Chapter 2

System Quality Indicators

The integration of systems on a chip, has led to a revolution in the electronic industry. Large, complex system functions can be integrated in a single IC, paving the road to many battery powered portable applications like the cellular phone, wireless products, MP3 players and so on. The constant drive to improve these applications and to include extra features has enormously increased the pace with which new generation portable products are introduced on the market. Keeping its main function, extra demands are put on the system realizing this function. Smarter integrated system solutions, which are cheaper, smaller, more power efficient, robust to interference, more flexible, etc. are required. In this chapter these additional system requirements are captured in five quality indicators which indicate the quality of the integrated system, and which help to structure the analysis complex systems. The five quality indicators used are: accuracy, robustness, efficiency, flexibility, and emission. The system and its quality indicators are presented in Sects. 2.1 and 2.2 respectively.

In Sect. 2.3 the quality indicators are used to motivate why it can be advantageous to shift analog functionality into the digital domain which implicates the need for high dynamic range and high bandwidth analog-digital interfaces. In Chap. 3, the quality indicators are used to find a power efficient receiver architecture for use in a mobile phone. The influence of system partitioning on the quality indicator requirements of the analog-digital interface used in such receiver is postponed to Chap. 4. The quality indicators are used to determine the quality of the analog-to-digital interface in Chaps. 5 to 8. In a later stage in this book (Chaps. 8 and 9), the quality indicators are used to compare the analog-to-digital interfaces presented in this book to the quality of analog-digital interfaces presented in literature with the help of a benchmark. In this benchmark, the same or similar analog-digital

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interfaces are compared, on their quality indicators as these indicators can be a key differentiator to a customer.

2.1 The System Function and Its In- and Outputs

A system could be defined as a group of interacting, interrelated, and interdependent elements executing a function. A system function has one or more input(s) X, which are processed in some way by the system function F, yielding one or more output(s) Y. This is schematically shown in Fig. 2.1. The system inputs

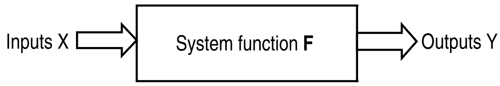

Figure 2.1: *System function with its inputs and outputs*

can be sub-divided in 2 categories, namely the primary inputs and the secondary inputs. The primary inputs are the wanted inputs, which have to be transferred by the system to the wanted outputs, a process which is called the primary process. The secondary inputs are inputs, which are unavoidable in some way, when implementing the system.

The secondary inputs are split up in 3 categories:

- Resources
- Outside world influences
- System interface

The first category describes the resources that are required for the systems' primary process (e.g. power source, material, design effort). The second category comprises the outside world influences, which describe inputs imposed by the outside world onto the system and can degrade the quality of the primary process (e.g. temperature, interference, manufacturing imperfections, noise). The last category represents inputs, which are required by the user or the system itself, to adapt and change the properties of the primary process to the current system application (e.g. volume control, or tuning function). The secondary inputs are shown in Fig. 2.2. The outputs of the system can also be sub-divided in the primary and secondary categories. The primary output is the output the system was designed for, the wanted output. A secondary output is an output, which was not

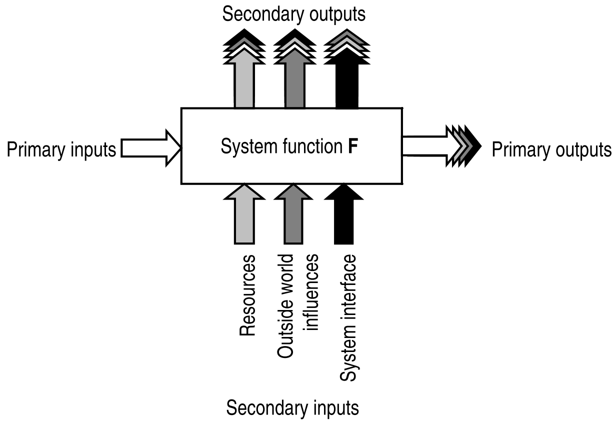

Figure 2.2: *System with its primary and secondary inputs and outputs*

intended to be an output of the system function, like the heat or interference generated by the system. The primary output might be a function of the secondary inputs. Next to that, the combination of primary and secondary inputs might cause cross-correlated secondary outputs. The different in- and outputs are shown in Fig. 2.2. It is very likely that some of the cross-correlation factors of F are zero. Of course there is also wanted correlation between inputs and outputs, examples are: primary input to primary output, secondary system interface input to primary output.

2.2 System Quality

An ideal system has infinite accuracy, uses its resources 100% efficiently, is unaware of influences from the outside world and is re-usable for different applications. However, during the system implementation phase, it will show, that there are limits to the accuracy and efficiency the system can achieve, including flexibility turns out to have its cost, the system will be susceptible to the outside world, and the system will generate secondary outputs which might interfere with the system itself or neighboring systems.

To determine the quality of a system it is judged on several quality indicators, which are divided into five groups:

1. Accuracy
2. Robustness to secondary inputs
3. Flexibility
4. Efficiency
5. Emission of secondary outputs

The quality indicators will be explained by the following sections.

2.2.1 Accuracy

The accuracy is the precision with which the primary system function can be fulfilled. The accuracy or performance of the system is measured on the quality of its primary outputs, compared to the quality of the primary inputs, and is determined by system choices.

2.2.2 Robustness to Secondary Inputs

Another measure to judge the quality of a system is the systems' robustness. The outside world can distort the primary function of the system in some way due to implementation aspects. The more insensitive the system is for influences from the outside, the more robust the system is. Examples of outside world influences are temperature, humidity, interference, noise, force, process spread and material imperfections. A few examples of different measures to quantify the systems' insensitivity to the outside world are durability, reliability, reproducibility and portability (technology independence).

2.2.3 Flexibility

The flexibility of a system indicates the re-configurability, adaptability and scalability a system, to meet changing requirements, or circumstances. It measures the extent in which (parts of) the system function can be changed into different system functions, for instance with a different accuracy. An adaptable system has the ability to respond to a changing outside world. To be able to respond, the system needs inputs measuring the changes in the outside world. Scalability describes the ability to scale or trade system parameters to meet the requirements of the current system function application. A re-configurable system is able to change from one system function into another system function, by changing the order or position of the different sub-systems of the main system.

The requirements on the flexibility of a system are often identified by use-case studies. It makes an inventory of expected human behavior and the way a system is expected to be used. To make an inventory of use-cases, marketing research has to be done.

2.2.4 Efficiency

Efficiency indicates how economical a resource is spent. Important efficiencies are power and area efficiency, as nowadays feature rich, battery powered and portable applications require low power consumption and small form factor. Other relevant efficiencies are testability, re-useability and design effort.

Testability describes the ease with which the required system accuracy of a system can be verified after manufacturing. Re-useability describes the extent in which parts of the system can be re-used for other systems. Sub-system functions can be categorized in libraries with clearly defined input and output conditions. In this way new system functions can be created with of the shelve parts coming out of the library, decreasing time to market, and reducing maintenance of different products as they share parts from the same library. Design effort describes the effort to build the system and is a resource which should be spent with great care, as it is costly and scarce.

Benchmarking is used to quantify the efficiency of a certain system. In a benchmark different system implementations, which have the same or similar system functionality are compared on their efficiencies. The efficiencies are bounded by fundamental limits (like thermal noise, maximum technology speed and availability of man power), but as the implementation of a system has additional cost, the maximum system efficiencies achievable are determined by the current state-of-art.

2.2.5 Emission of Secondary Outputs

Another system quality indicator is the amount in which the system generates secondary outputs. It is important to make an inventory of the secondary outputs the system emits as these outputs can distort the primary process of the system itself, or the primary process of other systems. Examples are heat, and electrical and magnetic interference.

2.3 The Digital Revolution

The quality indicators presented in the previous section, make the introduction of digital circuitry in nowadays integrated system functions unstoppable. A digitally implemented system is greatly in line with the quality indicators as will be shown in the next section, something that is not so obvious for the same system function implemented with analog circuits.

The application of digital enhancements to system functions is numerous. Below several examples are given of systems, which use digital functionality to implement tasks, which are very difficult to implement with analog circuits, if possible at all.

- The reliability of wireless transmission of speech and video streams is greatly improved by the introduction of digital data transmission. The digital modulation techniques used in these wireless links are much more robust to interference than completely analog modulation schemes. Digital error correction algorithms further improve the reliability of the wireless link.

- In medical imaging applications an A/D converter converts the sensor outputs of medical imaging equipment into the digital domain. The digital signal processing following the A/D converter for example allows for the construction of 3D images of the human body, leading to a diagnosis of better quality and potentially a longer life.

- A digital photo camera turns something visible into a digital representation using a photo sensor and A/D converter. After transferring the data to a PC, further image processing and retouching (like red-eye reduction) can easily be done in software.

The digital world is penetrating daily life everywhere. But it is not only the digital processing, which facilitates this increased quality of life and number of features; an interface is required between the analog and digital world. Although the outside world is analog, it is seems much easier to do advanced signal processing in digital hardware or software. It must be noted though that this shift from analog to digital signal processing, does not come for free and is bounded by the performance-cost ratio of A/D and D/A functions and by the speed limits of the technology the digital processing is made in.

2.3.1 The Analog-Digital Interface

Because the outside world is still analog and the processing is preferably done digitally, the introduction of analog-to-digital and digital-to-analog converters has been inevitable. Figure 2.3 shows a generalized implementation of a system function which has been (partly) digitized. From the figure it is evident that the quality of the A/D and D/A converters used in the signal path can be a quality determining factor in the overall system function. This opposes challenges on the design of the A/D and D/A converters. The more our world is captured digitally, the more we must convert from analog to digital and reconstruct from digital to analog, which implicates a trade-off between the amounts of analog and digital functionality and their implementation cost. The system of Fig. 2.3 is split into a receiver, a process-

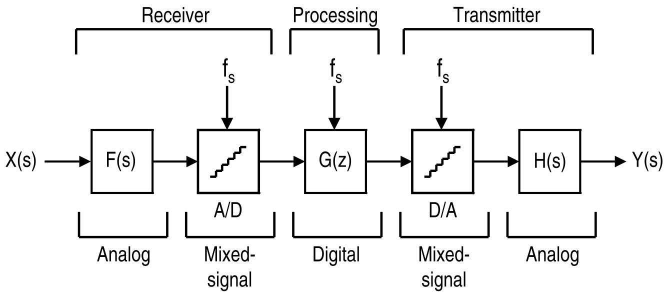

Figure 2.3: *Partially digitized system*

ing unit and a transmitter. The receiver receives an analog input X from a sensor, e.g. a microphone, a temperature sensor or an antenna. X is conditioned by F, which can include both gain and filtering, such that it most efficiently fits the input DR of the ADC. The ADC converts the analog input signal into its digital representation at a clock rate f_s. In the digital domain G represents the required digital signal processing which implements the task which is more efficient or powerful in digital hardware, or maybe even software. The output of the processing unit is connected to a D/A converter, which outputs the analog signal, which again is conditioned to the right amplitude and frequency content, yielding the desired output Y.

The more of the analog functionality represented by F and H is shifted into G, the more demands will be put on the A/D and D/A converter. This requires a system optimization which leads to realistic A/D and D/A converter requirements, which are in line with what is dictated by a benchmark of converters with state-of-the-art performance. This process will be described in Chap. 4.

Before going into the converter function, first it will be motivated why it is advantageous to replace as much as analog functionality by digital functionality. This is done in the next section, where digital functionality will be tested for its compliance to the quality indicators.

2.3.2 Digital Systems and the Quality Indicators

The advantages of digital signal processing compared to analog signal processing are clear. Once in the digital domain, the signal processing is much more powerful, and advanced features can be added in the signal processing path much easier. In this section the match between digital circuits and the quality indicators will be explored.

2.3.2.1 Accuracy

One of the primary advantages of digital circuits is the accuracy of digital circuits is 100% when operating well within the noise margin [5] and below the maximum speed of the technology. The maximum switching frequency of the technology chosen sets an upper bound for the sample frequency that can be used for the digital processing unit. If digital circuits are designed on the edge of the speed boundary of the technology and are processed in a slow technology corner, timing errors might occur leading to faulty outputs.

For analog circuits the accuracy analysis is much more difficult. The accuracy of the analog circuits is much more dependent on bias conditions and transistor parameters. Furthermore, once introduced, the offset, noise and distortion introduced by the analog circuits accumulates along the signal path, whereas in digital circuitry the accuracy is independent of transistor offset, distortion, circuit noise and interference, when operating well within the noise margin and below the maximum technology speed.

Because digital circuits are 100% accurate within the noise margin, they can be captured in a high level descriptive language. The mapping of the VHDL code functionality on the functionality extracted from the layout of the digital system normally is 100% when the digital circuits operate well within the maximum technology speed and noise margin. The maximum achievable accuracy is set by the sample frequency of the digital system, and the number of bits used for the calculations. If the required accuracy is proven by simulation, the hardware implementation of it will show exactly the same performance, under ideal outside world circumstances.

2.3.2.2 Robustness

The noise margin and maximum technology switching speed of digital circuits are subject to outside world influences, like process spread, process corners (slow, typical and fast processing), power supply variations (typical $+/-10\%$ of the nominal technology supply voltage), temperature (typical -40 and $125°C$). To characterize the influences of these conditions on the noise margin and speed of the technology, several standard digital cells are exposed to these conditions. The outcome of this characterization can than be generalized to define the performance of the technology. At the end of the design trajectory of a digital system, timing verification is done to verify if the accuracy is guaranteed by the system when exposed to these conditions. The extraction of the noise margin from the characterization of different digital cells, will lead to a general substrate, power supply and decoupling strategy.

For analog circuits a generalization of the design strategy is much more difficult. As the errors introduced by the outside world influences mentioned above accumulate along the signal path.

Due to the robustness of digital systems, they are almost push-button portable to newer technologies, which adds more flexibility to the system. Once available in VHDL code, the layout of a digital system can be ported from one technology to another in only limited amount of time, with a high degree of automation.

Although in the discussion above digital circuits seem very robust, the technology scaling of digital circuits predicts that interference within the digital system is an increasing threat. As the accuracy in lithography scales with s_T, wires are closer to each other, increasing mutual crosstalk. Furthermore the impedance of supply lines is increasing, which together with an increase of the current density per area increases the supply bounce. With the increasing number of switching transistors per area the dI/dt increases per area which causes the ground bounce to increase. Next to that the noise margin will become smaller as supply voltage and V_T are decreasing. This means that shifting analog functionality into the digital domain does not come for free, and noise margin, supply and substrate bounce, and decoupling strategy will become more and more important. As in this book the digital circuits which are used to replace the analog functions are comparably small in area, the (influence on the total digital) interference problem is only small.

2.3.2.3 Flexibility

As the performance overhead in the noise margin of digital circuits allows for a high abstraction level description (like VHDL) of digital systems, the flexibility potential of digital circuits is enormous. As analog design is mostly custom design it is much more difficult to make flexible. Moreover, adding flexibility to analog circuits introduces parasitic behavior which can even limit the maximum achievable accuracy of the analog circuit.

The VHDL code describing a digital system can be set up in a scalable way by using parameterization, to be able to program the systems' performance in line with the current application requirements. If the VHDL code describing a digital sub-system is set-up in a scalable way, with clearly defined input and output conditions, the main system function can easily be re-configured to a different system function re-using sub-system functions in a different way or order. A digital system function can be made adaptable to changing outside world circumstances, by reprogramming of the coefficients of the input-output matrix defining the system. To be able to respond to changes in the outside world, the digital system should be supplied with inputs which represent the changes in the outside world.

2.3.2.4 Efficiency

The power consumption of digital circuitry is related to $P = C \cdot V_{supply}^2 \cdot f_s$. As V_{supply} scales with s_T (for constant field scaling [4]), and C also scales with s_T, the consumed power of a digital circuit switching at a constant f_s scales with s_T^3 (for constant voltage technology scaling, consumed power scales with s_T). This makes it attractive to shift analog functionality in the digital domain, because power consumption of analog circuits[1] at best remains constant when scaled into to deep submicron technologies.

The area of digital circuitry scales with s_T^2 as the minimum gate length of the smallest transistor that can be used in logic cells, scales with s_T. As with power, the area of analog functions at best remains the same when scaling an analog function into deep submicron technologies. Looking into the future, the scaling of digital systems in deep submicron technologies shows promising area and power advantages compared to the scaling of analog systems.

[1] Note that the focus of this book is on A/D converters. For other analog circuits like for example oscillators, technology scaling also provides some advantages. The exact analysis of these advantages however is without the scope of this book.

Although difficult to measure, the effort to design a certain function (e.g. a channel filter) with analog circuits is more time consuming compared to the design of the same functionality with digital circuits. Moreover, for digital circuitry the generation of layout is automated to a great extent. Analog layout often still is handcraft, for sure for high-end analog functions. For analog functionality some design and layout automation methods have been published ([6, 7] and many more), but are often limited to a specific analog function.

To test high performance analog functionality, expensive equipment is required to be able to generate and qualify the analog signals going in or coming out of the analog block respectively. Complicated and difficult to generalize tests with high quality input signals have to be carried out, to be able to completely check if the analog system achieves the required performance under all conditions. The qualification of the system accuracy is difficult because it is degraded by the noise, distortion and interference introduced along the analog signal path.

In digital circuits test chains are introduced to verify the systems' performance. A pattern generator generates input vectors which sufficiently cover the system functionality. The output vectors of the system are either wrong or right. In general the testing of digital systems is much easier as the behavior of digital circuits is much more predictable, and the results are easier to interpret.

2.3.2.5 Emission

A drawback of digital circuits is the fact that they are notorious for their emission of interference to supplies and substrate. This asks for a good supply, substrate, and decoupling connection strategy. This way the interference generated by the digital system can be kept under control, and is no threat to the surrounding systems on the same chip or in the same application. As nowadays deep submicron technologies have a deep N-well technology option, at least the substrate bounce of digital circuits can be better shielded from other systems on the same chip.

2.4 Conclusions

The design of a system is not only about system functionality but also about system quality. The wish to create more efficient and flexible systems, insensitive to outside world influences, comes from the drive to get products faster to the market, at a lower price, and including more features in a smaller volume, making products more differentiating. This asks for the introduction of quality indicators, with which the quality of a system can be judged. In this chapter five quality indicators have been presented, which are: accuracy, robustness to secondary inputs, flexibility, efficiency, and emission of secondary outputs. Throughout the book these are used to judge a system's quality. Quality indicator emission is outside the scope of this book. The quality indicators are shown in Fig. 2.4. In Chap. 1

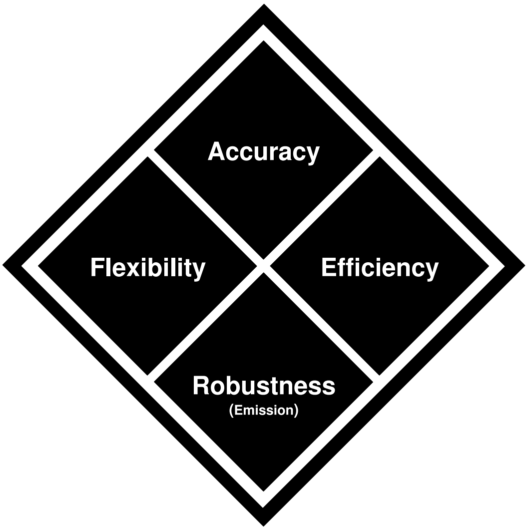

Figure 2.4: *The quality indicators introduced in this book*

it was shown that Moore's law predicts that if a digital function is ported to the next technology node, clear technology advantages like area scaling (s_T^2), increase of power efficiency ($1/s_T^2$) and speed increase ($1/s_T$) become available. Furthermore, as digital circuits have built-in performance overhead in their noise margin, a high degree of automation to do the port to the next technology node is possible. Next to that, digital circuits can be made re-configurable very easily as they are captured in a descriptive language like VHDL.

For a fixed analog function the area scaling in the next technology node is not that evident. The change of analog design parameters like power supply, V_T, etc., ask for a re-design of all the analog circuit blocks when going to the next technology node. This reduces the portability of these analog blocks and thus increases time-to-market. Next to that, analog circuits are much more difficult to make re-configurable.

Therefore, it is advantageous to increase the digitization of a system as digital circuits score high on the quality indicators. In this book the digitization process

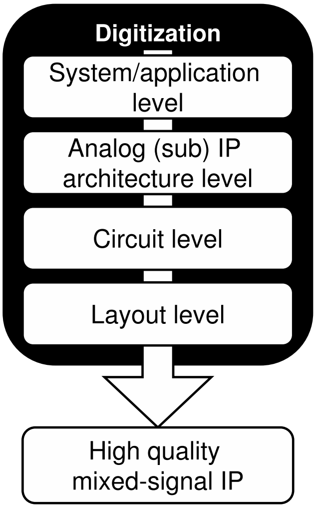

Figure 2.5: *Digitization of an analog system at different levels*

will be carried through four different abstraction levels, displayed in Fig. 2.5. At system level, this calls for an early introduction of the A/D and D/A conversion in the system pipe-line, which shifts the signal processing as much as possible into the digital domain. Once in the digital domain, the systems' accuracy is only determined by the accuracy described in the VHDL code when operating within the maximum achievable speed of the technology and within the noise margin. This makes the system robust to outside world influences. In the digital domain the signal processing is more powerful, can be setup in a flexible way more easily and shows increased power and area efficiencies in newer technologies, being future proof. However, shifting more of the signal processing in the digital domain, higher demands are put on the DR and bandwidth requirements of the ADC. It is the challenge to trade off analog and digital functionality with the ADC DR to come to a realistic but competitive system solution.

At analog IP architecture smart circuit choices should be made to reduce the amount of critical analog functions and replace or assist them with digital circuits as much as possible.

At circuit level, the circuits should be designed such that the analog blocks can be built up by a limited amount of unit cells, like in digital circuits. Due to the simplicity of the analog unit cells, the analog library can be ported to a next technology node very quickly, as its optimization process can be done by using simulation scripts for the analog simulator.

At layout level, each unit cell out of the analog unit cell library is turned into a parameterized layout (p-cell layout). Once these p-cell layouts are available, the routing tool normally used to layout digital circuits can be used, which reduces time-to-market tremendously.

This way digitally assisted systems and circuits are created which score high on the quality indicators.

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