

Chapter 2

Demand for Power Electronic Systems and Radio-Frequency Applications

This chapter deals with applications for power electronics using integrated circuits, providing intuitive access to lateral power transistors employed therein. For this purpose so-called *smart-power ICs* combining logic operation, memory and power electronic circuitry are presently employed. Additionally, integrated lateral power transistors are also the driving force in multi-stage *RF power amplifiers* (monolithic microwave integrated circuits) for base stations with a clear trend towards further incorporation of logic functionality and the implementation in the power amplifiers of mobile devices.

An overview of power electronic and power amplifier markets provides a basic understanding for the applications driven by these technologies and the implications involved in rolling out new developments. In particular, the impact of power electronics on energy conversion and the impact of power amplifiers on information technologies are presented. Power electronic and RF amplifier applications having a high impact on recent developments using integrated circuits are briefly reviewed. Examples of power electronic applications include motor control and drive inverters for window lifts in automobiles and switch-mode power supplies in battery chargers. Integrated circuits for radio-frequency (RF) applications are readily found in mobile communication base stations and in wireless local area network (WLAN) communication equipment.

Subsequently, the requirements of these applications regarding their commercial use will be summarized. This overview includes economic aspects like energy efficiency, reliability as well as costs of fabrication and operation. Moreover, technologically relevant aspects regarding power density, ruggedness and switching frequency will be elaborated upon.

2.1 Semiconductors in Integrated Power Electronics and Radio Frequency Amplifiers

One of the key enabling technologies for the success of monolithic integrated power electronic systems and RF applications has been the lateral double-diffused metal-oxide-semiconductor (LDMOS) field-effect transistor in silicon technology which

has easily surpassed the performance of integrated bipolar junction transistor in both of these fields.

2.1.1 Impact on Integrated Energy Conversion Systems

Although the first lateral drain extended *Metal-Oxide-Semiconductor Field Effect Transistors* (MOSFET) had already been reported in 1972 [1], and the *reduced surface field* (RESURF) principle was discovered in 1979 [2], it took until the end of the 1990s for commercial integration of LDMOS transistors into complementary MOS (CMOS) technology [3]. Before that, bipolar technology and double-diffused MOS (DMOS) technology using quasi-vertical (DMOS) transistors were the methods of choice to integrate power devices in a logic process [4]. Or from an application point-of-view, power semiconductor devices were first augmented by logic functionality on chip in the 1980s. This augmentation gave rise to the terminology *smart-power integrated circuit* (smart-power IC). At the end of the 1980s, fabrication of display drivers in Bipolar-CMOS-DMOS (BCD) processes began. These monolithic integrated drivers were able to directly drive displays at low current ratings and medium voltages [5]. This market had enough volume to further drive the development of more versatile smart-power IC technology. From the 1990s on, further integrated solutions arose for automotive applications, motor control, power supplies and factory automation equipment. Since that time, non-volatile memories and LDMOS transistors were also employed to improve versatility and ruggedness of power electronic equipment. Advanced options like the implementation of microprocessors, digital signal processors and control functions (e.g. fuzzy logic) became available [4]. The main driver for this development in power electronics, however, was cost-efficiency over similar discrete solutions. Again, large volume production staged the development of these integrated circuits. The timeframe for integrating different power devices into CMOS processes and a comparison to the development of stand-alone Power semiconductor devices is shown in Fig. 2.1.

Besides the bipolar transistor, which has a long track history in BiCMOS process technology, no advanced bipolar power device technologies have been as successful as MOS-based power devices in commercially available smart-power IC processes.

Today, smart-power ICs are part of most electronic equipment with the LDMOS transistors being the working horse among all available power electronic devices. High voltage CMOS (HV-CMOS) technology is particularly interesting due to the lower process complexity compared to BCD technologies. This also simplifies scaling to future technology nodes or the integration of advanced CMOS-related devices like embedded non-volatile memories [7]. Smart-Power ICs found their way into applications where the use of these LDMOS transistors ranges from integrated gate drivers for high power electronic applications using insulated gate bipolar transistors (IGBTs) or superjunction power MOSFETs over battery

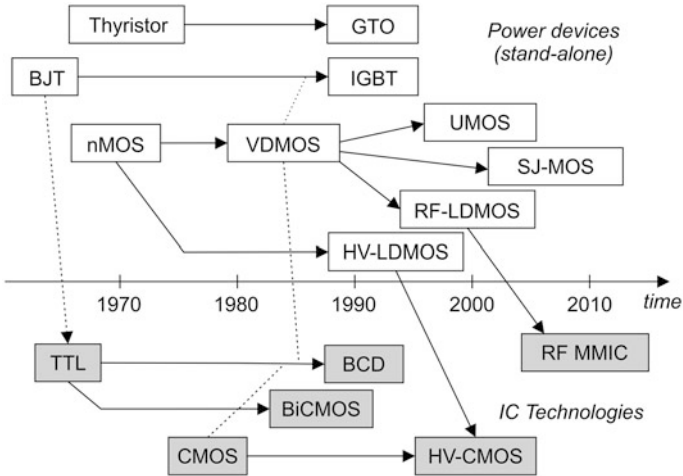


Fig. 2.1 Timeline for development of stand-alone power semiconductor devices and those integrated into CMOS processes, adopted from [4, 6]

monitoring and charging solutions to full-fledged integrated power supplies for on-board or on-chip power conversion. An overview of main-stream applications using smart-power ICs and their respective voltage ratings is given in Fig. 2.2.

Moreover, smart-power ICs are available both as “off-the-shelf”, ready-to-use chips and as *application-specific integrated circuits* (ASIC) fabricated on customer demand and even on customer design. The possibility to design individual circuits has given rise to the development of further HV-CMOS, BCD and BiCMOS technologies which silicon foundries are offering to their customers. Now, even for small production volumes these complex manufacturing technologies can be economically employed by sharing a common fabrication process among different customers. Additionally, the ability to reuse design blocks in subsequent

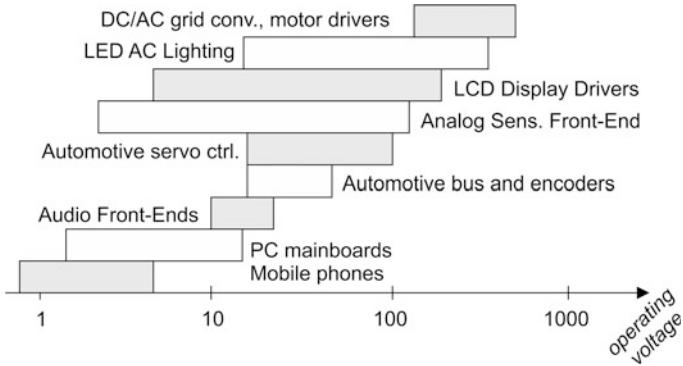


Fig. 2.2 Overview of typical applications employing smart-power IC technologies

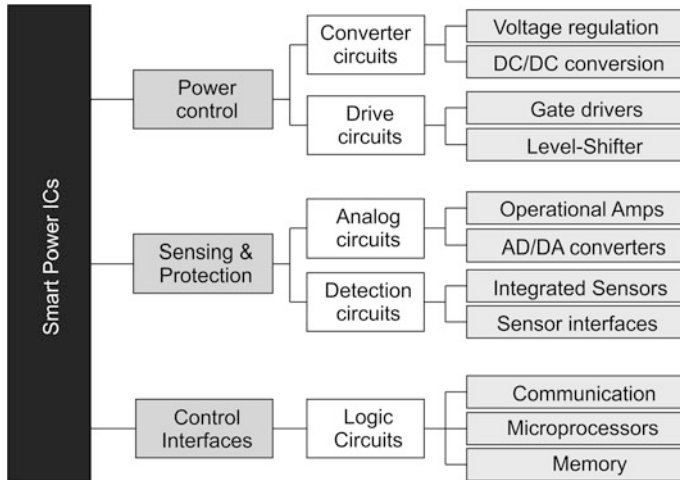


Fig. 2.3 Building blocks regularly encountered in smart-power ICs and RF integrated circuits, adopted from [5]

generations has led to the development of features far beyond simple control circuits for power devices. Typical design features that are included in smart-power ICs can be gathered from Fig. 2.3.

Sensing functionality in smart-power ICs has evolved from over-temperature and over-voltage sensing by on-chip silicon sensors to the integration of detection circuits using external sensors (e.g. humidity, chemical sensors, and optical sensors). The incorporation of high-performance microprocessors, dynamic random access memory and non-volatile memories as well as precision analog-to-digital and digital-to-analog converters has enabled the implementation of small highly specialized computers into a single silicon chip. Most commercially used data transfer protocols (e.g. SPI, UART, I²C, CAN, LIN, FlexRay) can also be integrated and allow for interaction with the outside world [7]. Often, the semiconductor foundries already offer a base set of these fundamental building blocks to their customers for ease of implementation in new technologies.

Advances from the development of new smart-power IC generations include a reduction in feature size and typically an improvement in device performance which arises from more metallization levels or more robust designs. With each new technology generation becoming available, more sophisticated and powerful solutions are implemented, driving cutting-edge solutions today and in the future. The technologies are based on BiCMOS, BCD or HV-CMOS technologies. A summary of foundry technologies and their typical feature sizes is provided in Fig. 2.4.

With a high investment in the design and development of these integrated circuits, smart-power ICs are often fabricated using a given technology for several years. Some are even fabricated for decades using the same technology node. For instance, some ASICs designed in 2 μm technology are still being fabricated today.

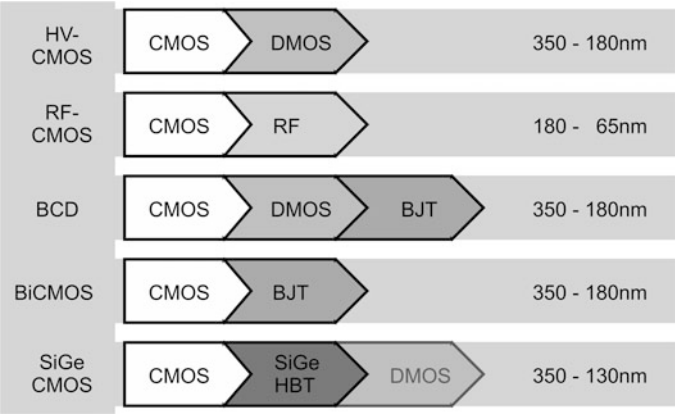


Fig. 2.4 Summary of CMOS-based process technologies available as foundry services and their typical technology nodes

2.1.2 Impact on Information Technologies

Availability of electronic systems capable of reliably operating at frequencies near 1 GHz has enabled the realization of wireless communication infrastructure and radio-frequency applications. A very diverse set of solutions which are part of present day life have evolved from this development ranging from mobile phones and wireless local-area-networks (LAN) over radar applications for avionics to digital video broadcast. An overview of different applications and their operating frequencies is given in Fig. 2.5 along with the year of introduction for the respective standards.

It is apparent that CMOS technology was not available for some of the technologies (e.g. W-LAN) at the year of introduction as the required switching

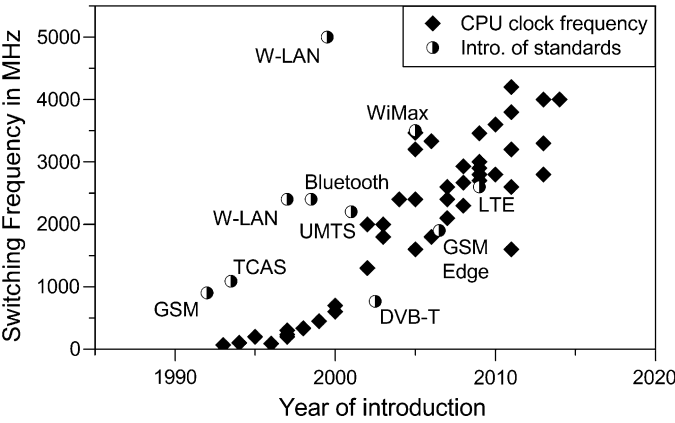


Fig. 2.5 Definition of standards for radio-frequency applications and their operating frequencies by year with comparison to CPU clock frequency by year of introduction to market

frequencies could not be achieved with high efficiency. Some applications have been manufactured by using different semiconductor materials, such as the GaAs heterojunction bipolar transistors for the power amplifier in mobile phones [8]. Nevertheless, CMOS in general and LDMOS technology in particular are recently catching up with even these demanding technologies [9].

Driven by the bipolar junction transistor (BJT), these technologies started emerging in the 1970s. Operating frequencies were, of course, limited by the availability of suitable device technology. The bipolar transistor offered quite mature processing technology and sophisticated design options making it viable for a wide range of solutions at frequencies close to 1 GHz [10]. For the simple modulation schemes of first generation RF power amplifiers, gain and linearity were sufficient for the demands of the information technologies of that era, and the bipolar transistor could readily be scaled to support the diverse power requirements of different applications [11].

Starting in the 1990s, the technology for LDMOS transistors tailored towards high operating frequencies had evolved so efficiently, that it started to replace the silicon bipolar transistor in radio-frequency applications [12]. A comparison between bipolar junction transistors and unipolar MOS transistors can be found in Chap. 4 of this textbook. Furthermore, higher operating frequencies and more sophisticated modulation schemes have been realized due to the high gain at better linearity of these unipolar RF transistors [13, 14]. This disruptive technology paved the way for today's third and fourth generation RF power amplifiers in mobile communication base stations. It has also enabled a tremendous leap in data transmission rates using wireless telecommunication equipment. A comparison to data transfer rates (downstream) with the year of introduction to the European market is given in Fig. 2.6.

As is evident from the data, mobile phones are now capable of providing similar data transfer rates to cable or DSL-based internet access. Presently, RF-LDMOS

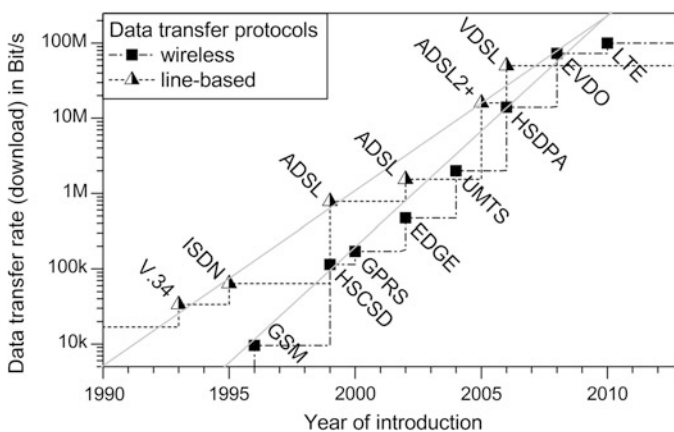


Fig. 2.6 Data transfer rates (downstream) of wireless and line-based telecommunication technologies and year of introduction into the European market

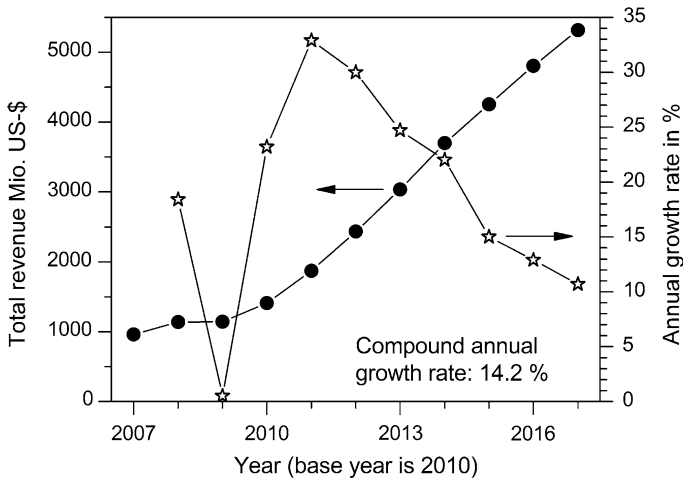


Fig. 2.7 Estimated market development for mobile communication RF amplifiers, adopted from [15]

transistors are the key element of modern mobile phone base stations. Here, market prospects are excellent, and a compound annual growth rate of up to 30 % is predicted for the next several years as depicted in Fig. 2.7.

The market volume for these RF amplifiers is expected to arrive at over 5 billion US-\$ in 2017. This includes a share of 75 million US-\$ for RF semiconductor devices [15]. The key drivers for RF semiconductor devices are the demand for new features, the increasing deployment of 3G and 4G mobile phones, and the penetration of new markets (e.g. LTE). Figure 2.8 summarizes the technologies currently used in RF amplifiers depending on power level and operation frequency.

Just recently, competitive performance of integrated silicon LDMOS transistors for application on mobile phone power amplifiers was reported, a terrain that has been traditionally occupied by GaAs transistors [17]. Similarly, the efficient operation of the first CMOS-based power amplifiers integrated into silicon for WiMax and LTE transmitters has been achieved [18]. For mobile phones, monolithic integration of circuits in system-on-chip solutions today is state-of-the-art. Manufacturers strive for a single-chip solution using a CMOS-based technology for cost reasons [15, 19]. The main advantages of using power devices for the RF power amplifier with operating voltages well above the CMOS level (typically 3.3 V or below) arises from the reduction of device current for the required output power of 1–3 W. This would both minimize electromigration effects through the metallization layers and the impact of parasitic inductances [20]. Therefore, it can be expected that the trend towards a fully integrated fabrication with LDMOS transistors will also be used in RF power amplifiers for mobile phones in the near future. This is particularly true, because the CMOS technology alone is not capable of providing cost-efficient RF power amplifiers for handsets due to diminishing returns from technology scaling [21].

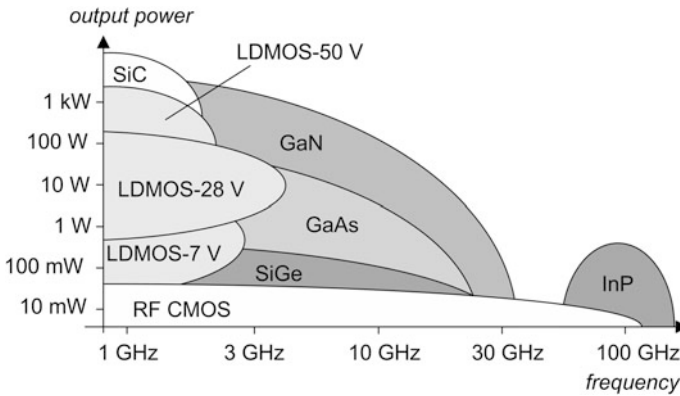


Fig. 2.8 Dominant semiconductor technologies currently used in RF power amplifiers (adopted from [16])

The implementation of monolithic microwave integrated circuits (MMICs) allows the concatenation of several amplifier stages on a single substrate. This minimizes parasitic capacitances and inductances and can offer higher output power.

2.2 Integrated Power Electronic and Radio-Frequency Applications

Monolithic integration of power semiconductor devices and the implementation of advanced circuit topologies have enabled a wide range of power electronic applications. Selected examples demonstrate the benefits of this approach.

2.2.1 Switch-Mode Power Supplies for DC-to-DC Conversion

A high efficiency well beyond 90 %, high tolerances regarding input voltage and grid frequency and a low weight and volume are the key benefits of switch-mode power supplies (SMPS) compared to fixed voltage regulators. Figure 2.9 depicts the building blocks of an SMPS.

For high power densities like in traction systems vertical power transistors (MOSFETs and IGBTs) on transfer substrates with water cooling for efficient heat management are usually employed. Low and medium power densities use packaged power devices and passive (air) cooling that can be augmented by a heat sink. The monolithic integration using lateral transistors together with the high energy efficiency of this circuit topology provides the basis for control, routing and regulation of medium power densities in smart-power ICs.

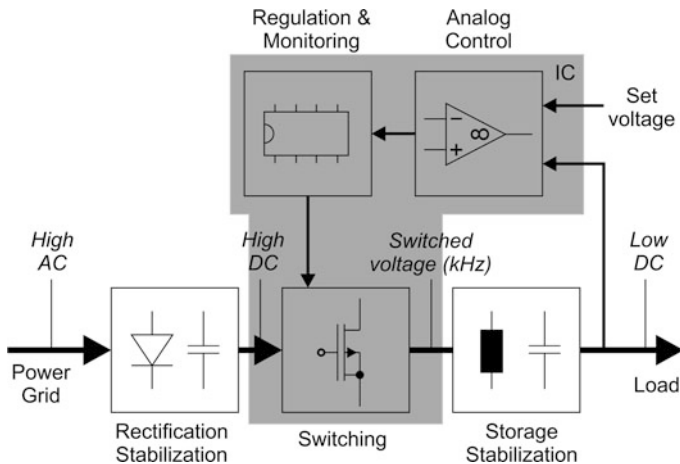


Fig. 2.9 Circuit topology of monolithic integrated switch-mode power supply

2.2.2 Motor Control and Drive Inverters for DC-to-AC Conversion

Traditionally, most three-phase induction motors are operated directly on the AC line at a fixed speed related to the net line cycle. For applications with varying loads, e.g. water pumps or ventilation in air conditioning, a higher energy-efficiency can be achieved by variable frequency drives. Using power electronics, the torque and speed of the electric motor can be directly controlled by supplying optimized voltages and currents to the motor. This is performed by converting the input power of this drive inverter to a sinusoidal wave with power adequate for the present demand of the motor. A schematic circuit topology for a DC-to-AC converter is shown in Fig. 2.10.

This topology can generally be used to convert direct current to alternating current. A “mobile AC plug” powered by the battery of an electric or hybrid vehicle is an example for this type of energy conversion.

Due to its high reliability, low fabrication effort (at high volumes) and high energy efficiency, monolithically integrated drivers for bidirectional variable frequency drives are applied in automotive applications, especially for power window lifts. A block diagram of such a power window lift using an integrated circuit is shown in Fig. 2.11.

2.2.3 Power Amplifiers for Mobile Communication Base Stations and Handhelds

One of the largest growing markets of the last and present decades is telecommunications enabling access to the internet. The introduction of higher data rates

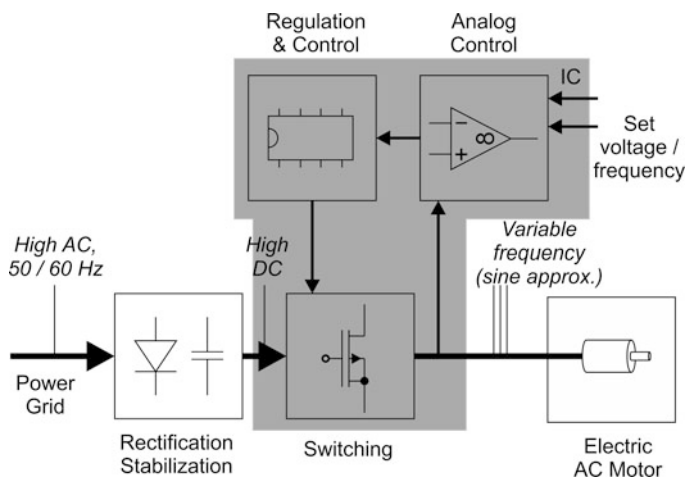


Fig. 2.10 Circuit topology of monolithic integrated variable frequency drive

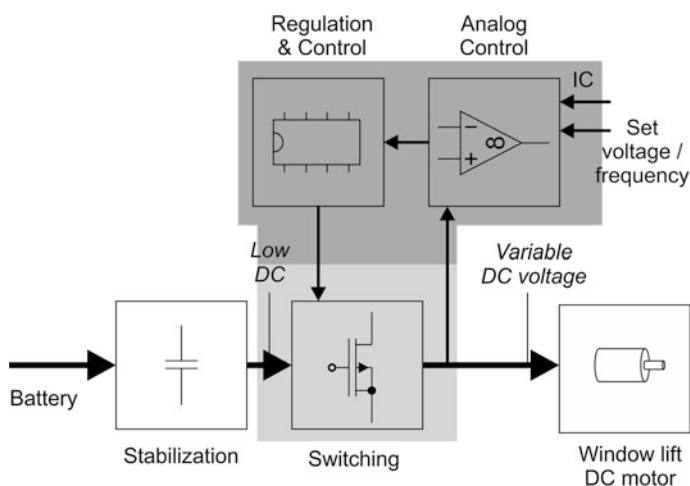


Fig. 2.11 Circuit topology of monolithic integrated power window lifts circuitry

has led to computer technology “to go” with laptops and smart phones on the forefront. At the core of this development is the transmission of information via radio waves in the lower GHz range. The underlying transmission infrastructure is schematically depicted in Fig. 2.12.

It consists of both a sender (signal source, e.g. microphone) and receiver (signal sink, e.g. loudspeaker). The signal source is encoded in the baseband processing hardware that typically consists of a digital signal processor and an ASIC [22]. Then, a radio frequency frontend is used to modulate the digital signal onto the

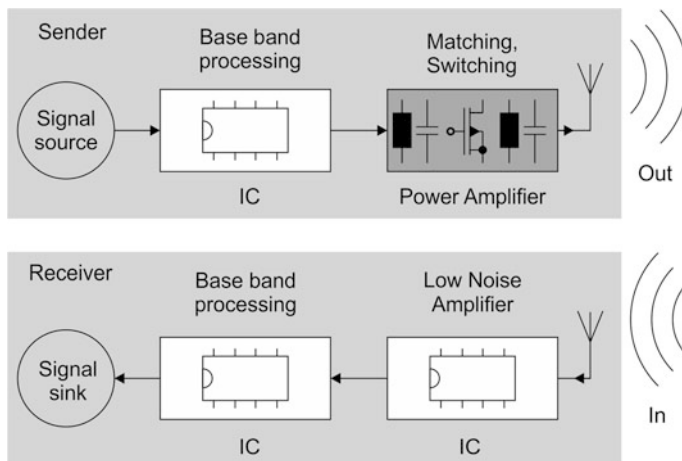


Fig. 2.12 Schematic representation of transmission link in telecommunications

carrier frequency. This modulated carrier signal is amplified by the RF power amplifier and broadcast using an antenna.

An RF power amplifier in base station equipment utilizes silicon RF LDMOS transistors and offers a peak output power of 120–180 W at a supply voltage of 26–28 V and frequencies of 900 MHz (GSM) to 3.6 GHz (UMTS) depending on the baseband technology. The power amplifier in the mobile phone is still fabricated using GaAs HBT transistors in MMIC technology [17].

When the transmitted signal is received, it is passed through a low noise amplifier to extract the signal from the hostile background noise: Assuming that the power of the received signal compares to the size of a pin (approximately one mm in diameter), the size of the haystack—given by the largest known interferer—would be the size of a field of 100 by 100 m [23]. Fortunately, the interferences occur at other frequencies than the desired signal and can be filtered out. The amplified signal can then be passed on to be decoded in the baseband processing hardware, where synchronization and data recovery take place [24]. This functionality can be clustered into a single silicon CMOS chip.

2.2.4 Transceivers for Wireless-LAN Communication

For the connection of mobile phones, laptops, desktop computers and peripherals through a local area network, wireless LAN was implemented following the IEEE 802.11 protocol [25]. The purpose of this protocol is to provide a communication frameset that achieves data rates similar to wire bound LAN connections for up to 52 potential clients. Usually, all clients are connected to a wireless access point. The wireless access point is often integrated into a router providing connection to a

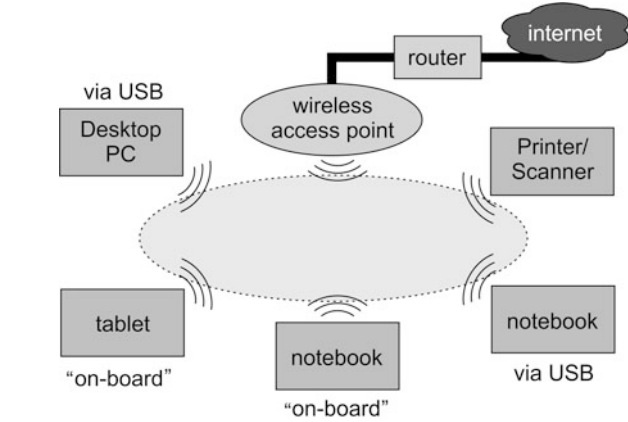


Fig. 2.13 System architecture for a wireless LAN with one central access point and participants connected through different hardware components

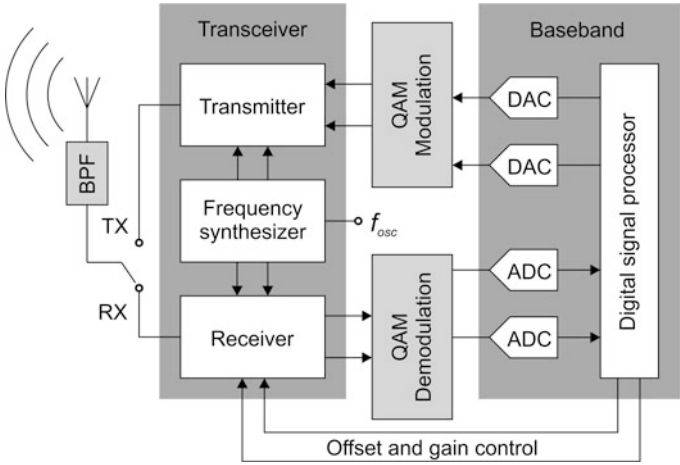


Fig. 2.14 Block diagram of a wireless LAN transceiver operating at 5 GHz (adopted from [26])

wire-bound intranet or the internet (e.g. DSL or cable TV). Figure 2.13 represents a system architecture regularly encountered in households or small companies.

Moreover, mobile phones with integrated wireless LAN functionality provide internet connectivity using wireless telecommunication data transfer (e.g. UMTS, LTE) in ad hoc networks. The block diagram for a wireless LAN transceiver is shown in Fig. 2.14.

In order to ensure that the information from up to 52 potential clients—represented by 52 subcarriers of the orthogonal frequency-division multiplexing (OFDM) signal—can be transmitted without distortion, the transmitter stage has to provide a peak-to-average ratio of at least 17 dB. This requires high power back-off

in the transmitter and a wide dynamic range in the receiver [26]. Owing to error correction topologies, these demanding constraints can be somewhat relaxed.

Due to the limited output power (of up to 1 W depending on the country) that is allowed for a wireless LAN, CMOS technology can be applied for the implementation of RF power amplifiers in wireless LAN transmitters, and integrated circuits are routinely used. Nevertheless, to boost the signal level of the clients to the access point, external power amplifiers can be hooked up to the CMOS output stage [27].

2.3 Requirements for Power Electronic and RF Amplifier Systems

2.3.1 Energy Efficiency

In modern power electronic systems, energy efficiency can be a key criterion for customers when buying products. This is particularly true for mobile systems where “infinite” power supply from a wall plug is not available. Also, this point holds for applications like white goods where a rating system with respect to energy efficiency has been implemented. The customer is made aware of the system’s efficiency, and the system facilitates low operating expenditures. Or, in the case of solar inverters, the revenue is increased from using more efficient equipment despite the higher initial costs [28].

Moreover, efficient energy usage produces less heat. Subsequently, the cooling system can be reduced in size and cost. This advantage becomes particularly apparent, when air instead of water cooling can be applied.

2.3.2 Size and Weight of Equipment

Reducing the size and weight of a power electronic system is particularly beneficial in mobile applications where large, bulky or heavy equipment is not accepted by the customer, e.g. mobile phones. While power semiconductor devices are usually not the constraint in size and weight of electronic equipment, they may affect these properties of related subassemblies. Two prominent examples are passives components and cooling systems.

- By applying higher switching frequencies in power converters, smaller inductances and capacitances are required.
- The usage of more efficient semiconductor devices allows for a reduction in the size of the cooling system. With a large benefit arising, when air cooling instead of a fluid cooling system is sufficient to remove the excess heat.

2.3.3 Power Density

From an application perspective, the power density of an energy conversion system depends on a wide range of factors. Passive components like inductors and capacitors typically require a lot of volume. Moreover, cooling components (heat sinks, pipes, fluids etc.) constitute to another mentionable portion. In contrast, the (power) semiconductor devices are not a key factor when power density of the system is concerned. However, as shown in Chap. 4, the power density of semiconductor devices is of concern, when chip costs have to be considered.

2.3.4 Reliability

Another important aspect of electronic equipment is reliability. It is defined as “the ability of a system to consistently perform its intended or required function or mission, on demand and without degradation or failure” [29]. In Industrial, Science and Medical applications, failed systems can usually be repaired. In this case, the reliability of a system can be estimated by the “mean-time-between-failures” (MTBF). When an electronic subsystem has failed, it is typically replaced by a new one, unless repair of the electronic component requires less labour and parts than the full replacement. Additionally, failure of power electronic equipment often causes irreparable damage to the whole subsystem. Then, the reliability of a system is usually predicted by the “mean-time-to-failure” (MTTF) which is equivalent to the total lifetime. The reliability requirements greatly vary between different markets, e.g. lighting on the lower end and aviation on the upper end of reliability demands. The failure probability of electronic equipment can be described using a “bathtub curve” (see Fig. 2.15).

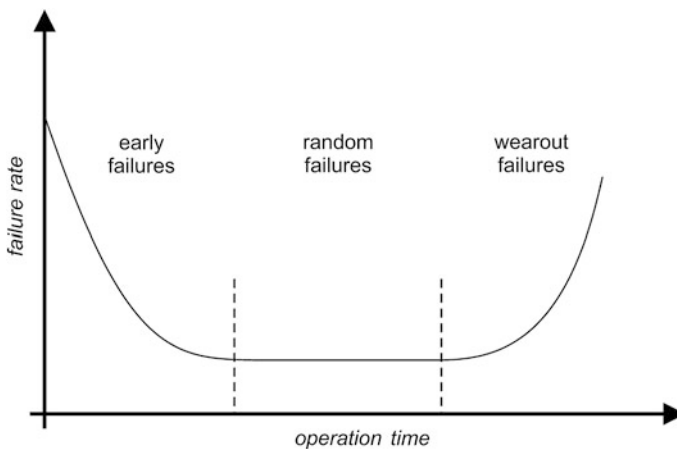


Fig. 2.15 Bathtub curve describing failure probability of electronic equipment

This curve predicts the end of a product's life during one of three different periods [30]:

- A high initial failure probability with a subsequent decline of failure rate. The term “infant mortality” refers to the first observation of this bathtub-like behaviour in human life expectancy [31].
- A low constant failure probability during the “useful life” of the product.
- An increase in failure probability occurs due to wear-out and its onset typically defines the usual operation time of electronic equipment.

It must be noted that this behaviour is not observed for all electronic systems, and that the applicability on a system level is at least questionable [32]. However, in the context of this textbook which focuses on power semiconductor devices and monolithic integration, the bathtub curve for modelling of device failures is well accepted. Early failures are routinely identified by burn-in tests. By measuring and modelling the wear-out region, it is possible to design electronic equipment for a specified operating lifetime with failure rates below 1 ppm (parts-per-billion). Moreover, doing so allows for the prediction of expected failures in the field. This is particularly important for markets where excessive failures cannot be tolerated (spaceflight) or preventive repair must be performed due to safety regulations (automotive). Of course, other markets are not as demanding of highly reliable equipment, e.g. consumer applications.

In microelectronics, device failure follows a Weibull failure distribution [33], which is a monotonic function. In order to apply the Weibull theory to the non-monotonic bathtub function, different modifications of the classical Weibull equation have been proposed [34].

2.3.5 Time-to-Market

In fast evolving markets like the mobile communications sector, the ability to be the “first to deliver” can make the difference between making a profit or making a loss. Therefore, time-to-market is an important factor when implementing new designs. Generally, development cycles for integrated circuits are more time consuming when a new design needs to be fabricated and tested. This is particularly true for RF amplifiers, where redesigns are frequently necessary to keep up the pace [21]. Under these conditions, where fully integrated System-on-Chip solutions become rapidly outdated, it can be favourable to have a solution with different sub-circuits where key components can be more easily changed. In contrast, wireless LAN applications or data transmission subsystems (e.g. using Bluetooth) are well established and do not readily change. Generally spoken, the benefit of a fast production ramp-up with previous engineering runs, the capability of using parts of previous designs and the availability of excellent modelling tools for all kinds of applications have turned the implementation of integrated circuits into a fast time-to-market approach.

2.3.6 System Cost

From an economic perspective, cost is a key factor when designing new systems. The cost issue is twofold in nature: The first consideration is capital expenditures (CAPEX) which relates to the installation price for the customer. This leads to careful calculation of fabrication, packaging and assembly costs necessary to derive cost-efficient solutions. These calculations then give a first indication on the feasibility of monolithic integration of power electronic systems. Unfortunately, there are other risks that cannot be easily converted into monetary considerations. For example, the implementation of a more reliable technology could be feasible even if it is more expensive. To this respect it should be noted that the costs for additional rework or service in the field are often difficult to estimate for companies along the whole value chain. Moreover, a reliable measure beyond previous experience within the company for customer satisfaction or recalls often does not exist. The second consideration is operational expenditures (OPEX) which contains the costs for operating the equipment. These recurring costs are particularly relevant in systems which consume a lot of energy or that are expensive to repair, e.g. in down-hole drilling [35].

Most conventional power electronic systems which operate in the range of up to 100 W could be integrated using smart-power ICs. However, the feasibility of doing so strongly depends on these economic considerations. Even though smart-power ICs achieve a higher reliability than circuits assembled from discrete devices, it is argued that the partitioning of logic, memory and power devices within a smart-power IC must be suitable to warrant integrated circuit design. If the additional cost for packaging and assembly still favours a lower cost for a discrete system, the monolithic integration of this particular circuit will usually be discarded [5]. Taking this to the extreme, monolithic integration of a drive inverter for an electric car using LDMOS transistors for the power switches is currently not cost efficient. This is, however, not so say that such a drive inverter does not employ smart-power ICs in the form of gate drivers etc.

2.3.7 Switching Frequency

For power electronic systems, an increase in switching frequency allows for smaller passive devices (e.g. inductance of a DC-DC converter). Given that switching frequency is typically limited by the parasitic components of the packaging and assembly techniques and not of the power switches themselves, it can be conceived that a high switching frequency can be achieved by monolithic integration in smart-power ICs. While the operation at RF frequencies is not of relevance when designing energy conversion circuits, there is a clear trend observable towards higher operating frequencies in order to reduce the size and weight of the electronic system.

A significantly stronger strive for increased operating frequencies holds true for radio-frequency applications where overall system performance strongly depends

on the choice of a suitable amplifier design. This development is also driven by military applications, where higher operating frequencies enable secure and uninterruptable communication.

2.3.8 Ruggedness

Finally, ruggedness determines the systems capability to withstand unexpected operation conditions. For example, these may arise from supply voltage fluctuations due to lightning strikes or a short-circuited load from a failing electric engine. In order to prevent excessive damage, these faults have to be detected and the electronic equipment must be quickly switched to a self-protection mode. A rugged system which is capable of surviving these kinds of faults requires both fast intelligent control circuitry and power devices that are not destroyed between the occurrence and detection of the fault.

2.3.9 Comparison of Requirements

The correlations between these requirements for power electronic systems and radio-frequency broadcasting equipment and their relevance for different applications are summarized in Table 2.1.

Table 2.1 Relevance of properties for power electronic systems and radio-frequency broadcasting equipment and their relevance depending on selected markets

<i>Power electronic systems</i>				
	Automotive	UPS	Consumer	Industrial
Cost	Very high	High	High	High
Size	High	Low	Low/Medium ^a	Low/Medium ^a
Efficiency	High	High	Medium	High
Frequency	Low	Low	Low	Low/Medium ^a
Time-to-market	Medium	Medium	Very high	High
Reliability/Rugged.	Very high	Very high	Medium	Medium/High ^a
<i>Radio-frequency broadcasting equipment</i>				
	Base station	Mobile phones	Office/Business	Aerospace
Cost	High	High	High	Medium
Size	Medium	High	Medium	Low/High ^a
Efficiency	Medium	High	Medium	Medium
Frequency	Very high	Very high	Very high	Very high
Time-to-market	High	Very High	High	Low
Reliability/Rugged.	High	Medium	Medium	Very high

^a depending on application

These requirements need to be considered when designing a competitive power electronic system. However, a significant proportion of these requirements depend on the particular market a system is designed for. Similar solutions may have different constraints coming from the customer base across countries (national customs and trends), competition and legislation (laws and regulations).

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