

Chapter 1

Introduction

According to (Shannon, 1948), the information capacity of all electronic systems is constrained by three fundamental limitations: noise, bandwidth and signal power. For each of the three limitations the system has to be optimized. In a structured design process, functionality of the system is split into subsystems that can be optimized separately of each other.

Structured design methodologies concentrating on all three fundamental limitations have been developed for subsystems like negative-feedback amplifiers, oscillators, filters, bandgap references etc. (Nordholt 1993; Verhoeven et al. 2003; Boon 1989; Westra 1998; Monna 1996; van Staveren 1997; Serdijn 1994). All subsystems, and the electronic system as a whole, however, are also subjected to another limitation: interference from, and to other electronic systems.

Which interfering signals are present outside the system to be designed is in general unknown. The current trend of more numerous, more mobile, and more communicating electronic devices, increases the interference burden generally. It will be shown that the effect of interference can be modelled under very broad assumptions. This makes it possible to compute the effect of interference and design in such a way that its effect on the system is minimal. Another reason why interference is important and has to be taken into account during design is that the susceptibility to interference from other systems, and conversely the interference on other systems, is regulated by law.

An important subsystem of nearly all designs is the negative-feedback amplifier. The focus of this work will be on design methods to minimize the adverse effects of interference on negative-feedback amplifiers.

1.1 Electromagnetic Compatibility

Apart from realizing the intended functionality of an electronic system, the designer has to take care that it will not be affected adversely by external and internal interfering sources. On top of that, the designer should also take care that the circuit will not

be a source of interference to other equipment. In other words, the designer has to realize adequate electromagnetic compatibility (EMC). EMC is defined as *the ability of an electronic system to function properly in its intended electromagnetic environment and not be a source of pollution (interference) to that environment* (Ott 1988). When an electronic system is not capable of functioning properly in a given electromagnetic environment, electromagnetic interference (EMI) is encountered. EMI is defined as *any disturbance that interrupts, obstructs, or otherwise degrades or limits the effective performance of electronics/electrical equipment*.¹

EMI can be separated into three elements. First of all, a *source* of potentially interfering emission has to be present. Secondly, the emission has to be transported by some kind of *coupling* path before it can reach a *receptor* (the third requirement).

Emission can occur due to conduction and radiation. In case of conduction, interfering electrical signals are transported from a source to the equipment being disturbed by connected wires and cables. In the case of radiation, interfering signals are transported by electromagnetic fields; there is no need for a physical connection.

The immunity of a receptor is a measure of the amount of electromagnetic energy that may be coupled to it before its functionality is hampered. The opposite of immunity is susceptibility. Susceptibility is the inability of equipment to function properly in a certain electromagnetic environment. Immunity and susceptibility are often confused. The latter, however, is a fundamental property; it will always be possible to find or generate an electromagnetic environment that hampers the functionality of an apparatus (Goedbloed 1993).

Sources, receptors and coupling paths are not only found between different electronic systems, but also in the electronic system itself. The term *inter-system compatibility* is used when EMC between two or more systems is considered. *Intra-system compatibility* refers to EMC aspects within the system itself (Goedbloed 1993). Figure 1.1 demonstrates the various levels of EMC. Inter-system compatibility is demonstrated by the arrows between systems I and II. Intra-system compatibility can be considered at different levels in a system. Between various devices in a system there has to be EMC, but also between the printed circuit boards (PCB) in the devices EMC has to be assured. EMC can even be considered at lower levels: the component level on the PCB and the component level in an integrated circuit.

In this work, the focus will be on the study of susceptibility problems. It is assumed that the source can't be controlled by the designer in case of inter-system incompatibility. Emphasis is placed on the coupling path and the receptor.

Total disregard of the coupling path during the design may result in large interfering signals reaching the receptor. This results in increased demands on the immunity. Design strategies to reduce the effectiveness of the coupling path as much as possible, thus relieving the immunity demands on the receptor, will be presented in Chap. 2. On top of that, design strategies to reduce the susceptibility of the receptor,

¹ The International Electrotechnical Committee (IEC) has proposed to use 'interference' for the electromagnetic phenomenon that may degrade the performance of a device itself and 'disturbance' for the interfering signal that actually degrades the performance of a device. In this work this distinction will be followed.

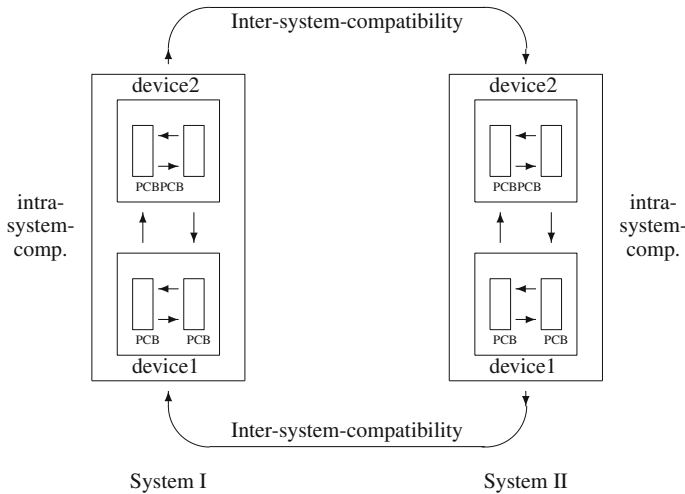


Fig. 1.1 Inter-system compatibility and intra-system compatibility and EMC on various levels in the system. Every system, device, component etc. can both be a source and a receptor of EMI. The arrows represent the directions of possible interference

in this work the negative-feedback amplifier, as much as possible are also given. In effect, the problem of reducing susceptibility of the negative-feedback amplifier is extensively dealt with in Chaps. 5 and 6.

The most obvious receptors are electronic devices, but also humans may be vulnerable to electromagnetic fields. For example, extremely low frequency fields may induce uncontrolled muscle movements and the experience of light flashes. Higher frequency fields will increase the temperature of tissue. The effects of electromagnetic fields on health will not be studied in this work. It is just mentioned for reasons of completeness. The interested reader is further referred to the literature, e.g., (van Rongen 2002) or (Collins 2004).

1.2 Possible Sources of Interference in Hospitals

In private homes and offices the effects of interference can be annoying, but usually do not result in dangerous situations. Interference in hospitals can result in dangerous, life threatening situations. Therefore most hospitals restrict the use of mobile communications systems and ban them from operating theaters and intensive care units.

Most hospitals use a wireless internal communications system at this moment. Mobile communications using the terrestrial trunked radio (TETRA) standard in the 380–400 MHz band, walkie-talkie transmissions in the 450 MHz band, and telemetry systems using the same band are well known sources of electromagnetic pollution

(Hershey and Hoctor 1999). Except for this, very little data is available on EMI measurement and characterization in hospitals. This is probably explained by the fact that characterization of one hospital complex could require 1 to 4 years to perform (Hershey and Hoctor 1999). Therefore, measurements are often performed in a part of the hospital and in certain frequency bands (Riemann and Evans 1999; Golombeck et al. 2001). A thorough study, however, does not seem to be available at the moment.

Hershey and Hoctor (1999) concluded from literature studies concerning field strengths in various hospitals that the electromagnetic field strength in the range 0.1–1000 MHz may vary considerably among hospitals. Maximum field strengths may vary between 0.4 and 5.6 V/m. Unfortunately the studies are not always clear in specifying how the measurements were performed, e.g., if average or maximum values were recorded, what type of antenna was used, the polarization of the antenna, etc.

What came clear from this study from 1999 is a cluster of possible interfering fields in the range of 0.4–0.5 GHz and 0.8–0.9 GHz in most hospitals. This may correspond to telemetry systems used by the hospitals themselves and older generation GSM cell phones. Nowadays some clustering in the 1.8–2.4 GHz range may be expected due to more modern communication systems.

Some equipment used for diagnostic or treatment purposes use high frequencies and/or powers and may therefore generate interference themselves. These are unintentional emitters of electromagnetic fields. Two well-known potential sources of interference are magnetic resonance imaging (MRI) and diathermy (i.e., electro-surgery) equipment (Golombeck et al. 2001).

An MRI system is used to produce images of the inside of the human body. While doing this, strong electromagnetic fields with high frequencies are generated. These fields may interfere with systems for bio-potential measurements. More about the interference generated by an MRI can be found in Sect. 7.3 of Chap. 7.

Electrosurgery is a form of surgery in which high-frequency currents from 100 kHz to approximately 6 MHz (Taunton 1981) are used.² The application of such currents to human tissue results in a heating effect that is used to incise, destroy and remove tissue, and to seal blood vessels in order to maintain hemostasis (Prutchi and Norris 2005; Takaki 1988).

The high-frequencies generated by electrosurgery equipment, coupled with the relatively high peak voltage of up to approximately 1 kV (Prutchi and Norris 2005) during cutting, results in EMI problems in adjacent equipment. Electrocardiogram (Takaki et al. 1987) and electroencephalogram (Takaki 1988) monitoring equipment may be especially hampered by electrosurgery equipment.

² Different references specify somewhat different frequency ranges, e.g., Health (1977) and Prutchi and Norris (2005) specify a range of 200 to 3.0 MHz.

1.3 Examples of Electromagnetic Interference

If an electronic system is too susceptible to the electromagnetic environment, its correct functioning may be hampered. The decrease in functionality may vary from hardly noticeable to complete malfunctioning. To get an idea of the effects of lack of immunity, some examples are given in this section. A distinction is made between EMI in medical and non-medical equipment, because EMI in medical equipment may result in life-threatening consequences, while in non-medical equipment the consequences may be bothersome but are often not life-threatening.

1.3.1 Examples of EMI in Medical Equipment

The past years showed an increase of reports that medical devices have failed to operate correctly because of interference from various emitters of high-frequency electromagnetic waves (IEEE 1998). The consequences of these failures ranged from inconvenience to serious injuries and death. It appears that reasons for this problem are twofold: increasing numbers of electronically-controlled medical equipment that are susceptible to EMI and a significant increase in the number of EMI sources in the (hospital) environment.

For example, some apnea monitoring equipment failed to alarm when subjected to electric field strengths as low as 0.1 V/m in the FM broadcast band (Ruggera and O'Bryan 1991), while it should be able to withstand electric field strengths of at least 10 V/m, which is a regulatory demand for life supporting systems (IEC 1993). In the mid-1980s the US Food and Drug Administration (FDA) had become aware that approximately 60 infants died in the United States while being monitored for breathing cessation by one model of apnea monitor (IEEE 1998). It was found that the devices failed to alarm because of EMI from mobile communication base stations several hundred meters away and FM radio broadcast stations more than one kilometer away.

Equipment for measuring bio-potentials like electrocardiogram (ECG), electroencephalogram (EEG), electromyogram (EMG), may be hampered by diathermy equipment (Gerhard 1990). Spikes may occur which may make it harder to interpret the measured bio-potentials. Sometimes the interference may even induce signals with larger amplitudes than the bio-potentials to be measured.

An additional problem area involves cardiac pacemakers and defibrillators. The dominant effect of EMI is loss of pacemaker adaptive control, causing the device to deliver stimuli either irregularly or at a preprogrammed fixed rate (IEEE 1998) so that the heart rhythm is not a function of the physical exertion to be delivered anymore. Also, pacemaker inhibition and/or asynchronous pacing are commonly observed when cellular phones are used up to distances of 23 cm (Stevenson 1997).

Erroneous displays and latch-up of anaesthetic gas monitors during surgery have occurred (Williams 1996). Investigations revealed that interference from certain types

of electrosurgery units disrupted the communication link between the monitor and a central mass spectrometer, causing the monitor to fail to display the concentration of anaesthetic gas in the operating room during surgery. Also, a type of anaesthetic gas monitor was found to present false measurement results when a C2000 communication system (using TETRA) was operated at 30 cm distance (Paus 2000).

Magnetic resonance imaging (MRI) systems may generate so much interference that synchronizing the MRI system to the cardiac cycle in order to minimize artifacts in the image of the heart is very hard to do without taking special measures (Damji et al. 1988).

Detection of GSM signals in hearing aids results in disturbing signals with a frequency of approximately 217 Hz (Verhagen 1996), which is in the audible range. Subjective perception of interference from handheld GSM telephones in hearing aids varies from barely perceptible to annoying and loud, starting when the phones are within one meter of the hearing aids and becoming louder when the phones are several centimeters away (IEEE 1998). This makes it almost impossible for wearers of hearing aids to use GSM telephones.

Powered wheelchairs and scooters show susceptibility to electric fields in the frequency range of 1 MHz to 1 GHz and field strengths varying between 3 V/m and 40 V/m (Witters and Ruggera 1994). An electric field of 40 V/m seems very high, but since the wheelchairs are mobile it is not unlikely that the wheelchairs come in an environment where such a strong electromagnetic field exists.

There are reports of powered wheelchairs spontaneously driving off kerbs or piers when police vehicles, harbor patrol boats or amateur radios were used in the vicinity. When the EMI susceptibility was investigated, susceptibilities of the motion controllers of the wheelchairs were found in the range of 5 to 15 V/m. At the lower end of the range, the electric brakes would release, which could result in rolling if the chair happened to be stopped on an incline; as the field strength at a susceptible frequency was increased, the wheels would actually begin turning, with speed being a function of field strength (Williams 1996).

1.3.2 Examples of EMI in Non-Medical Equipment

In principle all equipment may be disturbed by EMI. To limit the list, a few examples will be given. Most of them are adopted from Goedbloed (1993) and Williams (1996), unless otherwise stated.

Radio-amateurs are familiar with complaints about their amateur radios interfering with television sets (VERON 1983). Unintentionally, their broadcasts may interfere with certain television channels. While broadcasting, they were also capable of controlling the room temperature because a type of electronic thermostat was too susceptible to the fields generated by the amateur radio station.

Radio broadcasts from the Dutch ‘Wereldomroep’ could be followed by listening to the telephone instead of the radio in some parts of the Dutch province Flevoland;

the electronics in telephones acted as radio receivers.³ The same kind of disturbance occurred near a medium wave transmitter in North London. New telephones installed in the neighborhood were constantly affected by BBC radio programmes.

In Germany, a particular make of car would stall on a stretch of Autobahn opposite a high power broadcast transmitter. Eventually that section of the Autobahn had to be screened with wire mesh. Another type of car was equipped with a transmitter. When it was used, the central locking and electric sunroof would operate.

During the Falklands war the British HMS Sheffield was hit by a Exocet missile which damaged the ship (it sunk after several days). The radar was turned off because it interfered with the ship's satellite communications system.

EMI in aviation can become cumbersome. Between 1983 and 1996 over 97 EMI related events due to passenger 'carry on' electronic devices have been reported. Devices used by passengers, like phones, computers, CD players and video cameras may result in instrument or autopilot malfunction. Interference at airports has also been reported; interference to aeronautical safety communications at a US airport was traced to an electronic cash register a mile (1.6 km) away.

1.4 Regulations and Standards

To prevent too much interference, governments provided early regulations about power levels that may be conducted or radiated and about susceptibility levels. For instance, as early as 1904 in the Netherlands the 'Telegraaf en Telefoonwet' was introduced (Telecom 2004).

Presently, most European countries (including the Netherlands) have adopted their national regulations from the recommendations of international committees, like the International Electrotechnical Committee (IEC) and the Comité International Spécial des Perturbations Radioélectriques (CISPR). For the United States, the Federal Communications Commission (FCC) is responsible for regulations on interference.

In Europe regulations exist for both emission and susceptibility. Industrial, scientific and medical (ISM) equipment that does not use a form of radio communication is important because a lot of designs will have to comply with the standards of this group. As an example, emission and immunity levels of conducted disturbances are given in Table 1.1 and emission and immunity levels for radiated emissions are given in Table 1.2.

The radiated emission levels have to be measured at a distance of 10 m from the source. More details regarding the measurement of emission and immunity levels

³ Since 2007, the 'Wereldomroep' does not broadcast anymore from the Netherlands, but from other European countries (Agentschap 2009). This kind of EMI therefore probably does not occur anymore in Flevoland, but may occur at other places.

Table 1.1 Test levels regarding conducted emission and immunity to conducted disturbances of ISM equipment. See main text about levels

	Frequency band (MHz)	dB (μV)
Conducted emission levels	0.15 – 0.50	56 decreasing to 46
	0.5 – 5	46
	5 – 30	50
Immunity levels conducted disturbance	0.15 – 80	level 1: 120
		level 2: 130
		level 3: 140

Table 1.2 Test levels regarding radiated emission and immunity to radiated disturbances of ISM equipment. See main text about levels

	Frequency band (MHz)	
Radiated emission levels	30 – 230	30 dB (μV)
	230 – 1000	37 dB (μV)
	>1000	43.5 dB (μV) (Ott 2009)
Immunity levels radiated disturbance	80 – 1000	level 1: 1 (V/m)
		level 2: 3 (V/m)
		level 3: 10 (V/m)

can be found in IEC (1995, 1996, 1997), IEC1 (1997), Cenelec (1992). Tables 1.1 and 1.2 were constructed using these standards.⁴

Three different test levels are given for susceptibility measurements. The consequences of failure should be borne in mind in selecting the test level to be applied. Equipment may be used in a variety of locations, and therefore a variety of electromagnetic environments. The three different test levels correspond to three types of electromagnetic environments in which the equipment may have to function.

The three levels are defined as IEC (1995):

- Level 1 corresponds to a low-level electromagnetic radiation environment: levels typical of local radio/television stations located at more than 1 km, and transmitters/receivers of low power.
- Level 2 corresponds to a moderate electromagnetic radiation environment: low power portable transceivers (typically less than 1 W rating) are in use, but with restrictions on use in close proximity to the equipment. This is regarded to be a typical radiation level of a commercial environment.
- Level 3 corresponds to a severe electromagnetic environment: portable transceivers (2 W rating or more) are in use relatively close to the equipment but not less than 1 m. High power broadcast transmitters are in close proximity to the equipment and ISM equipment may be located close by. This is regarded as a typical industrial electromagnetic environment.

⁴ Since the regulations may change every few years, Tables 1.1 and 1.2 should be regarded as examples.

To simulate realistic, non-constant envelope interference, the immunity test signals specified in Tables 1.1 and 1.2 must be modulated with a 1 kHz sine wave at a modulation depth $m = 80\%$. Systems functionality may not seriously be hampered by these test signals. For the exact description of the amount of allowed functional deterioration and the description of the measurement set-up, the reader is referred to IEC (2006).

The standard for medical electrical equipment is comparable to the ISM standard and specifies an immunity to electromagnetic fields up to 3 V/m in the 26–1000 MHz range (IEC 1993). Life supporting medical systems should even be immune to electromagnetic fields up to 10 V/m (IEC 1993). Before being put to market, compliance with the appropriate (medical) EMC standards of medical systems often has to be confirmed by a ‘notified body’, i.e., a test laboratory that is appointed by the government. In the Netherlands ‘TNO Medical’ and ‘KEMA’ are the most commonly known notified bodies.

Apart from the regulation regarding ISM equipment, medical equipment, and transmitters, there are many more regulations focussing on special product groups. The immunity and radiation demands may vary between different product groups. Treatment of all regulations are beyond the scope of this work.

In some situations more stringent emission or immunity limits are required. These limits can then be determined prior to the design and are called desirable requirements in contrast with the regulatory requirements.

As stated earlier, the type and level of interfering signals that may be expected is generally not known a priori due to the unknown electromagnetic field levels. Apart from measurements, the regulations, however, can be used to determine the EMC levels that the electronic system must comply with.

1.5 Determining EMC Specifications

A system has to comply with both radiation and immunity regulatory/desirable requirements. To be safe, the design targets should be more restrictive than the requirements. Fig. 1.2a and b give a schematic that may be helpful to determine EMC specifications (Goedbloed 1993). ISM regulatory emission and immunity requirements are indicated in Fig. 1.2a and b, respectively.

First of all, a compatibility level is shown in both figures. This is the reference that can be used to come to emission and immunity levels in such a way that the system to be designed is EMC with all other equipment in the environment. The emission limit (Fig. 1.2a) is taken from the proper standard or should be chosen otherwise when the desired emission level is lower than the regulatory level. The designer has to make sure that the emission from his system is less than the emission limit. This can best be done by taking a design margin of 6 to 10 dB into account.

The immunity limit (Fig. 1.2b) is also taken from the proper standard or should be chosen such that interfering signal levels in the environment will always be less than

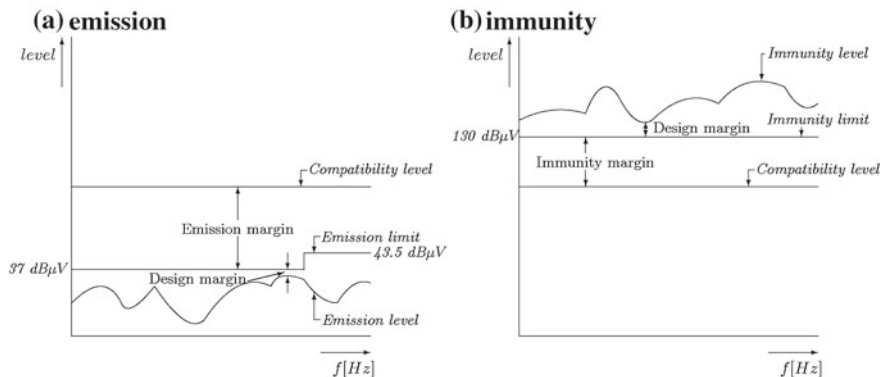


Fig. 1.2 Overview of EMC limits and margins. The designer has to make sure that emission levels remain below the emission limit **a** and the immunity level remains above the immunity limit **b**

the specified immunity limit. Again, a design margin of 6 to 10 dB ensures that the immunity level of the system will be adequate for that electromagnetic environment.

The design margin of 6 to 10 dB accounts for spread in component specifications that may influence EMC and also for variations in the EMC measurement set-up.

For an optimal design for EMC, the electromagnetic environment in which the system is going to be used has to be known prior to the design. The electromagnetic environment, however, is not static. It may change with time. When the changes are not too severe (e.g., because equipment is added that complies to the emission regulations) the emission margin will decrease, but the compatibility level will most probably not be exceeded.

Unfortunately, it is impossible to foresee all future changes in the electromagnetic environment. A system that is designed to be immune to electromagnetic field strengths of 1 V/m can function satisfactorily in its environment, for example a room in a laboratory. However, if at a later date a radio transmitter is put to use in the direct neighborhood of the laboratory, it may cause the electromagnetic field to exceed 1 V/m and result in malfunctioning of the system.

The remainder of this work focuses on obtaining an adequate immunity. For reduction of emission levels, the interested reader is referred to the open literature, e.g., (Goedbloed 1983; Paul 1992; Ott 2009; Reitsma 2005).

1.6 Origin of Electromagnetic Interference

Semiconductor devices, such as diodes and transistors, show a nonlinear behavior. Circuits realized with these devices will also show some kind of nonlinearity, even when they are supposed to be linear as in case of ‘linear’ negative-feedback amplifiers. The input-output relation of a nonlinear device like a transistor is given by:

Table 1.3 Overview of the detected (in-band) signal for some modulation types

Modulation type	Detected signal i_o (A)
Non-constant envelope	
AM	$a_2 \frac{\hat{u}_i^2}{2} \left(1 + \frac{m^2}{2}\right) + a_2 \hat{u}_i^2 m \cos(\omega_l t) + \frac{\hat{u}_i^2}{4} m^2 \cos(2\omega_l t)$
Constant envelope	
FM, PM, FSK, etc.	$\frac{\hat{u}_c^2}{2} a_2$
'Switched'	
TDMA	$\approx a_2 \hat{u}_c^2 \left(\sum_{n=1}^{\infty} \frac{1}{n\pi} \sin(nT_1) \cos(n\omega_l t)\right) + a_2 \hat{u}_c^2 \left(\sum_{n=1}^{\infty} \frac{1}{n\pi} (1 - \cos(nT_1)) \sin(n\omega_l t)\right)$

$$i_o = u_i a_1 + u_i^2 a_2 + u_i^3 a_3 + \cdots + u_i^n a_n, \quad (1.1)$$

when u_i is the disturbing voltage at the input terminals (base-emitter or gate-source) of the nonlinear device and a_n are the Taylor series coefficients. The second-order term $u_i^2 a_2$ is in practice the main source of EMI, although higher even order terms may also contribute to EMI. However, for practical nonlinear devices a_4, a_6, \dots increase less rapidly (or even get smaller) than a_2 , while u_i^4, u_i^6, \dots decrease in value, since $u_i \ll 1$ V for nonlinear devices in amplifiers. The higher even order terms $u_i^4 a_4, u_i^6 a_6, \dots$ are therefore (much) smaller than $u_i^2 a_2$, and may be neglected under certain conditions.

Nowadays, both analog and digital modulation are used. This classification, however, is on the basis of the modulating information being analog or digital. For determining EMI properties it is better to classify on the basis of the properties of the envelope of the high-frequency (ω_c) signal. Non-constant envelope modulation, constant envelope modulation, and constant envelope modulation that is periodically switched on and off can be distinguished. Both analog and digital modulation forms can be of the constant or non-constant envelope type.

Using Eq. (1.1) and the mathematical description of the modulated interfering signal, the in-band detection can be determined. Table 1.3 gives the expressions of the detected current i_o for some modulation types. Voltage \hat{u}_i will be defined in the next paragraph, \hat{u}_c is the amplitude of the carrier wave.

For illustration purposes, i_o is derived for an AM signal. The detected current for other modulation types can be determined using the same approach. An AM signal is mathematically described as: $u_i = \hat{u}_i [1 + m \cos(\omega_l t)] \cos(\omega_c t)$.

Here, m is the modulation index ($0 < m \leq 1$), ω_c is the carrier frequency and ω_l the information frequency. Substituting u_i into the second term of Eq. (1.1), it is found that the quadratic term generates signals at eight different frequencies, most of them being intermodulation products located near twice the carrier frequency (Weiner and Spina 1980). There are also signals at DC, at the information frequency ω_l , and at $2\omega_l$. For negative-feedback amplifiers, it may often be assumed that the signals at ω_l , at $2\omega_l$, and possibly at DC, are in the pass-band and that ω_c and its harmonics and intermodulation products are not. The in-band disturbing signals can

Table 1.4 Overview of some legal wireless communication standards using periodically on-off switched constant envelope waves (Anker 1995; Poole 2004)

	Frequency band (MHz)	P_{\max} (W)	Modulation type	T_1 (μs)	T (ms)	det. $f_{\text{fund.}}$ (Hz)
C2000/ TETRA	380 – 400	3	FDMA, TDMA ($\pi/4$ DQ)- PSK	14167	56.667	17.65
GSM-900	870–960	2	FDMA, TDMA	577	4.615	216.68
GSM-1800	1710–1880	1	FDMA, TDMA	577	4.615	216.68
DECT	1880–1900	0.25	FDMA, TDMA	417	10.000	100.00

not be distinguished from the desired signal and may obscure it. The dominating disturbance is:

$$i_o = a_2 \frac{\hat{u}_i^2}{2} \left(1 + \frac{m^2}{2} \right) + a_2 \hat{u}_i^2 m \cos(\omega_l)t + a_2 \frac{\hat{u}_i^2}{4} m^2 \cos(2\omega_l)t. \quad (1.2)$$

Since \hat{u}_i is smaller than 1 V and $m \leq 1$, the disturbing signal at $2\omega_l$ is at least four times smaller than the term at ω_l and may therefore often be disregarded. The direct current component may affect the integrity of the desired signal when DC is in the information band. However, since the disturbing signal at ω_l term is the largest, it will have the most detrimental effect.

Frequency modulation (FM), phase modulation (PM), frequency shift keying (FSK), and phase shift keying (PSK) are modulation methods resulting in carrier waves with a constant envelope, but with varying frequency resp. phase. The detected signal will be at DC only (see Table 1.3).

To make more efficient use of the available frequency spectrum, digital communication systems frequently use techniques like time division multiple access (TDMA) and frequency division multiple access (FDMA). TDMA is used by the global system for mobile communications (GSM) standard. TDMA uses short bursts of carrier wave interleaved by longer periods of silence, i.e., the carrier is switched on and off. Each phone has a time slot T_1 to transmit its message. If a time frame T has passed, the phone may transmit again (Anker 1995). Table 1.3 shows that pulses are detected, with T_1 being expressed in fractions of π , where T is equivalent to the full 2π radians of the sinusoid (the DC-term has been omitted, because it depends strongly on T_1). For instance, in case of GSM, $T_1 = \frac{\pi}{4}$ s and $\omega_l = 1361.47$ rad/s (216.68 Hz). Table 1.4 presents an overview of some wireless communication systems using periodically on-off switching.

The GSM standard also uses FDMA. Per time-frame the communication may switch to another channel (Anker 1995); a higher or lower frequency. This frequency shift

is relatively small compared to the mean frequency, so this frequency ‘hopping’ is expected to give minor EMI effects compared to TDMA. Other digital communication standards like C2000/terrestrial trunked radio (TETRA) and digital enhanced cordless telecommunications (DECT) also use TDMA or FDMA.

The universal mobile telecommunications system (UMTS) is used to deliver multimedia services to the user in the mobile domain (Dinan et al. 2002). It uses wideband code division multiple access (W-CDMA) as radio transmission technology. Two transmission duplex techniques are used in UMTS, frequency division duplex (FDD) and time division duplex (TDD) (Forkel and Jin 2002). Within the TDD operation, a transmission is split into 10 ms radio frames (Dinan et al. 2002; Forkel and Jin 2002) which may be detected and result in interference with a frequency of 100 Hz.

Bluetooth is a short range (0–10 m) wireless link technology aimed at replacing cables that connect phones, laptops, etc. (Golmie 2006). It uses modulation types like Gaussian frequency shift keying (GFSK), time division multiplexing (TDM) and frequency hopping with 1600 hops/s. The latter may cause detection to occur (van Dijk 2007), because the interference is not present at just one frequency, but at many frequencies.

Wireless local-area network (LAN) (IEEE 802.11a and g) and ultra wideband (UWB) use (orthogonal) frequency division multiplexing ((O)FDM) (van Dijk 2007; Maheshwari 2011). OFDM is a technique for transmitting data in parallel using a large number of modulated carriers with sufficient spacing so that the carriers are orthogonal. (O)FDM signals have a finite message length that depends on the data rate. Consequently, frame frequencies in the range from 363 Hz and 2.1 kHz can be expected, which may be detected (van Dijk 2007), causing interference.

The term UWB usually refers to a technology for the transmission of information spread over an (-10 dB) operating bandwidth exceeding 500 MHz or 20 % of the center frequency (FCC 2002). Different UWB technologies are used. The first is classical impulse radio technology (Cave et al. 2007), which is an on-off switching of the ultra wide band signal. Its interference effect can be analyzed using the third equation given in Table 1.3. The earlier mentioned OFDM technology is the second technology. Two modulation schemes, multiple carrier OFDM and pulsed direct sequence code division multiple access (DS-CDMA) are used. Interference effects comparable to that of wireless LAN and Bluetooth can be expected (van Dijk 2007). The third technology that is used, is UWB-FM using a low emission level (-41.3 dBm/MHz)(Chen 2007). It uses double FM: a low-modulation index digital FSK followed by a high-modulation index analog FM is used to create a constant envelope UWB signal (Gerrits et al. 2005). Hence, a DC-shift may be expected resulting from UWB-FM interference.

Table 1.5 presents an overview of legal transmitters in the Netherlands. It shows a variety of modulation types, transmitting power, and frequencies used. What interference source will be dominating depends on the circumstances. If equal amplitude of the interfering signal is assumed, constant envelope modulation (e.g., FM) is expected to result in less disturbance than the other modulation types. Amplitude modulated and on-off switched interference are expected to result in comparable values of disturbance. In the following chapters of this work, interfering signals will therefore be assumed to be AM for reasons of simplicity.

Table 1.5 Some legal transmitters in the Netherlands (Nationaal frequentieregister 2010). The maximum allowed power in AM-broadcasting depends on the licence. Maximum power (Radio 747 AM) is listed

	Frequency band (MHz)	P_{\max} (W)	Modulation type
Broadcast	0.15–26.1	<500 kW	AM
Amateur band	10.10–10.15	400	FM
Amateur band	10.10–21.45	400	AM
Amateur band	21.00–10.15	400	AM
Paging systems	26.1, 26.8875–26.9125	5W, 0.5	FSK
Amateur band	50.00–50.45	120	AM, FM
Broadcasting	87.5–108	≤ 200 kW	FM
Amateur band	144–146	400	FM
Telemetry	433.05–434.79	10 m	FM
Amateur band	430–440	400	FM
Bluetooth	2402–2480	0.1	GFSK, TDM, frequency hopping
Wireless LAN	2400–2483.5 (Golmie 2006; Maheshwari 2011)	0.1	(O)FDM
	5150–5825 (Chen 2007)	1	
UWB	3800–8500 (Nationaal frequentieregister 2010)	-41.3 dBm/MHz	(O)FDM, FM
UMTS	1899.9–2164.7 (Nationaal frequentieregister 2010)	0.125–0.250	W-CDMA, (Dinan et al. 2002) FDD, TDD (Forkel and Jin 2002)

Note that non-intentional sources of interference may also cause EMI due to envelope detection⁵ while having relatively low values of ω_c , e.g., MRI and electrosurgery equipment.

⁵ In the remainder of this work EMI may be used as an abbreviation for envelope detection.

1.6.1 Additional Circumstances Affecting Interference

The discussion so far has concentrated on the properties of the envelope of the interfering signal. Besides the envelope being constant or not, the received power of the interfering signal affects the amplitude of the disturbance. The received power depends on the distance between source and emitter and the efficiency of the transfer from the electromagnetic field to an interfering signal at the input of a nonlinear device. Usually wires and cables (interconnects) attached to the receptor behave like an antenna. The efficiency of the antenna behavior depends on the length of the wires and the orientation to the electromagnetic field. Besides the antenna behavior of the wires, the local field strength at the receptor is of importance. In practice, it is an important quantity as it is relatively easy to measure and it is also used in standards and regulations. The electromagnetic field strength (in the far field) can be approximated with (Goedbloed 1993):

$$E = \sqrt{\frac{Z_0 P G}{4\pi r^2}}, \quad (1.3)$$

with E being the electric field component, Z_0 the wave impedance of $120\pi \Omega$, P the transmitted power, G the antenna gain and r the distance between source and receptor. EMC engineers often assume a G of 1.64 (i.e., antenna gain of a half-wavelength antenna) when approximating the expected E-field.

Usually the distance between radio transmitters in, for instance, the AM or FM bands are located several tens or even hundreds of kilometers from the receptor. At these large distances the chance of interference may be acceptably low. That is, however, not always the case as was shown in a few examples in Sect. 1.3.

Nowadays, transmitters can also be found at relatively small distances from receptors. For example, an increasing number of homes, offices, and hospitals are equipped with some kind of mobile wireless communication system like WLAN or DECT, etc. Personal communication systems are also widely used (GSM and UMTS). Due to the mobility of the transmitter of these communication systems, it may come in close proximity to a receptor and, despite the low transmission power ($<3W$, see Table 1.4), interfere with it. Users of GSM cell phones, for instance, cause an audible disturbance when operating at a small distance from an audio system.

1.7 Negative-Feedback Amplifiers

Electronic systems are widely used to transport and condition information from a source to a destination. The source may, e.g., be any kind of sensor transferring a physical quantity to an electrical current or voltage. The destination usually is a transducer transferring an electrical voltage or current to another physical quantity.

The information may be processed while being transported from source to load. This processing may be done in a digital as well as in an analog way. Nowadays, most of the signal processing is done digitally. The information exchange between sensor and the system, however, is always analog and will remain analog in the future. The load may be analog or digital.

This analog part usually involves some kind of amplification or filtering function. Since amplification is perhaps the most basic electronic function, a linear negative-feedback amplifier is assumed for the analog part of the electronic system in this work. The goal of (negative-feedback) amplifiers is to increase the energy level of information by multiplying it with a constant. While doing so, the fidelity of the transfer from input to output of the amplifier has to be assured. Using a systematic design approach (Nordholt 1993; Verhoeven et al. 2003), this is accomplished by orthogonalization.

Firstly, the source and load are characterized. Usually the information is best represented by either a voltage or a current. The source impedance is usually not accurately known and might even be nonlinear. By assuring that the amplifier does not significantly load the source, these inaccuracies and nonlinearities do not appear in the transfer. If the load is also nonlinear or an inaccurately known impedance, the correct choice (i.e., voltage or current) for driving this impedance with maximum signal fidelity has to be made. From this characterization the required type of negative feedback follows.

The active part of the amplifier consists of components that are capable of increasing the energy level of a signal, i.e., transistors. Transistors are inherently nonlinear devices and measures have to be taken to realize a linear transfer. This may be accomplished by realizing the negative feedback using a linear resistor network.

The next step in the design process is to optimize the input stage for noise behavior and the output stage for preventing clipping distortion. Then the bandwidth is designed to meet the specifications. The complete design process and at what stage EMI aspects enter the design process are extensively dealt with in Chaps. 5 and 6.

1.7.1 A Classification of Errors in Negative-Feedback Amplifiers

The information handling capacity of negative-feedback amplifiers is constrained by three fundamental limitations: noise, signal power, and bandwidth (Verhoeven et al. 2003).

The three fundamental limitations lead to deviations from the intended output signal. Sometimes deviations from the intended output signal are called noise. Noise is, however, too narrow a term. Because of the different origin of the deviations and the (orthogonal) design steps that can be taken to minimize them, the term error will be used instead of noise. Noise will be used for errors that are stochastic in nature.

Apart from these fundamental limitations, errors generated by interference exist and they also negatively affect the information handling capacity of negative-feedback amplifiers. For convenience, a classification of the errors and an indication

if, and how, it is possible to minimize the errors from various origins is given. The errors given all occur at the same time (except perhaps interference) and may interact. Chap. 5 will present methods for minimizing the errors.

1.7.1.1 Errors Due to Noise

Noise is caused by stochastic processes in the circuit. Errors due to noise can be divided into:

- signal amplitude independent noise
- signal amplitude dependent noise

Thermal noise comes from thermal agitation of electrons in resistive material and is an example of signal independent noise. The spectral noise density for thermal noise is given by the equation $S_{u_{th}} = 4kTR$, where k is Boltzmann's constant, T is the temperature in kelvin, R is the resistance, and S is the spectral density. Thermal noise is also called Johnson or white noise in literature (Ott 1988) and has a Gaussian distribution.

When noise depends on biasing conditions, it may also be signal dependent due to small changes in the biasing due to the input signal. Some examples of these signal dependent types of noise are: shot noise, excess noise, and burst noise.

Shot noise is associated with the uncertainty in a current of charge carriers crossing a potential barrier, e.g., a p-n junction. The spectrum of this source is given by $S_i = 2qI$, where q is the electron charge and I is the barrier current. The spectrum is flat as long as the transition time of the charge carriers is small with respect to the reciprocal value of the frequency. Shot noise has a Gaussian distribution.

Every imperfect contact between two materials, such as switches and relay contacts, but also carbon resistors and transistors show a noise component that depends on the frequency (Verhoeven et al. 2003; Ott 1988). This noise contribution is called excess noise and is due to the statistical variations in the conduction, due to an imperfect contact between two materials or due to generation and recombination processes at the surface in semiconductor materials. The power density of these noise sources is inversely proportional to the frequency. That is why excess noise is often called $1/f$ -noise. It is described as $S_i = K_1 I^a \frac{f_l}{f^b}$. The noise corner frequency f_l is of importance because at this frequency the excess noise is equal to the white noise. K_1 is a constant for a particular device, a is a constant in the range 0.5 to 2, b is a constant of about unity (Gray et al. 2001) and I is the current.

Burst noise, also called popcorn noise, is found in some integrated circuits and discrete transistors. The source of this noise is not fully understood, although it has been shown to be related to the presence of heavy-metal ion contamination (Gray et al. 2001). Gold-doped devices show very high levels of burst noise. The spectral density of burst noise is of the form $S_i = K_2 I^c \frac{1}{1+(\frac{f}{f_c})^2}$. K_2 is a constant for a particular device, I is the bias current, c is a constant in the range 0.5 to 2 and f_c is the particular frequency for a given noise process. Burst noise is so named because

an oscilloscope trace of this type of noise shows bursts of noise on a number (two or more) of discrete levels. The repetition rate of the noise pulses is usually a few kilohertz or less. If it is amplified and fed into a loudspeaker, it sounds like corn popping, with thermal noise providing a background frying noise, thus the name popcorn noise (Ott 1988).

In properly designed negative-feedback amplifiers, current changes due to the input signal amplitude will not significantly change the bias conditions. But even when the input signal modulates the bias current up to 100 %, the noise is affected by (less than) only 2 dB. Signal dependent noise may therefore be neglected. The mean noise contribution is thus determined by the bias current. An exception may be a negative-feedback amplifier having a class-B stage as active part. For a class-B amplifier the current through the active device and therefore the shot noise is directly related to the signal level (van Staveren 1997).

In linear, time-invariant (negative-feedback) amplifiers all noise sources generated by the transistors and feedback resistors can be transferred to an equivalent noise source at the input. When the amplifier is properly designed, the input stage of the amplifier has a much larger contribution to the equivalent noise source than the subsequent stages. From the equation giving the equivalent noise source, the optimal biasing current of the input transistor can then be calculated (Verhoeven et al. 2003). The value(s) of the feedback resistor(s) are determined from both amplification and noise constraints.

1.7.1.2 Errors Due to Input Signal Power

When a signal is applied to an amplifier, errors due to distortion may occur. Characteristic for distortion is that frequency components can be found at the output that are not found in the input signal. Two types of distortion can be identified: weak and strong nonlinear distortion. Weak nonlinear distortion originates from the nonlinear device transfers; strong nonlinear distortion from clipping.

Input signals with a small amplitude may cause weak nonlinear distortion (Eq. 1.1). Strong nonlinear behavior resulting in clipping distortion is found when signals are that large that they no longer fit between the supply rails or the current driving capability of a stage is not sufficient (van Staveren 1997). As for an increasing input signal the output signal no longer increases, the signal which is fed back no longer changes and consequently the negative-feedback loop is broken. This severe type of distortion results in loss of information.

The errors due to the input signal can therefore be divided into errors resulting from:

- signals with small amplitude
- signals with large amplitude

Weak nonlinear distortion can be minimized by ensuring a small enough input signal is being applied to the active device(s). By ensuring enough loop gain this input signal can be made sufficiently small. Appropriate biasing of the amplifying stages

is also beneficial for low weak nonlinear distortion (Lantz and Mattisson 2002a,b; Lantz 2002; Verhoeven et al. 2003).

Clipping distortion can occur in every stage of the amplifier, but it most likely that it will occur in the output stage where the signals are often the largest. It can be avoided by ensuring large enough voltage and current driving capabilities.

1.7.1.3 Errors due to Bandwidth Limitations

The speed of any amplifier is limited. When considering a negative-feedback amplifier it simply means that the output frequency components are not in correct proportion for fast signals, i.e., the waveform changes. When considering speed limitations, it is possible to distinguish between:

- small-signal speed limitations
- large-signal speed limitations

In case of small signals it is found that, from a certain frequency, the poles in the transfer begin to dominate and start to introduce errors, i.e., the bandwidth of the transfer is limited. Since this is caused by the gain being not constant with frequency, this kind of distortion is called frequency distortion or linear distortion (Carlson 1986). Linear distortion in negative-feedback amplifiers can be minimized by ensuring a large enough bandwidth.

Application-specific negative-feedback amplifiers often have two (complex) dominant poles determining the small-signal bandwidth. Depending on the positioning of the (complex) poles, errors due to overshoot may result in the frequency domain and in the time-domain. By forcing the poles in ‘maximally flat magnitude’ or Butterworth positions, overshoot in the frequency domain can be avoided. Overshoot in the time domain (transient response) can be avoided by forcing the poles into Bessel positions.

Large signals force large current swings to occur in the amplifier. Capacitances in the active part of the amplifier limit the speed of the voltage swings. At a certain amplitude and frequency of the signal, the speed at which the capacitances can be charged and discharged is not sufficient enough and slew-rate limiting occurs.⁶ Slew-rate is defined as the maximum rate at which the output voltage can change (Franco 1988). To guarantee the required large-signal or full-power bandwidth, the slew-rate has to be large enough by assuring adequate current driving capabilities.

⁶ The dual discussion holds for inductances. Inductances are nowadays hardly used in negative-feedback amplifiers, because they are usually bulky and far from ideal. They are therefore disregarded when dealing with amplifier design in this work.

1.7.1.4 Errors due to Interference

Interference may lead to disturbing signals at the input of the amplifier. Once again, a distinction can be made between small-signal disturbances that are either in-band or out-of-band, and large disturbing signals.

When the disturbing signal lies within the bandwidth of the amplifier, it is processed as if it is the intended signal, and thus subject to the same limitations as the intended signal. It can not be distinguished from it.

The effects of small disturbing signals with frequencies higher than the bandwidth have been investigated in Sect. 1.6. The main conclusion is that DC shifts and low-frequency components related to the envelope of the carrier wave are present at the output of the amplifier. These signals are undistinguishable from the intended signal and also subject to the same limitations. Errors due to a small-signal out-of-band disturbance result from weak nonlinear behavior, just as nonlinear distortion. In fact, it may be regarded as a form of nonlinear distortion.

Large disturbing signals have the same effect as large intended signals; it may result in clipping and/or slew-rate induced distortion.

1.7.2 Signal-to-Error Ratio

The designer's concern is to minimize errors because they limit the signal handling capability. Small signals, for example, might be lost in noise, or be obscured by distortion products from another larger signal or by disturbing signals. Effort has to be made to make the intended signal large compared to these errors. The ratio of the intended signal and the errors, the signal-to-error ratio (SER), can be regarded as a figure of merit of the signal handling performance of an amplifier for a given input signal and electromagnetic environment.

Assuming weak nonlinear behavior, the signal-to-error ratio at the output of an amplifier is given by:

$$SER = \frac{S_1}{S_{n,eq} + S_2 + S_3 + S_d + S_{ENV}}, \quad (1.4)$$

where S_1 is the power of the desired signal. The subscript denotes the harmonic of the signal. $S_{n,eq}$ gives the total power of the noise generated by the negative-feedback amplifier. S_2 and S_3 represent the power of the second and third harmonic, respectively, of the desired signal.⁷ A disturbance is represented by S_d for the rms power of a signal in the bandwidth and by S_{ENV} for the rms power of the detected envelope variations from a disturbance (much) larger than the bandwidth.

⁷ The contributions of the amplitude of the second and/or third harmonic are assumed to be so much larger than the higher harmonics that it is common practice to limit the analysis to the third harmonic.

Under the (noise) conditions given in Subsection 1.7.1, it is reasonable to assume that noise will not have a significant effect on distortion and EMI behavior, and vice-versa. Distortion due to the intended signal will show no correlation with the effects due to disturbances (and vice-versa) since they originate from different sources. S_d and S_{ENV} both originate from disturbance(s) (which may be from different interfering sources), but the disturbances causing both are separated in the frequency domain, so there is no correlation. All errors in Eq. (1.4) are therefore uncorrelated.

In Eq. (1.4) the commonly known signal-to-noise ratio (SNR) $S_1/S_{n,eq}$ and the, somewhat less known, signal-to-distortion ratio $S_1/(S_2 + S_3)$ can be recognized. The signal-to-distortion ratio represents the relative distortion level in a similar manner as the SNR represents the relative random noise level. The SNR in a linear negative-feedback amplifier can be maximized through the separate optimization of the maximal tolerable signal power and the generated noise power (Verhoeven et al. 2003). Weak nonlinear distortion can be minimized by ensuring enough loop gain and appropriate biasing of the amplifying stages (Lantz and Mattisson 2002a,b; Lantz 2002; Verhoeven et al. 2003).

The signal-to-disturbance ratio is the desired signal power S_1 divided by the power of the signals resulting from the interfering signal $S_d + S_{ENV}$. Chapters 2 and 5 will present measures to reduce $S_d + S_{ENV}$.

1.8 Design for Electromagnetic Compatibility

Malfunctioning of equipment due to lack of EMC has a large impact on society because it may result in nuisances (e.g., radio programmes on the telephone) or life threatening situations (e.g., failing apnea monitoring systems). The examples given in Sect. 1.3 highlight that. EMC should therefore be part of the design process.

Some work on incorporating EMC into the design process has been done. For example, a general method for systematically designing electromagnetically compatible electronics is presented in (Reitsma 2005), and design techniques specifically aimed at the reduction of radiated electromagnetic fields are presented in (Leferink 2001). A systematic design method specifically aimed at realizing a specified SER (thus including EMI) of application specific negative-feedback amplifiers has not been available up to now.

As far as EMC in the design of amplifiers is concerned, it is stated in literature that high-frequency EMI should not reach the input of the amplifier because it is very difficult to calculate the resulting errors in advance (Goedbloed 1993). Typically, EMC textbooks therefore concentrate on filtering at the input of the amplifier (Goedbloed 1993; AD 1993; Ott 2009) and filtered, balanced input configurations (Williams 1996) to realize an acceptable SER. Unfortunately, this means that an input filter is realized without any knowledge of the EMI behavior of the amplifier itself. This results in design by trial and error, which should be avoided. Although filtering can give good results, there are other drawbacks. Filtering may degrade stability, worsen

the noise behavior and, in case of balanced amplifier configurations, deteriorate the common-mode rejection ratio (Williams 1996).

The purpose of this work is to present a design method for realizing the specified SER when (high-frequency) EMI reaches the input of the amplifier by decreasing the susceptibility of the amplifier itself. When it is found that the amplifier susceptibility can not be made low enough, the effects of an input filter can be examined by incorporating it in the calculations made during the design process. The filter can now be optimized for the specified susceptibility, without degrading noise performance or stability. The method presented may be regarded as additional to existing measures to reach EMC.

1.9 Outline of this Book

Chapter 2 will give methods to determine disturbance amplitudes at the input of an amplifier due to electromagnetic waves that couple into the interconnect and measures for reducing this disturbance are also presented. From this it follows how much immunity has to be designed into the negative-feedback amplifier. Since we are primarily interested in disturbance due to out-of-band interference (which is often caused by sources located far away), crosstalk will not be discussed.

EMI effects like DC-shifts and AM detection in negative-feedback amplifiers result from nonlinear behavior of components. Nonlinearities will therefore be investigated in detail and models for nonlinear behavior of active components will be presented in Chap. 3. Single active devices often behave rather poorly, e.g., regarding their high-frequency and nonlinear behavior. Special combinations of stages, the cascode and the differential stage, have therefore been developed. The cascode stage has improved high-frequency and the differential stage improved nonlinear behavior. Both combinations of stages are extensively dealt with in Chap. 4.

The design method for negative-feedback amplifiers with specified SER will be presented in Chaps. 5 and 6. It will enable the designer to design for an accurate signal transfer, and also for noise, bandwidth, and EMI behavior. Chapter 7 presents the verification of the design method by presenting examples of realized amplifiers and their measured susceptibility. Finally, Chap. 8 presents the conclusions.

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