f^2$

2.5.3.1 Purple or Violet Noise

Purple noise is also called violet noise with increasing power density of 6 dB per octave with increasing frequency (frequency content of f 2) over the range of finite frequency. Since it is being the result of white noise signal differentiation, it is also known as differentiated white noise [36].

2.5.3.2 Blue Noise

Blue Noise is considered as white noise with high frequency. The spectral density of this noise color is proportional to its frequency. As the blue color is the higher end of visible light frequency spectrum, this noise also named as azure noise which comes from optics. This means that as the frequency increases, the signal energy and power (density proportional to f) will increase.

In blue noise, each octave continuously increases by 3 dB. It is one of the unique characteristics of this noise which packs same amount of energy in each octave as it is in the combination of the amount of energy in two octaves below it [37, 38].

2.5.3.3 Pink Noise

In cases in which the spectral density power is proportional and in reverse direction of the signal frequency, the frequency spectrum belongs to pink noise which also known as 1/f noise. The amount of energy which is carried by each octave is equal in pink noise. The name pink noise is because of its power spectrum which appears in visible light. The pink noise is in contrast with white noise because of the equal intensity per frequency interval in white noise [39].

This type of noise is useful due to the same frequency which is hearable for human. Pink noise will be utilized as useful signal for testing the audio devices such as speakers and amplifiers. As the real example of pink noise, frequency of heart beats and activity of neural and DNA statistical sequences are worth to be mentioned [40].

2.5.3.4 Red/Brown Noise

As one of the colored noises, brown noise includes some other noises such as pink, white, and blue noises. This noise is named as brown because of the Robert Brown due to his research about the Brownian motion as the random particle motion. So that, because of the mentioned characteristic which is changing the sound signal during the time randomly, it is also known as Brownian noise.

This type of noise has a spectral density which is proportional to its frequency and contrariwise. This characteristic is completely in opposite definition of white noise which has even spectral density for all of the frequencies. It means brown noise power obviously decreases with increase in the frequency.

Therefore, at lower frequencies, brown noise has considerably higher energy compared with its higher frequencies. As the red light has the low frequency, the brown noise will be named as red noise in some cases. Brown and white noises are similar for our ear. The brown noise is much deeper, and it is like a roar but low. However, white noise is not this much deep and it is like a strong waterfall sound.

2.5.3.5 White Noise

In the middle of a spectrum which runs from purple trough red/brown is white noise. The term "white" corresponds to noise frequency domain characteristic of. Ideal white noise has equal power per unit bandwidth, which results in a flat power spectral density across the frequency range of interest. Therefore, the power in the frequency range from 100 to 110 Hz is the same as the power in the frequency range from 1000 to 1010 Hz [41]. It is not possible to achieve infinite bandwidth due to the infinite amount of required power when signal of white noise is generated in actual life. Nevertheless, it is possible to create signals of white noise over the desired frequencies. For a specified frequency range, power per hertz is equal for a uniform white noise. The noise color is associated with the distribution of the frequency domain of the noise signal power [42].

As the white noise is the main focused category of noise in this book, in the next chapter the white noise and its applications and different types of mathematical modeling belong to this noise and its applications is described.

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